

Qspice - Device Reference Guide by KSKelvin

KSKelvin Kelvin Leung

Created on 9-5-2023
Last Updated on 2-23-2024

B. Behavioral Source

B. Behavioral Source : Instance Parameters

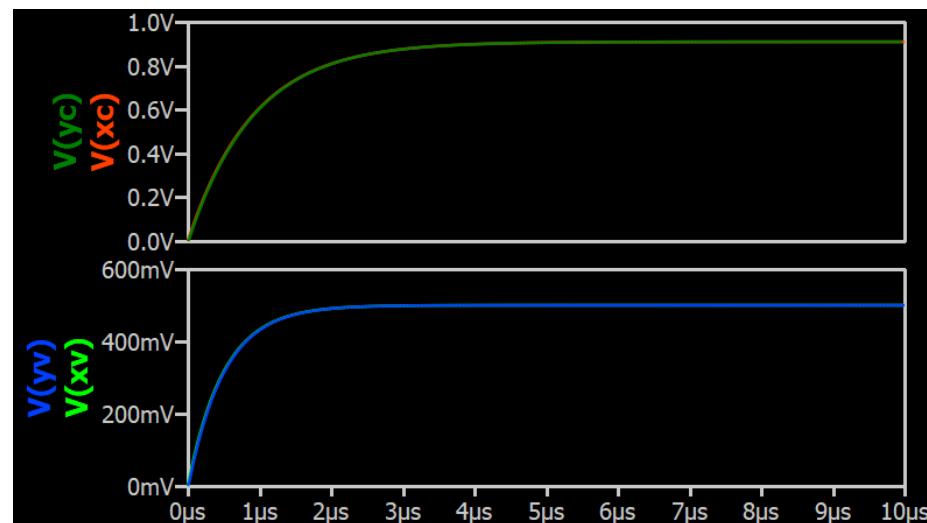
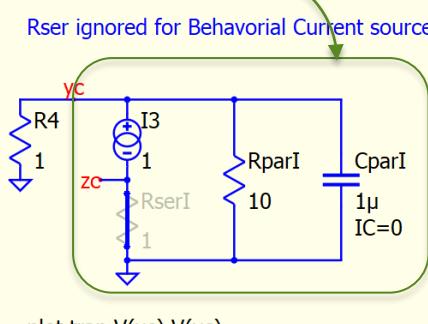
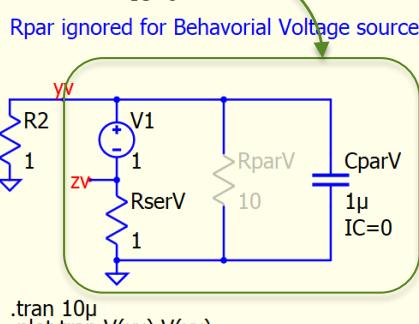
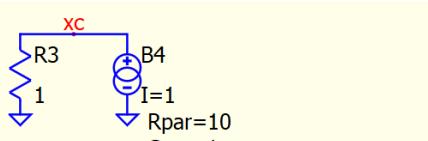
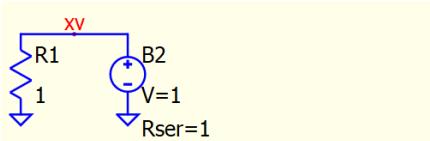
Behavioral Source Instance Parameters

| Name | Description | Units | Default |
|----------------|---|--------|-----------|
| CPAR | Parallel capacitance | F | 0.0 |
| I ¹ | Expression for current | A | (not set) |
| IC | Initial value | A or V | 0.0 |
| LAPLACE | Frequency dependence | | (none) |
| NORTON | Use a Norton equivalent for a behavioral resistance | | (not set) |
| R ¹ | Expression for resistance | Ω | (not set) |
| RPAR | Parallel resistance Ignore in V | Ω | Infinite |
| RSER | Series resistance Ignore in I and R (Norton) | Ω | 0.0 |
| SYNTHESIZE | Use the synthesized Laplacian circuit even for .AC | | (not set) |
| THEVENIN | Use the Thévenin equivalent for a behavioral resistance | | (not set) |
| V ¹ | Expression for voltage | V | (not set) |

B. Instance Params : Rser, Rpar and Cpar

Qspice : B Source - Rpar Rser Cpar in V and I.qsch

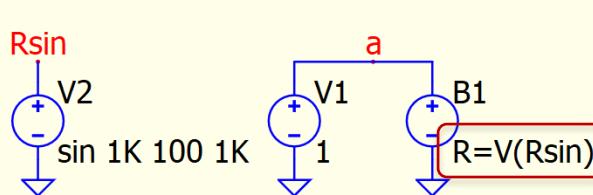
- Rser, Rpar and Cpar in Behavioral Voltage and Current Source
 - Behavioral Voltage ($V=<\text{expression}>$) : Only Rser and Cpar are active
 - Behavioral Current ($I=<\text{expression}>$) : Only Rpar and Cpar are active
 - I don't recommend to use Rser and Rpar in Behavioral Resistance as it will be very confusing depends on Norton or Thevenin equivalent
 - In this example, IC initial value is used to allow 0V or 0A for transient simulation. As behavioral source not have effect in .ac (except for Laplace), .tran is used to reveal these parameters characteristic



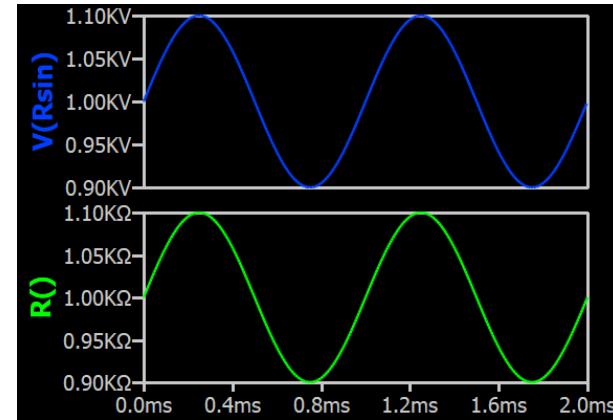
B. Instance Params : Behavioral Resistor

Qspice : B Source - Behavioral R.qsch

- Behavioral Resistor
 - Syntax : Bnnn n001 n002
 $R = <\text{expression}>$
 - Expression of resistance



```
.tran 2m
.func R() V(a)/I(B1)
.plot R()
.plot V(Rsin)
```

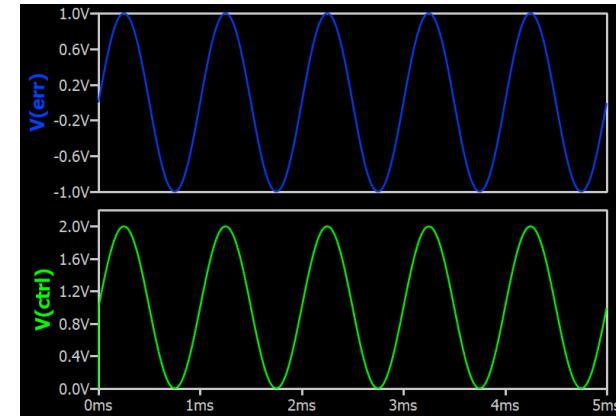
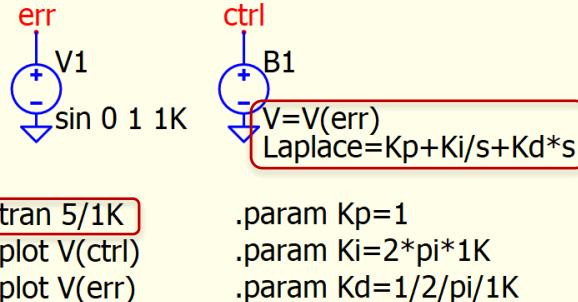


B. Instance Params : Laplace

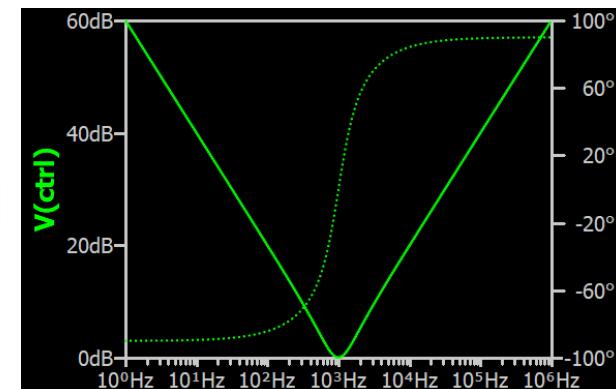
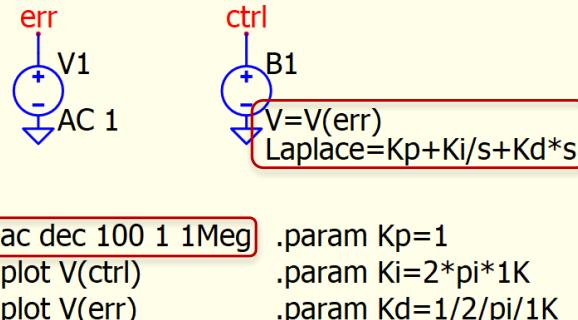
Qspice : B Source - Laplace (.tran).qsch | B Source - Laplace (.ac).qsch

- Laplace (.tran)
 - Laplace equation in B-source, by adding a new attribute Laplace=formula
 - In this simulation
 - $v_{ctrl} = \left(K_p + \frac{K_i}{s} + K_d s \right) v_{err}$
 - Laplace B-source support both transient (.tran) and ac (.ac) analysis

B-source with Laplace in .tran analysis



B-source with Laplace in .ac analysis



B. Function and Operators

HELP > Simulator > Device Reference > B. Behavioral Sources

Functions

| Name | Description |
|------------------------|---|
| abs(x) | Absolute value of x |
| acos(x) | arc cosine of x |
| arccos(x) | Synonym for acos() |
| acosh(x) | arc hyperbolic cosine of x |
| asin(x) | arc sine of x |
| arcsin(x) | Synonym for asin() |
| asinh(x) | Arc hyperbolic sine |
| atan(x) | Arc tangent of x |
| arctan(x) | Synonym for atan() |
| atan2(y,x) | Four quadrant arc tangent of y/x |
| atanh(x) | Arc hyperbolic tangent |
| buf(x) | 1 if $x > .5$, else 0 |
| ceil(x) | Integer equal or greater than x |
| cos(x) | Cosine of x |
| cosh(x) | Hyperbolic cosine of x |
| ddt(x) | Time derivative x |
| delay(x,y) | x delayed by y |
| delay(x,y,z) | x delayed by y, but store no more than z history |
| dlim(x,y,z) | x bounded by y which asymptotically starts to approach at y+z as a first inverse order Laurent series |
| exp(x) | e to the x |
| floor(x) | Integer equal to or less than x |
| hypot(x,y) | $\sqrt{x^2 + y^2}$ |
| idt(x,y,z) | Time integral of x with initial condition of y reset when $z > .5$ |
| $\int x \, dt$ ime + y | |

| | |
|----------------------|---|
| if(x,y,z) | If $x > .5$, then y else z |
| int(x) | Convert x to integer |
| inv(x) | 0. if $x > .5$, else 1. |
| limit(x,y,z) | Intermediate value of x, y, and z |
| In(x) | Natural logarithm of x |
| log(x) | Alternate syntax for ln() |
| log10(x) | Base 10 logarithm |
| max(x,y) | The greater of x or y |
| min(x,y) | The smaller of x or y |
| pow(x,y) | x^y |
| pwr(x,y) | $ x ^y$ |
| pwrs(x,y) | $abs(x)^y$ $sgn(x)*abs(x)^y$ |
| random(x) | Random number from 0. to 1. depending on the integer value of x. Interpolation between random numbers is linear for non-integer x. |
| sin(x) | sin x |
| sinh(x) | Hyperbolic sine of x |
| sqrt(x) | \sqrt{x} |
| table(x,a,b,c,d,...) | Interpolate x from the look-up table given as a set of pairs of constant values. |
| tan(x) | Tangent of x. |
| tanh(x) | Hyperbolic tangent of x |
| ulim(x,y,z) | x bounded by y which asymptotically starts to approach at y-z as a first inverse order Laurent series |

Operators grouped in reverse order of precedence of evaluation

| Operand | Description |
|---------|--|
| & | Boolean AND |
| | Boolean OR |
| > | True if expression on the left is greater than the expression on the right. |
| < | True if expression on the left is less than the expression on the right. |
| >= | True if expression on the left is greater than or equal the expression on the right. |
| <= | True if expression on the left is less than or equal the expression on the right. |
| + | Addition |
| - | Subtraction |
| * | Multiplication |
| / | Division |
| ** | ** / ^ Raise left hand side to power of right hand side. Same as '^'. |
| ! | Boolean not the following expression. |

Available Function in B source not listed

- Trunc(x) ; floor(x) ; int(x) : rounded down integer
- Rint(x) ; round(x) : rounded to nearest integer
- Ceil(x) : rounded up integer
- Ustep(x) : $x > 0 ? 1 : 0$
- Uramp(x) : $x > 0 ? x : 0$

Available Variable or Constant not listed in HELP

- Time : Simulation Time
- Temp : Temperature
- PI : 3.14159265358979323846
- E : 2.7182818284590452354
- K : 1.380649e-23 J/K
- Q : 1.602176487e-19 Coulomb

B. Function and Operators – delay(x,y) or delay(x,y,z)

Qspice : B Source - delay fix.qsch

- delay(x,y) or delay(x,y,z)
 - Delay(x,y,z) can reduce the amount of waveform memory that must be stored

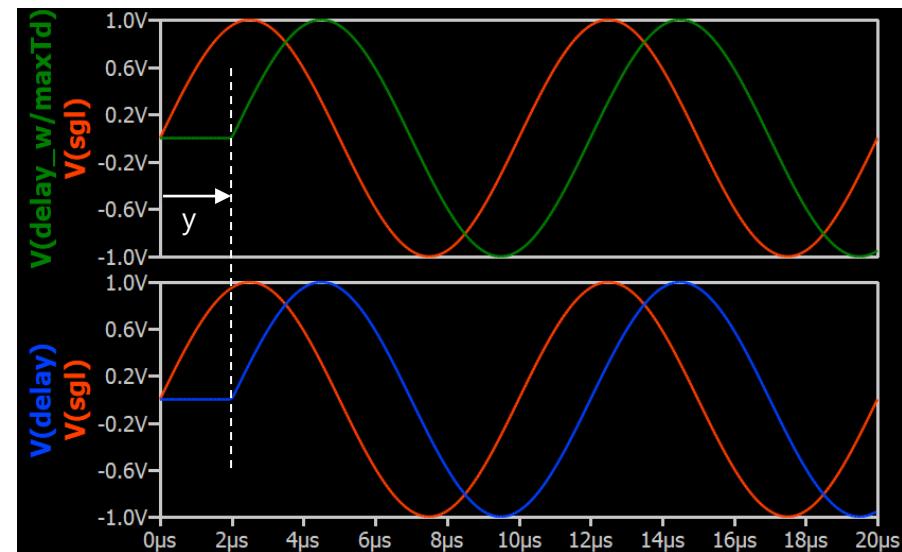
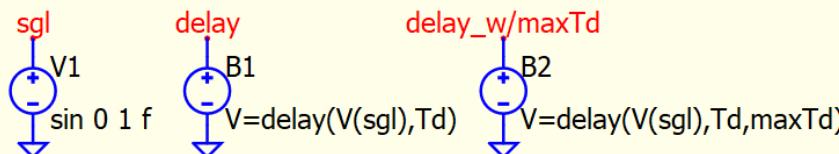
| | |
|---------------------------|--|
| delay(x,y) | x delayed by y |
| delay(x,y,z) ¹ | x delayed by y, but store no more than z history |

- y can be parameter and z must be fixed constant
- y must less than z or error will return

Syntax : delay(x,y) - x delayed by y

Syntax : delay(x,y,z) - x delayed by y, but store no more than z history

```
.param f = 100K  
.param Td = 2μ  
.param maxTd = 5μ
```

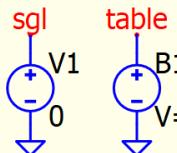


B. Function and Operators – table(x,a,b,c,d,...)

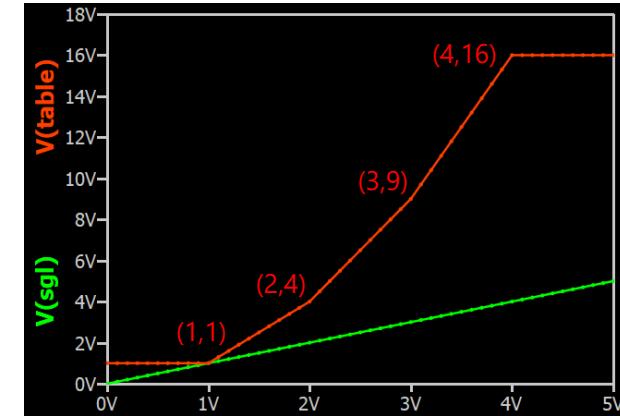
Qspice : B Source - table.qsch | B Source - table(.func).qsch | B Source - table(attribute).qsch

- Table(x,a,b,c,d,...)
 - Interpolate x from the look-up table given as a set of pairs of constant values
- Setup a table
 - As table may contain a lot of data points, for visual purpose in schematic, user can consider
 - Each pair of (x,y) data uses a bracket
 - Break table with 2nd or more attribute
 - Use .func to define a table

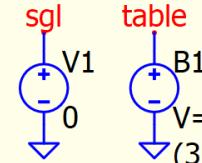
Basic table setup in B-source



```
V=table(V(sgl),1,1,2,4,3,9,4,16)  
.dc V1 0 5 0.1  
.plot V(sgl) V(table)
```

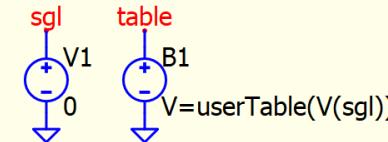


Define a table with 2nd or more attribute



```
V=table(V(sgl),(1,1),(2,4),  
(3,9),(4,16))  
.dc V1 0 5 0.1  
.plot V(sgl) V(table)
```

Define a table with .func and with + line break



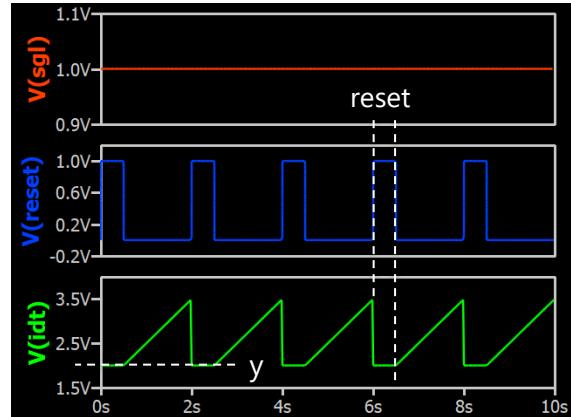
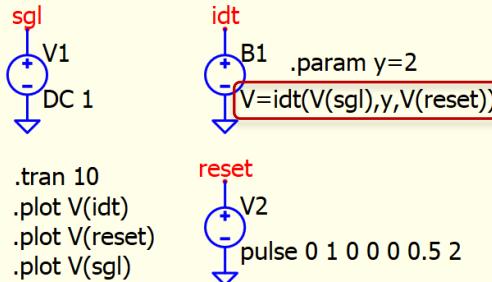
```
.dc V1 0 5 0.1  
.plot V(sgl) V(table)  
.func userTable(x) table(x,(1,1),(2,4),  
+(3,9),(4,16))
```

B. Function and Operators – Integral idt(x,y,z)

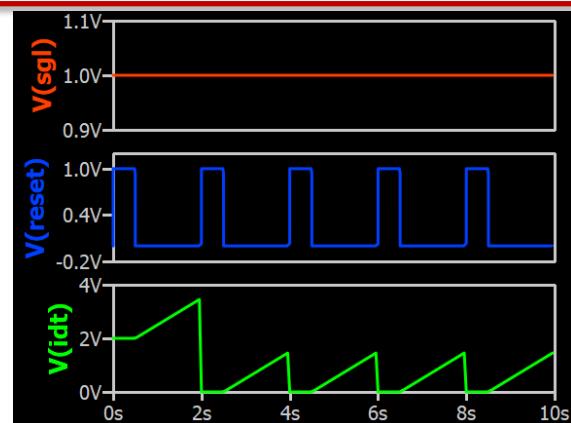
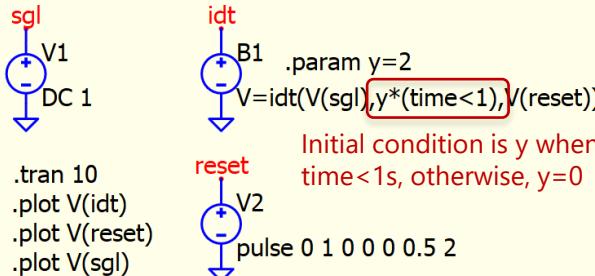
Qspice : B Source - idt.qsch | B Source - idt (y-conditional).qsch

- $\text{idt}(x,y,z)$
 - Time Integral of x
 - $= \int x dt + y$
 - y is initial condition, which is the DC value during integral function is reset
 - z is to reset integral
 - Special technique for initial condition
 - If initial condition needs to be changed over time, conditional function can be used
 - User can also use voltage source to control initial voltage y over time

Syntax : $\text{idt}(x,y,z)$
Time integral of x with initial condition of y
reset when $z > .5$



Syntax : $\text{idt}(x,y,z)$
Time integral of x with initial condition of y
reset when $z > .5$

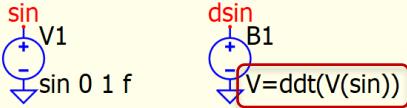


B. Function and Operators – Time Derivative ddt(x) and limit(x,y,z)

Qspice : B Source - ddt.qsch | B Source - limit.qsch

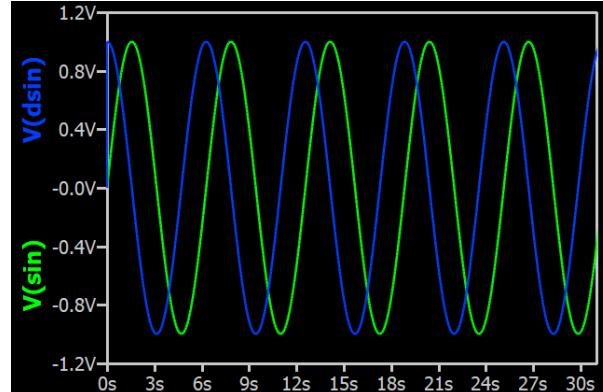
- $\text{ddt}(x)$
 - Time derivative
 - $= \frac{dx}{dt}$

Syntax : $\text{ddt}(x)$
Time derivative x

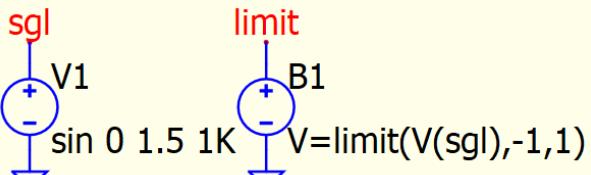


Formula
 $d(\sin(\omega t))/dt = \omega \cos(\omega t)$

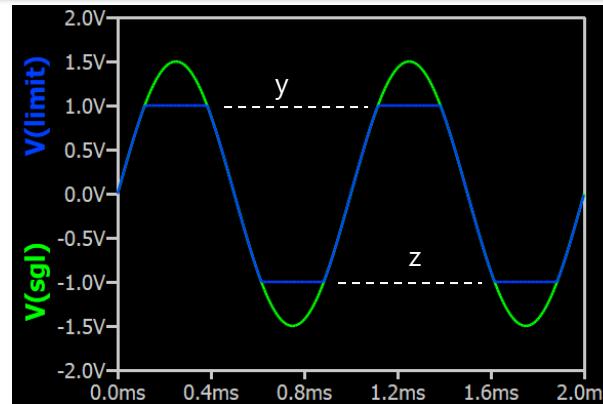
```
.param f=1/2/pi
.param omega=2*pi*f
.tran 5/f
.plot V(sin) V(ddsin)
```



- $\text{limit}(x,y,z)$
 - Intermediate value of x, y, and z



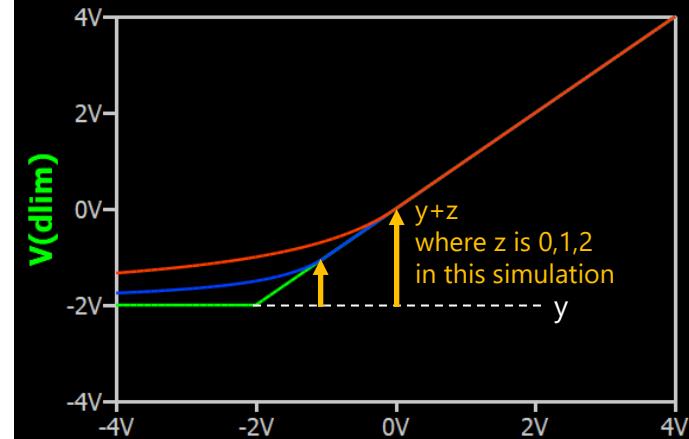
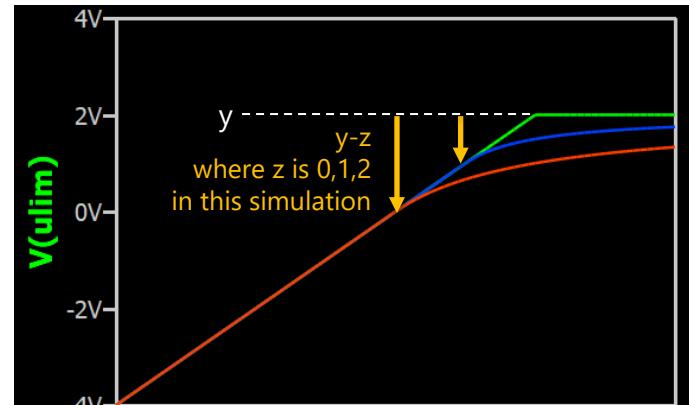
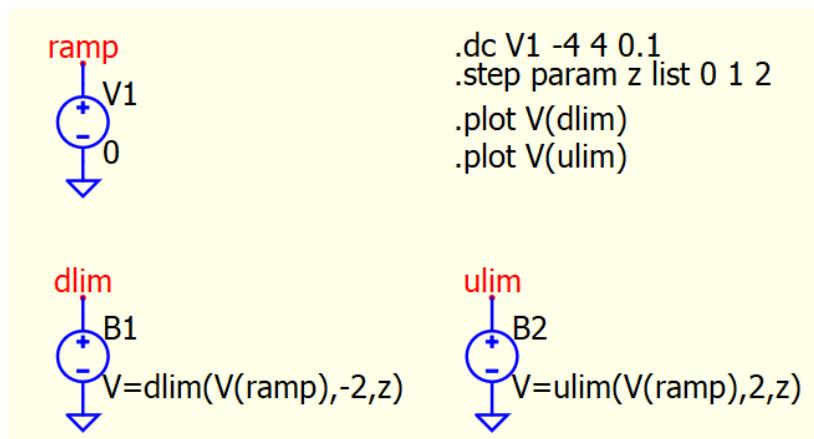
```
.tran 2m
.plot V(sgl) V(limit)
```



B. Function and Operators – dlim(x,y,z) and ulim(x,y,z)

Qspice : B Source - dlim ulim.qsch

- dlim(x,y,z) and ulim(x,y,z)
 - dlim(x,y,z) : x bounded by y which it asymptotically starts to approach at $y+z$ as a first inverse order Laurent series
 - ulim(x,y,z) : x bounded by y which it asymptotically starts to approach at $y-z$ as a first inverse order Laurent series
 - These functions are used for soft limit



B. Function and Operators – random(x) [Basic Concept]

Qspice : B Source - random (seed).qsch

• Random(x)

- Random(x) : Random number from 0 to 1 depending on the integer value of x
- This is pseudo random function which takes a seed and output a number "appears random"

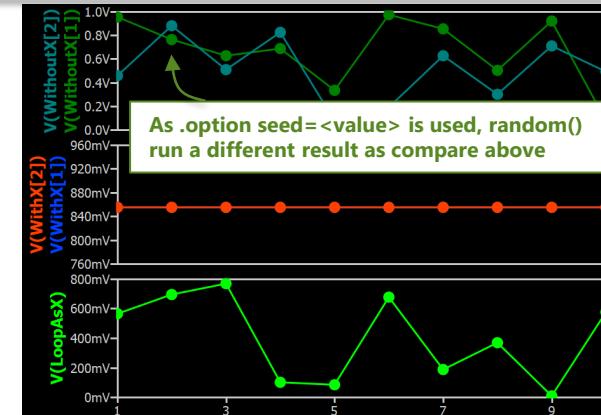
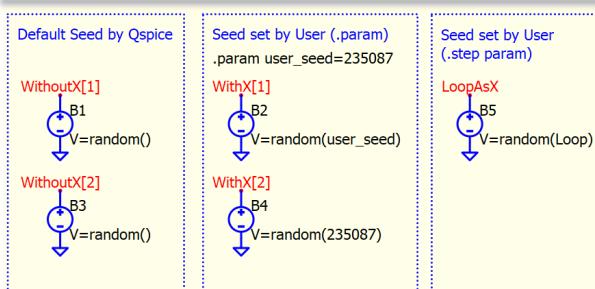
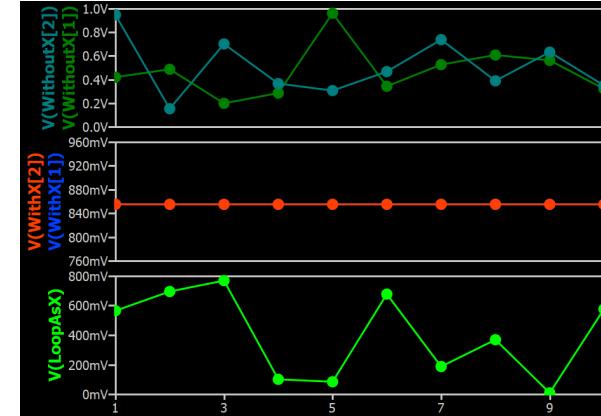
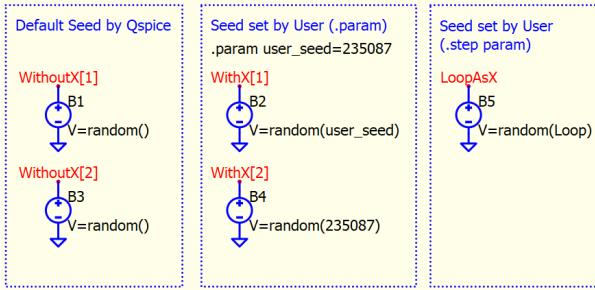
• Random()

- Seed is determined by Qspice
- If .option seed=<value> is used, user can assign an initial seed
- If .option seedclock is used, seed is from 10MHz clock and process ID, which appear random in every run

• Random(x)

- Seed is set by user
- Assign a fixed value (e.g. .param), or varying value (from .step param)

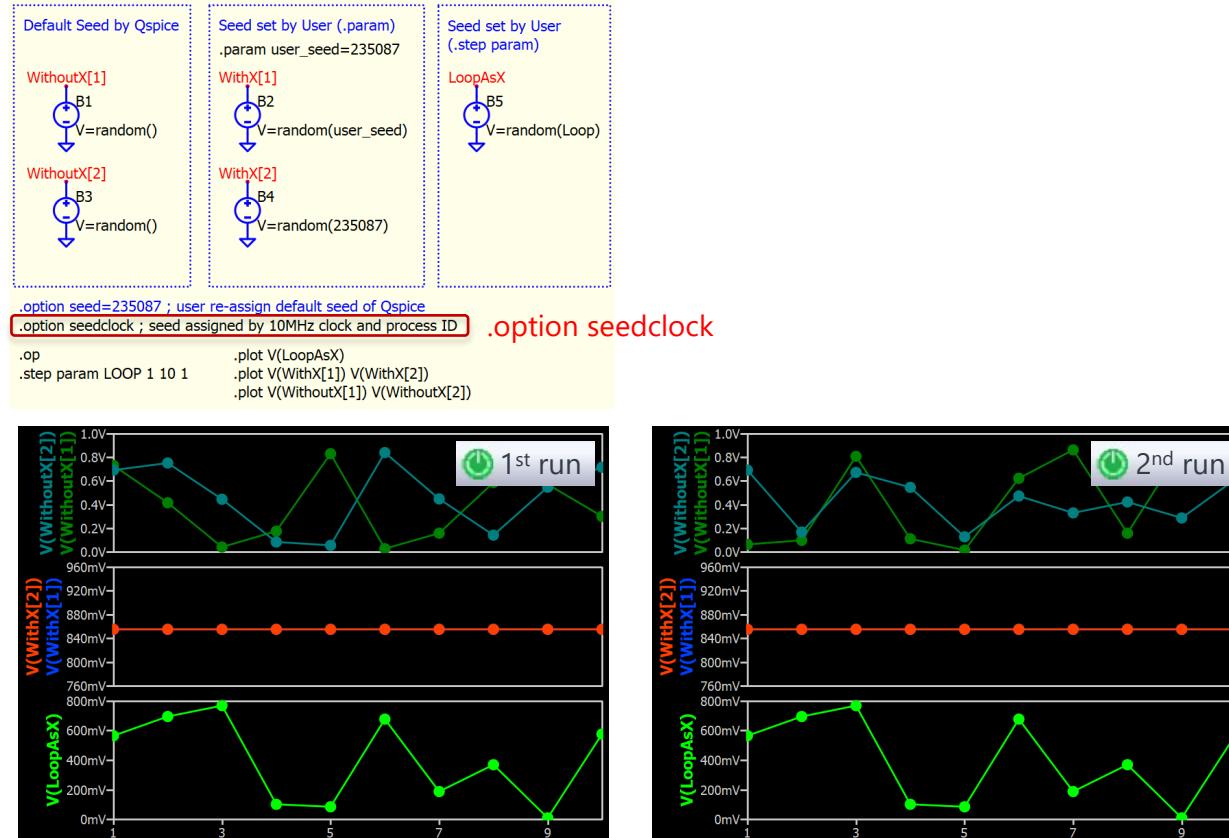
- These two examples run same results every time in Qspice as initial seed not be changed in each run



B. Function and Operators – random(x) [.option seedclock]

Qspice : B Source - random (seed).qsch

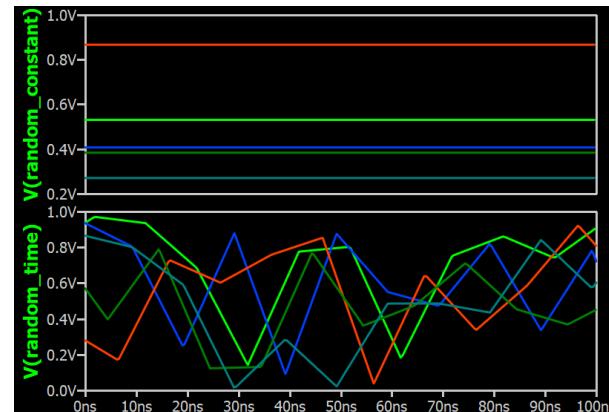
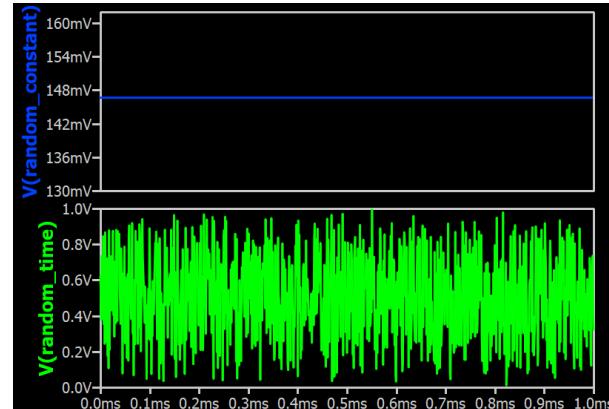
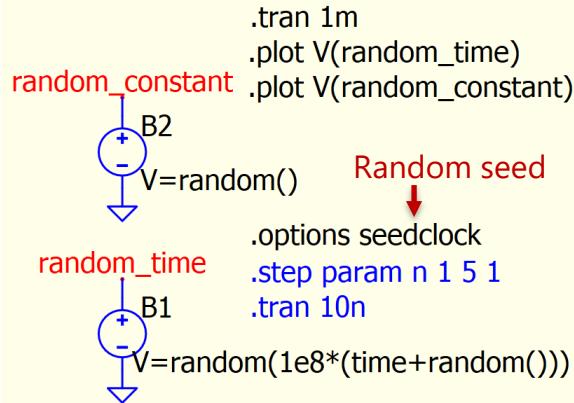
- Random(x)
 - .option seedclock
 - Initialize the random number generator with a 10Mhz clock and the process ID number
 - If seedclock is used, initial seed are different in every run
 - random() give different random pattern in every run
 - But random(x) with user defined seed and not be impacted



B. Function and Operators – random(x) [Random in .tran timestep]

Qspice : B Source – random (.tran).qsch

- Random(x)
 - Random number from 0 to 1 depending on the integer value of x
 - The one without arguments must be processed in the preprocessor (from Mike Engelhardt)
 - To create a random sequence in transient, x must change in each time step : i.e. $\text{random}(1\text{e}8 * \text{time})$, multiple time with $1\text{e}8$ is for x to be a large integer for random generation
 - For random run in each step, function can be
 - $\text{random}(1\text{e}8 * (\text{time} + \text{random}()))$



With **random(1e8*(time+random()))**, it allows random voltage also at 0s

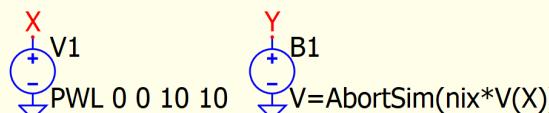
B. Function and Operators – AbortSim(x), variable/constant

Qspice : B Source - AbortSim.qsch ; B Source - Buildin Variable Constant.qsch

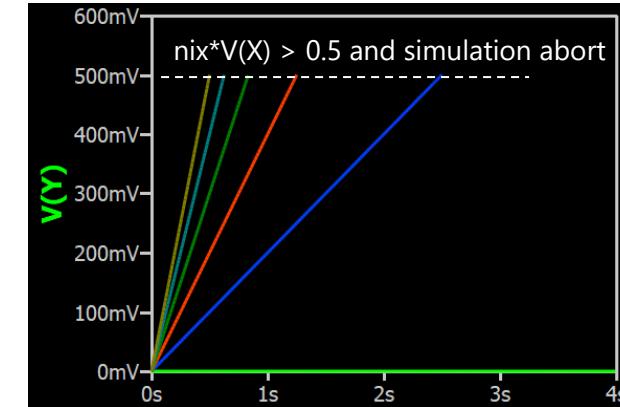
- AboutSim(x)

- To stop the current simulation from a behavioral source
- If $x > 0.5$: *abort simulation*
- else : *return x*
- The function works for .dc and .tran
- Refer to Ø-Device, MaxExtStepSize() for same feature but in .dll

syntax : AbortSim(double arg)
if arg > 0.5 : stops simulation and goes to next step (if any)
else : returns the argument

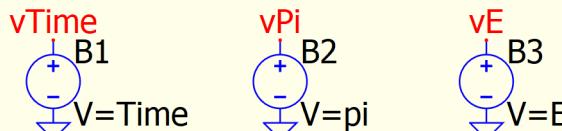


.tran 4
.step param nix 0 1 0.2



- Build-in Variable / Constant

- Time : Simulation Time
- Temp : Temperature
- PI : 3.14159265358979323846
- E : 2.7182818284590452354
- K : 1.380649e-23 J/K
- Q : 1.602176487e-19 Coulomb



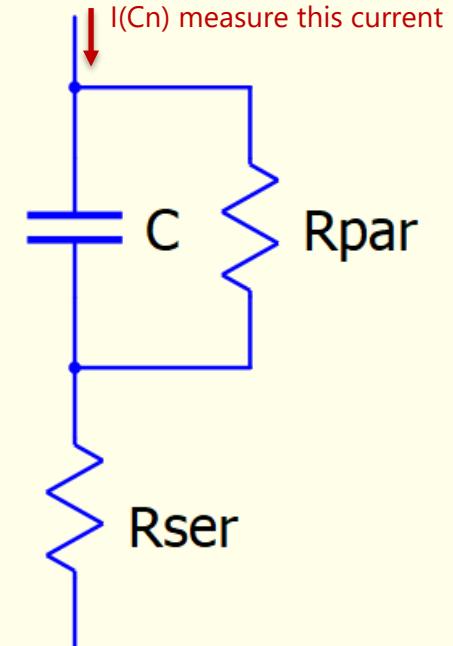
.tran 1

C. Capacitor

C. Capacitor Instance Parameters in Qspice HELP

| Capacitor Instance Parameters | | | |
|-------------------------------|---|-------------------------|---------------------|
| Name | Description | Units | Default |
| CAPACITANCE | Capacitance(not usually labeled) | F | 0.0 |
| CSAT | Capacitance asymptotically approached in saturation | F | 10% of CAPACITANCE |
| IC | Initial voltage on capacitor | V | 0.0 |
| L ¹ | Length | m | 0.0 |
| M | Number of identical parallel devices | | 1.0 |
| RPAR | Equivalent parallel resistance | Ω | Infinite |
| RSER | Equivalent series resistance | Ω | 0.0 |
| SATFRAC | Fractional drop in capacitance at VSAT | | 0.7 |
| TC | Polynomial temperature coefficient list | | 0.0 |
| TC1 | 1st order temperature coefficient | $^{\circ}\text{C}^{-1}$ | 0.0 |
| TC2 | 2nd order temperature coefficient | $^{\circ}\text{C}^{-2}$ | 0.0 |
| TEMP | Instance temperature | $^{\circ}\text{C}$ | Circuit temperature |
| TNOM | Temperature capacitance was measured(aka TREF) | $^{\circ}\text{C}$ | Circuit TNOM |
| VSAT | Voltage that drops capacitance to SATFRAC×CAPACITANCE | V | Infinite |
| W ¹ | Width | m | 0.0 |

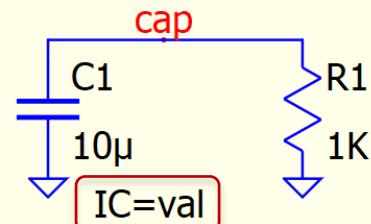
Rpar and Rser in C model



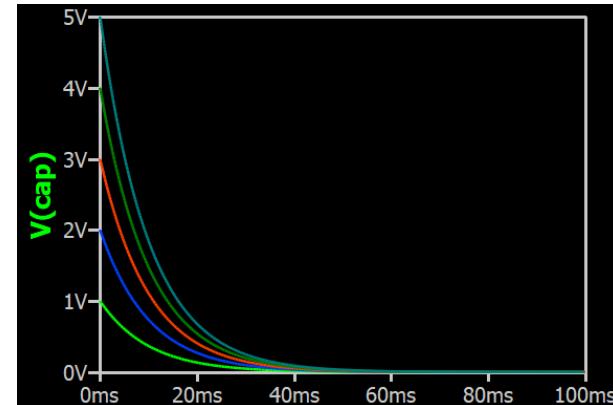
C. Instance Params : IC Initial Condition and TC Temp Coefficient

Qspice : Capacitor - IC.qsch

- IC
 - IC : Initial Condition
 - Default IC=0V
 - Use in transient analysis for initial voltage of capacitor at time=0s



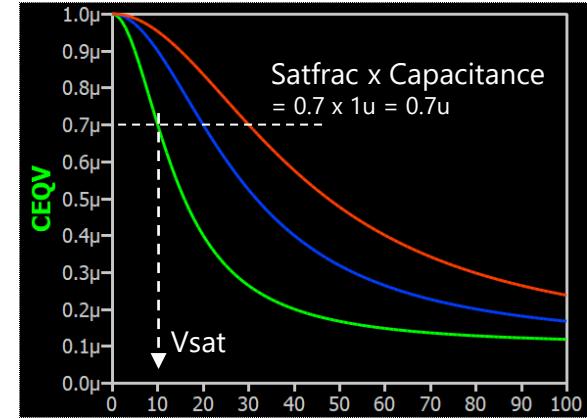
```
.step param val 1 5 1  
.tran 100m  
.plot V(cap)
```



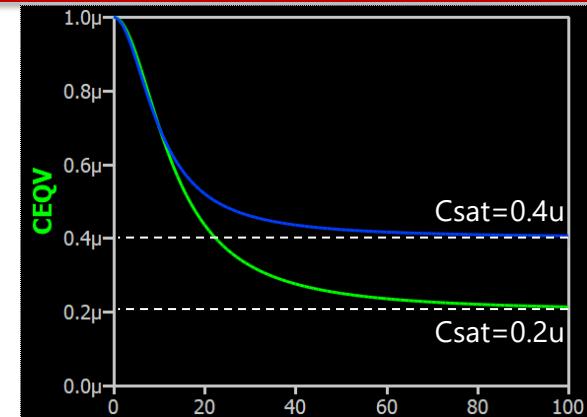
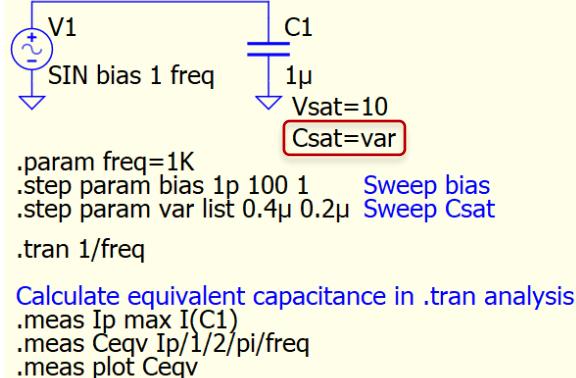
C. Instance Params : Vsat, Csat, Satfrac : For Nonlinear Capacitance

Qspice : C Capacitor - Vsat (.ac).qsch ; C Capacitor - Csat (.tran).qsch

- Vsat and Satfrac
 - Vsat : Voltage that drops capacitance to **Satfrac x Capacitance**
 - Satfrac : Fractional drop in capacitance at Vsat
 - **Default Vsat=Infinite (V)**
 - **Default Satfrac=0.7**



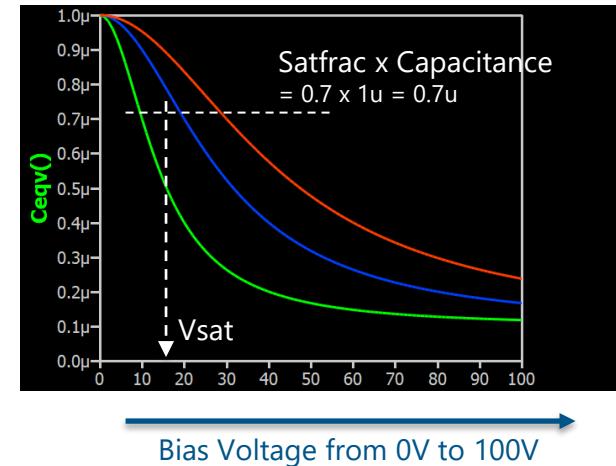
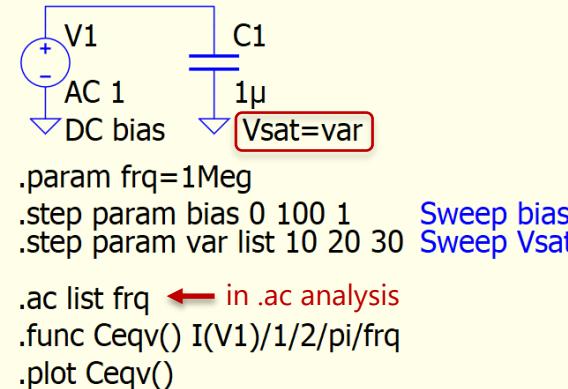
- Csat
 - Csat : Capacitance asymptotically approached in saturation
 - ** Vsat must be set to see its effect
 - **Default Csat=10% of C**



C. Instance Params : Replicate previous graph with .ac analysis

Qspice : C Capacitor - Vsat (.ac).qsch

- Vsat and Satfrac
 - Vsat : Voltage that drops capacitance to **Satfrac x Capacitance**
 - Satfrac : Fractional drop in capacitance at Vsat
 - **Default Vsat=Infinite (V)**
 - **Default Satfrac=0.7**



- Capacitance equation
 - $X_C = \frac{1}{\omega C} = \frac{V_c}{I_c}$
 - $C = \frac{|I_c|}{|V_c| \omega} = \frac{|I_c|}{2\pi f |V_c|}$
 - This formula is used to calculate equivalent capacitance (small signal model) at different capacitor bias voltage

C. Instance Params : Thermal Parameter

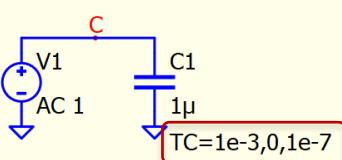
- Thermal Equation of Capacitor
 - $C = C_{nom} \times (1 + \sum TC_n (T - T_{nom})^n)$
 - Where T is operating temperature TEMP, which uses as `.temp`, `.dc temp` or `.step param temp`
 - Thermal Instance Parameter and equation relationship
 - TC : Polynomial of Thermal Coefficient where $TC = <TC1>, <TC2>, <TC3>, <TC4>, \dots$
 - $TC_n = TC_n$
 - $TC1, TC2$: 1st and 2nd order Thermal Coefficient
 - $TC1 = TC_1$ and $TC2 = TC_2$
- TEMP : Instance Temperature (Simulation Temperature of this capacitor)
- TNOM : Temperature Capacitance was measured
 - C_{nom} : Capacitance C @ TNOM

C. Instance Params : TC, TC1 and TC2

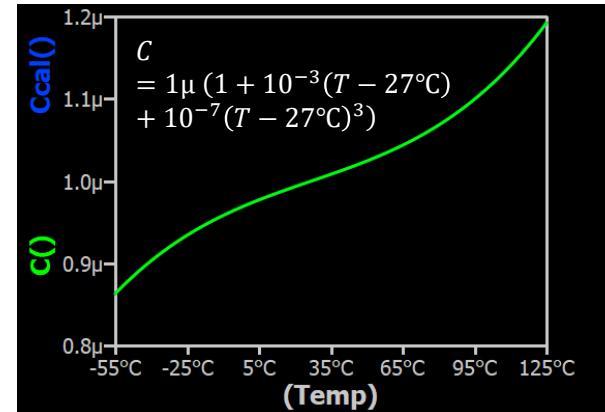
Qspice : C Capacitor - TC.qsch | C Capacitor - TC1 TC2.qsch

• TC

- TC : Temperature Coefficient list
- **Default TC=0**
- TC can be defined as
 $TC = <\text{value1}>, <\text{value2}> \dots$
- Formula
- $C = C_{nom}(1 + \sum TC_n(T - T_{nom})^n)$
- In this example, Default T_{nom} is used, which is 27°C .

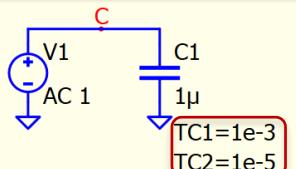


```
.step param TEMP -55 125 1  
.param frq=1Meg  
.ac list frq  
.func imZ() V(C)/I(C1)  
.func C() -1/2/pi/frq/imZ()  
.plot C() Ccal()  
.func Ccal() 1μ*(1+1e-3*(TEMP-27)+1e-7*(TEMP-27)^3)
```

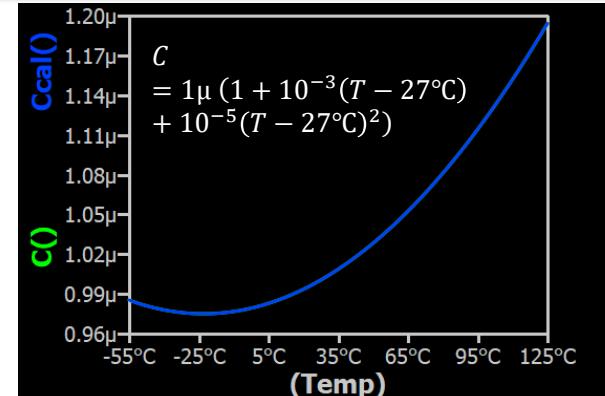


• TC1 and TC2

- TC1 : 1st order temp coeff
- TC2 : 2nd order temp coeff
- $C = C_{nom}(1 + TC_1(T - T_{nom}) + TC_2(T - T_{nom})^2)$



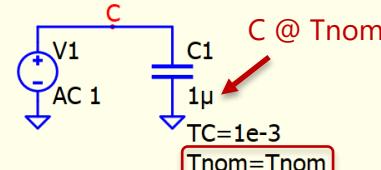
```
.step param TEMP -55 125 1  
.param frq=1Meg  
.ac list frq  
.func imZ() V(C)/I(C1)  
.func C() -1/2/pi/frq/imZ()  
.plot C() Ccal()  
.func Ccal() 1μ*(1+1e-3*(TEMP-27)+1e-5*(TEMP-27)^2)
```



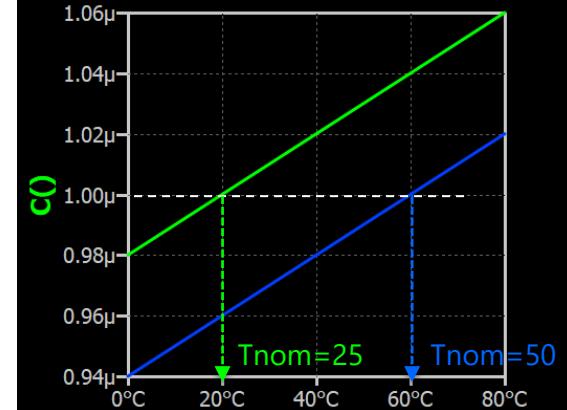
C. Instance Params : Tnom and TEMP

Qspice : C Capacitor - Tnom.qsch | C Capacitor - Temp.qsch

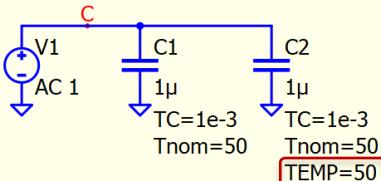
- Tnom
 - Nominal temperature
 - **Default Tnom=27°C**
 - Capacitance Cnom in thermal equation is measured at Tnom (i.e. at Tnom, calculated capacitance equal model capacitance)



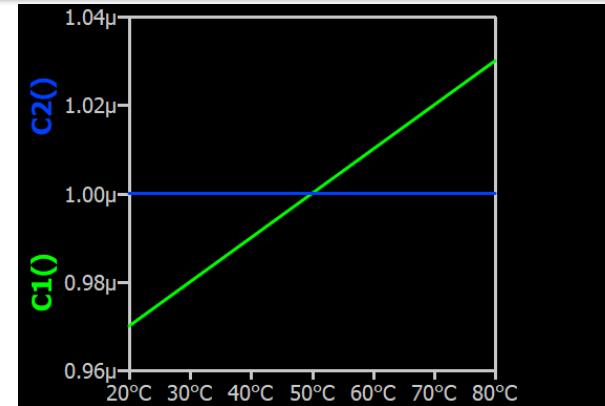
```
.step param TEMP 0 80 1  
.step param Tnom list 20 60  
.param frq=1Meg  
.ac list frq  
.func imZ() V(C)/I(C1)  
.func C() -1/2/pi/frq/imZ()  
.plot C()
```



- TEMP
 - Instance temperature
 - **Default TEMP=Circuit Temp**
 - With TEMP, capacitor is fixed at this temperature in regardless change of circuit temperature



```
.step param TEMP 20 80 1  
.param frq=1Meg  
.ac list frq  
.func imZ1() V(C)/I(C1)  
.func imZ2() V(C)/I(C2)  
.func C1() -1/2/pi/frq/imZ1()  
.func C2() -1/2/pi/frq/imZ2()  
.plot C1() C2()
```



C. Capacitor – Behavioral Capacitance (C)

Qspice : C Capacitor - Behavioral C.qsch

- C
 - Behavioral Capacitance
 - **Format : $C=<\text{equation}>$**
 - Qspice supports behavioral capacitance for a given equation which can include any circuit node voltage or device current

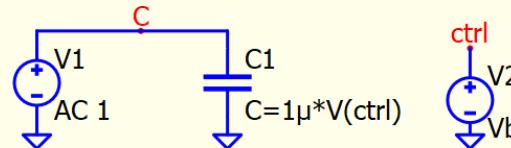
Arbitrary Capacitance-Based Capacitance Device

QSPICE also supports a behavioral capacitance where an equation for charge is not available. To use it, give an equation for the capacitance is given. The equation can include any circuit node voltages or device currents of devices modeled as Thévenin equivalents(V-, L-, E-, or H-devices). An original numerical method is used to track the charge on the capacitance not before seen in SPICE programs.

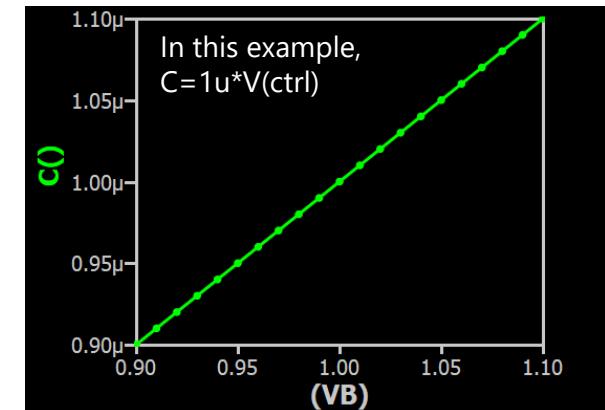
Syntax: Cnnn N1 N2 C=<expression> [additional instance parameters]

| Name | Description | Units | Default |
|-----------|---|--------------------|---------------------|
| C | Equation of charge | Coulomb | |
| IC | Initial voltage on capacitor | V | 0.0 |
| M | Number of identical parallel devices | | 1.0 |
| RPAR | Equivalent parallel resistance | Ω | Infinite |
| NOISELESS | Ignore the noise contribution from RPAR | | not set |
| TEMP | Instance temperature | $^{\circ}\text{C}$ | Circuit temperature |

Behavioral Capacitor Model with $C=<\text{eqn}>$



```
.step param Vb 0.9 1.1 0.01
.param frq=1Meg
.ac list frq
.func C() -1/2/pi/frq/(im(V(C)/I(C1)))
.plot C()
```



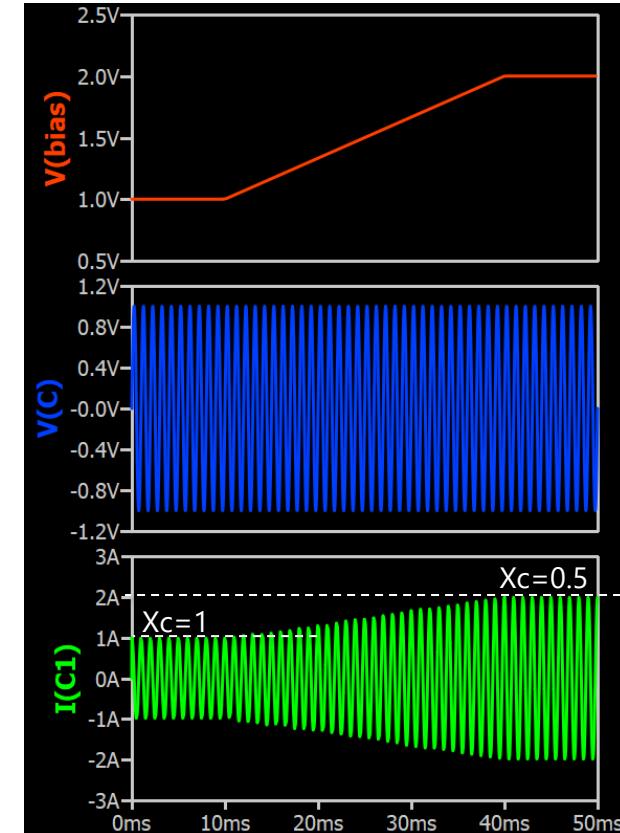
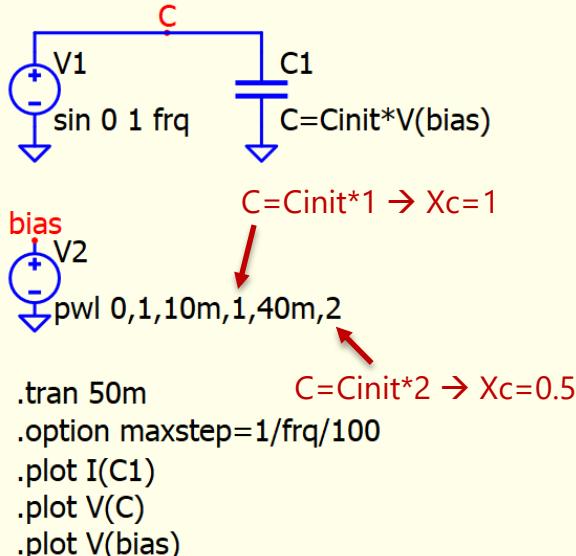
C. Capacitor – Behavioral Capacitance (C)

Qspice : C Capacitor - Behavioral C (.tran).qsch

- C
 - Behavioral Capacitance
 - This schematic demonstrate using behavioral capacitance model in transient (.tran) analysis

Behavioral Capacitor model with $C = <\text{eqn}>$

```
.param frq=1K  
.param Xc=1  
.param Cinit=1/2/pi/frq/Xc
```



C. Capacitor – Why Qspice not include parasitic inductance (ESL or Lser)

- Answer by Mike Engelhardt in Qspice forum
 - <https://forum.qorvo.com/t/parasitic-inductance-of-passive-components-lser/15608/3>
 - <https://forum.qorvo.com/t/esl-in-capacitor-model/16944/2>

 Engelhardt Oct '23

I did not implement Lser for capacitors because it usually caused more harm than good.

A series inductance is not a great way to model the internal inductance of a capacitor. For foil capacitors, you really need a ladder of series R & L driving a distributed capacitance, though I've been able to match the complex impedance within a few degrees over several decades of frequency with just two lumps.

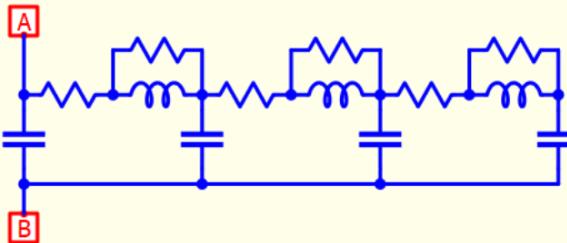
For ceramic capacitors, modeling their internal inductance is not really meaningful without modeling the parasitics of the PCB.

Anyway, when I watch people using Lser, it only increases simulation times without actually improving the integrity of the simulation.

Your mileage will vary,
-Mike



For any type of film capacitor, it is more of a distributed $R_{ser}/R_{par}/L_{ser}/C_{par}$ network. Poorly described with a single lumped series L. For a ceramic capacitor, a series inductance can be a more viable representation, but usually adds no accuracy to the simulation since connecting inductance often dominates. It was a mistake to support Lser as a part of a capacitor in LTspice. It did much more harm than good. Anyway, below would be a viable equivalent schematic of a film capacitor in lumped constants between nodes A and B:



The diagram shows a horizontal bus at the bottom with two vertical nodes, A and B, connected to it. Between these nodes are four parallel branches. Each branch consists of a resistor (wavy line), a capacitor (parallel lines), and an inductor (zigzag line). The inductor is positioned between the resistor and the capacitor. This represents a distributed model for the capacitor's internal behavior.

Notice there is nowhere a series inductance.

D. Diode

Model Parameters

Diode Model Parameters in Qspice HELP

| Diode Instance Parameters | | | |
|---------------------------|--------------------------------------|-------|---------------------|
| Name | Description | Units | Default |
| AREA | Relative area | | 1.0 |
| M | Number of identical parallel devices | | 1.0 |
| TEMP | Instance temperature | °C | Circuit temperature |

| Diode Model Parameters | | | |
|------------------------|--|-------|----------|
| Name | Description | Units | Default |
| AF | Flicker noise exponent | 1. | 1.0 |
| BV | Reverse breakdown voltage | V | Infinite |
| CJO | Zero-bias junction capacitance | F | 0.0 |
| EG | Activation energy | eV | 1.11 |
| FC | Forward-bias depletion capacitance coefficient | | 0.5 |
| GMAX | Maximum conductivity(straight-line extension) | Ω | 10000. |
| GP | Parallel conductivity added in lieu of global Gmin | Ω | 0. |
| IBV | Current at breakdown voltage | A | 1e-10 |
| IBVL | Low-level reverse breakdown knee current | A | 0.0 |
| IKF | High-injection knee current | A | 1e308 |
| IS | Saturation current | A | 1e-14 |
| ISR | Recombination current parameter | A | 0.0 |
| KF | Flicker noise coefficient | | 0.0 |
| M | Grading coefficient | | 0.5 |

| | | |
|--------|--|----------|
| ① N | Emission coefficient | 1.0 |
| ① NBV | Reverse breakdown emission coefficient | 1.0 |
| ① NBVL | Low-level reverse breakdown emission coefficient | 1.0 |
| ① NR | ISR emission coefficient | 2.0 |
| ① RS | Series resistance | Ω 0.0 |
| TBV1 | 1st order BV temperature coefficient | °C⁻¹ 0.0 |
| TBV2 | 2nd order BV temperature coefficient | °C² 0.0 |
| TIKF | IKF temp coefficient | °C⁻¹ 0.0 |
| TNOM | Parameter measurement temperature(aka TREF) | °C 27 |
| TG11 | 1st order GP temperature coefficient¹ | °C⁻¹ 0.0 |
| TGP2 | 2nd order GP temperature coefficient¹ | °C² 0.0 |
| TRS1 | 1st order RS temperature coefficient¹ | °C⁻¹ 0.0 |
| TRS2 | 2nd order RS temperature coefficient¹ | °C² 0.0 |
| ① TT | Transit-time² | sec 0.0 |
| ① VJ | Junction potential | V 1.0 |
| XTI | Saturation current temperature exponent | 3.0 |

.model available parameters but not in HELP

- VP : Soft reverse recovery parameter (Default VP=0.01)

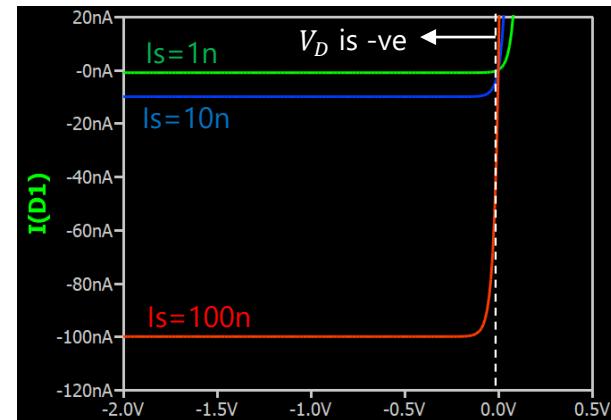
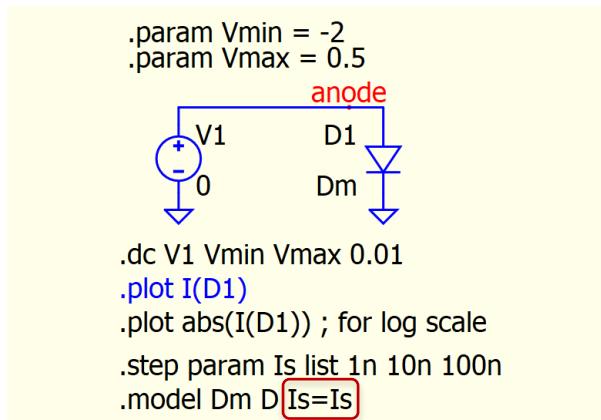
.model parameters only for information display but no electrical behavior

- MFG : manufacturer name
- Vrev : Peak reverse voltage
- Iave : Average current rating

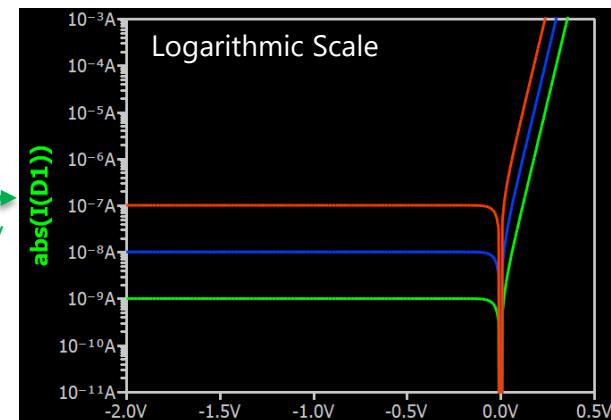
D. Diode Model (I-V Characteristic) : IS

Qspice : Dmodel - IS.qsch

- IS
 - Is : Saturation current
 - Saturation current in reverse region
 - **Default IS = 1e-14A**
 - $I_D = I_s (e^{\frac{qV_D}{nkT}} - 1)$
 - $\frac{kT}{q}$ is called thermal voltage
 - q : electronic charge
 - 1.602176487e-19 Coulomb
 - k : Boltzmann constant
 - 1.380649e-23 J/K
 - T : Temperature in Kelvin
 - $T = T_{celsius} + 273.15^\circ C$
 - V_D : Diode voltage
 - n : emission coefficient



$|I_d|$ →
Magnitude only



D. Diode Model (I-V Characteristic) : N and Rs

Qspice : Dmodel - N.qsch / Dmodel - Rs.qsch

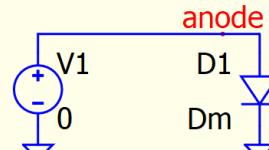
- N
 - n : emission coefficient

Default N=1

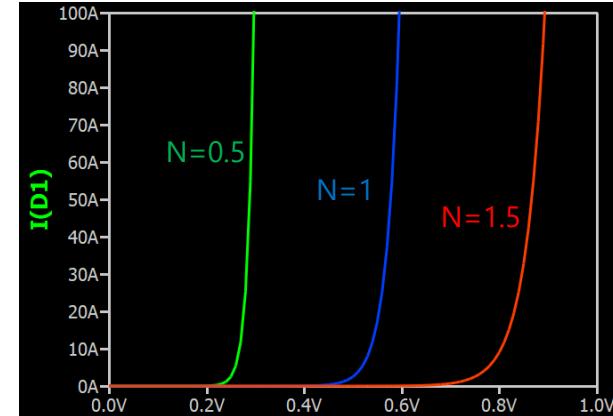
$$I_D = I_s \left(e^{\frac{qV_D}{nkT}} - 1 \right)$$

- N affects threshold voltage in forward bias

```
.param Vmin = 0  
.param Vmax = 1  
.step param n list 0.5 1 1.5
```



```
.dc V1 Vmin Vmax 0.01  
.plot I(D1)  
.model Dm D Is=10n N=n
```



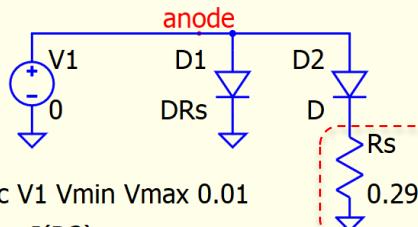
- RS
 - Rs : Series resistance

Default RS=0Ω

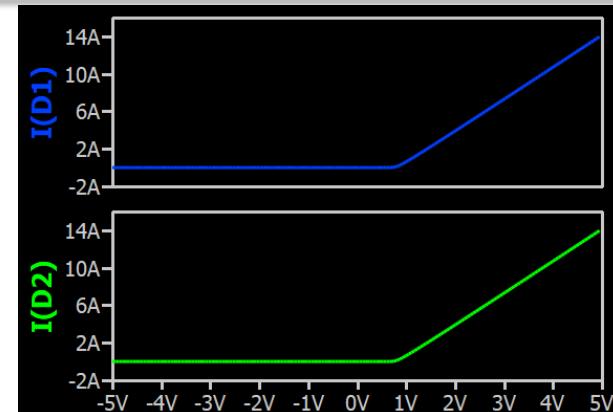
- This is equivalent to resistor added in series to diode

** V_D in $I_D = I_s \left(e^{\frac{qV_D}{nkT}} - 1 \right)$ formula only represent diode model voltage drop. If RS is added, diode model anode to cathode voltage is $V_D + I_D R_s$

```
.param Vmin = -5  
.param Vmax = 5
```



```
.dc V1 Vmin Vmax 0.01  
.plot I(D2)  
.plot I(D1)  
.model DRs D Rs=0.29
```



Forward Voltage (VF) or Threshold @ Specified Forward Current (IF)

** Condition : Recombination current is not used : ISR=0

- Background

- In datasheet, it generally specify forward threshold by defining as forward voltage drop (VF) at a specified forward current level (IF)

- Diode model include RS

- $V_{D,ext} = V_D + I_D R_S$ and $I_d = I_s \left(e^{\frac{qV_D}{nkT}} - 1 \right)$
 - where $V_{D,ext}$ is diode voltage drop including series resistance
- Re-arrange I_d formula : $V_D = n \frac{kT}{q} \ln \left(\frac{I_d}{I_s} + 1 \right)$
- Therefore,
 - $V_{D,ext} = n \frac{kT}{q} \ln \left(\frac{I_d}{I_s} + 1 \right) + I_D R_S$
- Substitute $V_{D,ext}$ by VF and I_D by IF and Qspice .model parameters
 - $V_F = N \frac{kT}{q} \ln \left(\frac{IF}{IS} + 1 \right) + IF \times RS$
 - where Qspice default temperature T is 27°C = 300.15K
 - $k=1.380649e-23 \text{ J/K}$ and $q=1.602176487e-19 \text{ C}$ $\rightarrow \frac{kT}{q} = 2.5865e-2$
 - Equation can be simplified with $IF \gg IS$ where $\left(\frac{IF}{IS} + 1 \right) \rightarrow \frac{IF}{IS}$

- Simplified Results in Qspice

- $VF = 2.5865e-2 * N * \ln(IF/IS) + IF * RS$
 - IS, N and RS are in diode .model
 - IF is specified forward current for diode threshold (e.g. IF=100mA)

Approximation formula to calculate Vd threshold at IF, @27oC
.param VF=2.5865e-2*N*ln(IF/IS)+IF*RS

Model Parameters

```
.param IS=5n  
.param N=2  
.param Rs=.58
```

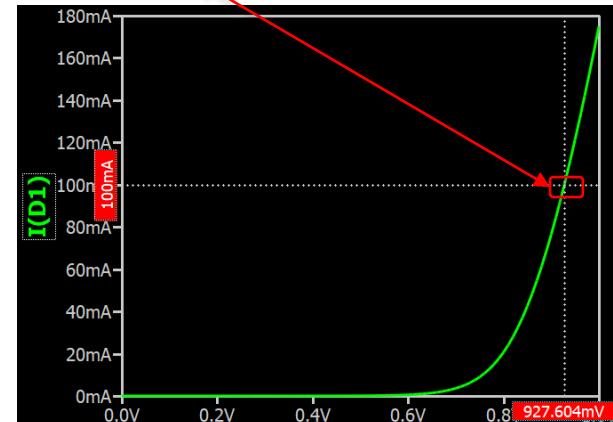
```
.dc V1 0 1 0.01  
.plot I(D1)  
.options listparam
```

IF forward Current

```
.param IF=100m  
.model 1N4148 D Is=5n Rs=.58 n=2  
+Cjo=.87p m=.025 tt=7.9n Nbv=2000  
+BV=100 IBV=150n XTI=6  
+mfg="ON Semiconductor"  
+Vrev=100 Iave=200m
```

Output Window

| | | |
|------|------------|-------------------------------|
| TEMP | = 27 | "CKTTEMP" |
| IS | = 5N | "5N" |
| N | = 2 | "2" |
| RS | = 580M | ".58" |
| VF | = 927.646M | "2.5865E-2*N*LN(IF/IS)+IF*RS" |
| IF | = 100M | "100M" |



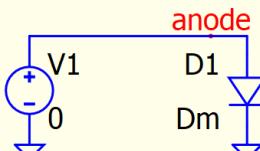
D. Diode Model (I-V Characteristic : Breakdown) : BV, IBV and NBV

Qspice : Dmodel - BV IBV.qsch / Dmodel - NBV.qsch

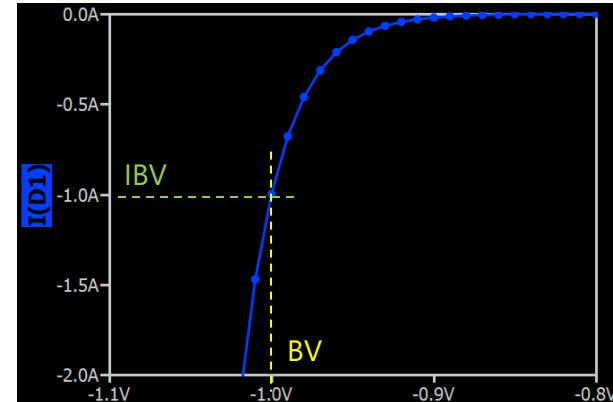
- BV and IBV

- BV : Breakdown Voltage
- IBV : Current at breakdown voltage
- Default BV=Infinite**
- Default IBV=1e-10**
- Breakdown region eqn
 - $I_D = -IBV e^{-\frac{q(BV+V_D)}{kT}}$

```
.param Vmin = -1.2  
.param Vmax = 0
```



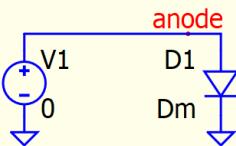
```
.dc V1 Vmin Vmax 0.01  
.plot I(D1)  
.model Dm D BV=1 IBV=1
```



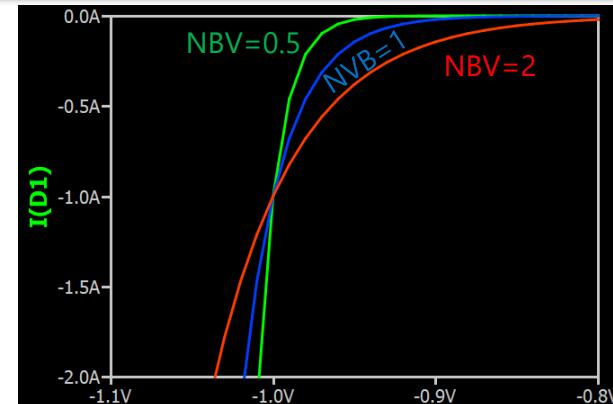
- NBV

- NBV : Reverse breakdown emission coefficient
- Default NBV=1**
- Change the sharpness of breakdown reverse current

```
.param Vmin = -1.2  
.param Vmax = 0
```



```
.dc V1 Vmin Vmax 0.01  
.plot I(D1)  
.model Dm D BV=1 IBV=1 NBV=nbv  
.step param nbv list 0.5 1 2
```



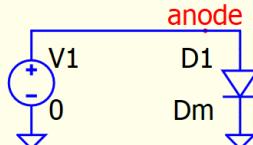
D. Diode Model (I-V Characteristic : Breakdown) : IBVL and NBVL

Qspice : Dmodel - IBVL.qsch / Dmodel - NBVL.qsch

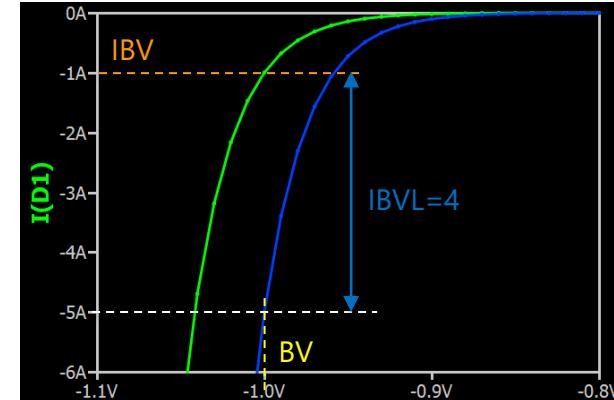
- **IBVL**

- IBVL : low-level reverse breakdown knee current
- **Default IBVL=1**

```
.param Vmin = -1.2  
.param Vmax = -0.6
```



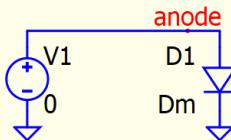
```
.dc V1 Vmin Vmax 0.01  
.plot I(D1)  
.step param ibvl list 0 4  
.model Dm D BV=1 IBV=1 IBVL=ibvl
```



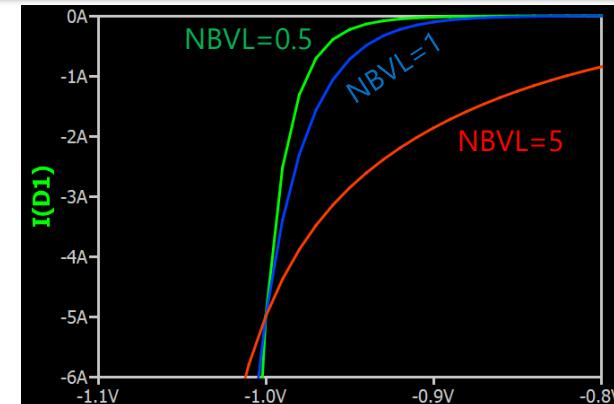
- **NBVL**

- NBVL : Low-level reverse breakdown emission coefficient
- **Default NBVL=1**
- Change the sharpness of breakdown reverse current when IBVL is used

```
.param Vmin = -1.2  
.param Vmax = -0.6
```



```
.dc V1 Vmin Vmax 0.01  
.plot I(D1)  
.step param nbvl list 0.5 1 5  
.model Dm D BV=1 IBV=1 IBVL=4  
+NBVL=nbvl
```

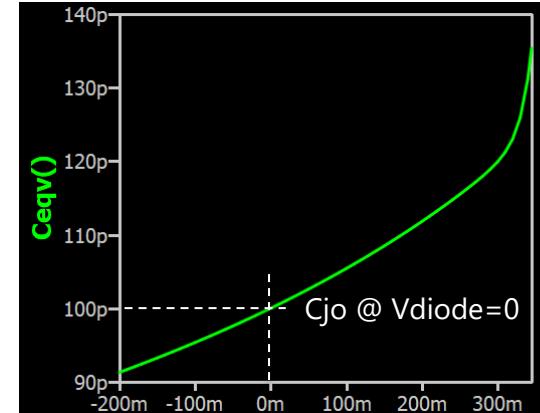


D. Diode Model (Capacitance) : CJO and M

Qspice : Dmodel - CJO.qsch / Dmodel - M.qsch

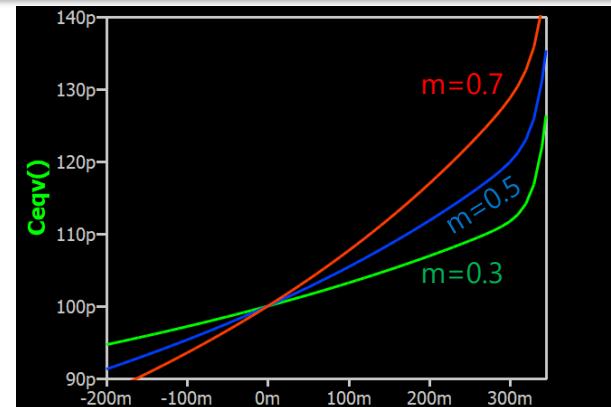
- CJO
 - Cjo : Zero-bias junction capacitance
 - **Default CJO=0F**
 - $C_j = \frac{C_{jo}}{\left(1 - \frac{V_D}{\Phi_0}\right)^m}$
 - Φ_0 : Junction potential (VJ)
 - m : Grading coefficient
 - M = 0.33 : linearly garded
 - M = 0.5 : abrupt junction

```
.param Vmin = -0.2
.param Vmax = 0.345
.param f = 1K
.anode
V1
D1
Dm
.model Dm D Cjo=100p
.func Zim() imag(V(anode)/I(D1))
.func Ceqv() -1/2/pi/f/Zim()
.ac list f
.step param var Vmin Vmax 0.01
.plot Ceqv()
```



- M
 - m : grading coefficient
 - **Default M=0.5**
 - $C_j = \frac{C_{jo}}{\left(1 - \frac{V_D}{\Phi_0}\right)^m}$
 - m : Grading coefficient
 - M = 0.33 : linearly garded
 - M = 0.5 : abrupt junction

```
.param Vmin = -0.2
.param Vmax = 0.345
.param f = 1K
.anode
V1
D1
Dm
.model Dm D Cjo=100p m=m
.func Zim() imag(V(anode)/I(D1))
.func Ceqv() -1/2/pi/f/Zim()
.ac list f
.step param var Vmin Vmax 0.01
.plot Ceqv()
.step param m list 0.3 0.5 0.7
```



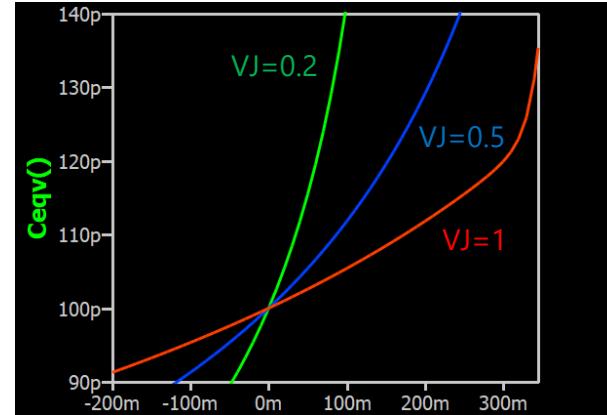
D. Diode Model (Capacitance) : VJ and FC

Qspice : Dmodel - VJ.qsch / Dmodel - FC.qsch

- VJ
 - V_j : Junction potential
 - **Default $VJ=1V$**
 - $C_j = \frac{C_{jo}}{\left(1 - \frac{V_D}{\Phi_0}\right)^m}$
 - Φ_0 : Junction potential (V_j)
 - may range from 0.2 to 1V

```
.param Vmin = -0.2
.param Vmax = 0.345
.param f = 1K
.anode
V1          .model Dm D Cjo=100p [VJ=vj]
DC var      .func Zim() imag(V(anode)/I(D1))
AC 1        .func Ceqv() -1/2/pi/f/Zim()
D1          Dm
```

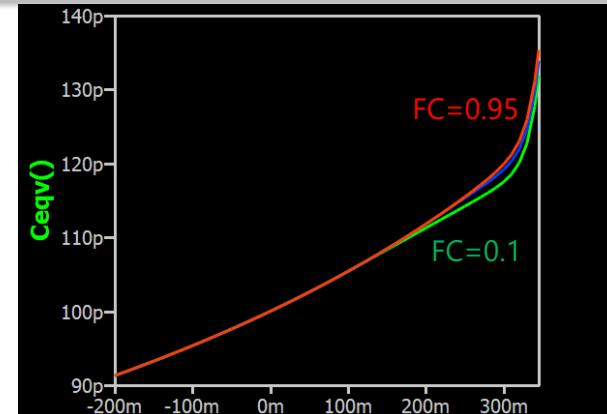
.ac list f
.step param var Vmin Vmax 0.01
.plot Ceqv()
.step param vj list 0.2 0.5 1



- FC
 - F_c : Forward-bias depletion capacitance coefficient
 - **Default $FC=0.5$**
 - A factor between 0 and 0.95 (limit by 0.95 in Qspice), which determines how the junction capacitance is calculated when the junction is forward-biased

```
.param Vmin = -0.2
.param Vmax = 0.345
.param f = 1K
.anode
V1          .model Dm D Cjo=100p [FC=fc]
DC var      .func Zim() imag(V(anode)/I(D1))
AC 1        .func Ceqv() -1/2/pi/f/Zim()
D1          Dm
```

.ac list f
.step param var Vmin Vmax 0.01
.plot Ceqv()
.step param fc list 0.1 0.2 0.95

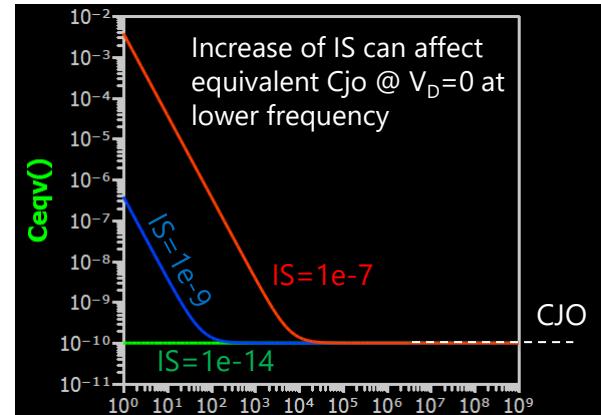


D. Diode Model (Capacitance) : Parameters can affect Cj in frequency

Qspice : Dmodel - Cj Effect – IS.qsch

- Params can affect Cj in frequency
 - IS : Saturation current

```
.param Vmin = -0.2
.param Vmax = 0.345
.param f = 1K
.anode
V1
DC 0
AC 1
D1
Dm
.func Zim() imag(V(anode)/I(D1))
.func Ceqv() -1/2/pi/f/Zim()
.ac list f
.step dec param f 1 1G 10
.plot Ceqv()
.model Dm D Cjo=100p Is=Is
.step param Is list 1e-14 1e-9 1e-7
```



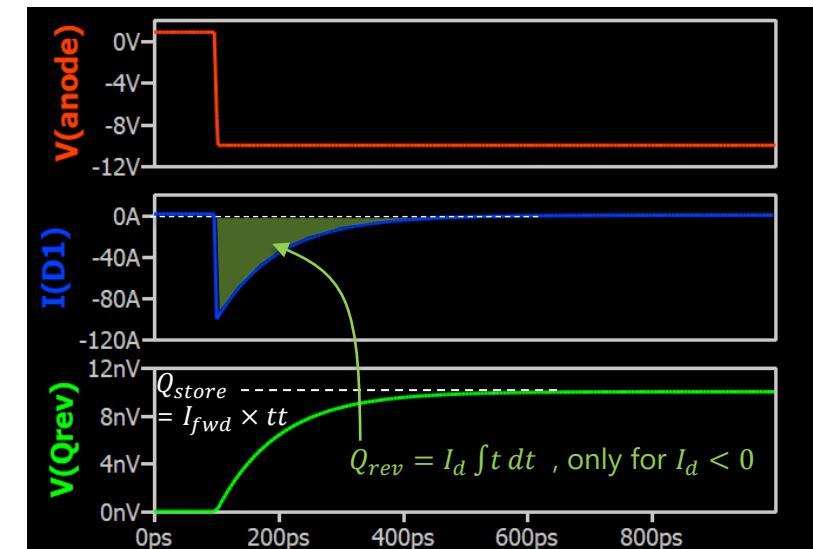
D. Diode Model (Reverse Recovery) : TT

Qspice : Dmodel - TT.qsch

- TT : Transit-time
 - TT is not the time it takes a diode to turn off. It's a measure of **the amount of charge that needs to be pulled out to turn the diode off**. Specifically, **the stored charge is TT times the forward current**. For the product to be Coulomb, the dimensions of TT must be time
 - $Q_{store} = I_{fwd} \times tt$, where tt is transit-time in Qspice
 - **Default TT=0s** [equivalent to disable reverse recovery from TT]
 - ** If TT is used, Rs must be non-zero (it can affect forward I-V characteristic if Rs=0 with a finite TT)

```
.param v fwd=0.834  
.param v rev=-10  
.param td=0.1n  
.param p=1p  
  
anode  
V1 D1 Dm  
pwl 0 v fwd td v fwd td+p v rev
```

```
.tran 10*td  
.option maxstep=p/50  
.plot V(Qrev)  
.plot I(D1)  
.plot V(anode)  
  
.param tt=10n  
.model Dm D Rs=1e-12 Tt=tt  
Mike's comment : If TT isn't zero,  
Rs can not be zero, because of the  
way QSPICE handles dQ/dT soft recovery.  
  
Integral negative diode current :  $Q = I \cdot t$   
Qrev  
B1  
V=idt(uramp(I(V1)),0)  
.meas Ifwd max -I(V1)  
.meas Qstore Ifwd*tt
```



D. Diode Model (Reverse Recovery) : VP

Qspice : Dmodel - VP.qsch

- VP : Soft reverse recovery parameter
 - No description in Qspice HELP
 - **Default VP=1e-2 (i.e. Default VP=0.01)**
 - It affect current amplitude at reverse recovery
 - Increase VP can reduce current amplitude but increase reverse recovery time

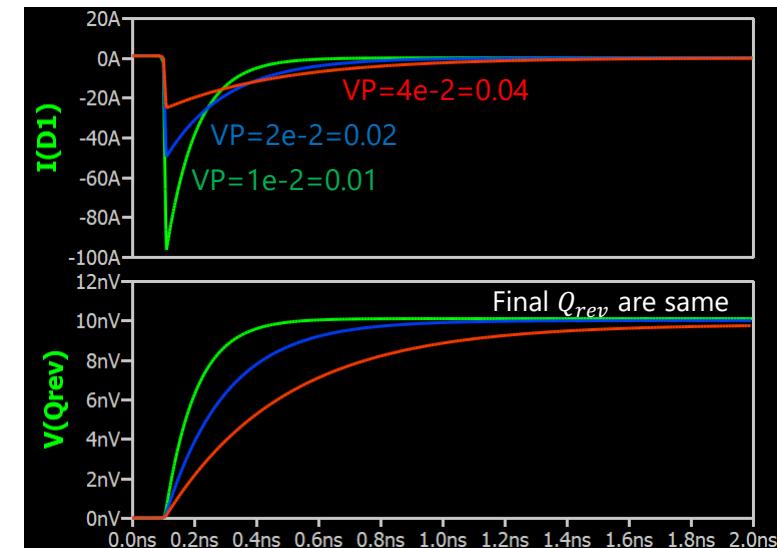
```
.param vfwd=0.834  
.param vrev=-10  
.param td=0.1n  
.param p=1p  
  
anode  
V1 D1 Dm  
  
pwl 0 vfwd td vfwd td+p vrev
```

```
.tran 20*td  
.option maxstep=p/50  
.plot V(Qrev)  
.plot I(D1)  
  
.step param vp list 1e-2 2e-2 4e-2  
.param tt=10n  
.model Dm D Rs=1e-12 Tt=tt Vp=vp
```

Integral negative diode current : $Q = \int I(V) dV$

Qrev

```
B1  
V=uramp(I(V1)),0  
.meas Ifwd max -I(V1)  
.meas Qstore Ifwd*tt
```



D. Diode Model (Reverse Current) : CJ

Qspice : Dmodel - CJO (RR).qsch

- CJ : Junction capacitance

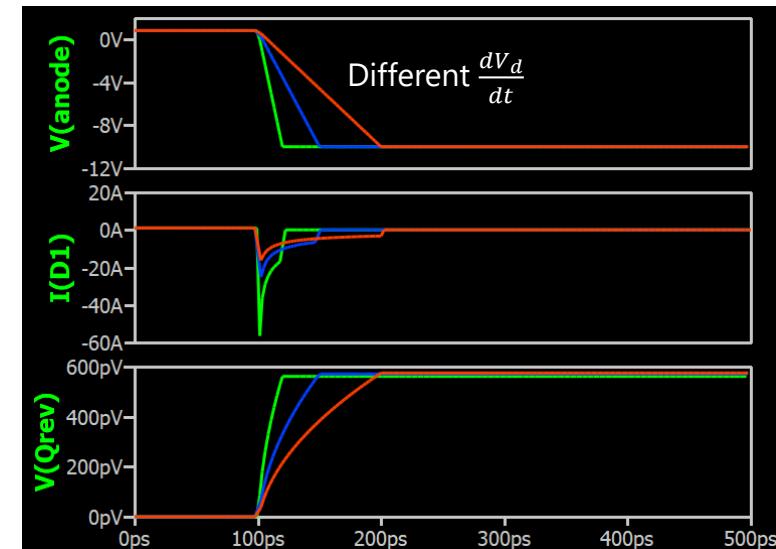
- Junction capacitance leads to reverse current but **NOT** a reverse recovery
 - For example, SiC has negligible reverse recovery and it model may not have TT but with CJO
- Reverse charge depends on junction capacitance and reverse voltage
- $\frac{dV_d}{dt}$ or $\frac{dI_d}{dt}$ are factor can affect peak reverse current in reverse recovery

```
.param vfwd=0.834  
.param vrev=-10  
.param td=0.1n  
.param p=duratio  
  
anode  
V1 D1 Dm  
  
.tran 5*td  
.option maxstep=p/50  
.plot V(Qrev)  
.plot I(D1)  
.plot V(anode)  
  
.step param duration list 20p 50p 100p  
.model Dm D CJO=100p
```

pwl 0 vfwd td vfwd td+p vrev

Integral negative diode current : $Q = I \cdot t$

Q_{rev}
B1
 $V = idt(uramp(I(V1)), 0)$



D. Diode Model (Reverse Current) : CJ

Qspice : Dmodel - CJ in Reverse Voltage.qsch / Dmodel - CJ in Reverse Current.qsch

- C_j Explanation

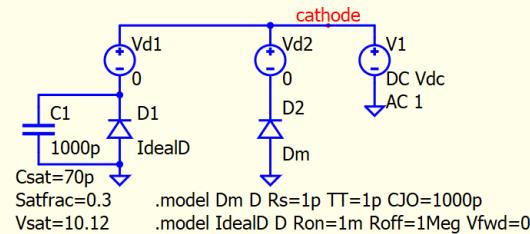
- Junction capacitance is in parallel to diode and its capacitance is a function of diode reverse voltage

- Simulation #1

- C_j is nonlinear to diode reverse voltage, to model C_j, it requires use non-linear capacitor with C_{sat}, Satfrac and V_{sat}

- Simulation #2

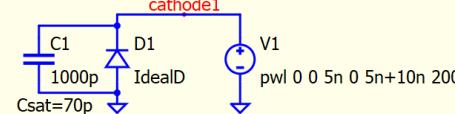
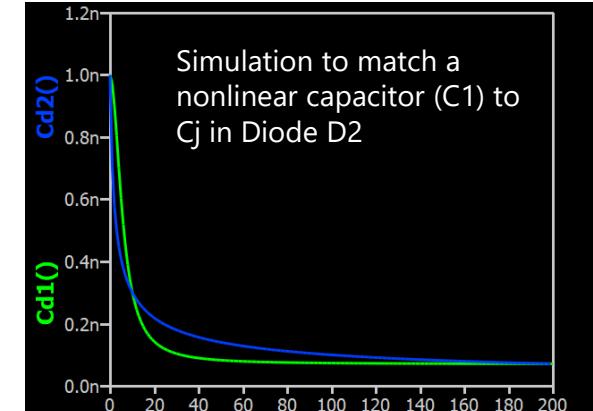
- Apply reverse voltage can simulate capacitor charging current, which act like reverse recovery but actually is not
- Reverse recovery rely on forward current as reverse recovery is to remove this charge to turn off the diode
- However, C_j is simply a mechanism that current charging a nonlinear capacitor



```

.ac list f .param f=1Meg .plot Cd1() Cd2()
.step param Vdc 0 200 1
.func imZD1() imag(V(drain)/I(Vd1))
.func imZD2() imag(V(drain)/I(Vd2))
.func Cd1() -1/2/pi/f/imZD1()
.func Cd2() -1/2/pi/f/imZD2()

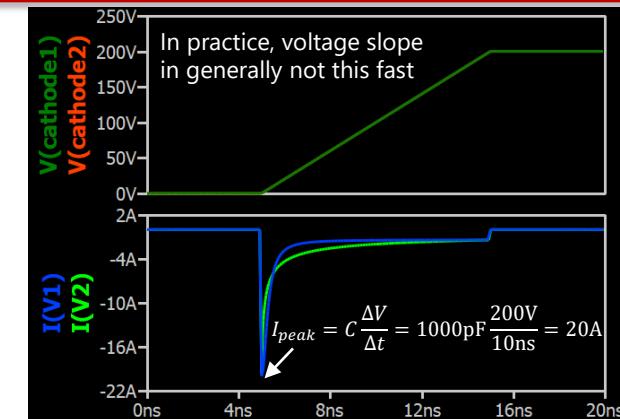
```



```

.tran 20n
.plot I(V2), I(V1)
.plot V(cathode2), V(cathode1)

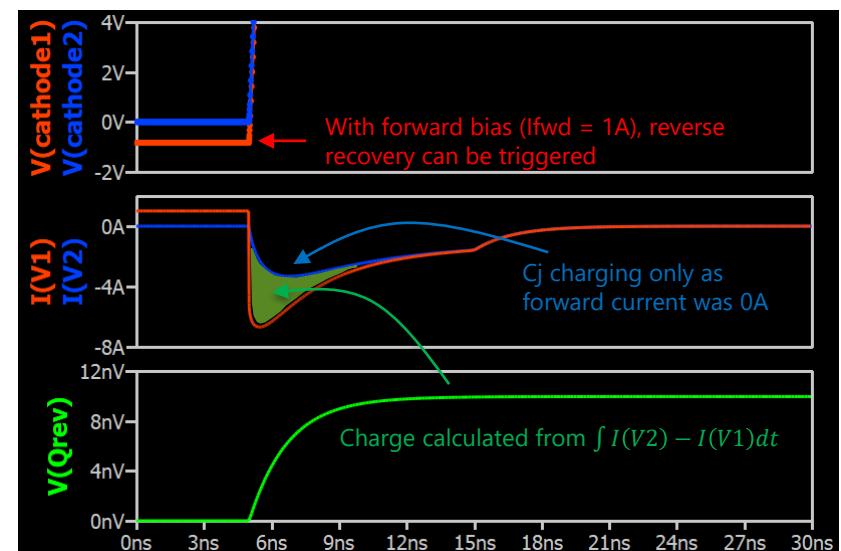
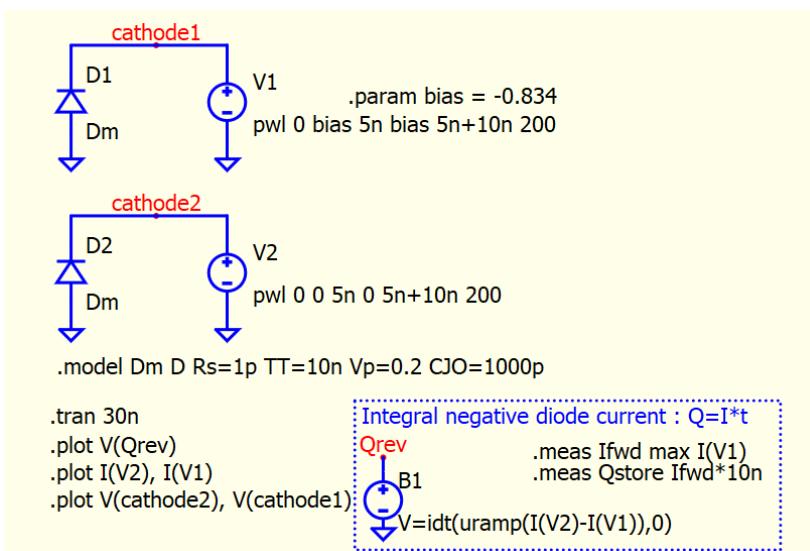
```



Explanation of Reverse Recovery and Junction Capacitance Charging

Qspice : Dmodel - Reverse Recovery and Capacitor Charging.qsch

- Explanation of Reverse Recovery and Junction Capacitance Charging Current
 - Reverse Recovery is only preset if forward current is applied
 - If forward current is 0A, reverse current is by charging junction capacitance (C_j), and this is a nonlinear capacitance (capacitance decrease with cathode voltage) and therefore, reverse current reduce over time even ramp of cathode voltage is constant, where $I_d = C_j \frac{dV_d}{dt}$, where C_j is a function of V_d
 - If forward current is preset, reverse recovery is applied (TT and Vp). A extra portion of reverse current is generated and this extra charge equal $I_{fwd} \times TT$



PSPICE Static Model Params (Recombination) : IKF, ISR and NR

** Modeling of Recombination Current

- Semiconductor Device Modeling with SPICE (Section 1.9.1)

- $$I_D = (K_{hli} I_F + K_{gen} I_R) - I_{Breakdown}$$

- $$I_F = I_S \left(e^{\frac{qV_D}{nkT}} - 1 \right)$$

- I_S is IS : Saturation current (default = 1e-14A)
 - n is N : Emission coefficient (default = 1)

- $$K_{hli} = \sqrt{\frac{I_{KF}}{I_{KF} + I_F}} \text{ for } I_{KF} > 0 : \text{ If } I_{KF} \rightarrow \infty, K_{hli} = 1$$

- I_{KF} is IKF : High injection knee current (default = 1e308)

- $$I_R = I_{SR} \left(e^{\frac{qV_D}{n_R kT}} - 1 \right)$$

- I_{SR} is ISR : Recombination current parameter (default = 0A)
 - n_R is NR : ISR emission coefficient (default = 2)

- $$K_{gen} = \sqrt{\left[\left(1 - \frac{V_D}{\Phi_0} \right)^2 + 0.005 \right]^m}$$

- m is M : Grading coefficient (default = 0.5)
 - Φ_0 is VJ : Junction potential (default = 1V)

- $$I_{Breakdown} = IBV e^{-\frac{q(BV+V_D)}{kT}}$$

- IBV is IBV : Current at breakdown voltage (default = 1e-10A)
 - BV is BV : Reverse breakdown voltage (default = Infinite V)
 - This is equation to describe breakdown region. Reverse leakage is described in $(K_{hli} I_F + K_{gen} I_R)$

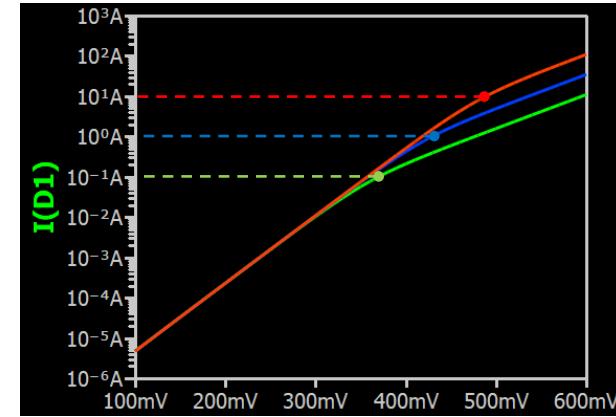
D. Diode Model (Recombination) : IKF

Dmodel - IKF.qsch

- IKF
 - IKF : High injection knee current
 - **Default IKF=1e308**
 - $I_D = (K_{hli}I_F + K_{gen}I_R)$
 - $I_D = K_{hli}I_F$
 - $K_{hli} = \sqrt{\frac{I_{KF}}{I_{KF} + I_F}}$ for $I_{KF} > 0$
 - The modification effect may only be easily observed with ID in log scale

```
.param Vmin = 0.1
.param Vmax = 0.6
.anode
V1 0 D1 Dm
.DC V1 {Vmin} {Vmax} 0.01
.PLOT I(D1)

.step param ikf list 0.1 1 10
.model Dm D Is=100n N=1 IKF={ikf}
```



D. Diode Model (Recombination) : ISR

Qspice : Dmodel - ISR.qsch

- ISR
 - Isr : Recombination current parameter
 - **Default ISR=0A**
 - $I_D = (K_{hli}I_F + K_{gen}I_R)$
 - In following examples, I_F is forced to be negligible as compare to $K_{gen}I_R$ in calculating I_D

$$\bullet I_D = K_{gen} I_{SR} \left(e^{\frac{qV_D}{n_R kT}} - 1 \right)$$

$$\bullet K_{gen} = \sqrt{\left[\left(1 - \frac{V_D}{\Phi_0} \right)^2 + 0.005 \right]^m}$$

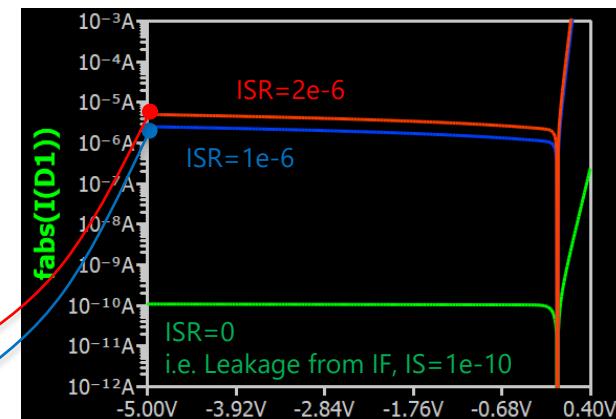
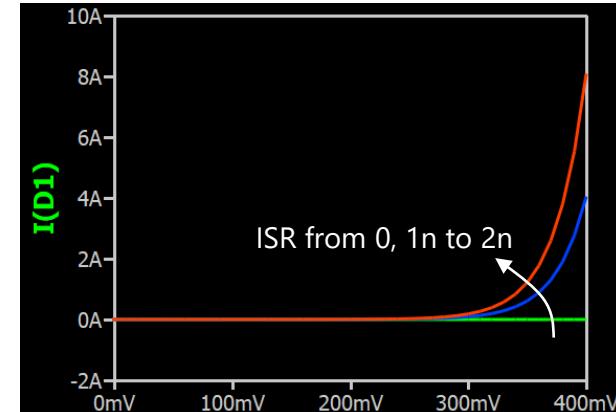
• n_R is NR : default = 2V

• m is M : default = 0.5

• Φ_0 is VJ : default = 1V

```
.param Vmin = -5
.param Vmax = 0.4
.anode
V1 0 D1
Dm
.dc V1 Vmin Vmax 0.01
.plot I(D1)
.step param isr list 0 1e-6 2e-6
.model Dm D Is=1e-10 N=2 ISR=isr NR=1
Is and N are set to equivalent with negligible If as
compare to Ir to demonstrate Ir effect
```

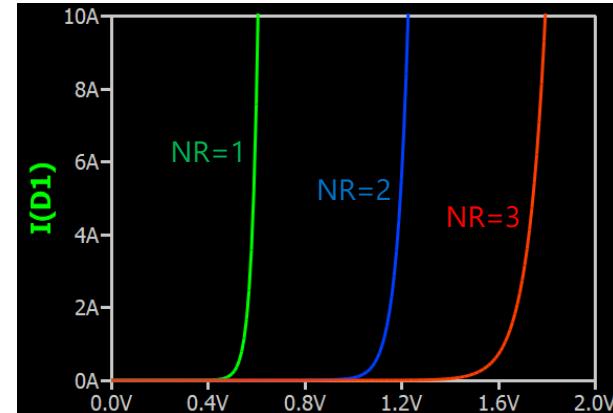
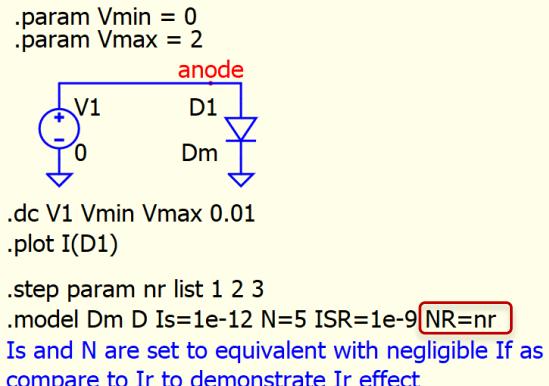
- Remark
 - As IS is set to 1e-12, in reverse and ISR=0, leakage current can still be observed through equation I_F
 - @ $V_D = -5V$
 - Therefore
 - ID for ISR=2e-6, $VD=-5$ is $4.8990\mu A$
 - ID for ISR=1e-6, $VD=-5$ is $2.4495\mu A$



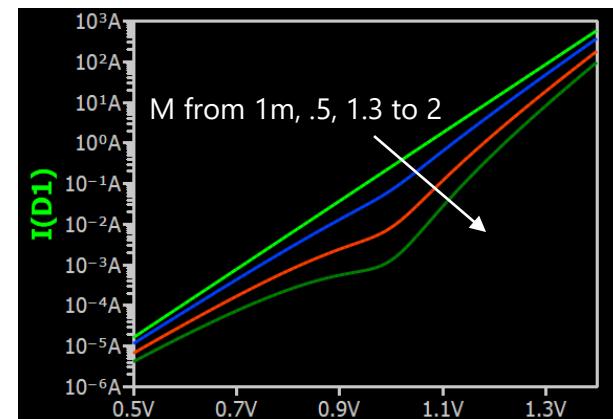
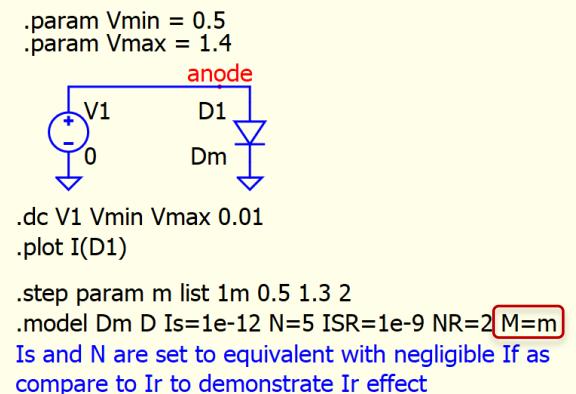
D. Diode Model (Recombination) : NR and M

Qspice : Dmodel - NR.qsch / Dmodel - M (Recombination).qsch

- NR
 - Nr : ISR emission coefficient
 - **Default NR=2**
 - $I_D = K_{gen} I_{SR} \left(e^{\frac{qV_D}{n_R kT}} - 1 \right)$



- M
 - M : Grading coefficient
 - **Default M=0.5**
 - $K_{gen} = \sqrt{\left[\left(1 - \frac{V_D}{\Phi_0} \right)^2 + 0.005 \right]^m}$
 - The modification effect may only be easily observed with ID in log scale

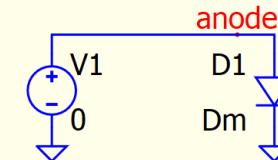


Textbook Diode Modeling

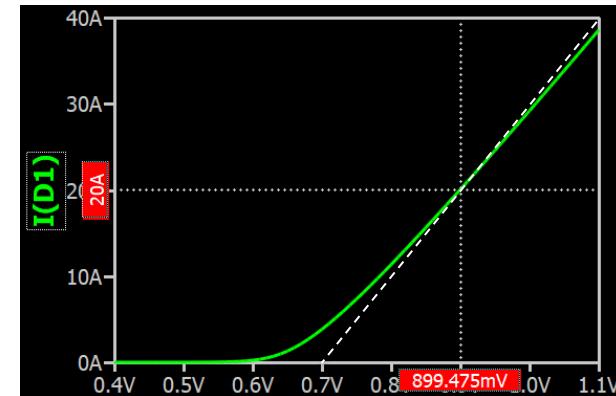
Qspice : Dmodel (Textbook).qsch

- Textbook Diode Modeling
 - $IS=1e-12$ to minimize leakage current when diode is OFF
 - $RS=\frac{\Delta V_D}{\Delta I_D}$ in the region that diode is ON
 - $N=\frac{VF-IF\times RS}{0.025865\times \ln\left(\frac{IF}{IS}\right)}$: IF is current at VF
- Assume textbook requirement is
 - Threshold = 0.7V and $\frac{\Delta I_D}{\Delta V_D} = 100A/V$
 - By $VF = \frac{IF}{\frac{\Delta I_D}{\Delta V_D}} + \text{Threshold}$
 - We use a higher IF to determine the curve,
 - @ IF=20A $\rightarrow VF = \frac{20A}{100A/V} + 0.7V = 0.9V$
 - Therefore
 - $IS=1e-12$
 - $RS=1/100=0.01$
 - $N=\frac{0.9-20\times 0.01}{0.025865\times \ln\left(\frac{20}{1e-12}\right)}=0.883$

```
.param Vmin = 0.4  
.param Vmax = 1.2
```



```
.dc V1 Vmin Vmax 0.01  
.plot I(D1)  
.model Dm D Is=1e-12 N=0.883 RS=0.01
```



D. Diode

Behavioral Diode Model Parameters

Behavioral Diode Model Parameters in Qspice HELP

QSPICE includes a simplified, behavioral, diode. To use those device equations, specify a non-zero RON.

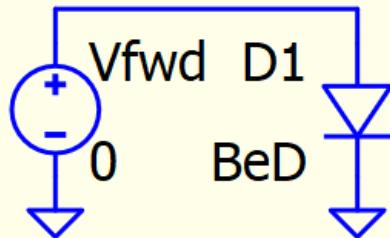
Behavioral Diode Model Parameters

| Name | Description | Units | Default |
|------------|---|----------|-----------|
| RON | Forward on resistance | Ω | 0.0^3 |
| ROFF | Off resistance | Ω | $1./GMIN$ |
| RZEN | Breakdown resistance(aka RREV) | Ω | RON |
| VFWD | Forward voltage drop | V | 0.0 |
| VREV | Reverse voltage drop | V | 0.0 |
| EPSILON | Width of quadratic region splining off and on regions | V | 0.0 |
| REVEPSILON | Width of quadratic region splining breakdown and on regions | V | 0.0 |
| CJO | Shunt capacitance | F | 0.0 |

^{3]} The value of zero means don't use these equations, but the conventional SPICE semiconductor diode equations.

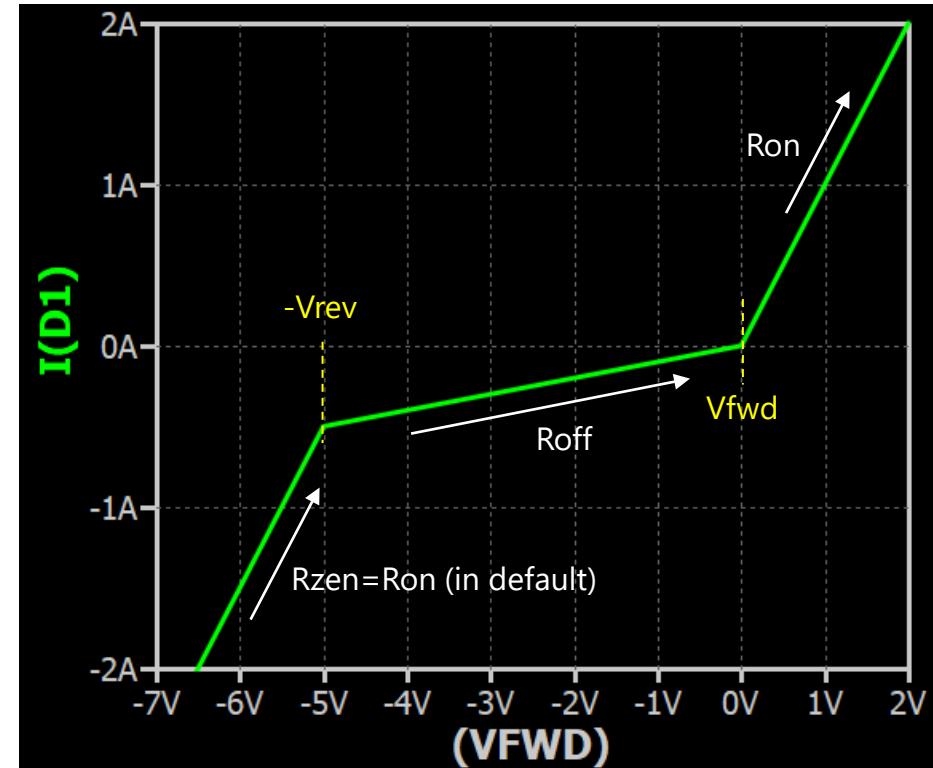
Behavioral Diode Model Params : Ron, Roff, Vfwd, Vrev

Qspice : Behavioral D Model - Ron Roff Vfwd Vrev.qsch



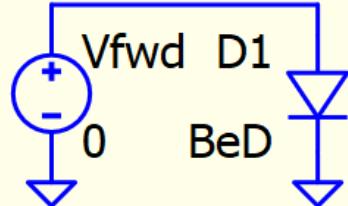
```
.model BeD D Ron=1 Roff=10  
+ Vfwd=0 Vrev=5  
+ Epsilon=0 Revepsilon=0  
.dc Vfwd -7 2 0.1  
.plot I(D1)
```

** Important Note : Refer to Qspice help, Ron must include and set to non-zero to activate behavioral diode model



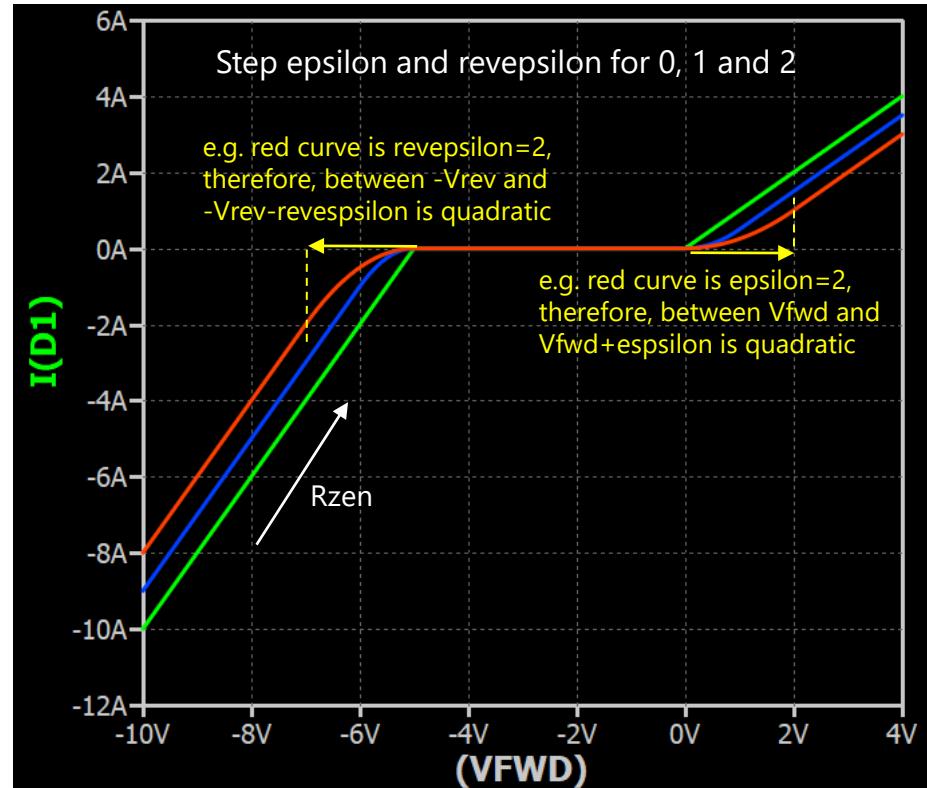
Behavioral Diode Model Params : Rzen, Epsilon, Revepsilon

Qspice : Behavioral D Model - Epsilon Revepsilon Rzen.qsch



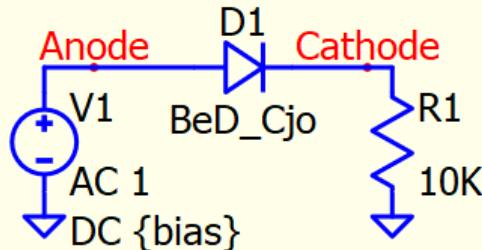
```
.model BeD D Ron=1 Roff=10Meg  
+ Vfwd=0 Vrev=5  
+ Epsilon={val} Revepsilon={val}  
+ Rzen=0.5  
  
.step param val 0 2 1  
.dc Vfwd -10 4 0.1  
.plot I(D1)
```

* Roff change to 10Meg in this study



Behavioral Diode Model Params : Cjo

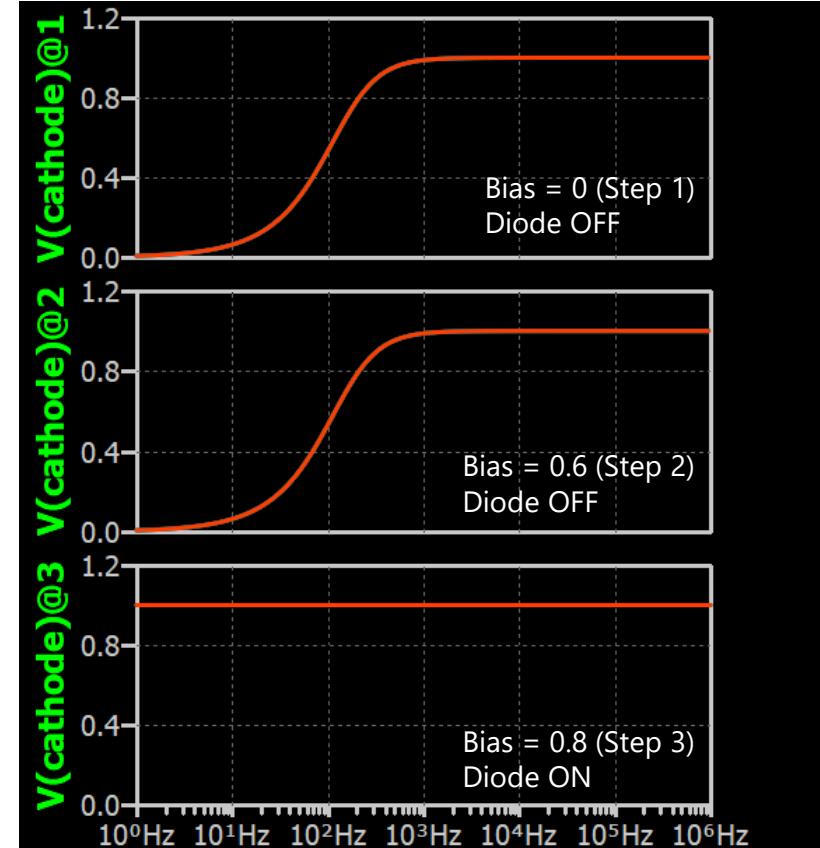
Qspice : Behavioral D Model - Cjo.qsch



```
.param bias = 0  
.model BeD_Cjo D Ron=1m Roff=1Meg  
+ Vfwd=0.7 Cjo=100n
```

Cjo is equivalent to a capacitor parallel the behavioral diode

```
.ac dec 100 1 1Meg  
.step param bias list 0 0.6 0.8  
  
.plot V(cathode)@3  
.plot V(cathode)@2  
.plot V(cathode)@1
```



D. Diode

Ideal Diode .model

Ideal Diode Model

Qspice : Special - IdealD (.dc).qsch / Special - IdealID (.tran).qsch

- Ideal Diode Characteristic
 - No breakdown current
 - No reverse leakage
 - No capacitance effect
 - No reverse recovery
- Ideal Model with Diode .model
 - .model Idlm D N=0.01 RS=10 μ ; Vf@1A=0
 - .model Idlm D N=0.36 RS=10 μ ; Vf@1A=0.3
 - .model Idlm D N=0.85 RS=10 μ ; Vf@1A=0.7
 - ** RS is added to prevent gmin stepping without series resistance
- Ideal Model with Behavioral Diode .model
 - .model IdealD D Vfwd=0 Ron=1m Roff=100Meg ; Vf,th=0
 - .model IdealD D Vfwd=0.3 Ron=1m Roff=100Meg ; Vf,th=0.3
 - .model IdealD D Vfwd=0.7 Ron=1m Roff=100Meg ; Vf,th=0.7

Diode Type

- Germanium
 - Bandgap : 0.67eV
- Silicon
 - Bandgap : 1.1eV
- Ultra-fast Recovery
- Silicon-Schottky
 - Bandgap : 0.69eV
- SiC-Schottky
 - Bandgap : 3.2eV
- GaN
 - Bandgap : 3.4eV
- Zener

E. F. G. H. Dependent Sources

E. F. G. H. Dependent Sources

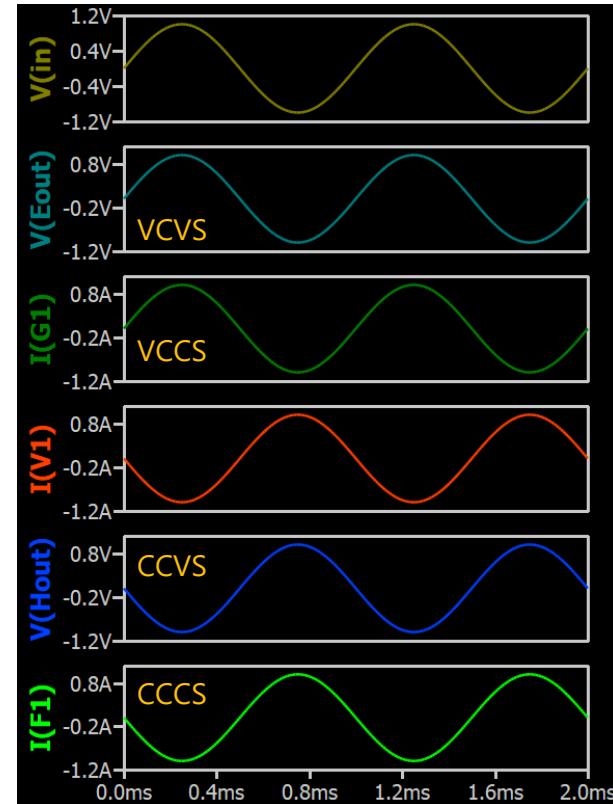
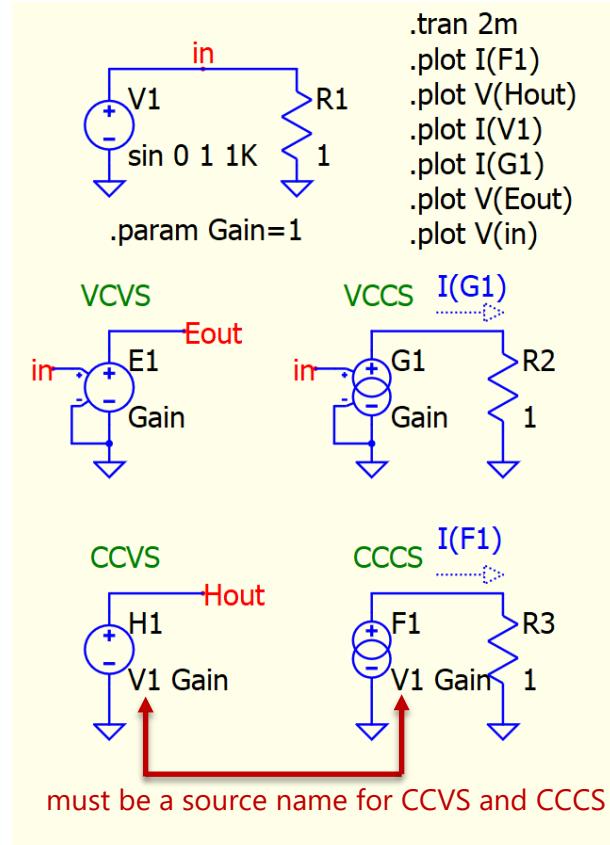
Qspice : Dependent Source - Basic.qsch

- Dependent Sources

- [E] VCVS : Voltage Dependent Voltage Source
- [G] VCCS : Voltage Dependent Current Source
- [H] CCVS : Current Dependent Voltage Source
- [F] CCCS : Current Dependent Current Source

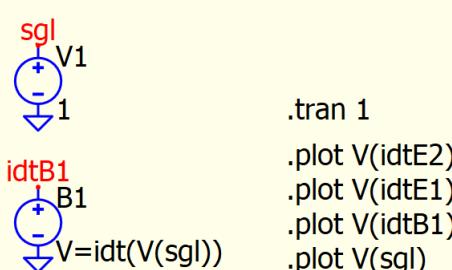
- ** Current Dependent Src

- For current dependent source, the current sense has to come from voltage source instead of current source
- A 0V voltage source can be used for current sensing
- (Explanation from Mike Engelhardt) Sensing the current in a current is complicated because it might have VSAT or VSAT2, meaning it's not a current source



E-Source Alternative Syntax

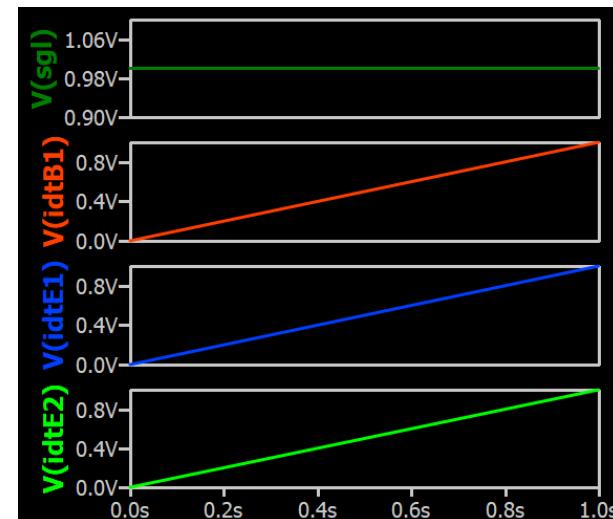
- E-source
 - Syntax: $E_{xxx} n+ n- \text{ value}=\{\text{<expression>}\}$
 - This is an alternative syntax of the behavioral voltage source (B-source)
 - This syntax only available in using text, no Qspice symbol support this format, for Qspice to backward compatible to legacy spice syntax



Syntax: $E_{xxx} n+ n- \text{ value}=\{\text{<expression>}\}$
alternative syntax of the behavioral source with E-source
formula must have curly bracket {}

E1 idtE1 0 Value $\{\text{idt}(V(\text{sgl}))\}$ ← Can accept without "="
E2 idtE2 0 Value= $\{\text{idt}(V(\text{sgl}))\}$

```
* C:\QspiceKSKelvin\01 User Gu
V1 sgl 0 1
B1 idtB1 0 V=idt(V(sgl))
E1 idtE1 0 Value {idt(V(sgl)) }
E2 idtE2 0 Value={idt(V(sgl)) }
.plot V(idtE2)
.plot V(idtE1)
.plot V(idtB1)
.plot V(sgl)
.tran 1
.end
```



I. Current Source

I. Current Source : Instance Parameters

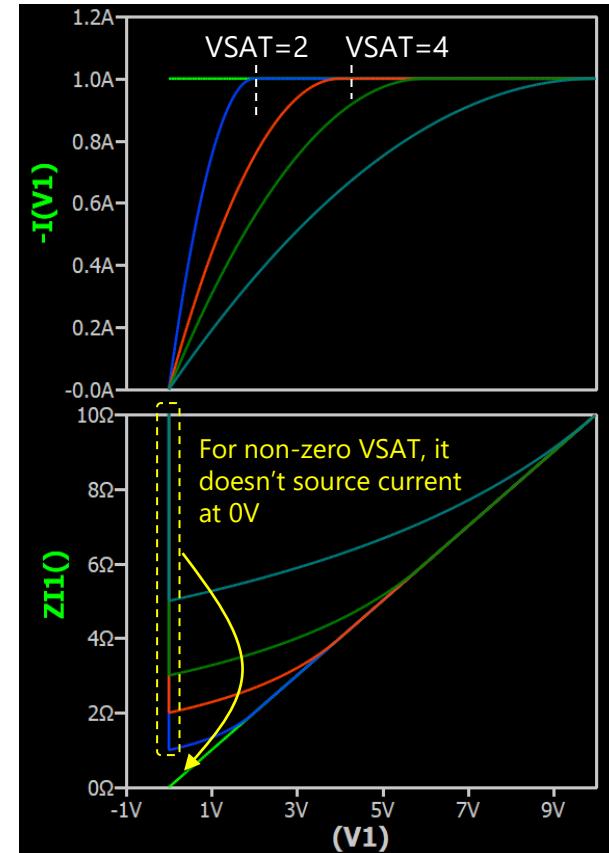
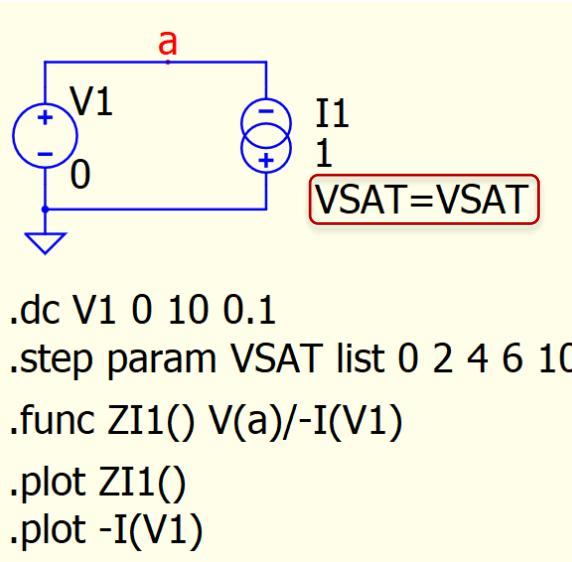
Current Source Instance Parameters

| Name | Description | Units | Default |
|-------------------|---|--------|-----------|
| AC | AC magnitude, optionally followed by phase angle | A, ° | 0. |
| ACMAG | AC magnitude | A | 0. |
| ACPHASE | AC phase | ° | 0. |
| DC | DC value of source | A | 0. |
| EXP | Exponential source description | | |
| LOG | Interpolate between PWL and CHIRP points | | (not set) |
| PULSE | Pulse description | | |
| PWL | Piecewise linear description | | |
| SFFM | Single frequency FM description | | |
| SINE | Sinusoidal source description(aka SIN) | | |
| TIMECTRL | Time step control, one of NONE, LIMITS ¹ , BREAKS ² , or BOTH | String | LIMITS |
| VSAT ³ | Don't source power(example) | V | 0. |
| VSAT2 | Don't source power and don't conduct in reverse | V | 0. |
| XTRAP | Extrapolate beyond PWL and CHIRP points | | (not set) |

I. Instance Params : VSAT

Qspice : I Source - VSAT.qsch

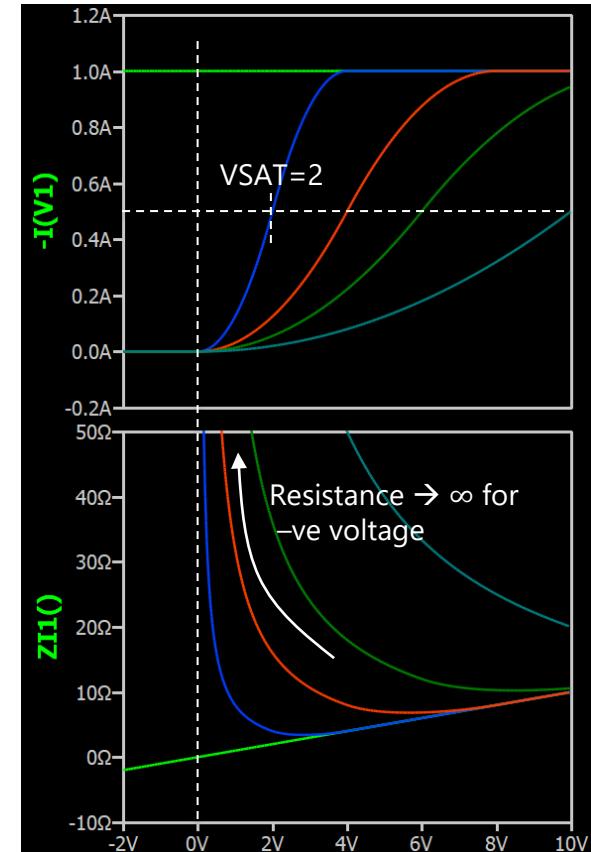
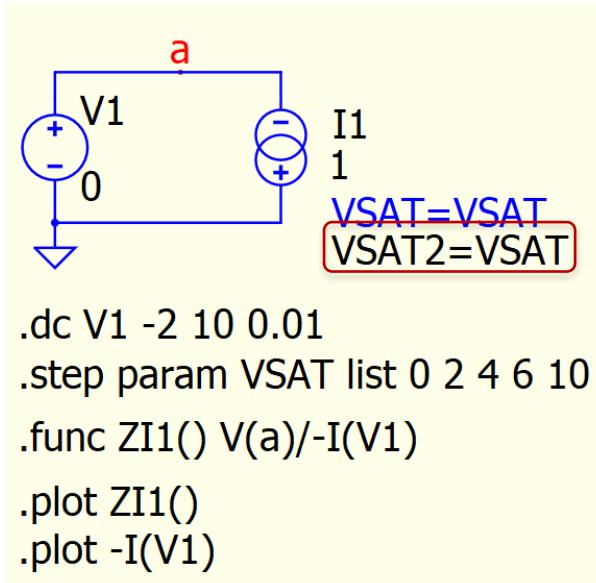
- VSAT
 - VSAT : Does **NOT** source power
 - **Default VSAT=0V**
 - Characteristic
 - Only source current when $V(-ve,+ve) > VSAT$
 - Current source doesn't source current at $V(-ve,+ve)=0$
 - Equivalent to Open
 - Not to apply negative voltage between $V(-ve,+ve)$ as it will have current flow out from -ve
 - Usage
 - Useful for modeling an active load or a bias current in a macromodel



I. Instance Params : VSAT2

Qspice : I Source - VSAT2.qsch

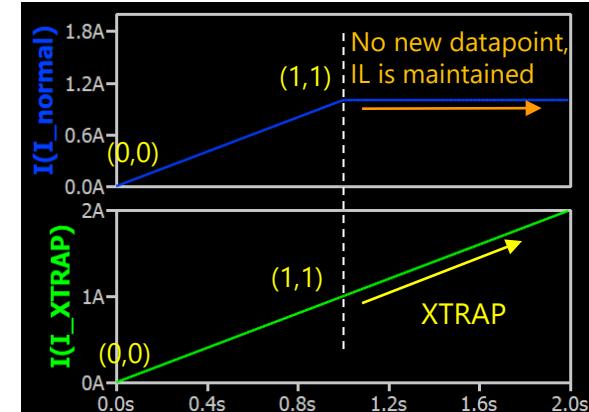
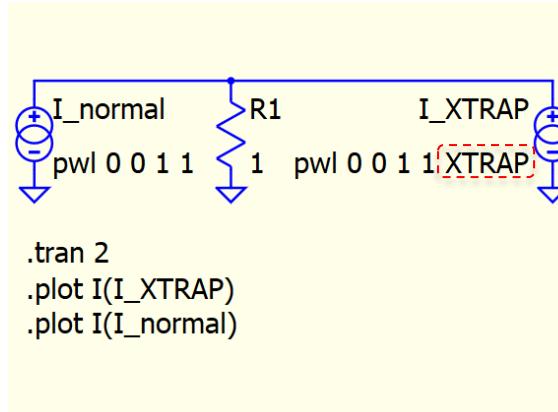
- VSAT2
 - VSAT2 : Does **NOT** source power and **NOT** conduct in reverse
 - **Default VSAT2=0V**
 - If VSAT2 is used, VSAT will be overridden



I. Instance Params : XTRAP

Qspice : I Source - XTRAP.qsch

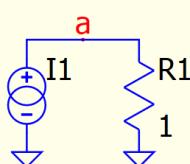
- XTRAP
 - Xtrap : Extrapolate beyond PWL and CHIRP points
 - **Default XTRAP is not set**
 - Without XTRAP, the current stays constant with the value specified with the last time point



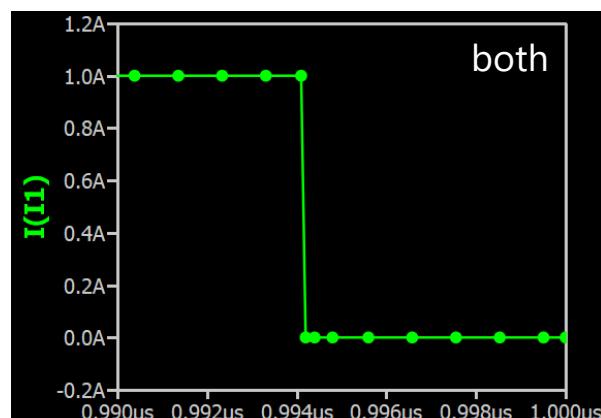
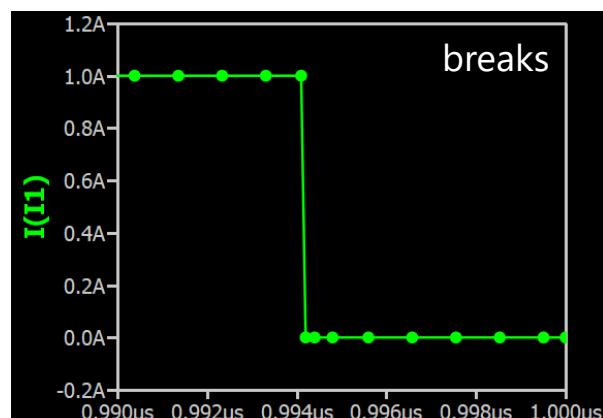
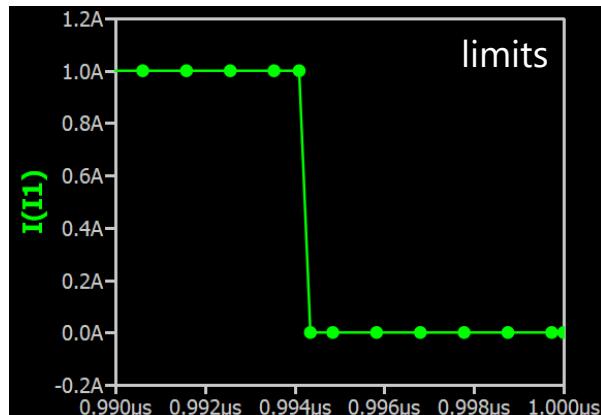
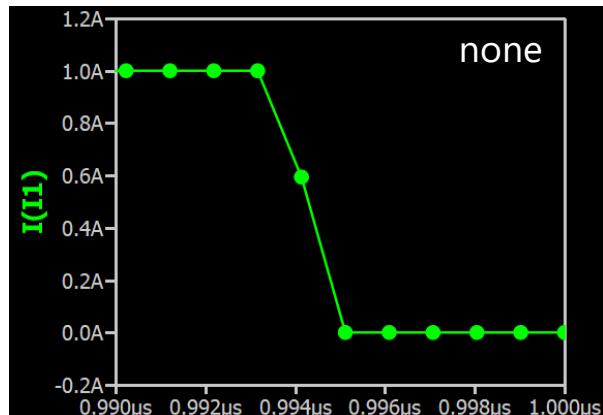
I. Instance Params : Timectrl

Qspice : I Source - TIMECTRL.qsch

- TIMECTRL
 - Timectrl : Time step control
 - None
 - Limits
 - Breaks
 - Both
 - **Default Timectrl=Limits**



pulse 0 1 4n 0 0 10n 20n
Timectrl=none
Timectrl=limits
Timectrl=breaks
Timectrl=both
.tran 1000n
.plot I(I1) I(I2)



J. JFET Transistor

J. JFET Model Parameters

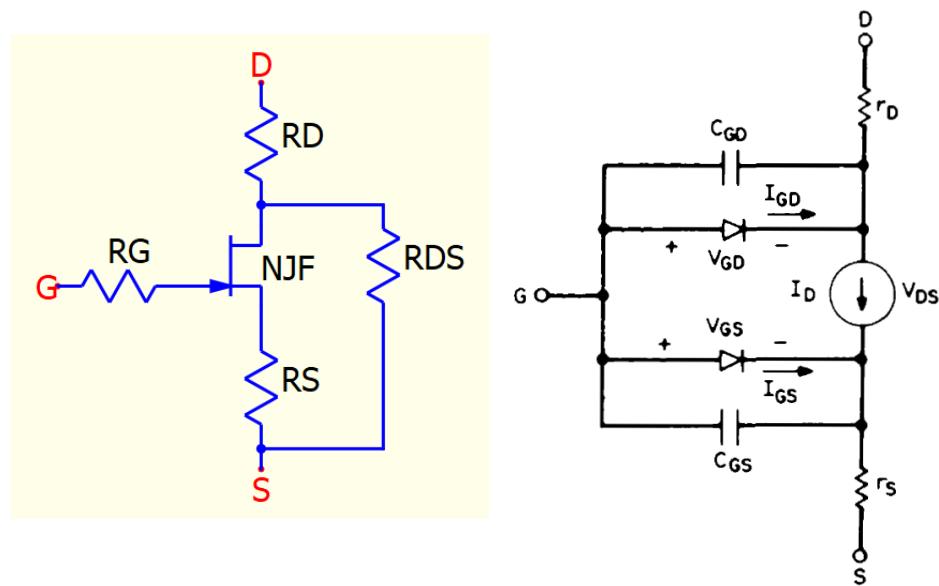
JFET Model Parameters

| Name | Description | Units | Default |
|---------|--|------------------|---------|
| AF | Flicker noise exponent | | 1.0 |
| ALPHA | Impact ionization coefficient | V ⁻¹ | 0.0 |
| B | Doping tail parameter | | 0.0 |
| BETA | Transconductance parameter | A/V ² | 0.0001 |
| BETATCE | Exponential transconductance parameter temperature coefficient | %/°C | 0.0 |
| CGD | Zero-bias G-D junction capacitance | F | 0.0 |
| CGDO | G-D overlap(i.e. constant) capacitance | F | 0.0 |
| CGS | Zero-bias G-S junction capacitance | F | 0.0 |
| CGSO | G-S overlap(i.e. constant) capacitance | F | 0.0 |
| ETA | Philips, et al.-style subthreshold conduction parameter | | 0.0 |
| ETATC1 | ETA first order tempco | °C ⁻¹ | 0.0 |
| ETATC2 | ETA second order tempco | °C ⁻² | 0.0 |
| FC | Forward bias junction fit parameter | | 0.5 |
| GDSNOI | Shot noise coefficient for nlev = 3 | A | 2.0 |
| GMAX | Maximum junction conductivity(straight line extension) | Ω | 10K |
| IS | Junction saturation current | A | 1e-14 |
| ISR | Recombination current parameter | A | 0.0 |
| KF | Flicker Noise Coefficient | | 0.0 |
| LAMBDA | Channel length modulation parameter | V ⁻¹ | 1.0 |
| M | Grading coefficient(aka MJ) | | 0.5 |
| N | Emission coefficient | | 1.0 |

| | | | |
|--------|---|------------------|----------|
| NLEV | Noise level(equation selector) | | 0.0 |
| NR | ISR emission coefficient | | 2.0 |
| PB | Gate junction potential | V | 1.0 |
| RD | Drain resistance | Ω | 0.0 |
| RDTC1 | RD first order tempco | °C ⁻¹ | 0.0 |
| RDTC2 | RD second order tempco | °C ⁻² | 0.0 |
| RDS | Additional Drain-Source leakage resistance | Ω | infinite |
| RDSTC1 | RDS first order tempco | °C ⁻¹ | 0.0 |
| RDSTC2 | RDS second order tempco | °C ⁻² | 0.0 |
| RG | Gate resistance | Ω | 0.0 |
| RGTC1 | RG first order tempco | °C ⁻¹ | 0.0 |
| RGTC2 | RG second order tempco | °C ⁻² | 0.0 |
| RONX | Channel conductivity multiplier in linear region ¹ | | 1.0 |
| RS | Source resistance | Ω | 0.0 |
| RSTC1 | RS first order tempco | °C ⁻¹ | 0.0 |
| RSTC2 | RS second order tempco | °C ⁻² | 0.0 |
| TNOM | Parameter measurement temperature(aka TREF) | V | 0.0 |
| VK | Impact ionization knee current | V | 0.0 |
| VT0 | Threshold Voltage(aka VTO or VT) | V | -2.0 |
| VTOTC | Threshold Voltage temperature coefficient | °C ⁻¹ | 1.0 |
| XTI | Saturation current temperature exponent | | 3.0 |

J. JFET Basic Equation

- JFET equation in Semiconductor Device Modeling with SPICE Section 3.1.3)
 - For channel pinched off : $V_{GS} - V_{T0} \leq 0$
 - $I_D = 0$
 - For saturated region : $0 \leq V_{GS} - V_{T0} \leq V_{DS}$
 - $I_D = \beta (V_{GS} - V_{T0})^2 (1 + \lambda V_{DS})$
 - For linear region : $0 < V_{DS} < V_{GS} - V_{T0}$
 - $I_D = \beta [2 (V_{GS} - V_{T0}) - V_{DS}] (1 + \lambda V_{DS})$

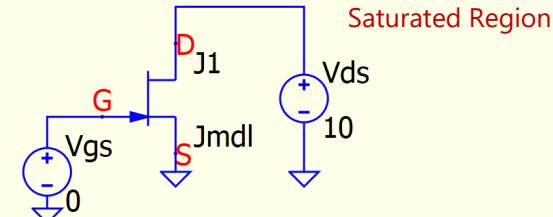


J. JFET Instance Params (I_D) : BETA and VTO

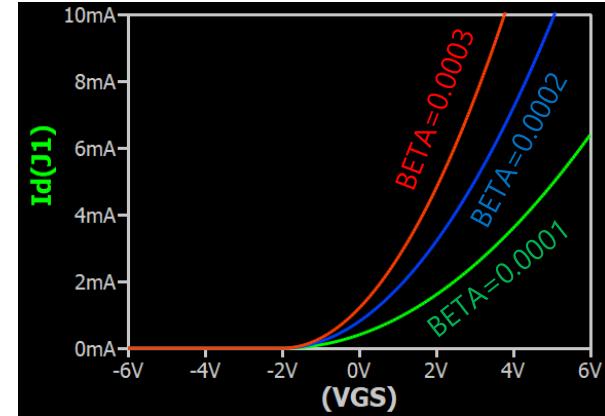
Qspice : JFET - Beta.qsch / JFET - VTO.qsch

- BETA

- Beta : Transconductance parameter
- Default BETA=0.0001A/V²**
- $I_D = \beta (V_{GS} - V_{T0})^2 (1 + \lambda V_{DS})$

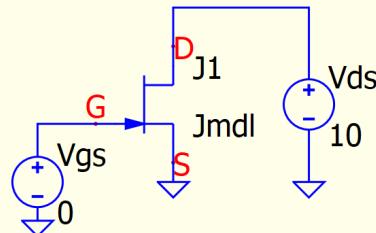


```
.dc Vgs -5 5 0.01  
.plot Id(J1)  
.step param beta list 0.0001 0.0002 0.0003  
.model Jmdl NJF BETA={beta}
```

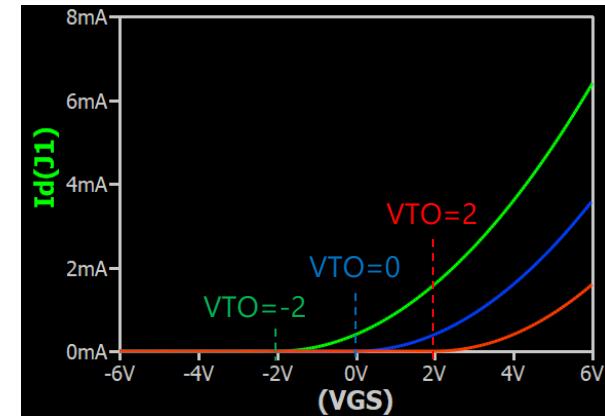


- VTO (aka VT0 or VT)

- VTO : Threshold Voltage
- Default VTO=-2V**
- $I_D = \beta (V_{GS} - V_{T0})^2 (1 + \lambda V_{DS})$



```
.dc Vgs -6 6 0.01  
.plot Id(J1)  
.step param vto list -2 0 2  
.model Jmdl NJF VTO={vto}
```

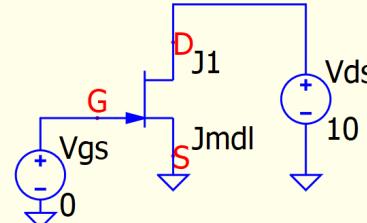


J. JFET Instance Params (I_D) : Lambda and Betatce

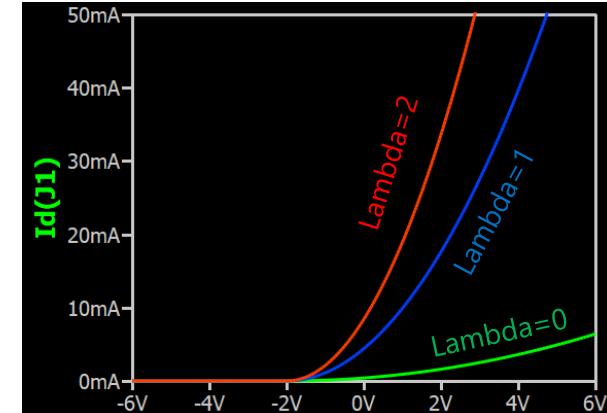
Qspice : JFET - LAMBDA.qsch / JFET - BETATCE.qsch

LAMBDA

- Lambda : Channel length modulation parameter
- **Default LAMBDA=0V⁻¹**
- $I_D = \beta (V_{GS} - V_{T0})^2 (1 + \lambda V_{DS})$

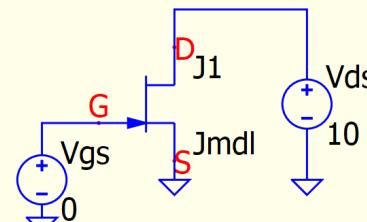


```
.dc Vgs -6 6 0.01  
.plot Id(J1)  
.step param lambda list 0 1 2  
.model Jmdl NJF LAMBDA={lambda}
```

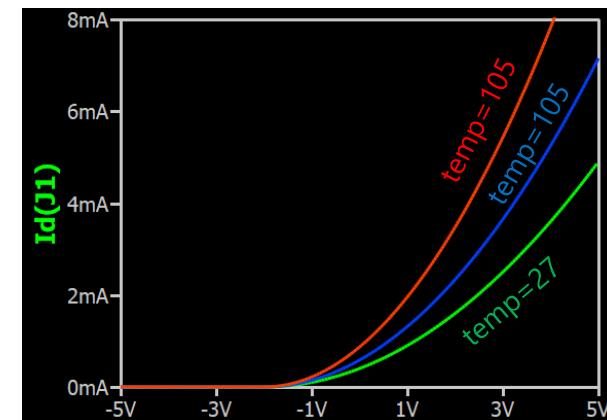


BETATCE

- Betatce : Exponential transconductance parameter temperature coefficient
- **Default BETATCE=0 (%/°C)**



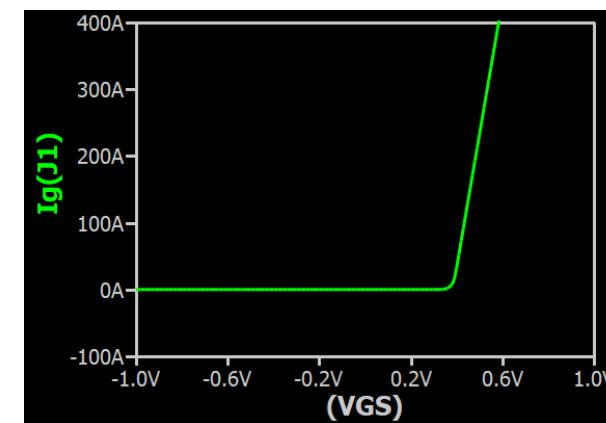
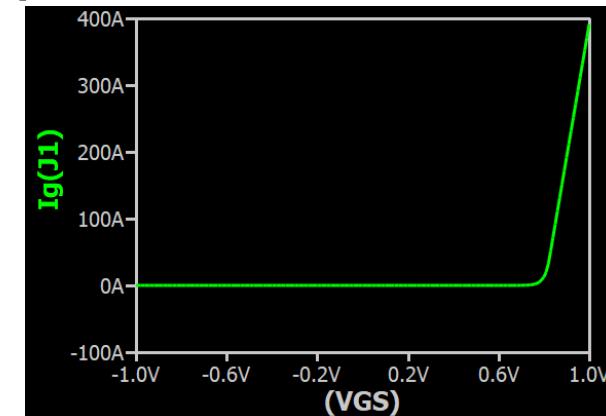
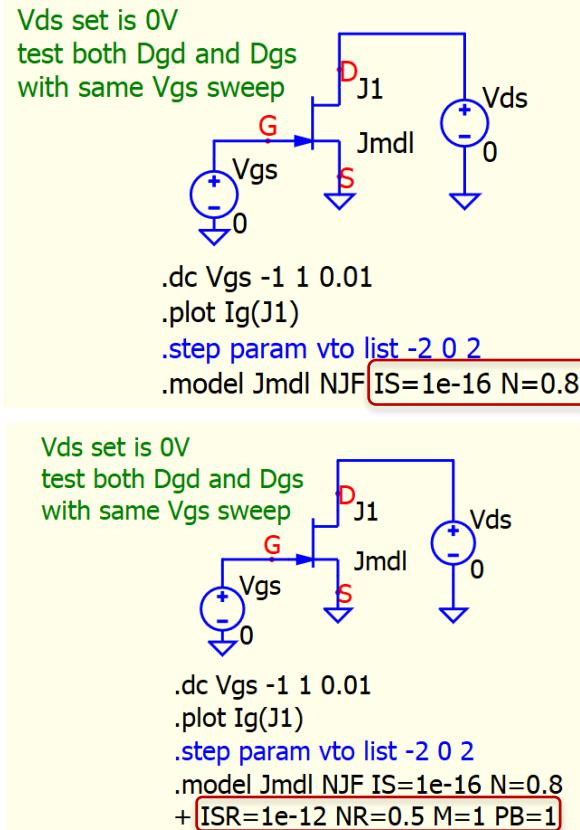
```
.dc Vgs -5 5 0.01 .temp 27 65 105  
.plot Id(J1)  
.param betatce=1  
.model Jmdl NJF BETATCE={betatce}
```



J. JFET Instance Params (Diode GD and GS) : IS, N, ISR, NR, M and PB

Qspice : JFET - IS N.qsch / JFET - ISR NR M PB.qsch

- Two diodes in JFET
 - DGD and DGS
 - These two diodes are identical model, with recombination current included
 - $I_{GS} = (I_F + K_{gen}I_R) + I_I$
 - $I_F = I_S \left(e^{\frac{qV_D}{nKT}} - 1 \right)$
 - $I_R = I_{SR} \left(e^{\frac{qV_D}{n_RKT}} - 1 \right)$
 - $K_{gen} = \sqrt{\left[\left(1 - \frac{V_D}{\Phi_0} \right)^2 + 0.005 \right]^m}$
 - I_S : IS Junction saturation current (Default IS=1e-14A)
 - n : N emission coefficient (Default N=1)
 - I_{SR} : ISR Recombination current parameter (Default ISR=0A)
 - n_R : ISR emission coefficient (Default NR=1)
 - m : M Grading coefficient (Default M=0.5)
 - Φ_0 : PB Gate junction potential (Default PB=1V)
- Diode modeling refer to D. Diode section



J. JFET Instance Params (Diode GS) : Alpha and VK

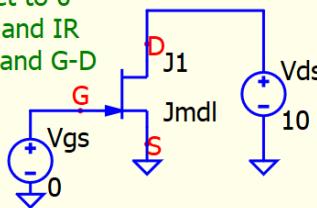
Qspice : JFET - ALPHA VK.qsch

- Gate Source Diode in Pspice model

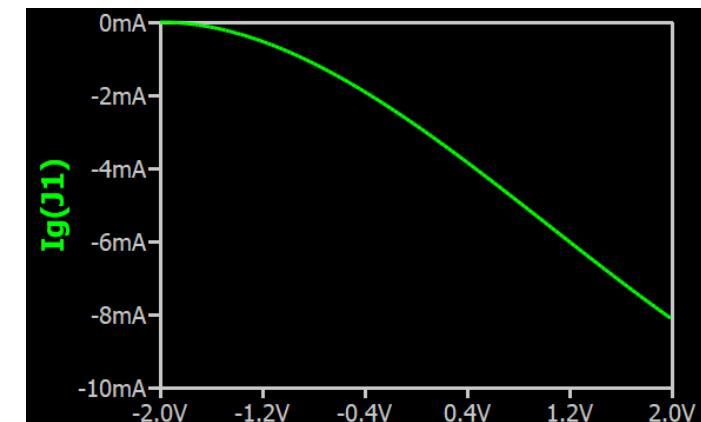
$$I_{GS} = (I_F + K_{gen} I_R) + I_I$$

- $I_I = \alpha I_D [V_{DS} - (V_{GS} - V_{TO})] e^{\frac{V_k}{V_{DS} - (V_{GS} - V_{TO})}}$ for $0 < G_{GS} - V_{TO} < V_{DS}$
- $I_I = 0$ otherwise
- α is ALPHA Impact ionization coefficient (Default ALPHA=0V⁻¹)
- V_k is VK Impact ionization knee current (Default VK=0V)

IS and ISR set to 0
to disable IF and IR
in diode G-S and G-D



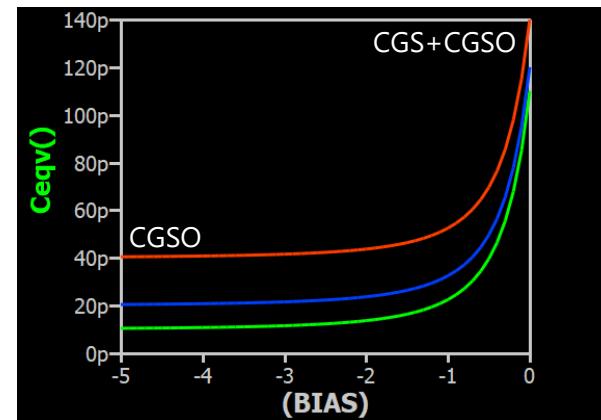
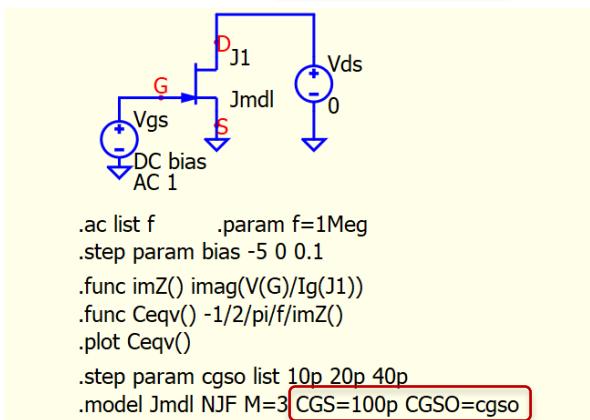
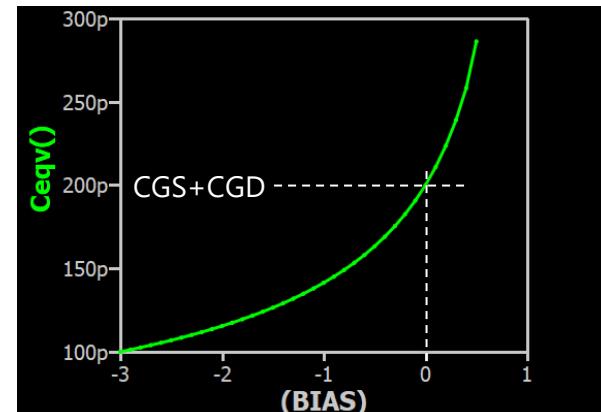
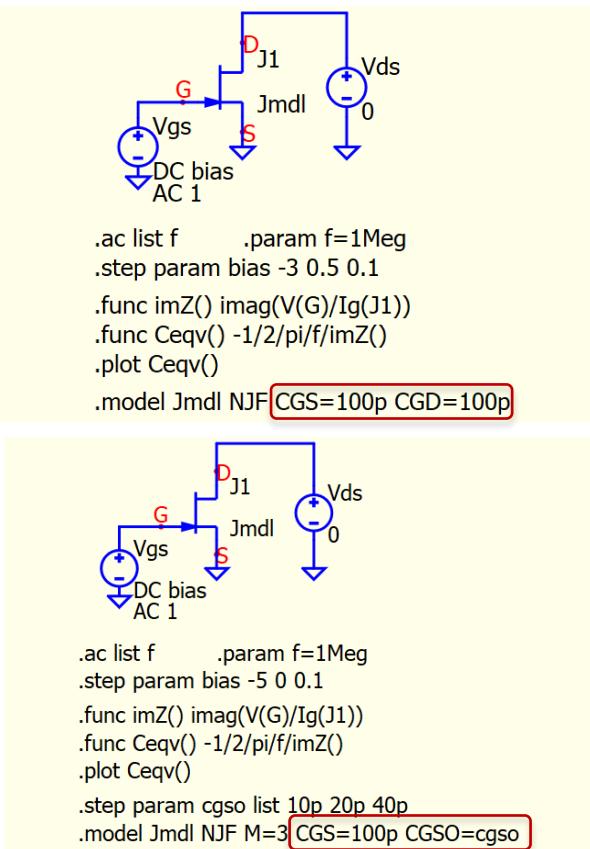
```
.dc Vgs -2 2 0.01
.plot Ig(J1)
.step param vto list -2 0 2
.model Jmdl NJF IS=0 ISR=0
+ALPHA=1 VK=1
```



J. JFET Instance Params (Capacitance) : CGS, CGD, CGSO, CDSO

Qspice : JFET - CGS CGD.qsch / JFET - CGSO CGDO.qsch

- CGS, CGD
 - CGS : Zero-bias G-D junction capacitance
 - CGD : Zero-bias G-S junction capacitance
 - **Default CGS=0F**
 - **Default CGD=0F**
 - This example simulate with both CGS and CGD
- CGSO, CDSO
 - CGSO : G-S overlap capacitance
 - CDSO : D-S overlap capacitance
 - **Default CGSO=0F**
 - **Default CDSO=0F**
 - This example only simulate CGS with CGSO. GDSO has same effect but to affect CDSO
 - ** M, PB, FC has effect in junction capacitance, refer to D. diode



K. Mutual Inductance

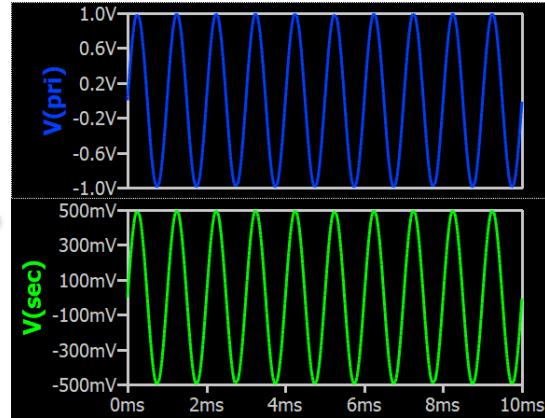
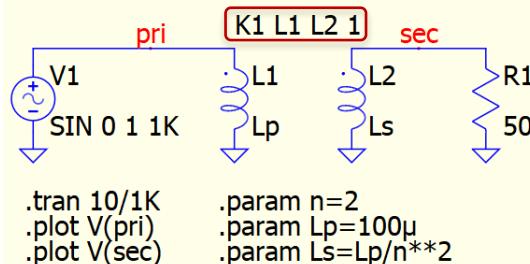
K. Mutual Inductance

Qspice : K Mutual - Two Winding.qsch / K Mutual - Three Winding.qsch

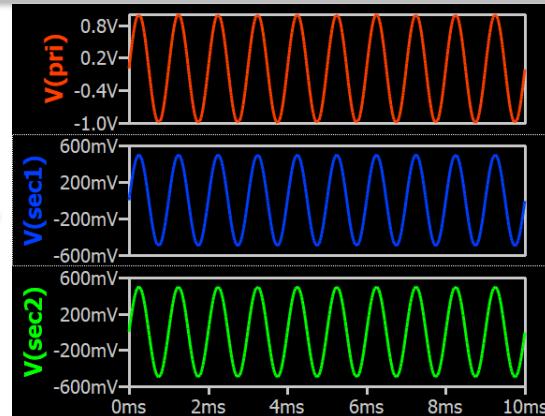
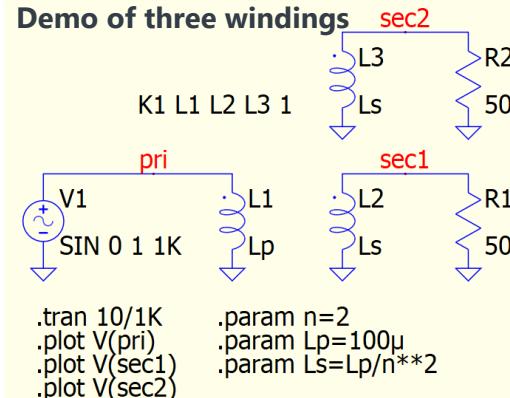
- K Mutual Inductance
 - K : coupling coefficient of coupled inductors
 - Ideal coupling : 1
 - Range : -1 to 1
 - Two or more coupled inductors are required
 - Press L two times to get symbol with a dot notation (not necessary, but recommend for current direction)

- Inductors as Transformer
 - $\frac{L_p}{N_p^2} = \frac{L_s}{N_s^2}$ and $n = \frac{N_p}{N_s}$
 - N is number of turns
 - $L_p = n^2 L_s$ or $L_s = \frac{1}{n^2} L_p$
 - In practice, L_p is measured from primary with secondary open

Demo of two windings



Demo of three windings



L. Inductor

Inductor L Instance Parameters in Qspice HELP

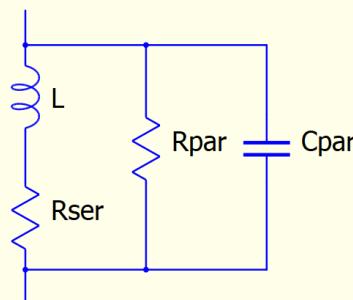
| Inductor Instance Parameters | | | |
|------------------------------|---|-------|-------------------------|
| Name | Description | Units | Default |
| AU | Wire or stripline is made of gold | | |
| AL | Wire or stripline is made of aluminum | | see below |
| AG | Wire or stripline is made of silver | | |
| BEND | Fractional inductance correction for wire bend or proximity effects | | 1. |
| CPAR | Parallel capacitance | F | 0. |
| CU | Wire or stripline is made of copper | | see below |
| DIAMETER | Diameter of wire or air coil | m | |
| FREQUENCY | Frequency at Q. Also used to compute Rser due to skin effect | | |
| HEIGHT | Height of PCB stripline above ground plane | m | |
| IC | Initial current if uic is specified on .tran statement | A | none |
| INDUCTANCE | Inductance of inductor | H | 0.0 |
| ISAT | Current causing inductance to drop to SATFRAC×INDUCTANCE | A | Infinite |
| LENGTH | Length of wire, stripline, or air coil | m | |
| LSAT | Inductance asymptotically approached in saturation | H | 10% of INDUCTANCE |
| M | Number of parallel inductors | | 1.0 |
| NI | Wire is made of nickel | | |
| Q | Quality factor at FREQUENCY | | |
| RPAR ¹ | Equivalent parallel resistance | Ω | INDUCTANCE÷(15.91×GMIN) |
| RSER | Equivalent series resistance | Ω | 0.0 |
| SATFRAC | Fractional drop in inductance at ISAT | | 0.7 |
| TC ² | Temperature coefficient polynomial | | (none) |
| TC1 ² | 1st order temperature coefficient | | 0.0 |
| TC2 ² | 2nd order temperature coefficient | | 0.0 |
| THICK | Thickness of stripline on top of a PCB | m | 0.0 |
| TNOM | Temperature inductance was measured(aka TREF) | °C | Circuit TNOM |
| TURNS | Number of turns of an air coil | | |
| VERBOSE | Print wire L, Rser, Rpar results on the console | | (not set) |
| WIDTH | Width of stripline on top of a PCB | m | |

Arbitrary Inductance Device

QSPICE also supports an arbitrary inductance device. To use it, give an equation for the flux due to the inductor. The equation can include any circuit node voltages or device currents of devices modeled as Thévenin equivalents(V-, L-, E-, or H- devices). In the interest of completeness, the device supports transinductance.

Syntax: Cnnn N1 N2 Q=<expression> [additional instance parameters]

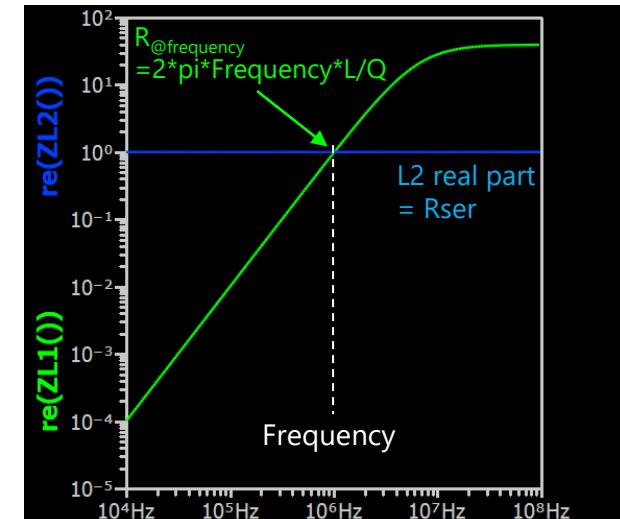
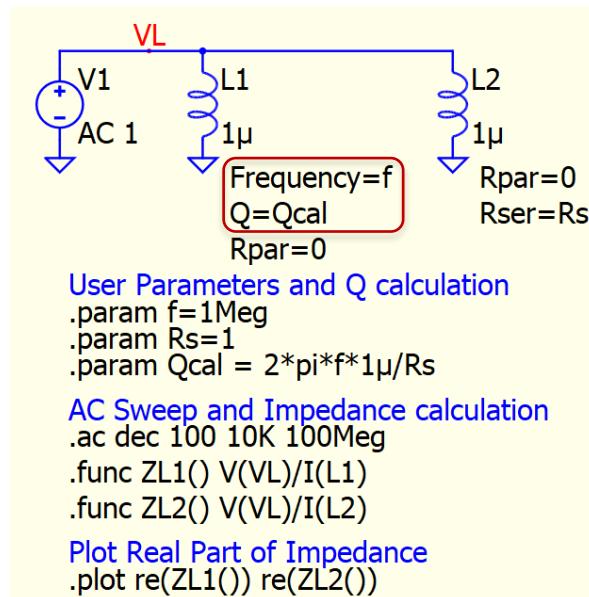
| Name | Description | Units | Default |
|-----------|--|-------|---------------------|
| FLUX | Equation of flux(aka F) | Weber | |
| IC | Initial flux due to the inductor | Weber | |
| M | Number of identical parallel devices | | 1.0 |
| RPAR | Equivalent parallel resistance | Ω | Infinite |
| RSER | Equivalent series resistance | Ω | 0.0 |
| NOISELESS | Ignore the noise contribution from RPAR and RSER | | not set |
| TEMP | Instance temperature | °C | Circuit temperature |



L. Instance Params : Rser, Frequency and Q

Qspice : L - Rser Frequency Q.qsch

- Rser
 - Equivalent series resistance
 - Default Rser=0
 - Rser is a constant over entire frequency
- Frequency and Q
 - Frequency : Frequency at Q, also used to compute Rser due to skin effect
 - Q : Quality factor at FREQUENCY
 - Formula
 - $Q = \frac{x_L}{R} = \frac{2\pi f L}{R_{@f}}$
 - Therefore, series resistance can change over frequency to simulate skin effect if Frequency and Q are used

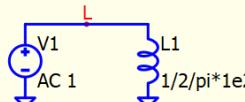


L. Instance Params : Rpar – Equivalent Parallel Resistance

Qspice : L - Rpar Prove.qsch | L - Rpar (.option LFT).qsch

- Rpar
 - Equivalent parallel resistance
 - Default
Rpar=Inductance/(15.91*Gmin)
 - 15.91 is only an approximate, exact formula is $\frac{10^2}{2\pi}$
 - Gmin is minimum conductance in .option, default gmin=1e-12
 - To calculate Rpar, .ac analysis is used, with Lp-Rp model (Rpar=Rp)
 - Impedance : $Z = \frac{V}{I}$
 - Admittance : $Y = \frac{Z}{jB} = G + jB$
 - $Rp = \frac{1}{G}$, where G is conductance
- .option LFT for Rpar
 - If circuit option LFT is sent, then the resistance is chosen to be equal to the reactance at frequency LFT
 - Rpar formula changed to **Rpar = $2\pi LFT * Inductance$**

Default Rpar=Inductance/(15.91*Gmin) in HELP
**15.91 is approximation from $1/2/\pi*1e2$



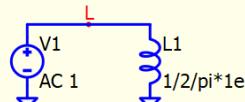
.ac dec 100 1 100Meg
Default gmin in Qspice is 1e-12
.option gmin=1e-12

Formula to calculate Rp from Lp-Rp model
.func Z() V(L)/I(L1)
.func Y() 1/Z()
.func Rp() 1/re(Y())
.plot Rp()

** Inductor always with a default Rpar!



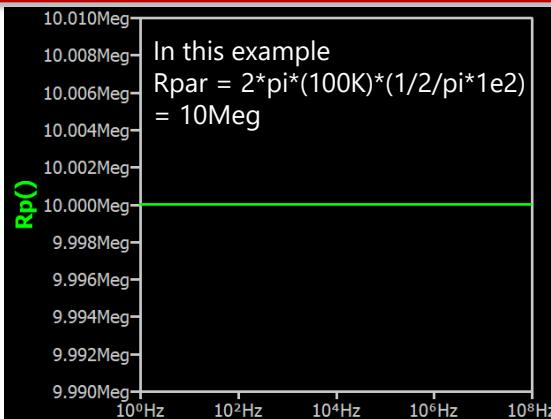
Default Rpar=Inductance/(15.91*Gmin) in HELP
**15.91 is approximation from $1/2/\pi*1e2$



.option LFT=100K
.ac dec 100 1 100Meg
Default gmin in Qspice is 1e-12
.option gmin=1e-12

Formula to calculate Rp from Lp-Rp model
.func Z() V(L)/I(L1)
.func Y() 1/Z()
.func Rp() 1/re(Y())
.plot Rp()

** If .option LFT is used, Rpar formula is changed



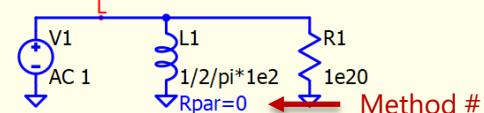
L. Instance Params : Rpar – Equivalent Parallel Resistance

Qspice : L - Rpar=0 Gmin=1e-308 LFT=1e308.qsch

- Force Rpar to Infinite

- If simulation requires to set Rpar to infinite, three method can be considered
- #1 : Set Rpar=0
 - This method is mentioned by Mike Engelhardt in Qspice forum and not documented in HELP
- #2 : Set gmin=1e-308
 - As $1/gmin$ is infinite, Rpar becomes infinite
 - This is useful if multiple inductors in schematic, but be caution it may introduce other problem if non-linear device in schematic when gmin is required
- #3 : Set .option LFT=1e308
 - As LFT is infinite, Rpar becomes infinite
 - I suggest to use this method
- In this demonstration, a R1 is added in parallel for visual aids, as Rpar=infinite will return NaN in Rp() and nothing is shown in waveform viewer.

Default Rpar=Inductance/(15.91*Gmin) in HELP
**15.91 is approximation from $1/2/\pi^2 \cdot 10^2$



.ac dec 100 1 100Meg

Default gmin in Qspice is 1e-12

.option gmin=1e-308

.option LFT=1e308

Method #1

Method #2 : $Rpar = Inductance / (1591 * Gmin)$

Method #3 : $Rpar = 2 * \pi * LFT * Inductance$

Formula to calculate Rp from Lp-Rp model:

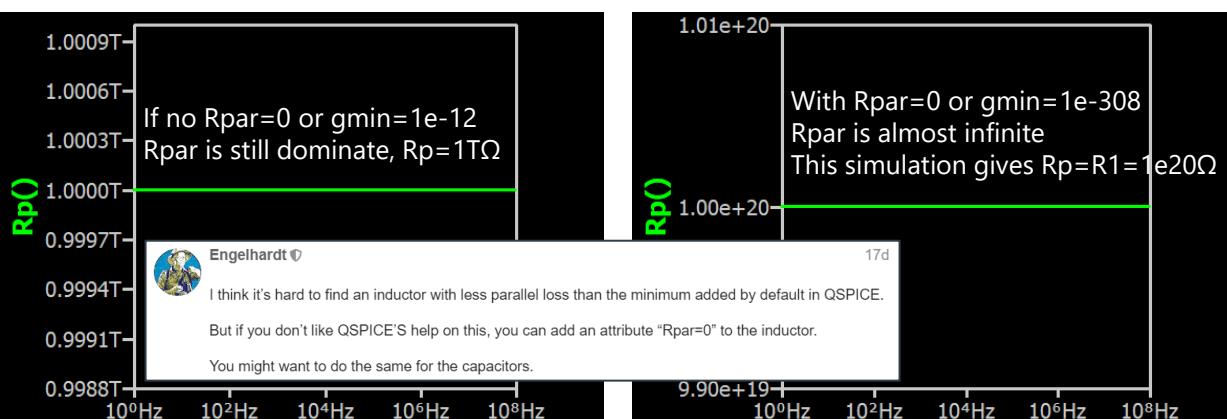
.func Z() V(L)/-I(V1)

.func Y() 1/Z()

.func Rp() 1/re(Y())

.plot Rp()

Impedance calculated from source V1 for this demonstration



L. Instance Params : Rpar – Equivalent Parallel Resistance

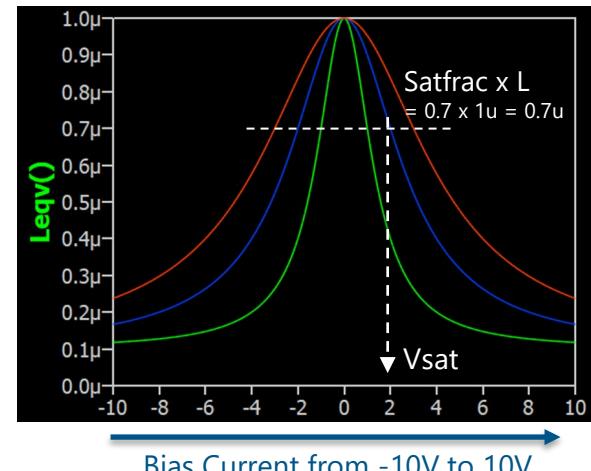
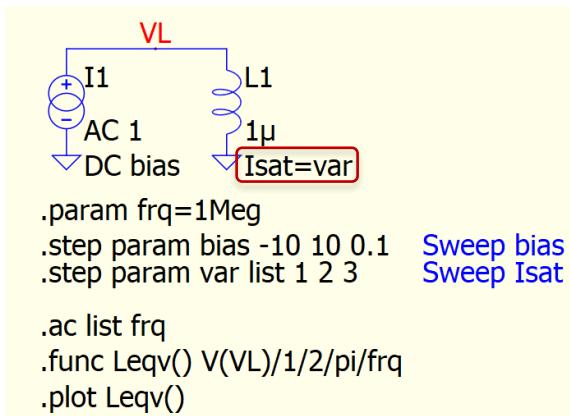
- Quick Summary of Rpar
- Rpar formula priority
 - 1st priority : If **Rpar=<value>**, Rpar is set to equal <value>
 - 2nd priority : If **.option LFT** is set and **without Rpar**, $Rpar = 2\pi LFT * \text{Inductance}$
 - 3rd priority : If **no .option LFT** and **without Rpar**, $Rpar = \text{Inductance}/(15.91*gmin)$
- Force Rpar to Infinite
 - #1 : Set Instance parameter Rpar=0 individually
 - #2 : Set **.option LFT=1e308**
 - #3 : Set **.option gmin=1e-308** (not recommend)

L. Instance Params : Isat, Lsat, Satfrac - For Nonlinear Inductance

Qspice : L Inductor - Isat (.ac).qsch

- Isat and Satfrac

- Isat : Current that drops inductance to **Satfrac x Inductance**
- Satfrac : Fractional drop in inductance at Isat
- **Default ISAT=Infinite (A)**
- **Default SATFRAC=0.7**
- Nonlinear effect is valid in +ve and -ve current direction



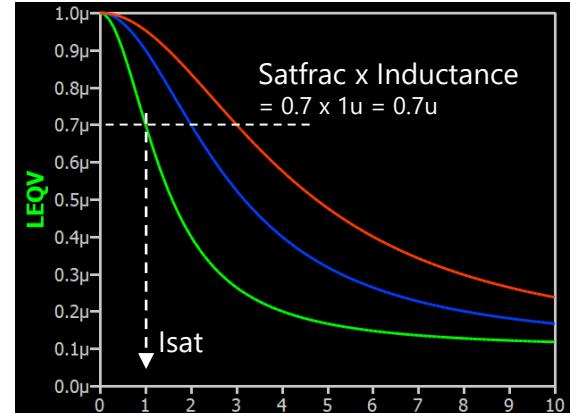
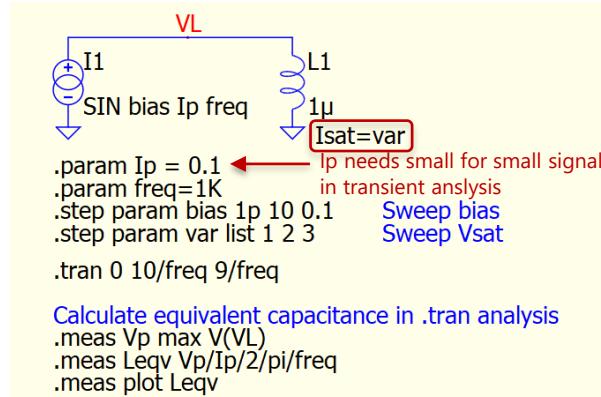
- Inductance equation

- $X_L = \omega L = \frac{V_L}{I_L}$
- $L = \frac{|V_L|}{|I_L|} \frac{1}{\omega} = \frac{|V_L|}{2\pi f |I_L|}$
- This formula is used to calculate equivalent inductance (small signal model) at different inductor bias current

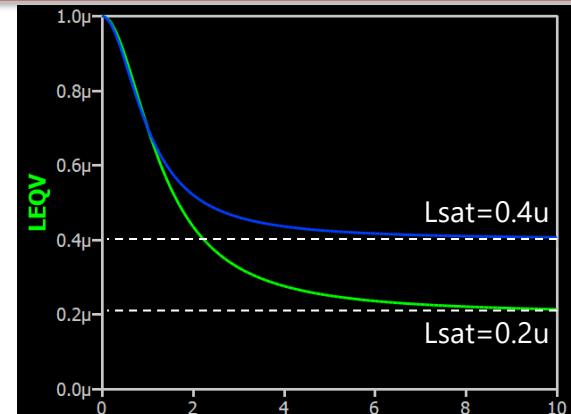
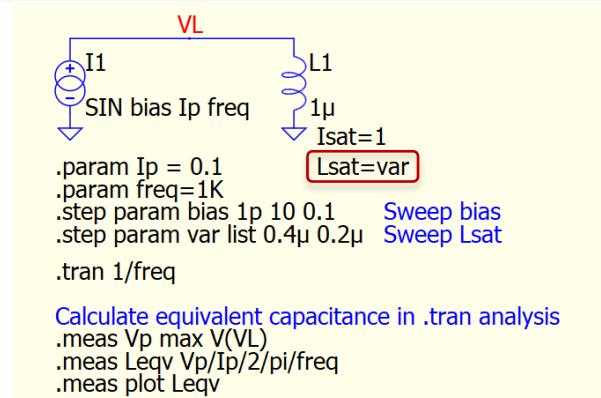
L. Instance Params : Isat, Lsat, Satfrac - For Nonlinear Inductance

Qspice : L Inductor - Isat (.tran).qsch / L Inductor - Lsat (.tran).qsch

- Isat and Satfrac
 - **Isat** : Current that drops inductance to **Satfrac x Inductance**
 - **Satfrac** : Fractional drop in inductance at Isat
 - **Default ISAT=Infinite (A)**
 - **Default SATFRAC=0.7**



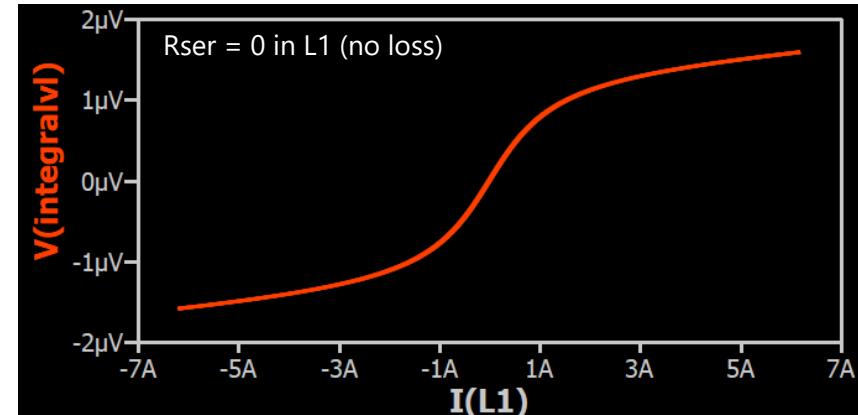
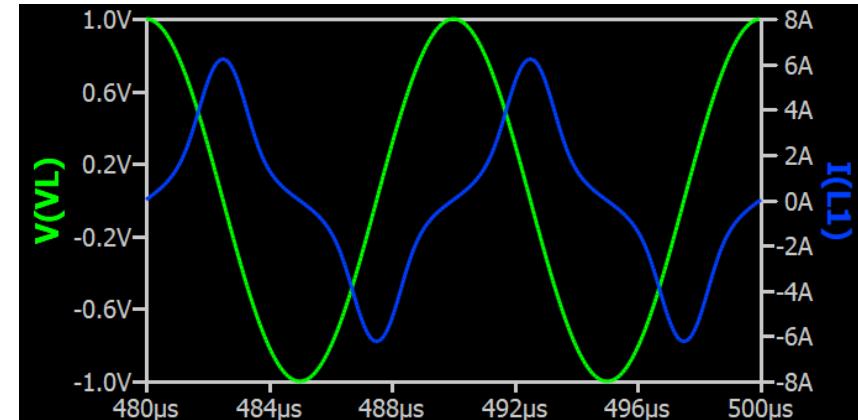
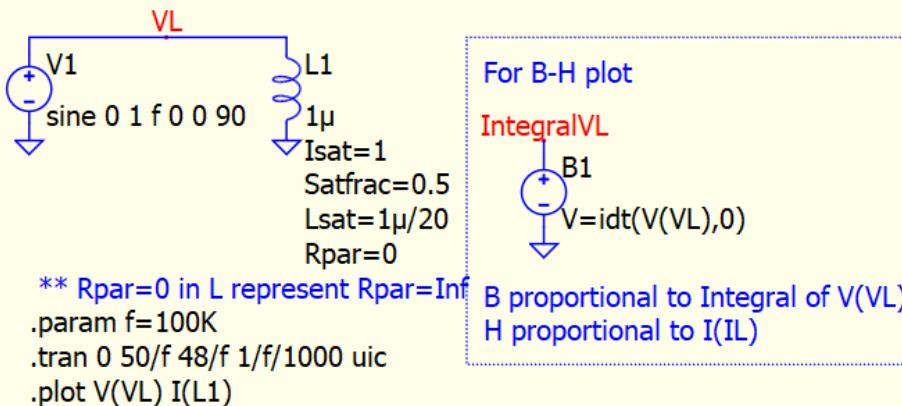
- Lsat
 - **Lsat** : Inductance asymptotically approached in saturation
 - ** Lsat must be set to see its effect
 - **Default LSAT=10% of L**



Demonstration of Nonlinear Inductor (model B-H saturation)

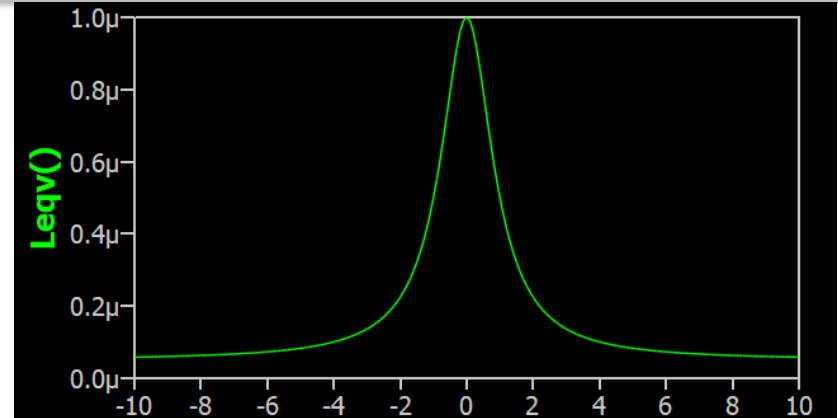
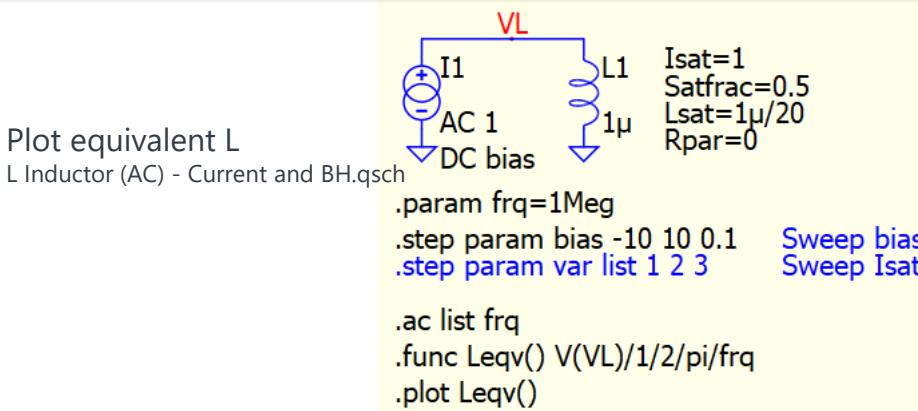
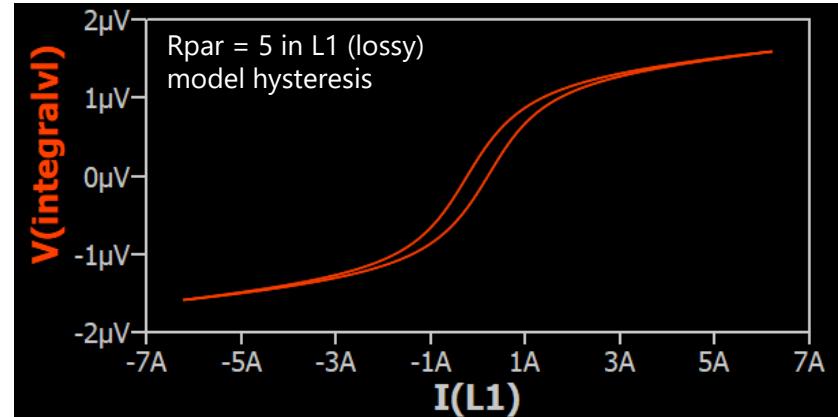
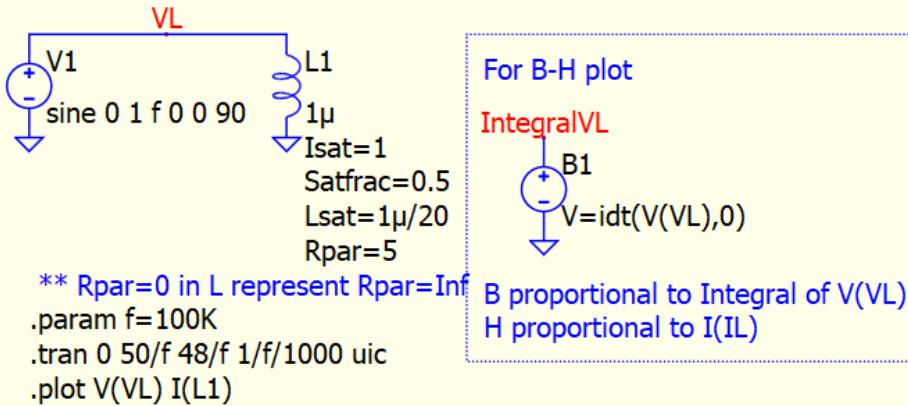
Qspice : L Inductor Nonlinear (Tran) - Current and BH.qsch

- Nonlinear Inductor in Qspice
 - This simulation demonstrate transient of non-linear inductor with a sinusoidal voltage source, which can expect a non-linear current
- Reference : B and H for inductor
 - Magnetic field intensity $H = \frac{B}{\mu} = \frac{N}{l_e} i_L$ (unit : A/m)
 - Magnetic field strength $B = \frac{\phi_B}{A_e} = \frac{1}{N A_e} \int v_L dt$ (unit : Tesla)
 - B also called magnetic flux density



Demonstration of Nonlinear Inductor (model B-H hysteresis : lossy)

Qspice : L Inductor Nonlinear (Tran) - Current and BH.qsch



Comment about Saturation and Hysteresis of B-H curve

Isat, Lsat and Satfrac are key parameters in Qspice for non-linear inductance modeling. General interest is just a saturating include. This represents inductor saturating when current reach certain level (i.e. inductance drop according to current, which can model by Isat, Lsat and Satfrac). This characteristic is saturation in B-H curve.

For hysteresis of B-H curve, it can generally model with a parallel resistor Rpar to represent loss.

May be some people prefer to model non-linear inductor with other way, but I found Qspice definition generally good enough as L vs bias current can be easily measure practically.

L. Arbitrary Inductance : Inductor modeling with FLUX

- Arbitrary Inductance Device
 - To use arbitrary inductance device, give an equation for the flux due to the inductor

Arbitrary Inductance Device

QSPICE also supports an arbitrary inductance device. To use it, give an equation for the flux due to the inductor. The equation can include any circuit node voltages or device currents of devices modeled as Thévenin equivalents(V-, L-, E-, or H- devices). In the interest of completeness, the device supports transinductance.

Syntax: Cnnn N1 N2 Q=<expression> [additional instance parameters]

| Name | Description | Units | Default |
|-----------|--|--------------------|---------------------|
| FLUX | Equation of flux(aka F) | Weber | |
| IC | Initial flux due to the inductor | Weber | |
| M | Number of identical parallel devices | | 1.0 |
| RPAR | Equivalent parallel resistance | Ω | Infinite |
| RSER | Equivalent series resistance | Ω | 0.0 |
| NOISELESS | Ignore the noise contribution from RPAR and RSER | | not set |
| TEMP | Instance temperature | $^{\circ}\text{C}$ | Circuit temperature |

- Basic Formula between Inductance and Flux

- [equation 1] : Inductor Voltage v_L and Flux ϕ relationship : $v_L = \frac{d\phi}{dt}$
- [equation 2] : Inductor Voltage v_L and Inductor Current i_L relationship : $v_L = L \frac{di_L}{dt}$
- By $\frac{d\phi}{dt} = L \frac{di_L}{dt} \rightarrow \text{Inductance } L = \frac{d\phi}{di_L}$

L. Arbitrary Inductance : Inductor modeling with FLUX

Qspice : Flux formula.qsch

- Qspice inductor modeling with Flux ϕ
 - For linear inductor, if $\frac{d\phi}{di_L}$ is constant $\rightarrow \phi = L i_L$
 - Therefore, $L = \frac{\phi}{i_L}$
 - In Qspice : $\text{flux} = L * I(\text{Lnnn})$
 - where Lnnn is the name attribute of inductor symbol (e.g. L1, L2)
 - For nonlinear inductor, ϕ can be expressed by
$$\phi = a \tanh(b i_L)$$
 - Therefore, $L = \frac{d\phi}{di_L} = \frac{d a \tanh(b i_L)}{di_L} = a b (1 - \tanh^2(b i_L))$
 - In Qspice : $\text{flux} = a * \tanh(b * I(\text{Lnnn}))$
 - $L_{0A} @ 0A = a * b$: L_{0A} is inductance at 0A
 - b determines the spread
 - If $b i_L$ is large, $(1 - \tanh^2(b i_L)) = 0$, therefore, this formula will give 0H inductance when i_L is large
 - Nonlinear and linear flux formula can be combined to handle 0H inductance when i_L is large
 - In Qspice : $\text{flux} = a * \tanh(b * I(\text{Lnnn})) + L_{\min} * I(\text{Lnnn})$
 - $L_{\min} @ i_L = \infty$: L_{\min} : L_{\min} is inductance at current $\rightarrow \infty$
 - $L_{0A} @ i_L = 0$: $a * b - L_{\min}$
 - b determines the spread

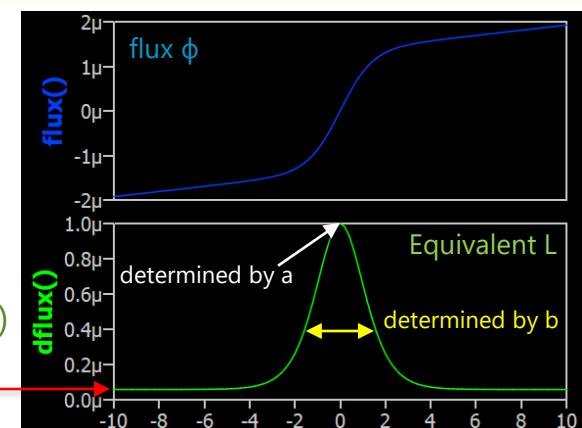
$$L = \frac{d\phi}{di_L} = \text{dflux}()$$

determined by L_{\min}

Assume flux formula is $a * \tanh(b * IL) + L_{\min} * IL$
.param b = 0.7
.param L0A = 1u
.param a = (L0A-Lmin)/b
.param Lmin=58n
.func flux() a*tanh(b*IL)+Lmin*IL

Calculate Inductance by dflux/dIL
.func dflux() D(flux())

Sweep IL from -10A to 10A
.step param IL -10 10 0.2
.op
.plot dflux()
.plot flux()

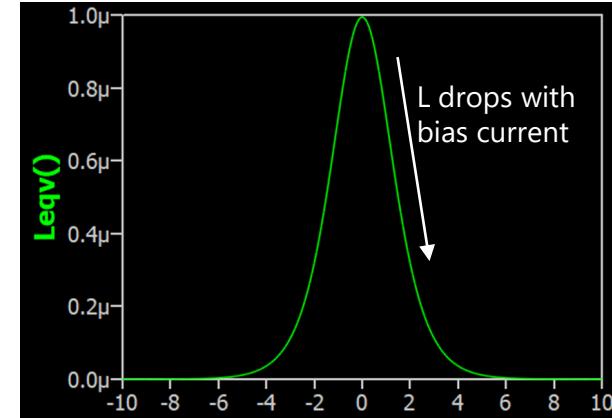
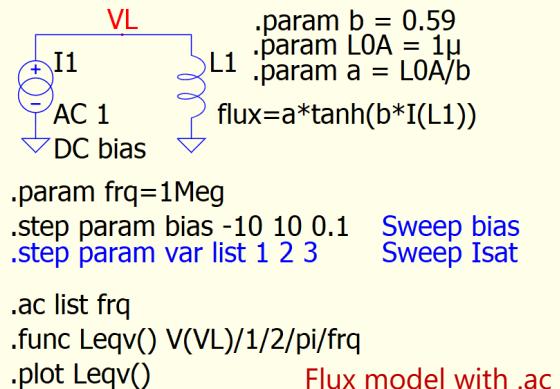


L. Arbitrary Inductance : Inductor modeling with FLUX

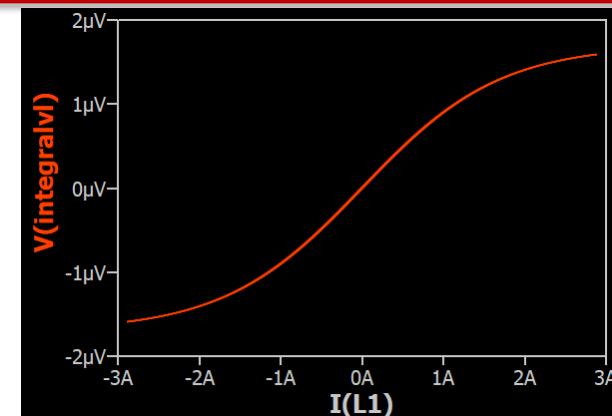
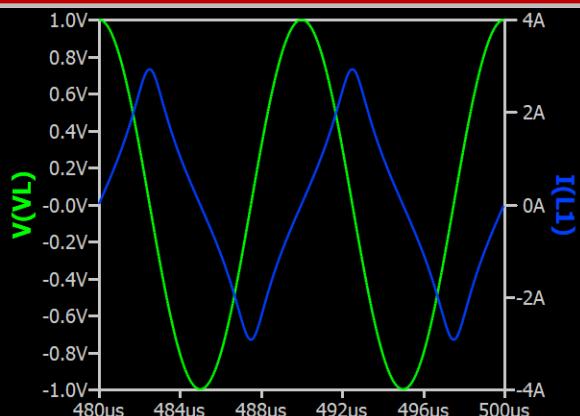
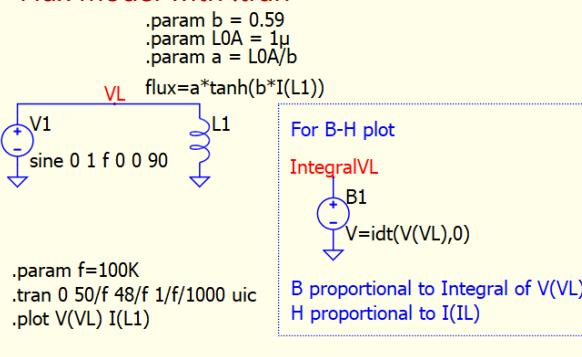
Qspice : L Inductor (AC) - Flux eqn 1.qsch ; L Inductor Nonlinear (Tran) - Flux eqn 1.qsch

- Flux model

- .ac is used to calculate inductance and bias current relationship
- .tran is used to demonstrate non-linear inductor current and proportional B-H curve
- Flux equation uses format
 - Flux = $a \tanh(b \cdot I(L1))$



Flux model with .tran



L. Arbitrary Inductance : Inductor modeling with FLUX – Nonlinear with Lmin

Qspice : L Inductor (AC) - Flux eqn 2.qsch ; L Inductor Nonlinear (Tran) - Flux eqn 2.qsch

- Flux Model

- This is nonlinear flux model include Lmin at large inductor current
- Flux equation uses format
 - Flux = $a \tanh(b \cdot I(L)) + L_{min} \cdot I(L)$

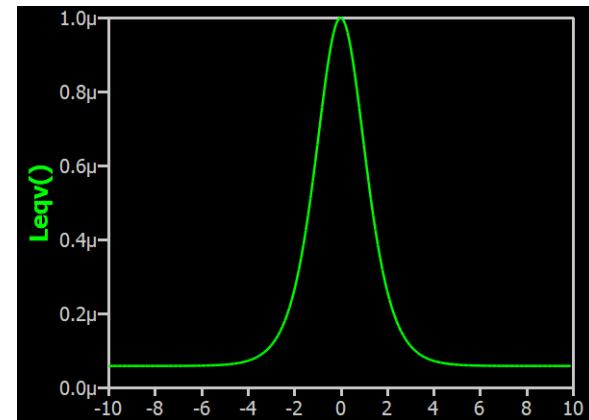
```

.param b = 0.7
.param LOA = 1μ
.param a = (LOA-Lmin)/b
.param Lmin=58n
flux=a*tanh(b*I(L1))+Lmin*I(L1)

.param frq=1Meg
.step param bias -10 10 0.1 Sweep bias
.step param var list 1 2 3 Sweep Isat

.ac list frq
.func Leqv() V(VL)/1/2/pi/frq
.plot Leqv()

```



```

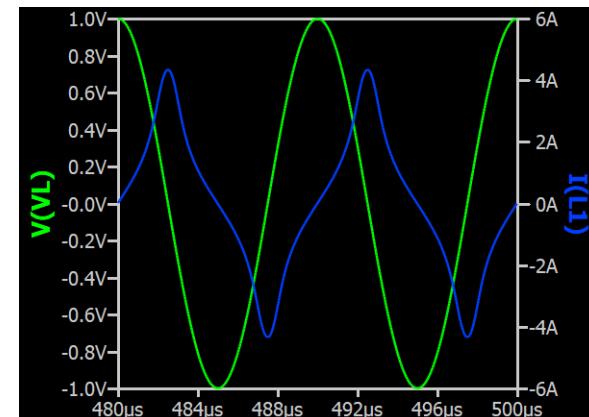
.param b = 0.7
.param LOA = 1μ
.param a = (LOA-Lmin)/b
.param Lmin=58n
flux=a*tanh(b*I(L1))+Lmin*I(L1)

.sine V1 0 1 f 0 0 90

.param f=100K
.tran 0 50/f 48/f 1/f/1000 uic
.plot V(VL) I(L1)

For B-H plot
IntegralVL
B1
V=idt(V(VL),0)
B proportional to Integral of V(VL)
H proportional to I(IL)

```

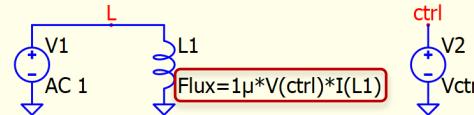


L. Behavioral Inductance with Flux (Arbitrary Inductance)

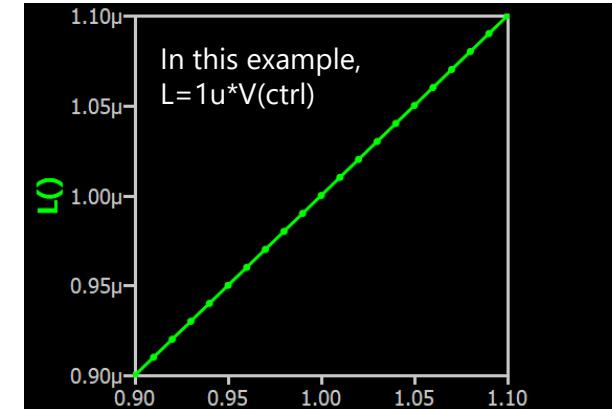
Qspice : L - Behavioral L with Flux.qsch

- Behavioral L with Flux
 - For linear inductor
 - $\phi = L \times I_L$
 - In Qspice
 - Flux = <eqn> * I(Ln)
 - <eqn> is inductance equation supports voltage node or device current
 - Ln is name attribute of inductor

Linear Inductor flux formula : Flux = L * IL
Therefore, behavioral inductance model can be derived using Arbitrary Inductance Device



```
.step param Vctrl 0.9 1.1 0.01
.param frq=1Meg
.ac list frq
.func imZ() V(L)/I(L1)
.func L() imZ()/2/pi/frq
.plot L()
```



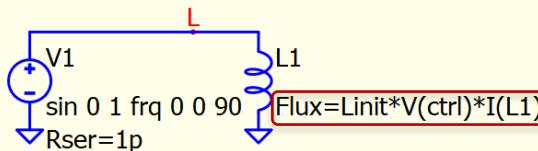
L. Behavioral Inductance with Flux (Arbitrary Inductance)

Qspice : L - Behavioral L with Flux (.tran).qsch

- Flux
 - Behavioral Inductance with flux
 - This schematic demonstrate using behavioral inductance (with flux) model in transient (.tran) analysis

Linear Inductor flux formula : $\text{Flux} = L * \text{IL}$
Therefore, behavioral inductance model can be derived using Arbitrary Inductance Device

```
.param frq=1K  
.param XL=1  
.param Linit=XL/2/pi/frq
```



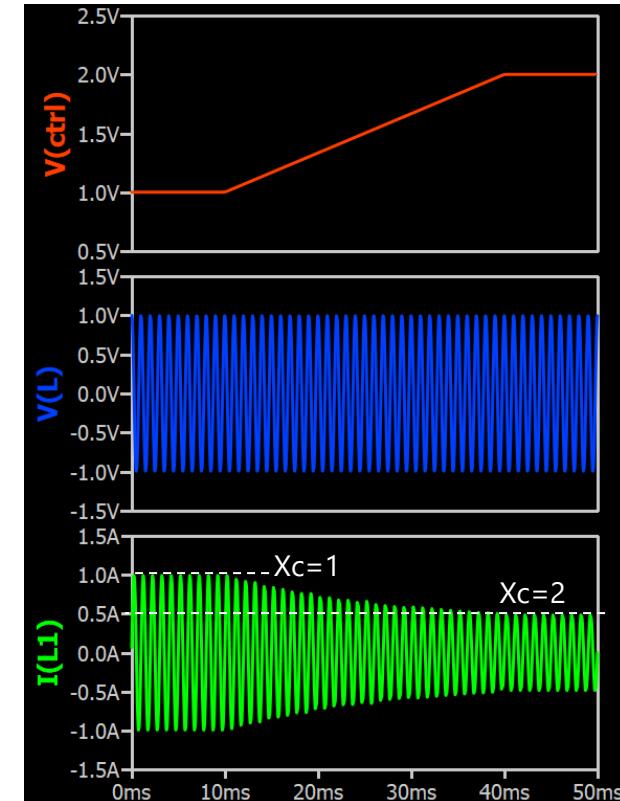
ctrl

V_2
pwl 0,1,10m,1,40m,2

$L = \text{Limit} * 1 \rightarrow XL = 1$

$L = \text{Limit} * 2 \rightarrow XL = 2$

```
.tran 50m uic  
.option maxstep=1/frq/100  
.plot I(L1)  
.plot V(L)  
.plot V(ctrl)
```

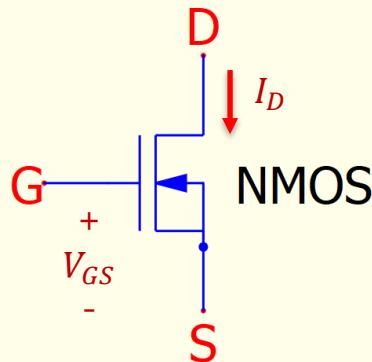


M. MOSFET

(VDMOS)

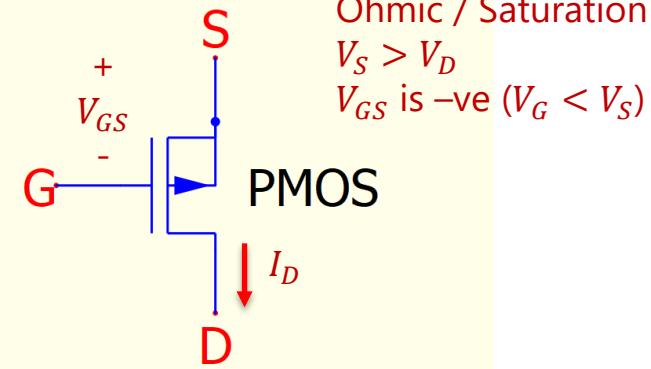
** VDMOS with different
default as monolithic MOSFET
models, it popularly used in
board level SMPS

M. MOSFET NMOS and PMOS



Ohmic / Saturation
 $V_D > V_S$
 V_{GS} is +ve ($V_G > V_S$)

NMOS



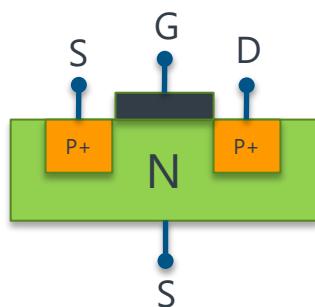
Ohmic / Saturation
 $V_S > V_D$
 V_{GS} is -ve ($V_G < V_S$)

PMOS

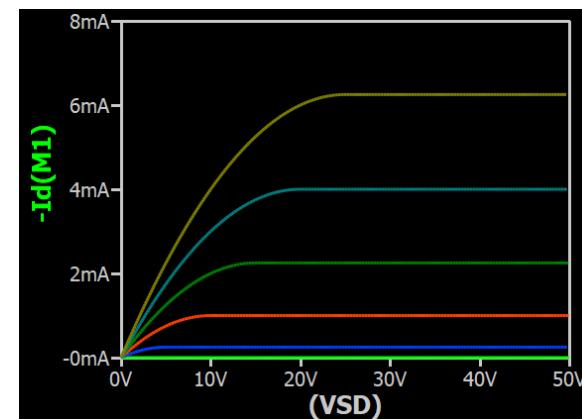
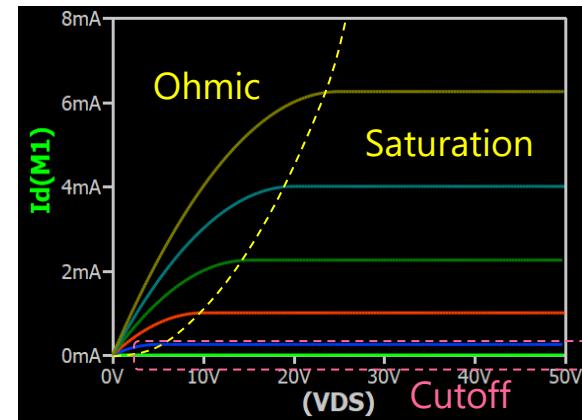
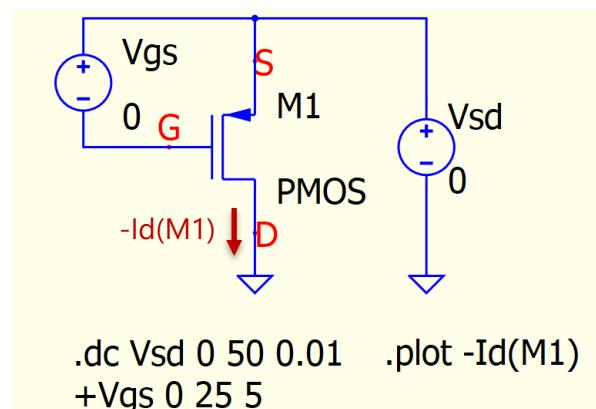
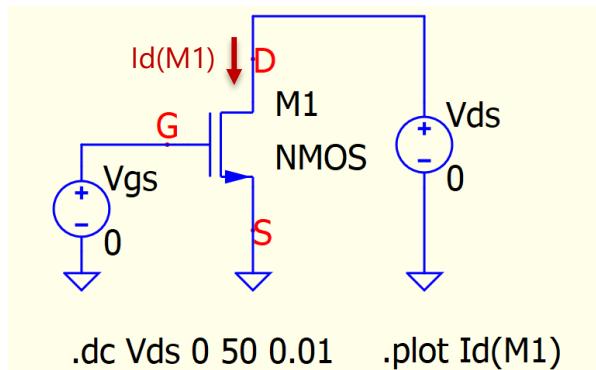
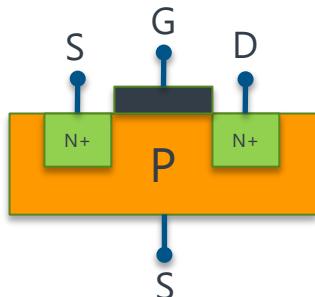
| Voltage Relations | NMOS |
|--|--------------------------|
| $V_{GS} > V_{th}$ $V_{DS} < V_{GS} - V_{th}$ | Ohmic (Triode/Linear) |
| $V_{GS} > V_{th}$ $V_{DS} \leq V_{GS} - V_{th}$ | Saturation (Active) |
| $V_{GS} < V_{th}$ | Cutoff |

M. MOSFET NMOS and PMOS Ohmic, Saturation and Cutoff

- NMOS
 - N-channel MOSFET



- PMOS
 - P-channel MOSFET



MOSFET Level 1 Model Parameters

MOSFET Level 1 Model Parameters

| Name | Description | Units | Default |
|---------------------|---|------------------|----------|
| A | Additional non-linear Gate-drain capacitance abruptness | | 1.0 |
| AD | Default drain area | m ² | 0.0 |
| AF | Flicker noise exponent | | 1.0 |
| AS | Default source area | m ² | 0.0 |
| BV | Body diode breakdown voltage | V | Infinite |
| CAPOP ⁹ | Charge(Capacitance) model | | 1 |
| CBD | Zero-bias B-D junction capacitance | F | 0.0 |
| CBS | B-S junction capacitance | F | 0.0 |
| CGBO | Gate-bulk overlap capacitance | F/m | 0.0 |
| CGDMAX ⁸ | Maximum additional non-linear Gate-Drain capacitance | F | 0.0 |
| CGDMIN ⁸ | Minimum additional non-linear Gate-Drain capacitance | F | 0.0 |
| CGDO | Gate-drain overlap capacitance | F/m | 0.0 |
| CGS | Gate-source capacitance that doesn't scale with width | F | 0.0 |
| CGSO | Gate-source overlap capacitance | F/m | 0.0 |
| CJ | Bottom junction cap per area | F/m ² | 0.0 |
| CJO | Body diode zero-bias capacitance | F | 0.0 |
| CJSW | Side junction cap per length | F/m | 0.0 |
| EG | Body diode activation energy | V | 1.11 |
| ETA ⁸ | Philips, et al.-style subthreshold conduction parameter | | 0.0 |
| ETA2 | Inverse sharpness of Ids limit for non-square law variation | | 0.0 |
| FC | Forward bias junction fit parameter | | 0.5 |
| GAMMA | Bulk threshold parameter | V ^{1/2} | 0.0 |
| GDSNOI | Channel shot noise coefficient(nlev=3) | | 1.0 |
| GM | Ideal transconductance for non-square law variation | Ω | none |
| GMAX | Maximum bulk PN conductivity | Ω | 1000. |
| IBV | Body diode current at breakdown voltage | A | 1e-10 |
| IDS | Maximum drain current for non-square law variation | A | Infinite |
| IGSS | Gate-Source leakage current | A | 0.0 |
| IS | Bulk junction saturation current | A | 1e-14 |
| JS | Bulk junction saturation current density | A/m ² | 0.0 |
| K1 ¹⁰ | Threshold voltage sensitivity to bulk node | V ^{1/2} | 0.25 |
| KF | Flicker noise coefficient | | 0.0 |
| KP | Transconductance parameter | A/V ² | 2e-5 |
| L | Default channel length | m | 1e-5 |
| LAMBDA | Channel length modulation | V ⁻¹ | 0.0 |

| | | | |
|---------------------|--|------------------------|----------|
| LD | Lateral diffusion | m | 0.0 |
| MJ | Bulk grading coefficient | | 0.5 |
| MJSW | Side grading coefficient | | 0.33 |
| N | Bulk(or Body) PN junction emission coefficient | | 1.0 |
| NBV | Body diode breakdown emission coefficient | | 1.0 |
| NLEV | Noise level(equation selector) | | 0 |
| NRD | Default drain squares | | 0.0 |
| NRB | Default bulk squares | | 0.0 |
| NRG | Default gate squares | | 0.0 |
| NRS | Default source squares | | 0.0 |
| NSS | Surface state density | cm ⁻² | 0.0 |
| NSUB | Substrate doping | cm ⁻² | 0.0 |
| PB | Bulk junction potential | V | 1.0 |
| PD | Default drain perimeter | m | 0.0 |
| PHI | Surface potential | V | 1.0 |
| PCHAN | Flag to specify vertical PMOS geometry | | not set |
| PS | Default source perimeter | m | 0.0 |
| RB | Bulk resistance | Ω | 0.0 |
| RD | Drain resistance | Ω | 0.0 |
| RDS | Additional Drain-Source shunt resistance | Ω | Infinite |
| RG | Gate resistance | Ω | 0.0 |
| RON | Ron at zero drain current for non-square law variation | Ω | none |
| RONX ⁸ | Channel conductivity multiplier in linear region | | 1.0 |
| RS | Source resistance | Ω | 0.0 |
| RSH | Sheet resistance | Ω/□ | 0.0 |
| TNOM | Parameter measurement temperature(aka TREF) | °C | 27.0 |
| TOX | Oxide thickness | m | 1.5e-8 |
| TPG | Gate type | | 1 |
| TT | Bulk PN junction Transit-time | sec | 0.0 |
| U0 | Surface mobility(aka UO) | cm ² /V×sec | 600 |
| VDMOS ⁸ | Flag to specify vertical geometry | | not set |
| VFB ¹⁰ | Flat band voltage | V | -1.0 |
| VIGSS | Voltage at which IGSS was measured | V | 5.0 |
| VJ | Body diode Junction potential | V | 1.0 |
| VT0 | Threshold voltage(aka VTO) | V | 0.0 |
| W | Default channel width | m | 1e-5 |
| XPART ¹⁰ | Channel charge partitioning | | 1 |
| XTI | Body diode Saturation current temperature exponent | | 3 |

Display purpose only

- Vds : VDS rating
- Qq : Gate charge
- Mfg : manufacturer

Linear and Saturation Region : VTO, KP, W, L, LD, LAMBDA

- From Semiconductor Device Modeling with Spice (Section 4.2.3)

- Linear region : $V_{GS} > V_{TH}$ and $V_{DS} < V_{GS} - V_{TH}$
 - $I_{DS} = KP \frac{W}{L-2X_{jl}} \left(V_{GS} - V_{TH} - \frac{V_{DS}}{2} \right) V_{DS} (1 + \lambda V_{DS})$
- Saturation region : $V_{GS} > V_{TH}$ and $V_{DS} > V_{GS} - V_{TH}$
 - $I_{DS} = \frac{KP}{2} \frac{W}{L-2X_{jl}} (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS})$
- where
 - V_{TH} : VTO , zero-bias threshold voltage (Default VTO=0 V)
 - KP : KP , transconductance (Default KP=1 A/V²)
 - W : W, channel width (Default W=1e-4 m)
 - L : L, channel length (Default L=1e-4 m)
 - X_{jl} : LD, lateral diffusion (Default LD=0 m)
 - λ : LAMBDA channel-length modulation (Default LAMBDA=0 V⁻¹)

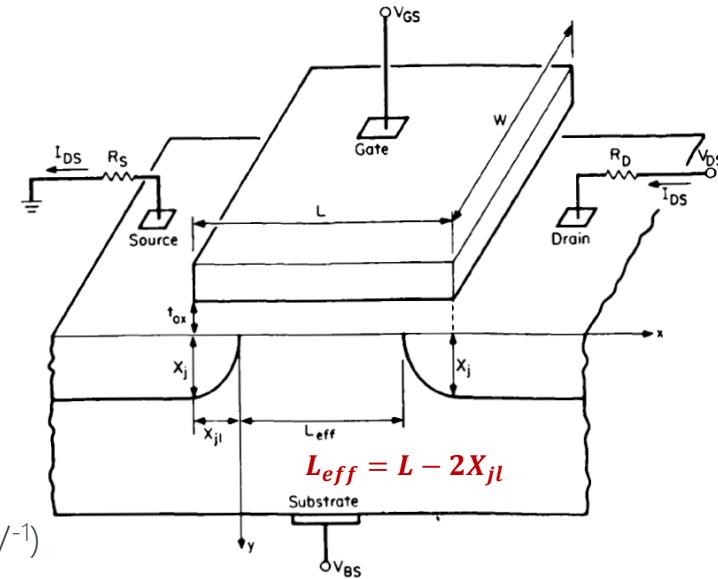


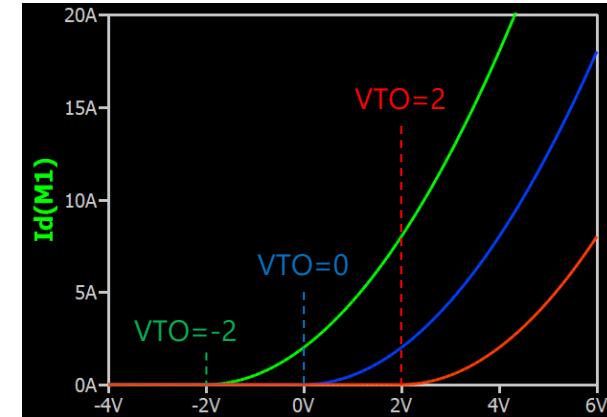
Figure 4-1 Structure of the MOST.

M. MOSFET Params : VTO, KP, W and L

Qspice : VDMOS - VTO.qsch / VDMOS - KP.qsch / VDMOS - W.qsch / VDMOS - L.qsch

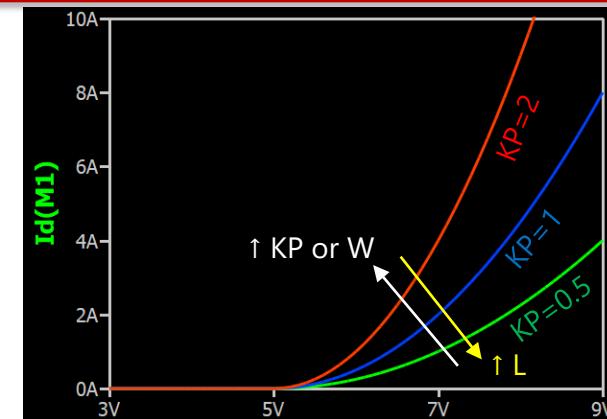
- VTO
 - VTO : Zero-bias threshold voltage
 - **Default VTO=0V**

```
.param Vdrain=10  
.dc Vgate -4 6 0.1 .plot Id(M1)  
  
d  
M1  
Mmdl  
V2  
Vdrain  
Vgate 0  
  
.step param vto list -2 0 2  
.model Mmdl VDMOS VTO=vto
```



- KP
 - KP : transconductance
 - **Default KP=1 A/V²**

```
.param Vdrain=10  
.dc Vgate 3 9 0.1 .plot Id(M1)  
  
d  
M1  
Mmdl  
V2  
Vdrain  
Vgate 0  
  
.step param kp list 0.5 1 2  
.model Mmdl VDMOS VTO=5 KP=kp
```



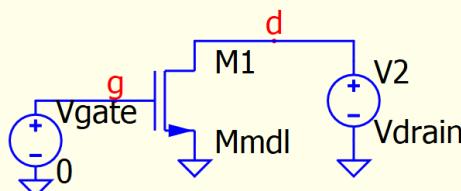
- W and L
 - W : Channel Width (Default 1e-4)
 - L : Channel Length (Default 1e-4)
 - Effect is similar to KP as a gain
 - $\frac{KP}{2} \frac{W}{L-2X_{jl}}$ (for saturation region)

M. MOSFET Params : LD and ETA

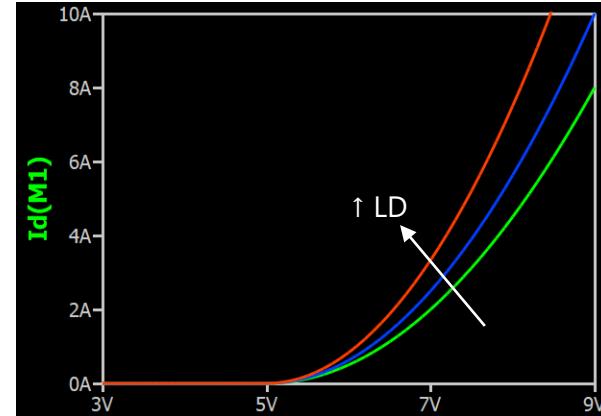
Qspice : VDMOS - LD.qsch / VDMOS - ETA.qsch

- LD
 - LD : lateral diffusion
 - **Default LD=0 m**
 - $L_{eff} = L - 2LD > 0$
 - Therefore, $0 < LD < \frac{L}{2}$

```
.param Vdrain=10  
.dc Vgate 3 9 0.1 .plot Id(M1)
```

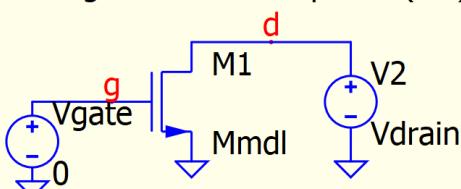


```
.step param Id list 0 0.1e-4 0.2e-4  
.model Mmdl VDMOS VTO=5 LD=Id
```

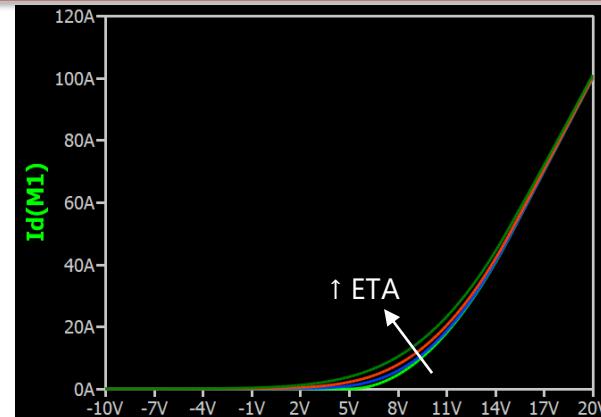


- ETA (aka ksubthres)
 - ETA : Vds dependence of threshold voltage
 - Static feedback on threshold voltage
 - **Default ETA=0**
 - Qspice accepts parameter name as ETA or ksubthres

```
.param Vdrain=10  
.dc Vgate -10 20 0.1.plot Id(M1)
```



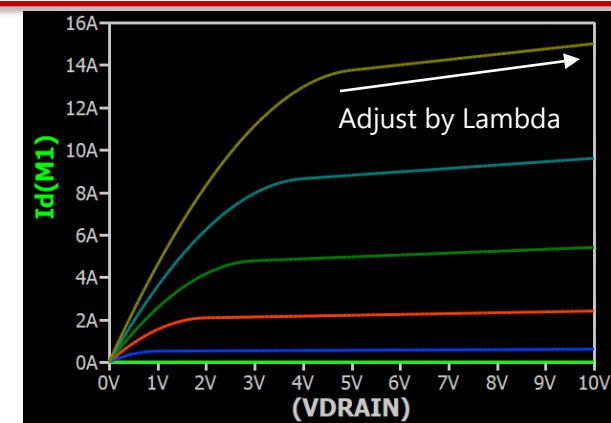
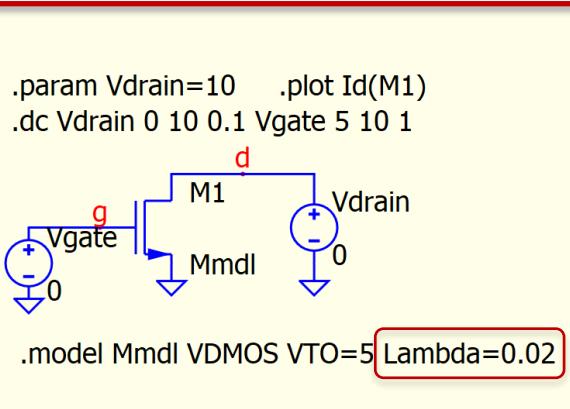
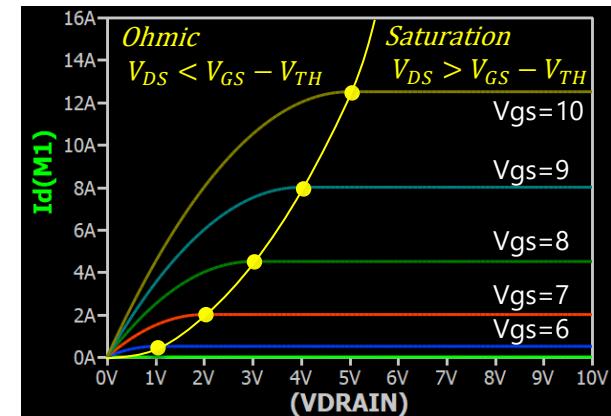
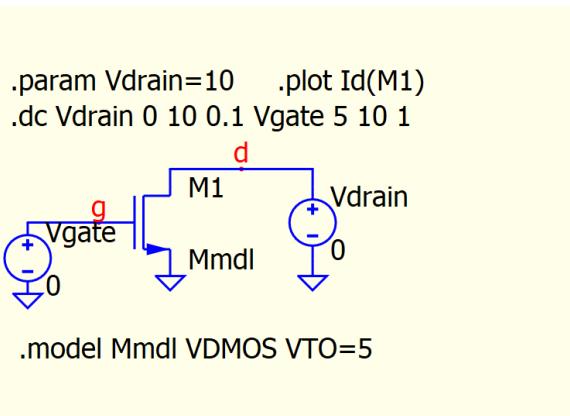
```
.step param eta list 0 2 3 4  
.model Mmdl VDMOS VTO=5 ETA=eta
```



M. MOSFET Params : Lambda

Qspice : VDMOS -LAMBDA.qsch

- LAMBDA
 - Labmda : channel-length modulation
 - Default LAMBDA=0 V⁻¹**



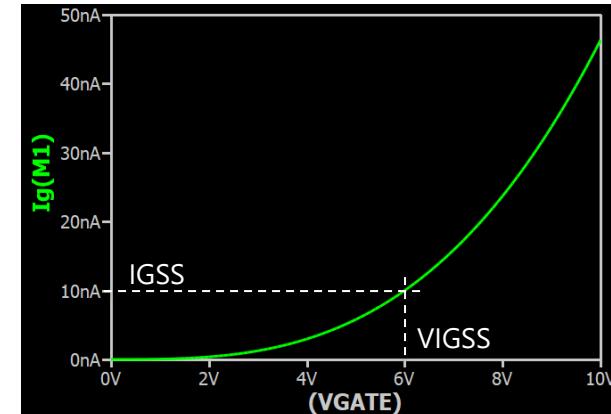
M. MOSFET Params (Gate) : VIGSS and IGSS, RG and CGS

Qspice : VDMOS - VIGSS IGSS.qsch / VDMOS - Rg Cgs.qsch

VIGSS and IGSS

- Vigss : Voltage at which IGSS was measured
- Igss : Gate-Source leakage current
- **Default VIGSS=5V**
- **Default IGSS=0A**
- Parameters to determine Igss in relates to Vgs

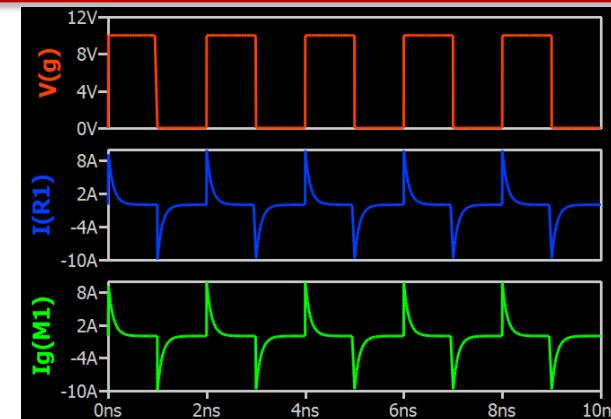
```
.param Vdrain=10  
.dc Vgate 0 10 0.1 .plot Ig(M1)  
  
M1  
Vdrain  
V2  
Vgate  
Mmdl  
d  
  
.model Mmdl VDMOS VTO=5 VIGSS=6 IGSS=10n
```



RG and CGS

- Rg : Gate Resistance
- Cgs : Gate-source capacitance that doesn't scale with width
- **Default RG=0Ω**
- **Default CGS=0F**
- Parameters to determine gate resistance and capacitoance

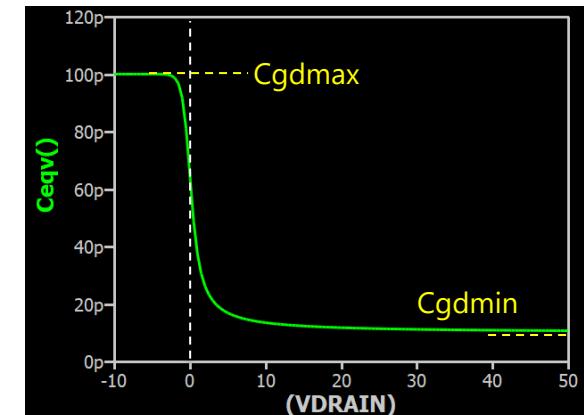
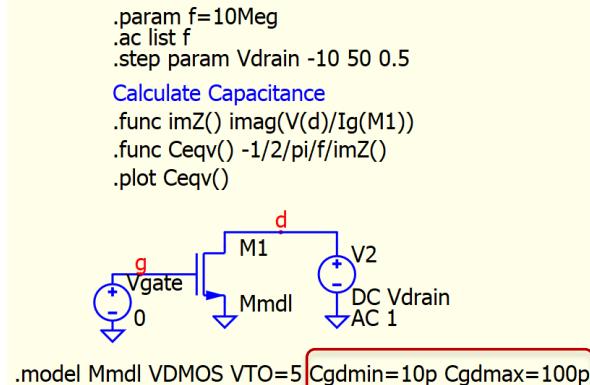
```
Equivalent Rg and Cgs  
R1  
C1  
100p  
1  
d  
M1  
Mmdl  
V2  
Vdrain  
Vgate  
pulse 0 10 0 0 0 1n 2n  
.model Mmdl VDMOS VTO=5 Rg=1 Cgs=100p
```



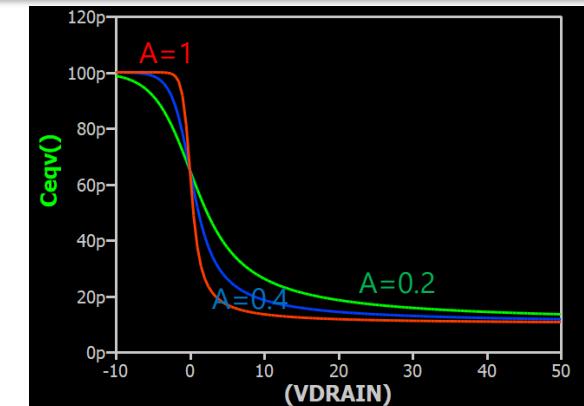
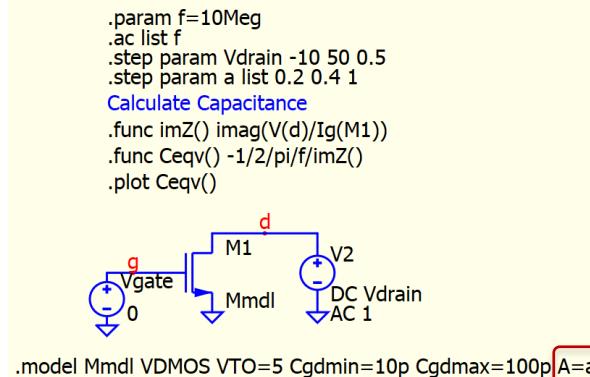
M. MOSFET Params (Cgd) : CGDMAX, CGDMIN and A

Qspice : VDMOS - CGDMIN CGDMAX.qsch / VDMOS - A.qsch

- CGDMAX and CGDMIN
 - Cgdmax : Maximum additional non-linear Gate-Drain capacitance
 - Cgdmin : Minimum additional non-linear Gate-Drain capacitance
 - Default Cgdmax=0F**
 - Default Cgdmin=0F**
 - Model non-linear of Cgd capacitance



- A
 - A : Additional non-linear Gate-drain capacitance abruptness
 - Default A=1**
 - Modify Cgd vs drain voltage profile

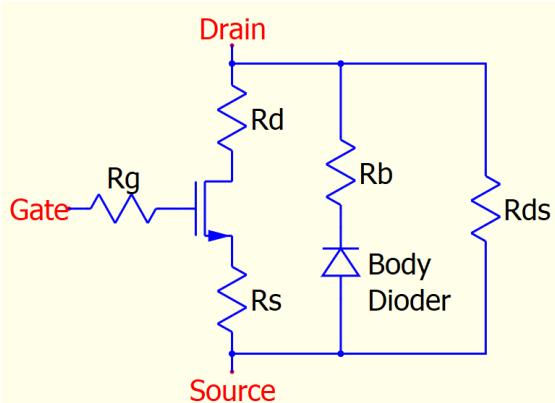


M. MOSFET Params :

Qspice : VDMOS - BodeDiode.qsch / VDMOS - Rb Rd Rds Rg Rs.qsch

- Resistance

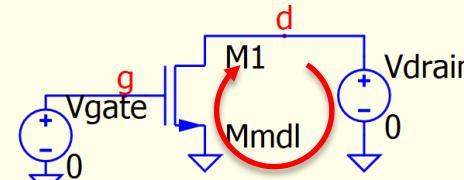
- R_b : Bulk resistance
- R_d : Drain resistance
- R_{ds} : Additional Drain-Source shunt resistance
- R_g : Gate resistance
- R_s : Source resistance
- **Default R_b=R_d=R_g=R_s=0Ω**
- **Default R_{ds}=Infinite**



- Body Diode

- Parameters same as diode model parameters
- Refer to section : D. Diode Diode Model Parameters
- This ideal diode also provide C_{ds} capacitance with its junction capacitance C_j

```
.dc Vdrain -1 4 0.01  
.plot Id(M1)
```



```
.model Mmdl VDMOS VTO=5 N=0.3
```



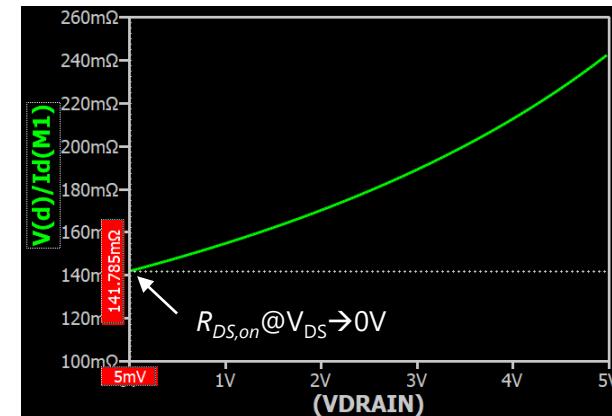
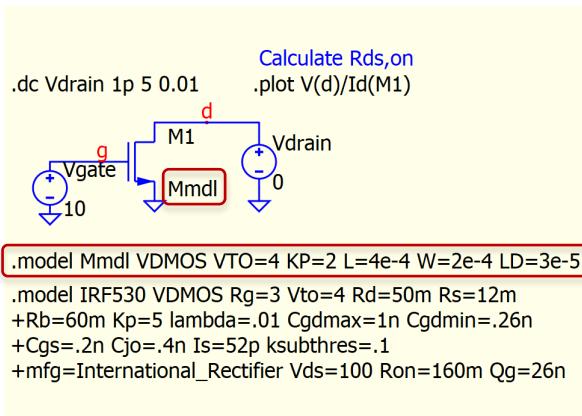
M. MOSFET : Drain-Source Turn ON Resistance : R_{ds,on}

- R_{ds,on}
 - This is not a direct parameters, but as to design SMPS, you may want to know what parameters in MOSFET model affect R_{ds,on}
 - In SMPS, R_{ds,on} is generally considered as MOSFET fully turn ON, where
 - $V_{GS} \gg V_{TH}$ and V_{DS} is low, MOSFET in linear region, and $R_{DS,ON} = \frac{V_{DS}}{I_{DS}}$
 - Linear region formula : $V_{GS} > V_{TH}$ and $V_{DS} < V_{GS} - V_{TH}$
 - $I_{DS} = KP \frac{W}{L-2X_{jl}} \left(V_{GS} - V_{TH} - \frac{V_{DS}}{2} \right) V_{DS} (1 + \lambda V_{DS})$
 - Therefore
 - $R_{DS,ON} = \frac{V_{DS}}{I_{DS}} = \frac{V_{DS}}{KP \frac{W}{L-2X_{jl}} \left(V_{GS} - V_{TH} - \frac{V_{DS}}{2} \right) V_{DS} (1 + \lambda V_{DS})} = \frac{1}{KP \frac{W}{L-2X_{jl}} \left(V_{GS} - V_{TH} - \frac{V_{DS}}{2} \right) (1 + \lambda V_{DS})}$
 - $\lim_{V_{DS} \rightarrow 0} R_{DS,ON} = \frac{1}{KP \frac{W}{L-2X_{jl}} \left(V_{GS} - V_{TH} - \frac{0}{2} \right) (1 + \lambda \times 0)} = \frac{1}{KP \frac{W}{L-2X_{jl}} (V_{GS} - V_{TH})} = \frac{L-2X_{jl}}{KP \cdot W \cdot (V_{GS} - V_{TH})}$
 - With Qspice model parameters, also consider drain and source resistance in model
 - @ $V_{DS} \rightarrow 0V$: $R_{DS,ON} = \frac{L-2 LD}{KP \cdot W \cdot (V_{GS} - VTO)} + RD + RS$
 - Where in default, VTO=0, KP=1, L=1e-4, W=1e-4, LD=0, Rd=0 and Rs=0

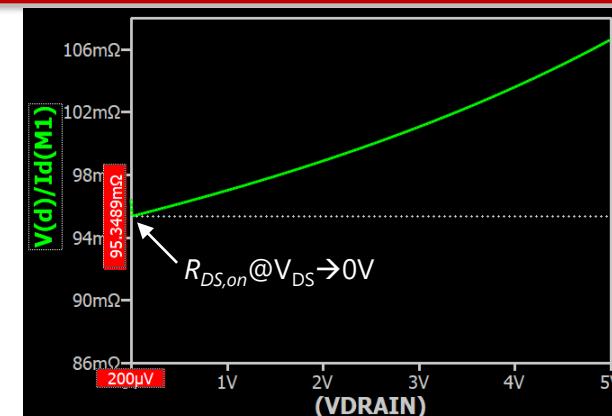
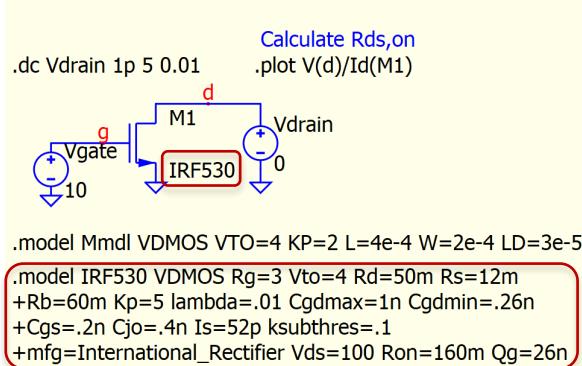
M. MOSFET : Drain-Source Turn ON Resistance : R_{ds,on}

Qspice : VDMOS - (Calculate) Rdson.qsch

- Example #1
 - Mmdl model
 - @V_{DS} → 0V
 - $R_{DS,ON} = \frac{L-2 LD}{KP \cdot W \cdot (V_{GS}-VTO)} + RD + RS$
 - RD=0
 - RS=0
 - $R_{DS,ON} @ V_{DS} \rightarrow 0V = 141.67m\Omega$



- Example #2
 - Mmdl model
 - @V_{DS} → 0V
 - $R_{DS,ON} = \frac{L-2 LD}{KP \cdot W \cdot (V_{GS}-VTO)} + RD + RS$
 - VTO=4, KP=5
 - L=W=1e-4, LD=0
 - RD=50m
 - RS=12m
 - $R_{DS,ON} @ V_{DS} \rightarrow 0V = 95.33m\Omega$



M. MOSFET
Level 2010 (SiC FET)
Model

M. MOSFET Level 2010 (SiC FET) Model

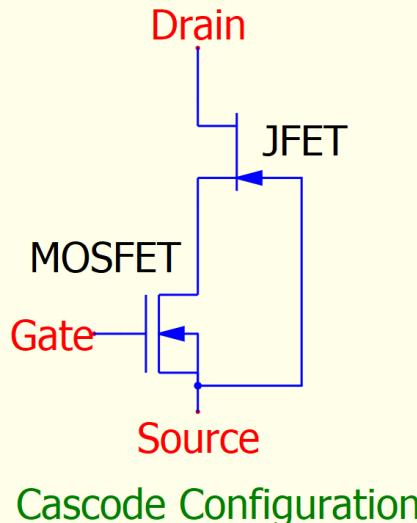
| Name | Description | Units | Default |
|----------|---|-------------------------------|----------|
| A | Sharpness of transition from CGDMIN to CGDMAX | | 1.0 |
| AF | MOSFET Flicker noise exponent | | 1.0 |
| BV | Body diode breakdown voltage | V | Infinite |
| CGDMAX | Gate-Drain maximum capacitance | F | 0.0 |
| CGDMIN | Gate-Drain minimum capacitance | F | 0.0 |
| CGS | Gate-source overlap capacitance | F | 0.0 |
| CJO | Body diode zero bias cap | F | 0.0 |
| EG | Body diode activation energy | V | 1.11 |
| ETA | Philips, et al.-style subthreshold conduction | V | 0.0 |
| ETATC1 | ETA first order tempco | V/ $^{\circ}$ C ⁻¹ | 0.0 |
| ETATC2 | ETA second order tempco | V/ $^{\circ}$ C ⁻² | 0.0 |
| GDSNOI | Noise equation selector | | 0 |
| GMAX | Maximum conductivity of any PN junction | Ω | 1000. |
| IBV | Body diode current at breakdown voltage | A | 1e-10 |
| IGSS | Gate-Source leakage | A | 0.0 |
| IS | Body diode saturation current | A | 1e-14 |
| JAF | JFET Flicker Noise Exponent | | 1.0 |
| JALPHA | JFET impact ionization coefficient | V ⁻¹ | 0.0 |
| JB | JFET doping tail parameter | | 0.0 |
| JBETA | JFET transconductance parameter | A/V ² | 1.0 |
| JBETATCE | JFET exponential temperature coefficient | %/ $^{\circ}$ C | 0.0 |
| JCGD | JFET G-D junction cap | F | 0.0 |
| JCGDO | JFET G-D junction cap | F | 0.0 |
| JCGS | JFET G-S junction capacitance | F | 0.0 |
| JCGSO | JFET G-S junction capacitance | F | 0.0 |
| JFC | JFET forward bias junction fit parm. | | 0.5 |
| JIS | JFET gate junction saturation current | A | 1e-14 |
| JISR | JFET recombination current parameter | A | 0.0 |
| JKF | JFET Flicker Noise Coefficient | | 0.0 |
| JLAMBDA | JFET Channel length modulation parameter | V ⁻¹ | 0.0 |

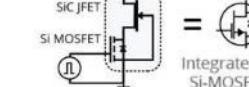
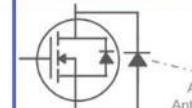
| | | | |
|----------|---|----------------------------|----------|
| JM | JFET grading coeff. | | 0.5 |
| JN | JFET emission coefficient | | 1.0 |
| JNR | JFET Is _r emission coefficient | | 2.0 |
| JPB | JFET gate junction potential | V | 1.0 |
| JRD | JFET drain ohmic resistance | Ω | 0.0 |
| JRDS | JFET additional Drain-Source leakage resistance | Ω | Infinite |
| JRDSTC1 | JFET RDS first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| JRDSTC2 | JFET RDS second order tempco | $^{\circ}$ C ⁻² | 0.0 |
| JRDTCl | JFET RD first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| JRDTC2 | JFET RD second order tempco | $^{\circ}$ C ⁻² | 0.0 |
| JRG | JFET gate ohmic resistance | Ω | 0.0 |
| JRGTC1 | JFET RG first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| JRGTC2 | JFET RG second order tempco | $^{\circ}$ C ⁻² | 0.0 |
| JRONX | JFET channel conductivity multiplier in linear region | | 1.0 |
| JRS | JFET source ohmic resistance | Ω | 0.0 |
| JRSTC1 | JFET RS first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| JRSTC2 | JFET RS second order tempco | $^{\circ}$ C ⁻² | 0.0 |
| JVK | JFET ionization knee current | V | 0.0 |
| JVTO | JFET threshold voltage | V | -2.0 |
| JVTOTC | JFET V _{t0} 's temperature coefficient | $^{\circ}$ C ⁻¹ | 0.0 |
| JXTI | JFET IS temperature coefficient | | 3.0 |
| KF | MOSFET flicker noise coefficient | | 0.0 |
| KP | MOSFET transconductance parameter | A/V ² | 1.0 |
| LAMBDA | MOSFET channel length modulation | V ⁻¹ | 0.0 |
| LG | JFET gate inductance | H | 0.0 |
| LGRPAR | JFET gate inductance parallel loss | Ω | Infinite |
| LMID | Inductance making cascode connection | H | 0.0 |
| LS | MOSFET Source Inductance | H | 0.0 |
| LSRPAR | MOSFET Source inductance parallel loss | Ω | Infinite |
| LMIDRPAR | Cascade inductance parallel loss | Ω | Infinite |
| M | Body diode grading coefficient(MJ) | Ω | 0.5 |

| | | | |
|-----------|--|----------------------------|----------|
| N | Bulk diode emission coefficient | | 1.0 |
| NBV | Body diode breakdown emission coeff | | 1.0 |
| NLEV | MOSFET noise equation selector | | 0 |
| NOISELESS | The device does not contribute to a noise | | |
| RB | Body diode series resistance | Ω | 0.0 |
| RBTC1 | MOSFET RB first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| RBTC2 | MOSFET RB second order tempco | $^{\circ}$ C ⁻² | 0.0 |
| RD | MOSFET drain ohmic resistance | Ω | Infinite |
| RDS | MOSFET drain-source shunt resistance | Ω | Infinite |
| RDTC1 | MOSFET RD first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| RDTC2 | MOSFET RD second order order | $^{\circ}$ C ⁻² | 0.0 |
| RG | MOSFET gate resistance | Ω | 0.0 |
| RONX | MOSFET conductivity multiplier in linear region | | 1.0 |
| RS | MOSFET Source ohmic resistance | Ω | 0.0 |
| RSTC1 | MOSFET RS first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| RSTC2 | MOSFET RS second order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| THETA | MOSFET V _{gs} dependence on mobility ala mos3 | V ⁻¹ | 0.0 |
| TNOM | Parameter measurement temperature(TNOM) | $^{\circ}$ C | 27.0 |
| TRB1 | MOSFET RB first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| TRB2 | MOSFET RB second order tempco | $^{\circ}$ C ⁻² | 0.0 |
| TRD1 | MOSFET RD first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| TRD2 | MOSFET RD second order tempco | $^{\circ}$ C ⁻² | 0.0 |
| TRS1 | MOSFET RS first order tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| TRS2 | MOSFET RS second order tempco | $^{\circ}$ C ⁻² | 0.0 |
| TT | Bulk diode transit time | s | 0.0 |
| VJ | Body diode Junction potential | V | 1.0 |
| VTO | MOSFET threshold voltage | V | 0.0 |
| VTOTC | MOSFET's V _{t0} tempco | $^{\circ}$ C ⁻¹ | 0.0 |
| XTI | Body diode Saturation current temperature exp. | | 3.0 |

M. MOSFET Level 2010 (SiC FET) Cascode Configuration

- MOSFET Level 2010 (SiC FET) Model Parameters
 - SiC Cascode Configuration for SiC FET, which contains a JFET and MOSFET
 - SiC JFET
 - Si MOSFET
 - Reference
 - "Cascode Configuration Eases Challenges of Applying SiC JFETs", United SiC, App Note USCI_AN0004
 - "Origins of SiC FETs and their evolution towards the perfect switch", United SiC, White Paper

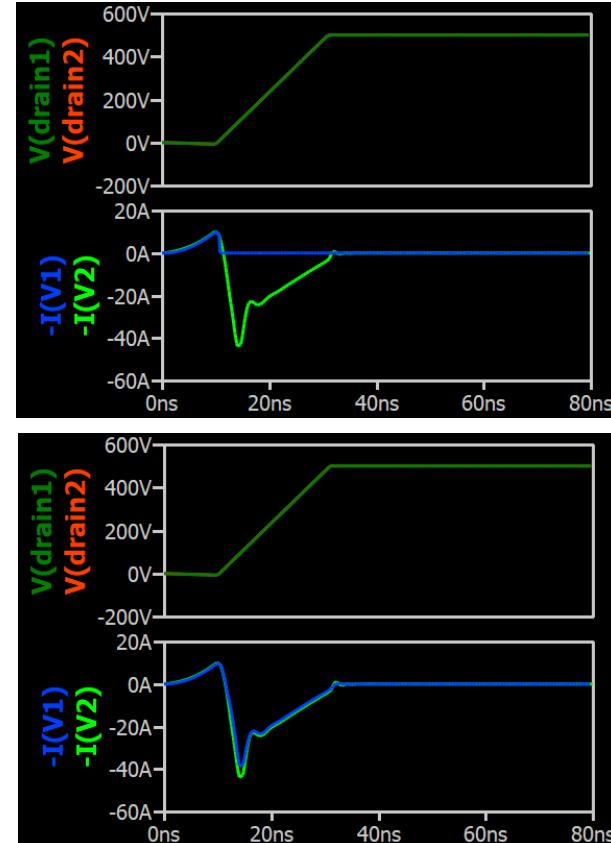
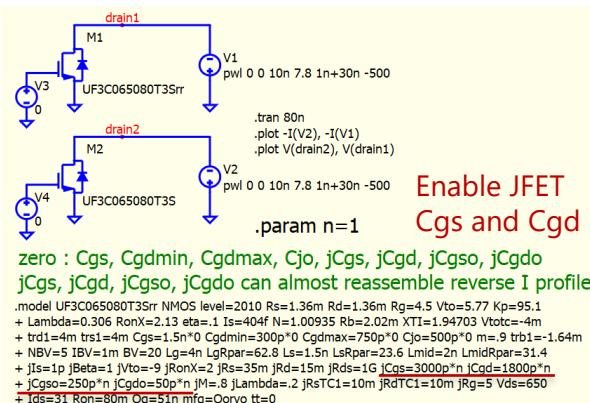
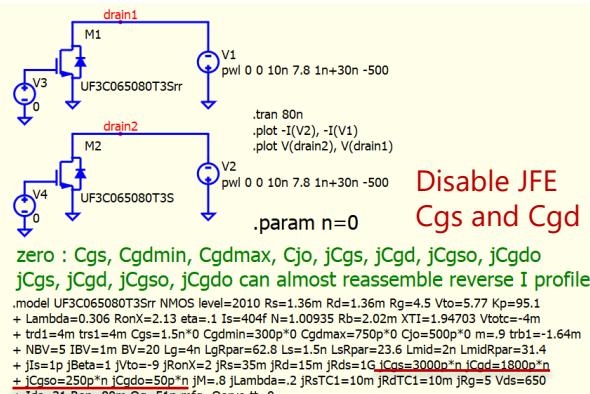


| Normally Off UnitedSiC Cascode | | Normally Off Typical SiC MOSFET |
|-----------------------------------|---|---|
| SiC Cascode Configuration |  |  |
| Die Size | (Smaller) $R_{DS(A)} \sim 1.75 \text{ m}\Omega\cdot\text{cm}^2$ | (Larger) $R_{DS(A)} \sim 3.1 - 4.5 \text{ m}\Omega\cdot\text{cm}^2$ |
| Gate Drive | (Standard) $V_{GS} = 0V$ to $12V$ OR (SiC) $V_{GS} = -10V$ to $20V$ | $V_{GS} = -5V$ to $20V$ |
| Threshold | $V_{GS(TH)} = 5V$ Typical | $V_{GS(TH)} = 2.2V$ Typical |
| Intrinsic Diode | Low Qrr, +10% Over Temperature | High Qrr, High VF 3X Over Temperature |
| Avalanche | Yes | Yes |
| Short Circuit | Yes | Low |

M. MOSFET Level 2010 : Reverse Current

Qspice : UF3C065080T3S Reverse Current.qsch

- Reverse Current
 - TT (transit-time) is set to 0 in Qorvo SiC FET, reverse recovery of bulk diode is not be used
 - Reverse current is simulated by parasitic capacitance in SiC FET
 - From Qorvo SiC FET model, reverse current is mainly contributed from Cgs and Cgd of JFET
 - j_{Cgs}, j_{Cgso}
 - j_{Cgd}, j_{Cgdo}

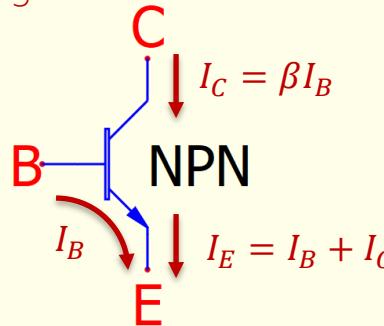


**Q. Bipolar Transistor
(Level 1, Extended
SPICE Gummel-Poon)**

Q. Bipolar Transistor : NPN and PNP

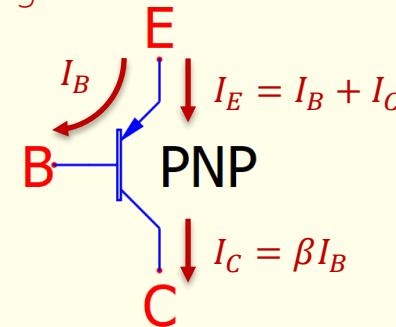
Active Region

$$V_C > V_E$$



Active Region

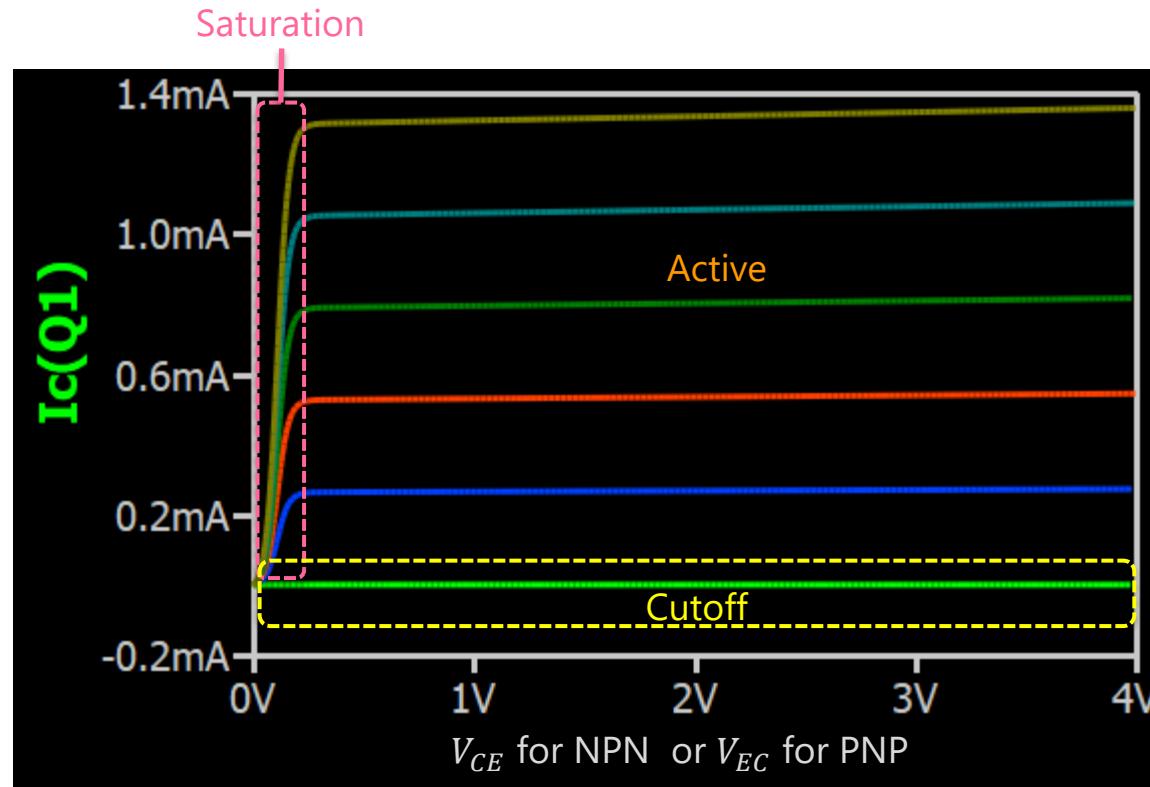
$$V_E > V_C$$



| Voltage Relations | NPN |
|-------------------|------------|
| $V_E < V_B < V_C$ | Active |
| $V_E < V_B > V_C$ | Saturation |
| $V_E > V_B < V_C$ | Cutoff |
| $V_E > V_B > V_C$ | Reverse |

| Voltage Relations | PNP |
|-------------------|------------|
| $V_E < V_B < V_C$ | Reverse |
| $V_E < V_B > V_C$ | Cutoff |
| $V_E > V_B < V_C$ | Saturation |
| $V_E > V_B > V_C$ | Active |

Q. Bipolar Transistor : NPN and PNP : Active, Saturation and Cutoff



Q. Bipolar Transistor Model Parameters

| Bipolar Transistor Model Parameters | | | |
|-------------------------------------|---|------------------|------------------------|
| Name | Description | Units | Default |
| AF | Flicker Noise Exponent | | 1.0 |
| BF | Ideal forward beta | | 100. |
| BR | Ideal reverse beta | | 1.0 |
| BRS | Substrate parasitic transistor beta | | .0 |
| CJC | Zero bias B-C capacitance | F | 0.0 |
| CJE | Zero bias B-E capacitance | F | 0.0 |
| CJS | Zero bias C-S capacitance(aka CCS) | F | 0.0 |
| CN ¹ | Tempco for hole mobility | °C ⁻¹ | NPN: 2.42 PNP: 2.20 |
| D ¹ | Tempco for scattering-limited hole carrier velocity | V ⁻¹ | NPN: 0.87 PNP: 0.52 |
| EG | Energy gap for IS temp. dependency | V | 1.11 |
| FC | Forward bias junction fit parameter | | 0.5 |
| GAMMA ¹ | Epitaxial region doping factor | | 1e-11 |
| GMAX | Maximum PN conductivity(straight-line extension) | Ω | 1000. |
| IBC | B-C saturation current | A | 0.0 |
| IBE | B-E saturation current | A | 0.0 |
| IKF | Forward beta roll-off corner current(aka IK) | A | Infinite |
| IKR | Reverse beta roll-off corner current | A | Infinite |
| IRB | Current for base resistance=(rb+rbm)/2 | A | Infinite |
| IS | Saturation Current | A | 1e-16 |
| ISC | B-C leakage saturation current(aka C4) | A | IS |
| ISE | B-E leakage saturation current(aka C2) | A | IS |
| ISS | Substrate junction saturation current | A | 0.0 ² |
| ITF | High current dependence of TF | A | 0.0 |
| KF | Flicker Noise Coefficient | | 0.33 |
| MJC | B-C junction grading coefficient(aka MC) | | 0.33 |
| MJE | B-E junction grading coefficient(aka ME) | | 0.0 |
| MJS | Substrate junction grading coefficient(aka MS) | | 0.0 |
| NC | B-C leakage emission coefficient | | 2.0 |
| NE | B-E leakage emission coefficient | | 1.5 |
| NEPI ¹ | Epitaxial region emission coefficient | | 1.0 |
| NF | Forward emission coefficient | | 1.0 |
| NK | High-current roll-off coefficient | | 0.5 |
| NR | Reverse emission coefficient | | 1.0 |
| NS | Substrate junction emission coefficient | | 1.0 |
| PTF | Excess phase | ° | 0.0 |
| QCO ¹ | Epitaxial region charge factor | C | 0.0 |

| QUASIMOD ¹ | Temperature dependence equation selector | | 0 |
|-----------------------|--|-------------------|----------|
| RB | Zero bias base resistance | Ω | 0.0 |
| RBM | Minimum base resistance | Ω | 0.0 |
| RC | Collector resistance | Ω | 0.0 |
| RCO ¹ | Epitaxial region resistance | Ω | 0.0 |
| RE | Emitter resistance | Ω | 0.0 |
| SUBS | Set to 2 to specify lateral geometry. | | 1 |
| TF | Ideal forward transit time | sec | 0.0 |
| TNOM | Parameter measurement temperature(aka TREF) | °C | 27.0 |
| TR | Ideal reverse transit time | sec | 0.0 |
| TRB1 | Rb 1st order temperature coefficient | °C ⁻¹ | 0.0 |
| TRB2 | Rb 2nd order temperature coefficient | °C ⁻² | 0.0 |
| TRBM1 | Rbm 1st order temperature coefficient(aka TRM1) | °C ⁻¹ | 0.0 |
| TRBM2 | Rbm 2nd order temperature coefficient(aka TRM2) | °C ⁻² | 0.0 |
| TRC1 | RC 1st order temperature coefficient | °C ⁻¹ | 0.0 |
| TRC2 | RC 2nd order temperature coefficient | °C ⁻² | 0.0 |
| TRE1 | RE 1st order temperature coefficient | °C ⁻¹ | 0.0 |
| TRE2 | RE 2nd order temperature coefficient | °C ⁻² | 0.0 |
| TVAF1 | 1st order tempco of forward Early voltage | V/°C ¹ | 0.0 |
| TVAF2 | 2nd order tempco of forward Early voltage | V/°C ² | 0.0 |
| TVAR1 | 1st order tempco of reverse Early voltage | V/°C ¹ | 0.0 |
| TVAR2 | 2nd order tempco of reverse Early voltage | V/°C ² | 0.0 |
| VAF | Forward Early voltage(aka VA) | V | Infinite |
| VAR | Reverse Early voltage(aka VB) | V | Infinite |
| VG ¹ | Extrapolated band gap voltage at 0°K | V | 1.206 |
| VJC | B-C junction built in potential(aka PC) | V | 0.75 |
| VJE | B-E junction built in potential(aka PE) | V | 0.75 |
| VJS | Substrate junction built in potential(aka PS) | V | 0.75 |
| VO ¹ | Carrier mobility knee voltage | V | 10.0 |
| VTF | Voltage giving VBC dependence of TF | V | Infinite |
| XCJC | Fraction of CJC connected to intrinsic base ³ | | 1.0 |
| XCJC2 | Fraction of CJC connected to intrinsic base ⁴ | | 1.0 |
| XCJS | Fraction of CJS connected internally to RE | | 1.0 |
| XTB | Forward and reverse beta temp. exp. | | 0.0 |
| XTF | Coefficient for bias dependence of TF | | 0.0 |
| XTI | Temperature exponent for IS(aka PT) | | 3.0 |

Q. Bipolar Transistor Basic Equation

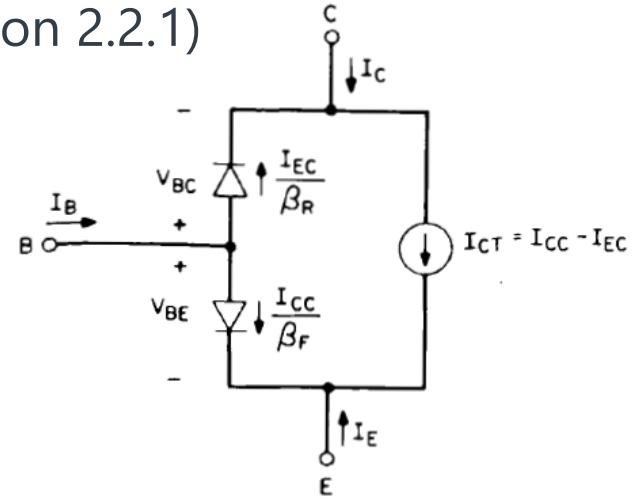
- Semiconductor Device Modeling with SPICE (Section 2.2.1)

- Basic equation from BJT Ebers-Moll static model

- $$\begin{aligned} I_C &= I_{CT} - \frac{I_{EC}}{\beta_R} \\ I_{CT} &= I_{CC} - I_{EC} \\ I_E &= -\frac{I_{CC}}{\beta_F} - I_{CT} \\ I_B &= \frac{I_{CC}}{\beta_F} + \frac{I_{EC}}{\beta_R} \end{aligned}$$

- Therefore

- $$\begin{aligned} I_C &= I_{CC} - I_{EC} - \frac{I_{EC}}{\beta_R} = \beta_F \left(I_B - \frac{I_{EC}}{\beta_R} \right) - I_{EC} - \frac{I_{EC}}{\beta_R} \\ I_C &= \beta_F I_B - \left(\frac{\beta_F}{\beta_R} + \frac{1}{\beta_R} + 1 \right) I_{EC} \end{aligned}$$



- Understanding (Approximation approach)

- If $V_{CE} \gg V_{BE}$, diode D_{BC} is reverse bias, where $I_{EC} \rightarrow 0$

- $$I_C = \beta_F I_B$$

- If $V_{BE} \gg V_{CE}$, diode D_{BC} is forward bias, and with $\beta_F \gg \beta_R$

- $$I_C = \beta_F I_B - \frac{\beta_F}{\beta_R} I_{EC}$$

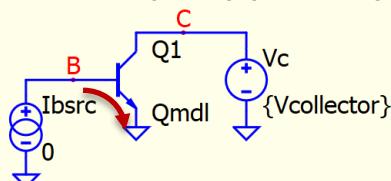
Q. Bipolar Params ($\beta_F | \beta_R$) : BF and BR

Qspice : NPN - BF.qsch / NPN - BR.qsch

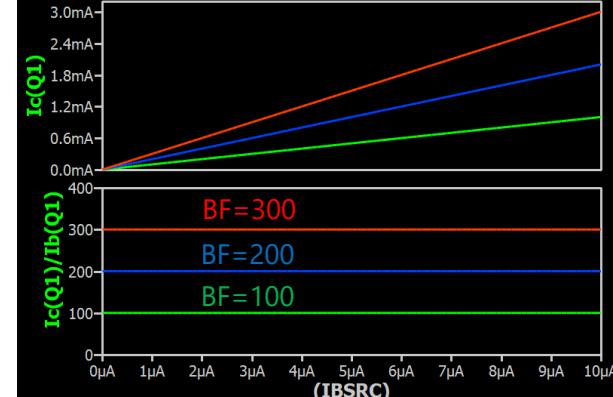
- BF
 - BF : Ideal forward beta
 - **Default BF=100**
 - $I_C = \beta_F I_B$ for $V_{CE} \gg V_{BE}$

- BR
 - BR : Ideal reverse beta
 - **Default BR=1**
 - $I_C = \beta_F I_B - \frac{\beta_F}{\beta_R} I_{EC}$
 - This effect is mainly observed when both BE and BC diode are forward bias, where collector-emitter voltage is close to 0V
 - Smaller β_R , larger $\frac{\beta_F}{\beta_R}$ and less I_C and less $\frac{I_C}{I_B}$

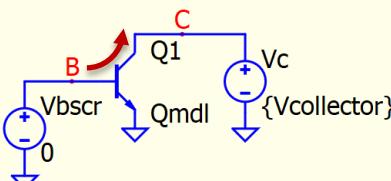
Sweep Parameters
`.param Vcollector = 10
.param Ibmax=10μ
.dc Ibsrc 10n {Ibmax} {Ibmax/100}`



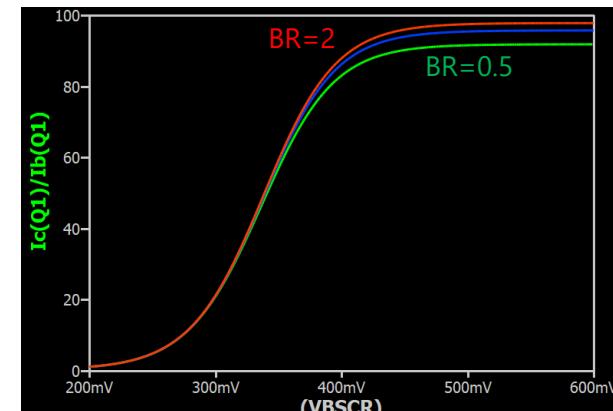
`.step param bf list 100 200 300
.model Qmdl NPN BF={bf}`



Sweep Parameters
`.param Vcollector = 0.2
.param Ibmin=10p
.dc Vbscr 0.2 0.6 0.001`



`.step param br list 0.5 1 2
.model Qmdl NPN BR={br} BF=100`

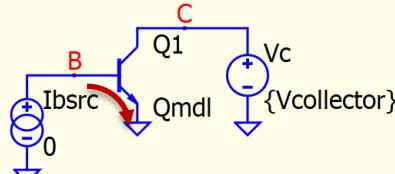


Q. Bipolar Params ($\beta_F | \beta_R$) : IKF

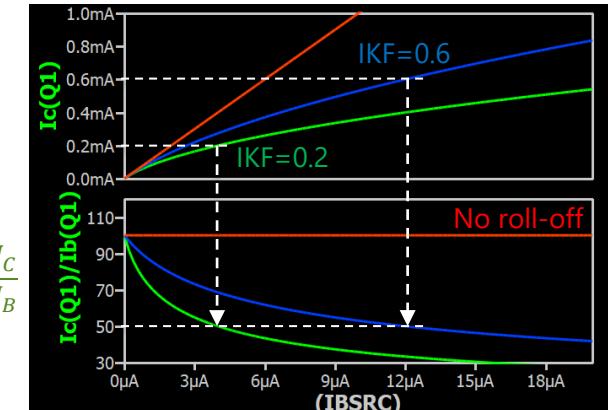
Qspice : NPN - IKF.qsch / NPN - IKR.qsch

- IKF
 - IKF : Forward beta roll-off corner current
 - Default IKF=infinite (A)**
 - IKF models β_F drop when I_C increase
 - IKF is I_C where effective BF (β_F) reduces multiple approximate by $(1-NK)$
 - This example Default NK=0.5, effective BF is reduced to 50 @ $I_C=IKF$

Sweep Parameters
`.param Vcollector = 10
.param Ibmax=20μ
.dc Ibsrc 10n {Ibmax} {Ibmax/100}`

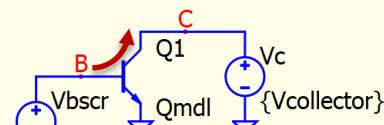


`.step param ikf list 0.2m 0.6m 1e12
.model Qmdl NPN BF=100 IKF=ikf`

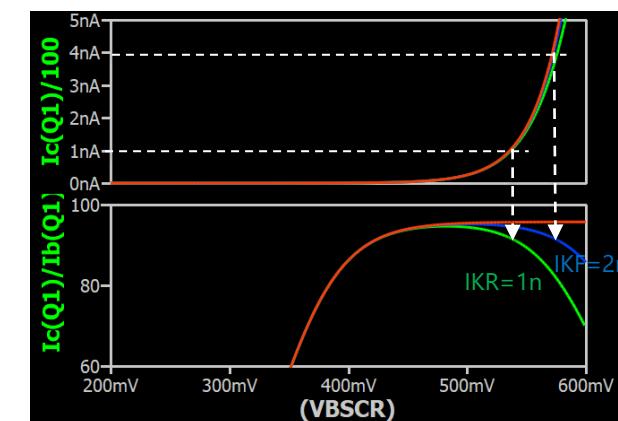


$$\beta_{F,\text{eff}} = \frac{I_C}{I_B}$$

Sweep Parameters
`.param Vcollector = 0.2
.param Ibmin=10p
.dc Vbscr 0.2 0.6 0.001`



`.param bf=100
.step param ikr list 1n 4n 1e12
.model Qmdl NPN BR=1 BF=bf IKR=ikr`



- IKR
 - IKR : Reverse beta roll-off corner current
 - Default IKR=infinite (A)**
 - IKR models β_F drop when I_C increase
 - IKR is $\frac{I_C}{BF}$ where effective BR (β_R) reduces to 50%

Q. Bipolar Params ($\beta_F | \beta_R$) : NK

Qspice : NPN - NK.qsch

- NK
 - NK : High-current roll-off coefficient
 - **Default NK=0.5**
 - This parameter is only be used if IKF not infinite

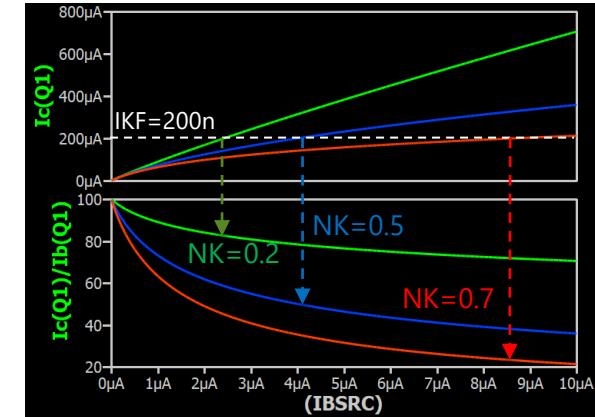
Sweep Parameters
.param Vcollector = 10
.param Ibmax=20 μ
.dc Ibsrc 10n {Ibmax} {Ibmax/100}

Plot Output
.plot Ic(Q1)/Ib(Q1)
.plot Ic(Q1)

Diagram

Model Definition

```
.step param nk list 0.2 0.5 0.7  
.model Qmdl NPN BF=100 IKF=200 $\mu$  NK=nk
```



Q. Bipolar Params (B-E and B-C Diode) : IS, NF, BF, NR, BR

Qspice : NPN - IS NF BF.qsch / NPN - IS NR BR.qsch

- Diode of Base-Emitter
 - **IS** : Saturation Current
 - **NF** : Forward emission coefficient
 - Default **IS** = $1e-16A$
 - Default **NF** = 1
 - In this case

$$I_B = I_{BE} = \frac{I_{CC}}{\beta_F}$$

$$= \frac{1}{\beta_F} I_S \left(e^{\frac{qV_{BE}}{n_F kT}} - 1 \right)$$

where β_F is **BF**

- Diode of Base-Collector
 - **IS** : Saturation Current
 - **NR** : Reverse emission coefficient
 - Default **IS** = $1e-16A$
 - Default **NR** = 1
 - In this case

$$I_B = I_{BC} = \frac{I_{EC}}{\beta_R}$$

$$= \frac{1}{\beta_R} I_S \left(e^{\frac{qV_{BE}}{n_R kT}} - 1 \right)$$

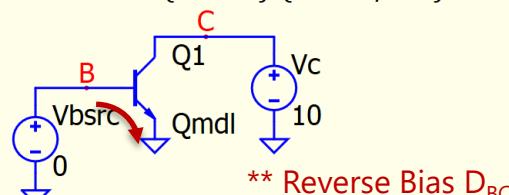
where β_R is **BR**

Sweep Parameters

.param Vcollector = 10
.param Vbmax=0.8

Plot Output

.plot Ib(Q1)
.dc Vbsrc 0n {Vbmax} {Vbmax/100}



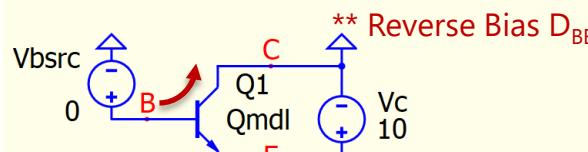
.model Qmdl NPN IS=1e-16 NF=0.7 BF=100

Sweep Parameters

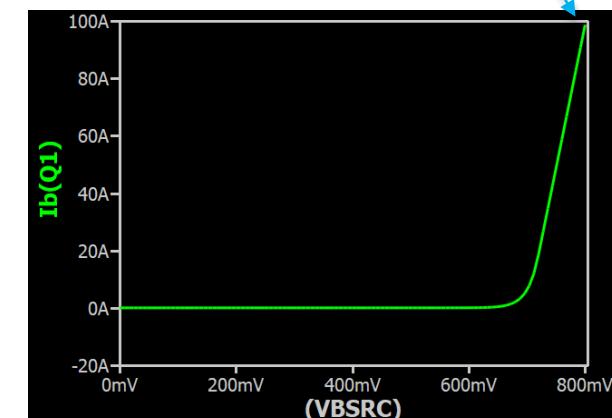
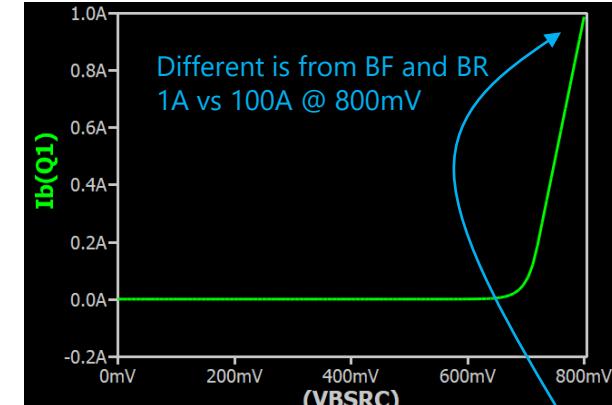
.param Vcollector = 10
.param Vbmax=0.8

Plot Output

.plot Ib(Q1)
.dc Vbsrc 0n {Vbmax} {Vbmax/100}



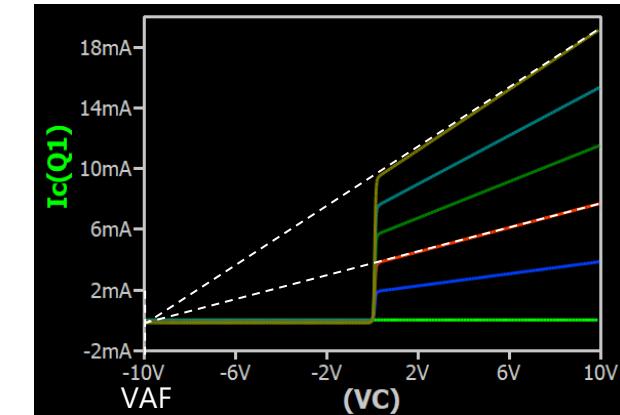
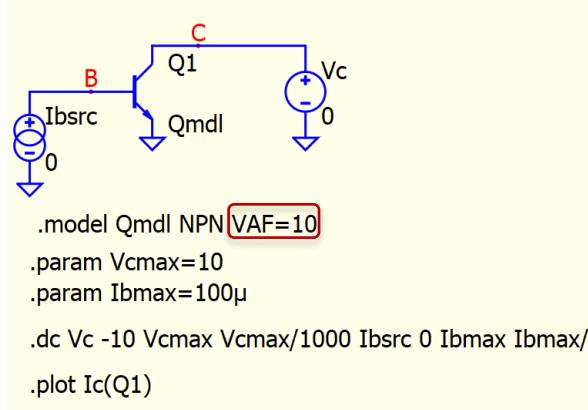
.model Qmdl NPN IS=1e-16 NR=0.7 BR=1



Q. Bipolar Params (Active Region) : VAF

Qspice : NPN - VAF.qsch

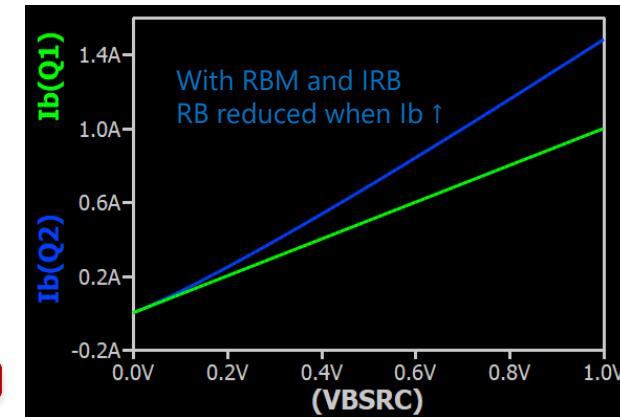
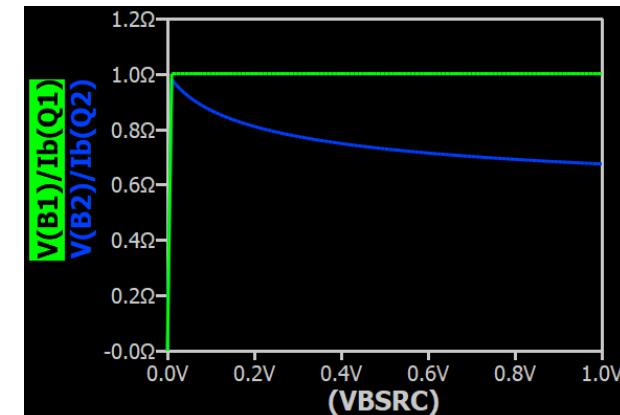
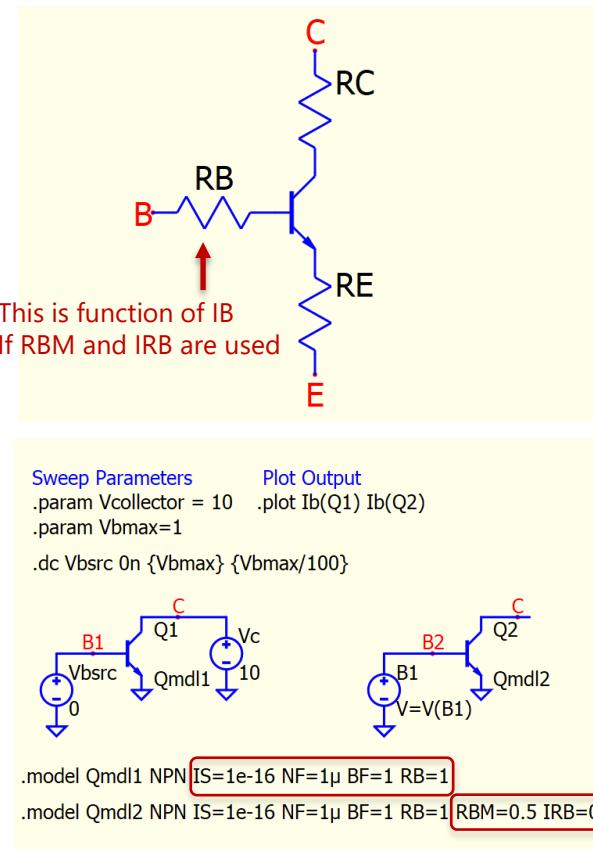
- VAF (aka VA)
 - VAF : Forward Early voltage
 - **Default VAF=Infinite (V)**



Q. Bipolar Params (Resistance): RB, RC, RE, RBM and IRB

Qspice : NPN - RBM IRB.qsch

- RB, RC, RE
 - RB : Zero bias base resistance
 - If RBM and IRB are used, base resistor is current dependent
 - RC : Collector resistance
 - RE : Emitter resistance
- RBM, IRB
 - RBM : Minimum base resistance
 - IRB : Current for base resistance
 - $R_{B, \text{effective}} @ \text{IRB} = \frac{1}{2} (\text{RB} + \text{RBM})$
 - Default RBM=0Ω
 - Default IRB=Infinite(A)
 - If these 2 parameters are defined, base resistance is function of base current



Q. Bipolar Params (Capacitance) : CJC, MJC, VJC, CJE, MJE, VJE

- B-C, B-E and C-S nonlinear capacitance
 - Model nonlinear capacitor between B-C, B-E and C-S
 - Parameters definition follows diode CJO, M and VJ
 - $C_j = \frac{\text{CJO}}{(1 - \frac{V_D}{V_J})^M}$
 - CJO : Zero-bias junction capacitance
 - M : Grading coefficient
 - VJ : Junction potential

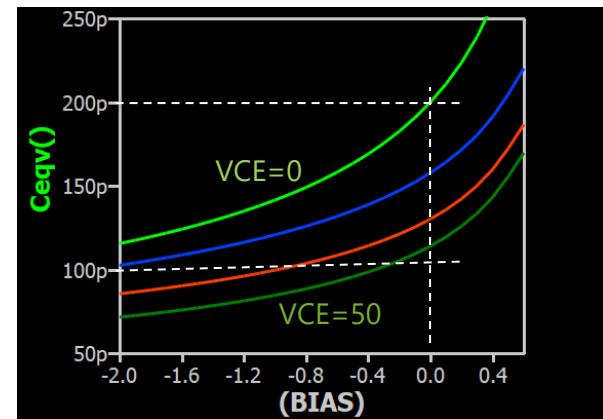
| Diode | CJO | M | VJ |
|-------|-----|-----|-----|
| B-C | CJC | MJC | VJC |
| B-E | CJE | MJE | VJE |
| C-S | CJS | MJS | VJS |

- Refer to D. Diode CJO, M and VJ
- C-S normally not modeled

```
.param f=1Meg
.ac list f
.step param bias -2 0.6 0.1
.step param VCE list 0 2 10 50
.func Zim() imag(V(B)/Ib(Q1))
.func Cequiv() -1/2/pi/f/Zim()
.plot Cequiv()

C
Q1
Qmdl
E
V2
VCE
Vbsrc
DC bias AC 1

.model Qmdl NPN CJE=100p MJE=0.5 VJE=1
+CJC=100p MJC=0.5 VJC=1
```



Q. Bipolar Params (Capacitance) : CJC, MJC, VJC, CJE, MJE, VJE

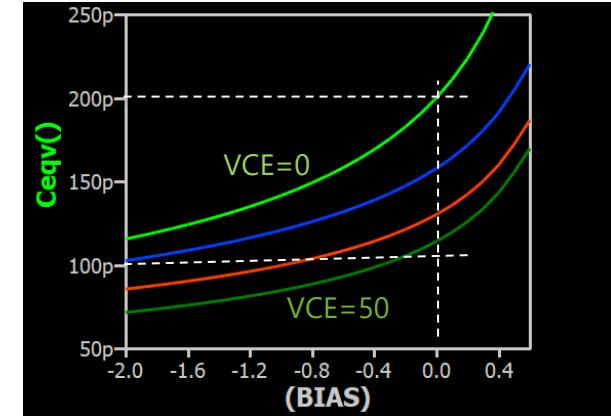
Qspice : NPN - CJC CJE.qsch

- B-C, B-E and C-S nonlinear capacitance
 - Model nonlinear capacitor between B-C, B-E and C-S
 - Parameters definition follows diode CJO, M and VJ
 - $C_j = \frac{C_{JO}}{(1 - \frac{V_D}{V_J})^M}$
 - CJO : Zero-bias junction capacitance
 - M : Grading coefficient
 - VJ : Junction potential
- Simulation
 - This simulation modeled both capacitance between B-C and B-E. Change VCE to observe overall capacitance effect in different bias voltage

```
.param f=1Meg
.ac list f
.step param bias -2 0.6 0.1
.step param VCE list 0 2 10 50
.model Qmdl NPN CJE=100p MJE=0.5 VJE=1
+CJC=100p MJC=0.5 VJC=1
```

Calculate Equivalent C

```
.func Zim() imag(V(B)/Ib(Q1))
.func Ceqv() -1/2/pi/f/Zim()
.plot Ceqv()
```



| Diode | CJO | M | VJ |
|-------|-----|-----|-----|
| B-C | CJC | MJC | VJC |
| B-E | CJE | MJE | VJE |
| C-S | CJS | MJS | VJS |

- Refer to D. Diode CJO, M and VJ
- C-S normally not modeled

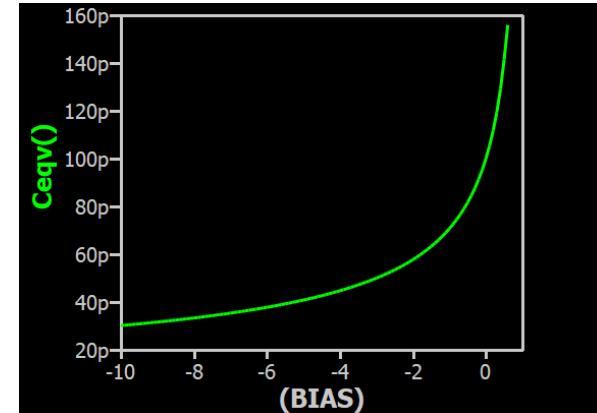
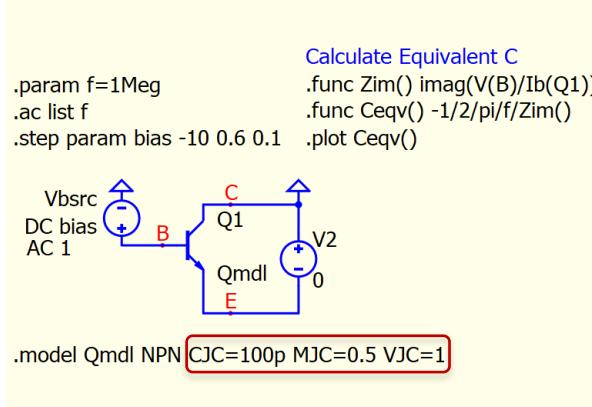
- Simulation Explanation
 - CBC and CBE are nonlinear capacitance of junction diode from B to C and B to E
 - Higher reverse voltage, lower capacitance
 - Therefore, increase VCE, increase reverse voltage of B-C and affects B-C capacitance. However, increase VCE doesn't affect VBE, and no effects in B-E capacitance
 - @VB=0V, when VCE=0, no reverse in both B-C and B-E and capacitance equals CJC+CJE

Q. Bipolar Params (Capacitance) : CJC, MJC, VJC, CJE, MJE, VJE

Qspice : NPN - CJC MJC VJC.qsch / NPN - CJE MJE VJE.qsch

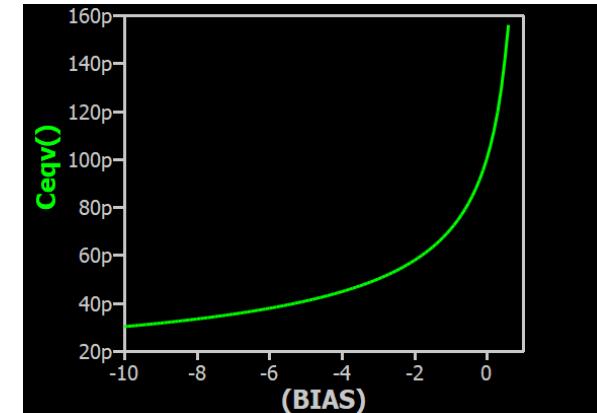
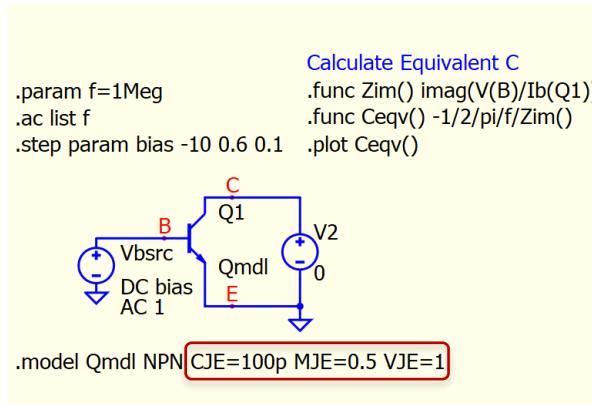
CJC, MJC and VJC

- CJC : Zero bias B-C capacitance
- MJC : B-C junction grading coefficient
- VJC : B-C junction built in potential
- **Default CJC=0F**
- **Default MJC=0.5**
- **Default VJC=1**



CJE, MJE and VJE

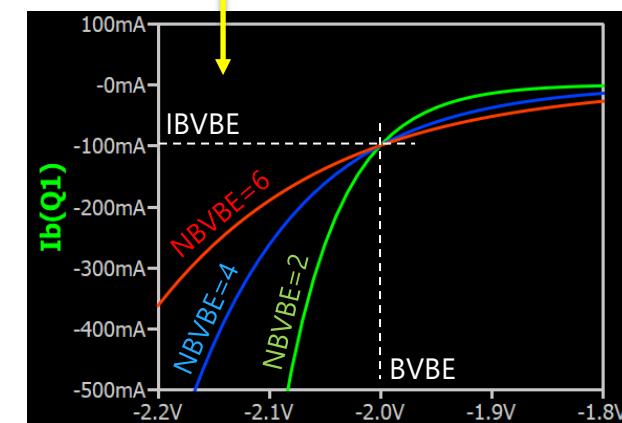
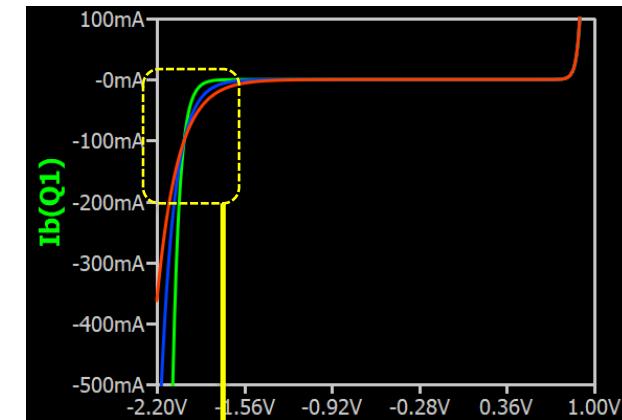
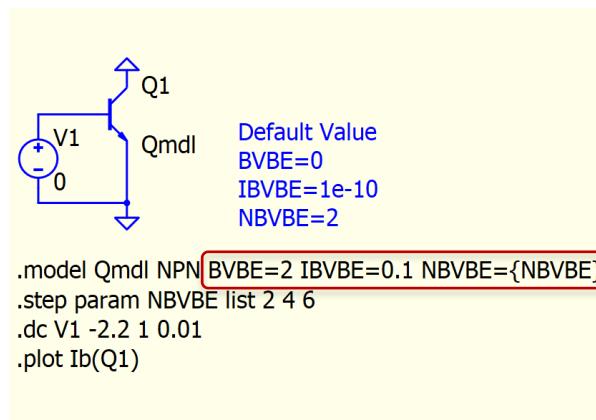
- CJE : Zero bias B-E capacitance
- MJE : B-E junction grading coefficient
- VJE : B-E junction built in potential
- **Default CJE=0F**
- **Default MJE=0.5**
- **Default VJE=1**



Q. Bipolar Params (B-E Diode) : BVBE, IBVBE, NBVBE

Qspice : NPN - BVBE IBVBE NBVBE.qsch

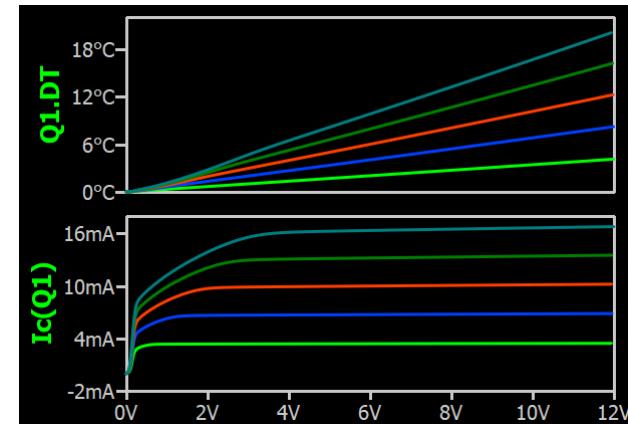
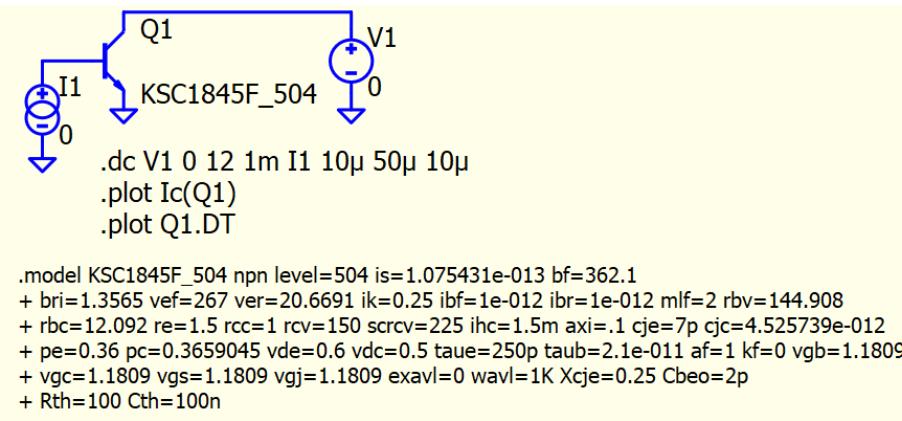
- BVBE, IBVBE, NBVBE
 - Qspice Revision History
 - 12/30/2023 Implemented bipolar B-E breakdown via model parameters BVBE, IBVBE, AND NBVBE.
 - Parameters to model breakdown characteristic of Base-Emitter Diode
 - BVBE : Reverse breakdown voltage
 - IBVBE : Current at breakdown voltage
 - NBVBE : Emission coefficient
 - **Default BVBE=0V**
 - **Default IBVBE=1e-10A**
 - **Default NBVBE=2**



**Q. Bipolar Transistor
(MEXTRAM 504, Level
504 by NXP)**

Q. Transistor (MEXTRAM 504)

- MEXTRAM 504
 - Release history
 - Qspice Revision History : 11/29/2023 Released a MEXTRAM 504(rev 12) implementation
 - <https://forum.qorvo.com/t/models-of-transistors-with-thermal-parameters/15809/5>
 - Comment from Mike Engelhardt
 - It's the current minor revision level, 12
 - It should be able to properly run that model without the collector current going to zero
 - If no self heating node is specified, it will make one called Q1.DT. Otherwise you can make a five terminal transistor and connect a thermal network the temperature node



R. Resistor

R. Resistor Instance and Model Parameters

- Resistor Syntax
 - Rnnn N1 N2 [<model>] <resistance> [instance parameters]
 - .model <model> RES [model parameters]

Resistor Instance Parameters

| Name | Description | Units | Default |
|------------------|---|------------------|---------------------|
| AC | Value to use for .ac analysis | Ω | RESISTANCE |
| B ¹ | NTC coefficient | | 0.0 |
| CTH ² | Thermal capacitance | F | Model value |
| RESISTANCE | Resistance | Ω | none |
| RTH ² | Thermal resistance | Ω | Model value |
| L ³ | Length | m | 1.0 |
| W ³ | Width | m | 1.0 |
| M | Number of identical parallel instances | | 1.0 |
| TC ¹ | Polynomial temperature coefficient list | | 0.0 |
| TC1 ¹ | 1nd order temperature coefficient | °C ⁻¹ | 0.0 |
| TC2 ¹ | 2nd order temperature coefficient | °C ⁻² | 0.0 |
| TEMP | Instance temperature | °C | Circuit temperature |
| TNOM | Temperature resistance was measured(aka TREF) | °C | Circuit TNOM |

Resistor Model Parameters

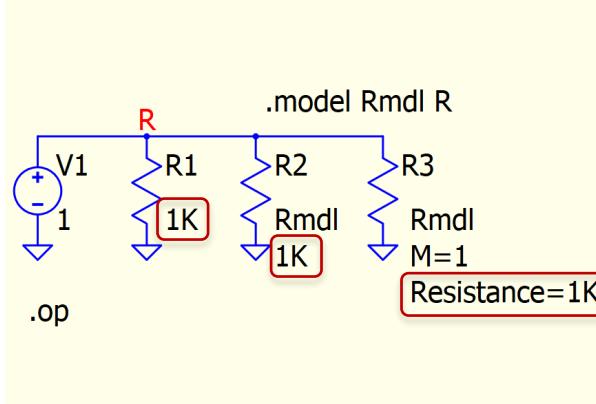
| Name | Description | Units | Default |
|---------------------|---|------------------|--------------|
| CTH ² | Thermal capacitance | F | 0.0 |
| DEFW | Default device width | m | 1.0 |
| NARROW ³ | Narrowing of resistor | m | 1.0 |
| R | Resistor multiplier | | 1.0 |
| RTH ² | Thermal resistance | Ω | 0.0 |
| RSH ³ | Sheet resistance(for instance L and W) | Ω/□ | 0.0 |
| TC ¹ | Polynomial temperature coefficient list | | 0.0 |
| TC1 ¹ | 1nd order temperature coefficient | °C ⁻¹ | 0.0 |
| TC2 ¹ | 2nd order temperature coefficient | °C ⁻² | 0.0 |
| TCE ¹ | Exponential order temperature coefficient | %/°C | 0.0 |
| TNOM | Parameter measurement temperature(aka TREF) | °C | Circuit TNOM |

R. Resistor – Resistance and AC

Qspice : R - Resistance.qsch | R - AC.qsch

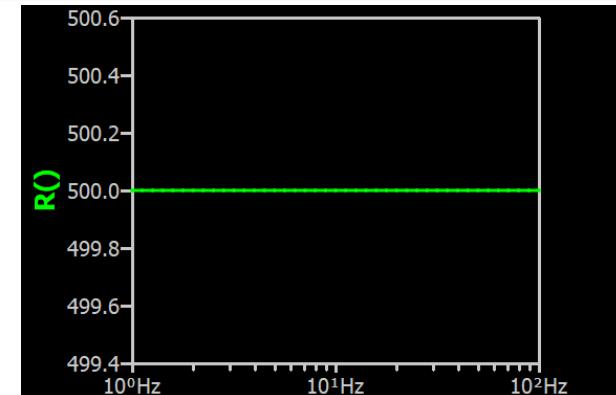
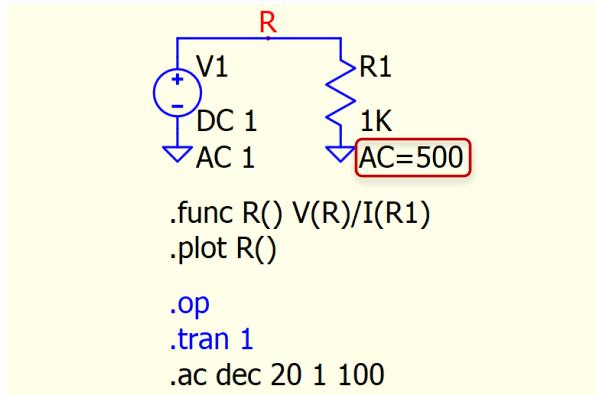
- Resistance

- Resistance can be specified in three way
 - #1 : Resistance value at 1st attribute
 - #2 : <model> at 1st attribute and resistance value at 2nd attribute
 - #3 : <model> at 1st attribute, resistance value after 2nd attribute with **Resistance=<value>**



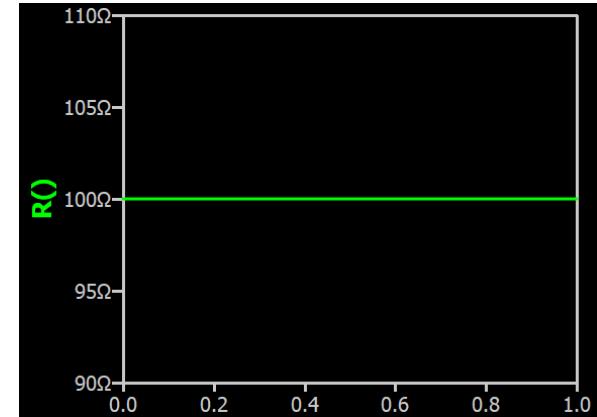
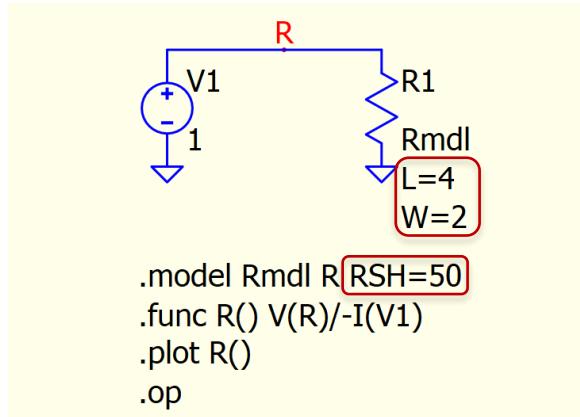
- AC

- Value to use for .ac analysis
- **Default = RESISTANCE**
- In this example, .op or .tran set R1=1Kohms but .ac set R1=500ohms



R. Resistor – RSH, L and W (Sheet Resistance)

- RSH, L and W
 - RSH : Sheet Resistance
 - L : Length
 - W : Width
 - RSH is model param and L, W are instance params
 - If RESISTANCE is defined, RSH, L and W will be ignored
 - Sheet resistance is the resistance of a square of the conductive thin film with uniform thickness
 - $R = R_{SH} \times \frac{L}{W}$



R. Resistor – Thermal Related Parameters

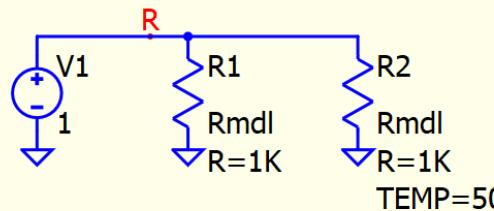
- Resistor Thermal Equation
 - Formula with temperature coefficient list TC : $R_T = R_{nom}(1 + \sum T_{Cn}\Delta T^n)$
 - TC supports a list of temperature coefficient in format TC=<value1>,<value2>,<value3>,...
 - Formula with temperature coefficient TC1 and TC2 : $R_T = R_{nom}(1 + T_{C1}\Delta T + T_{C2}\Delta T^2)$
 - Formula with temperature coefficient TCE : $R_T = R_{nom} e^{\frac{T_{CE}}{100}\Delta T}$
 - Formula with B (or beta) for thermistor (NTC) : $R_T = R_{nom} e^{B \times \left(\frac{1}{T} - \frac{1}{T_{nom}}\right)}$
 - where Temperature in above formula is in Kelvin, $\Delta T = T - T_{nom}$

R. Resistor Params : Tnom and TEMP (Instance param), TC

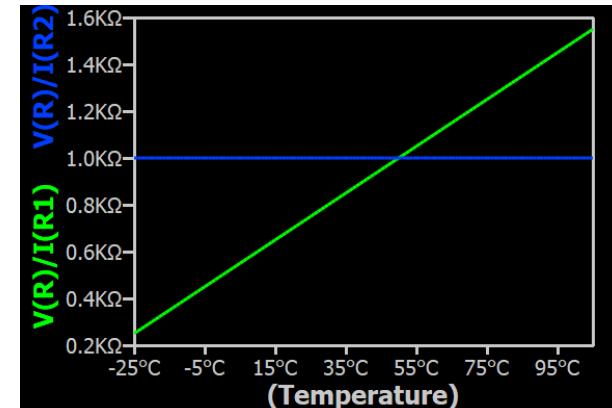
Qspice : R - TNOM TEMP.qsch | R - TC.qsch

- Tnom and TEMP

- Tnom : Parameter measurement temperature
- TEMP : Instance temperature in Instance param
- Default Tnom=27oC**
- Default TEMP=Circuit**
- Temperature
- In this example, instance temperature TEMP is assigned for R2, which forced R2 at TEMP instead of circuit temperature

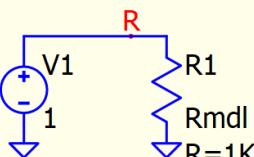


```
.model Rmdl R Tnom=50 TC1=0.01  
.plot V(R)/I(R1) V(R)/I(R2)  
.dc Temp -25 105 1  
.op
```

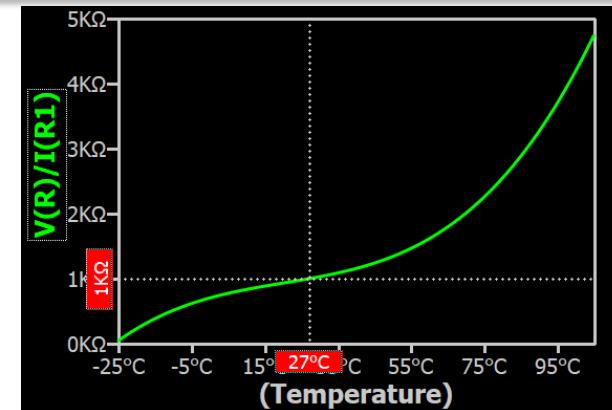


- TC

- TC : Polynomial temperature coefficient list
- Default TC=0**
- $TC = <value1>, <value2>, <value3>, \dots$
- $R_T = R_{nom}(1 + \sum T_{cn} \Delta T^n)$
- where Tnom is R defined measurement temperature



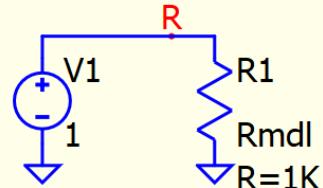
```
.model Rmdl R TC=0.01,0.0001,0.000005  
.plot V(R)/I(R1)  
.dc Temp -25 105 0.001  
.op
```



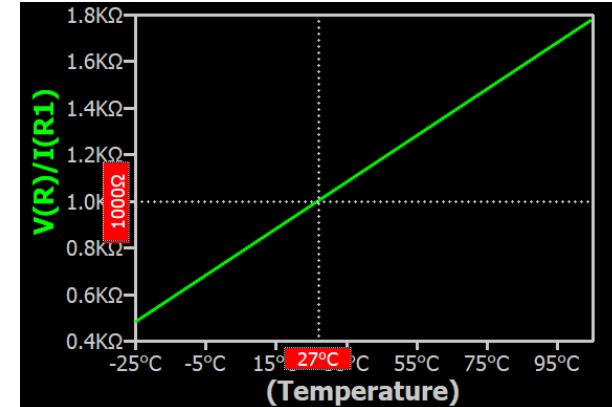
R. Resistor Params : TC1 and TC2

Qspice : R - TC1.qsch / R - TC2.qsch

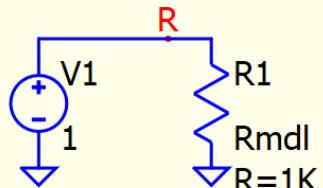
- TC1
 - TC1 : 1nd order temperature coefficient
 - **Default TC1=0°C⁻¹**
 - $RT = R * (1 + TC1 * (T - T_{nom}))$
 - Where T_{nom} is R defined measurement temperature



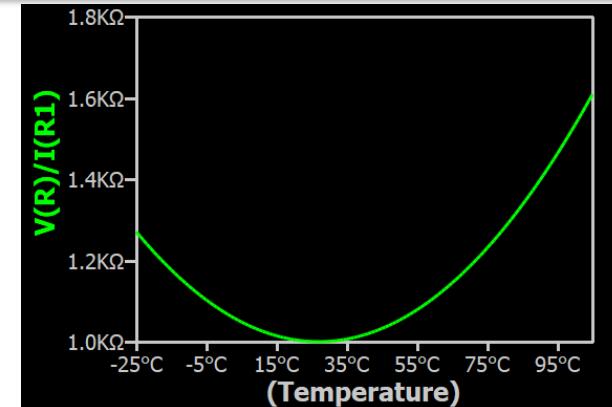
```
.model Rmdl R TC1=0.01  
.plot V(R)/I(R1)  
.dc Temp -25 105 0.001  
.op
```



- TC2
 - TC2 : 2nd order temperature coefficient
 - **Default TC2=0°C⁻²**
 - $RT = R * (1 + TC2 * (T - T_{nom})^2)$
 - TC2 and TC1 can be used together



```
.model Rmdl R TC2=0.0001  
.plot V(R)/I(R1)  
.dc Temp -25 105 1  
.op
```

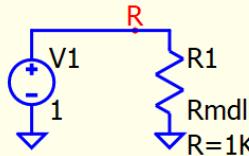


R. Resistor Instance Param : TCE and B for Thermistor (NTC)

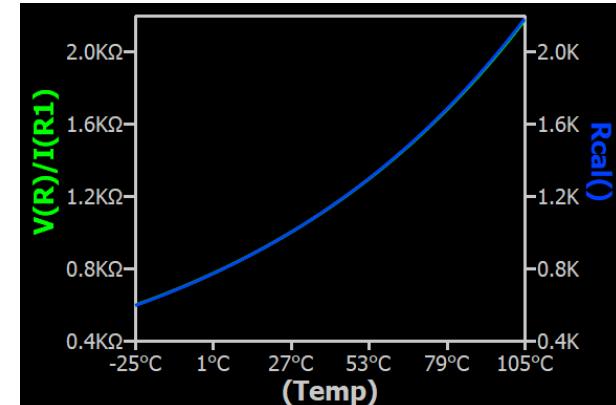
Qspice : R - TCE.qsch | R - B.qsch

TCE

- TCE : Exponential order temperature coefficient
- **Default TCE=0%/ $^{\circ}\text{C}$**
- $R_T = R_{\text{nom}} \cdot e^{TCE \cdot (T - T_{\text{nom}})}$
- If TCE is specified non-zero, TC1 and TC2 are ignored

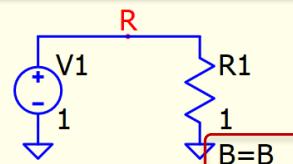


```
.model Rmdl R TCE=1  
.plot V(R)/I(R1) Rcal()  
.dc Temp -25 105 1  
.step param Temp -25 105 1  
.op  
.func Rcal() 1K*exp((Temp-27)/100*1)
```

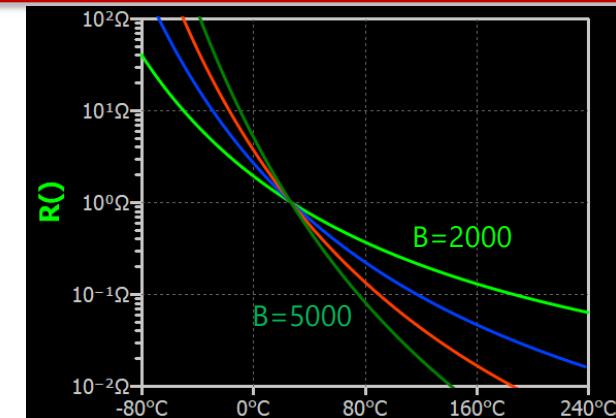


B (for thermistor/NTC)

- NTC Coefficient
- **Default B=0**
- $R_T = R_{\text{nom}} e^{B \times \left(\frac{1}{T} - \frac{1}{T_{\text{nom}}} \right)}$
- Refer to TDK NTC thermistor general information, B value of common NTC materials range is from 3000 to 5000



```
.op  
.step param TEMP -80 240 1  
.step param B 2000 5000 1000  
.func R() V(R)/I(R1)  
.plot R()
```

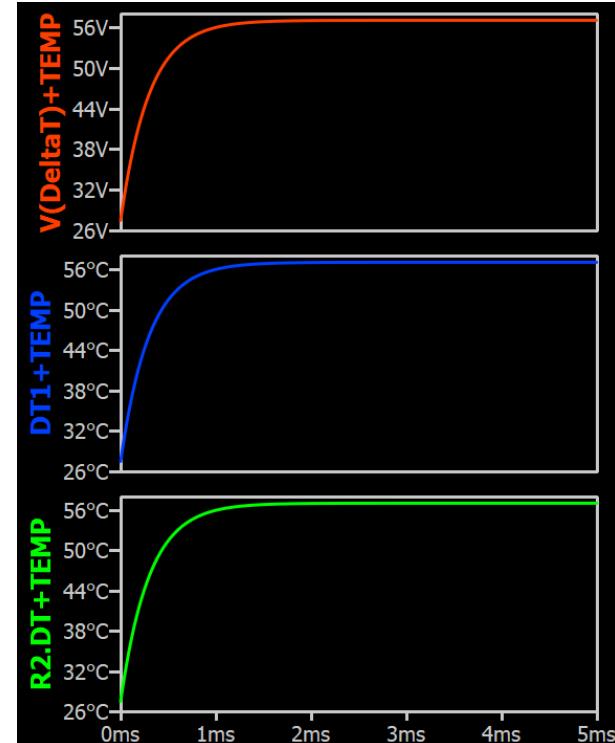
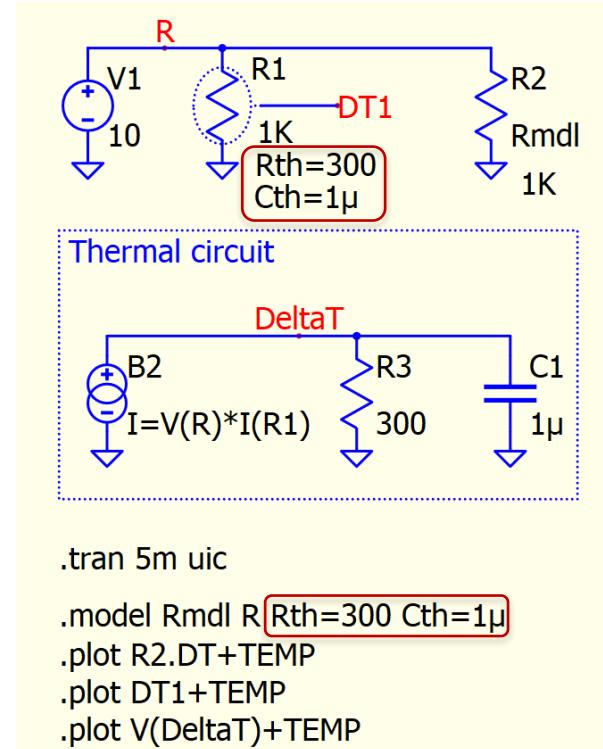


R. Resistor Params : Rth and Cth (Thermal Resistance and Capacitance)

Qspice : R - Rth Cth (Thermal Circuit).qsch

- RTH and CTH

- RTH : Thermal Resistance
- CTH : Thermal Capacitance
- **Default RTH=0**
- **Default CTH=0**
- Cth and Cth supports both instance (e.g. R1) and .model parameters (e.g. R2)
- DT (Delta Temperature ΔT)
 - DT is rise in temperature above ambient of resistor
 - 3-terminal resistor (3rd node in square braces) : ΔT is returned at 3rd node
 - 2-terminal resistor : ΔT is returned as Rnnn.DT

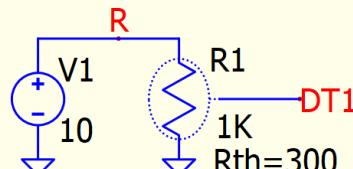


R. Resistor Params : Rth and Cth (Thermal Resistance and Capacitance)

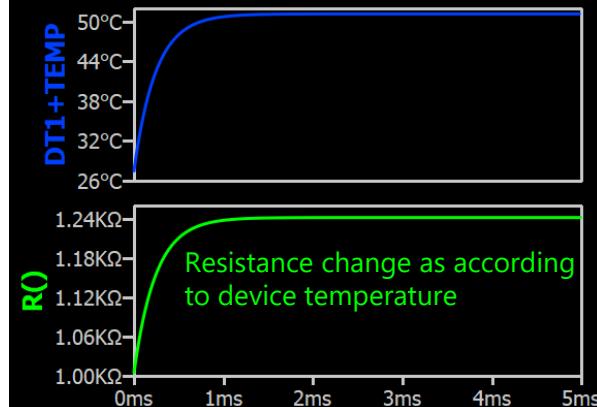
Qspice : R - Rth Cth (Self Heating).qsch

- Self Heating Resistor
 - This is an example for resistor with positive temperature coefficient
 - Resistance and temperature relationship is controlled by temperature coefficient TC. Rth and Cth determine thermal response to achieve self heating simulation

Self Heating Resistor Modeling

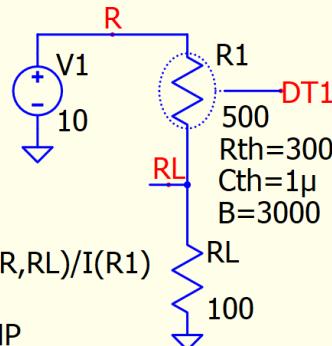


```
.tran 5m uic  
.func R() V(R)/I(R1)  
.plot R()  
.plot DT1+TEMP
```

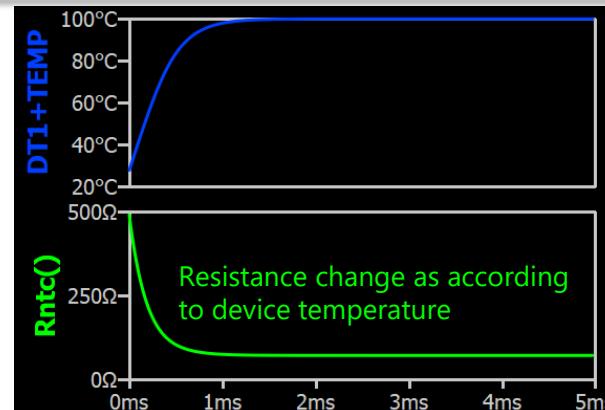


- Thermistor Self Heating
 - This example use NTC coefficient B to setup a thermistor for self heating simulation
 - A loading resistor is required to limit maximum current for simulation to reach steady state with using NTC

Self Heating Thermistor Modeling



```
.tran 5m uic  
.func Rntc() V(R,RL)/I(R1)  
.plot Rntc()  
.plot DT1+TEMP
```



R. Resistor : Behavioral Resistor (R)

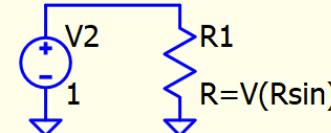
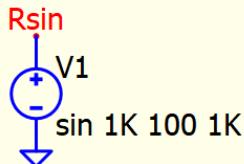
Qspice : R - Behavioral R Demo 01.qsch | R - Behavioral R Demo 02.qsch

- Behavioral Resistor

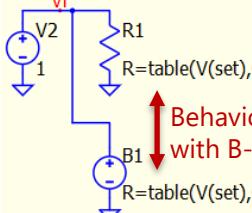
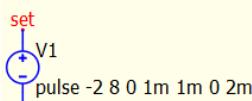
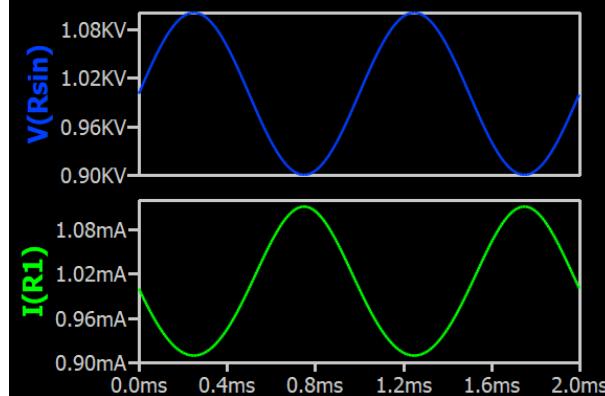
- To use formula or voltage/current node for resistance, type $R=...$ in $<\text{val}>$ of resistor
- Also support to use Behavioral source (B) for behavioral resistor

- Replace $V=\text{expression}$ with $R=\text{expression}$

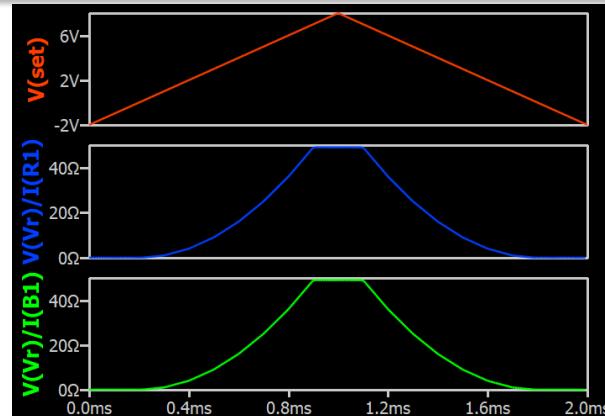
Behavioral Resistance with $R=$ <eqn>



```
.plot I(R1)  
.plot V(Rsin)
```



```
.plot V(set)  
.plot V(Vr)/I(R1)  
.plot V(Vr)/I(B1)
```



Behavioral R can also be implemented with B-source with syntax $R=...$

S. Voltage Controlled Switch

S. Voltage Controlled Switch Model Parameters

- S. Voltage Controlled Switch Model Parameters
 - It is common to define Switch Model for usage as multiple switches in a schematic
 - Syntax: Snnn N1 N2 NC+ NC- <model> [instance parameters]
 - .model <model> SW [model parameters]

Voltage Controlled Switch Model Parameters

| Name | Description | Units | Default |
|------------------|--------------------------------|----------|---------|
| ETA ¹ | Sub-/over-Threshold conduction | V | 0.0 |
| ROFF | Off resistance | Ω | 1e6 |
| RON | On resistance | Ω | 1.0 |
| TTOL | Temporal tolerance | sec | 1e308 |
| VH | Hysteresis voltage | V | 0.0 |
| VOFF | Voltage when open | V | 0.0 |
| VON | Voltage when closed | | |
| VT | Threshold voltage | | |

Input Control
Voltage

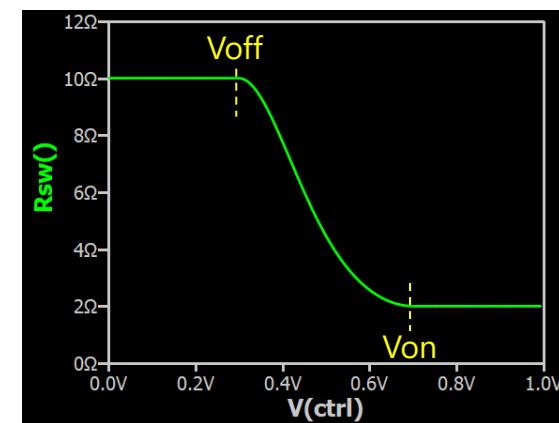
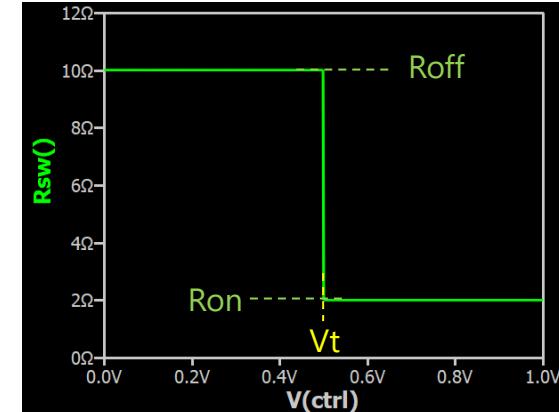
S. Switch Model Params : Ron, Roff, VT, Von and Voff

Qspice : Switch - Ron Roff VT.qsch

- RON, ROFF, VT
 - Ron : On resistance
 - Roff : Off resistance
 - VT : Threshold voltage
 - **Default RON=1Ω**
 - **Default ROFF=1MegΩ**
 - **Default VT=0V**
- VON, VOFF
 - Von : Voltage when closed
 - Voff : Voltage when open
 - **Default VON=0V**
 - **Default VOFF=0V**
 - switch smoothly transitions between on and off
 - If VT and VH are specified, VON and VOFF are ignored

```
.model mSW SW Ron=2 Roff=10 Vt=0.5 VH=0
pulse 0 1 0 1 1 1 4
.tran 4
.func Rsw() V(sw)/I(I1)
.plot Rsw()
.plot V(ctrl)
```

```
.model mSW SW Ron=2 Roff=10 Von=0.7 Voff=0.3
pulse 0 1 0 1 1 1 4
.tran 4
.func Rsw() V(sw)/I(I1)
.plot Rsw()
.plot V(ctrl)
```



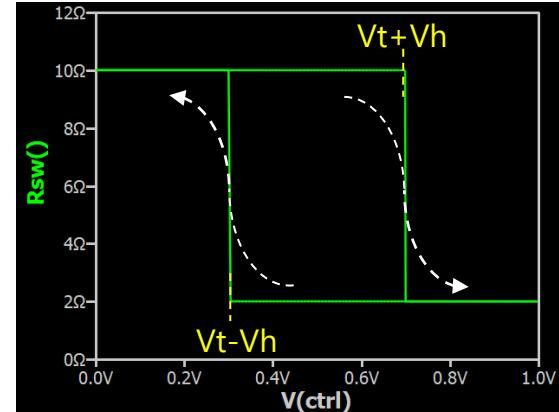
S. Switch Model Params : VH

Qspice : Switch - VH.qsch

- VH
 - V_h : Hysteresis voltage
 - **Default VH=0V**
 - Switch is ON
 - $V(+)-V(-) > V_t + V_h$
 - Switch is OFF
 - $V(+)-V(-) < V_t - V_h$
 - Switch maintain its state
 - $V_t - V_h < V(+)-V(-) < V_t + V_h$

```
.model mSW SW Ron=2 Roff=10 Vt=0.5 Vh=0.2  
+ve Vh
```

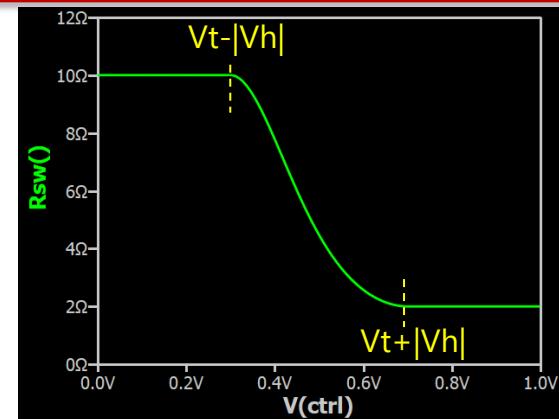
```
pulse 0 1 0 1 1 1 4  
.tran 4  
.func Rsw() V(sw)/I(I1)  
.plot Rsw()  
.plot V(ctrl)
```



- VH (-ve explained)
 - Negative V_h
 - If V_H is negative the switch smoothly transitions between on and off

```
.model mSW SW Ron=2 Roff=10 Vt=0.5 Vh=-0.2  
-ve Vh
```

```
pulse 0 1 0 1 1 1 4  
.tran 4  
.func Rsw() V(sw)/I(I1)  
.plot Rsw()  
.plot V(ctrl)
```



S. Switch Model Params : (VON, VOFF) vs (VT, VH)

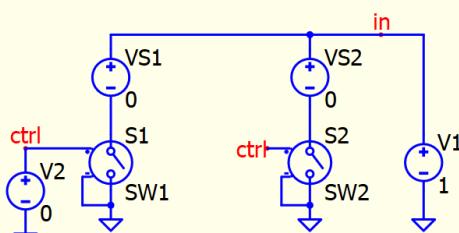
- Change between [VON, VOFF] and [VT, VH]
 - Important Note
 - VH must be negative for smooth transition
 - VON and VOFF is Pspice syntax which must be a smooth transition
 - For VON > VOFF
 - $VT = (VON + VOFF)/2$
 - $VH = |VON - VOFF|/2 * (-1)$: negative for smooth transition
 - For discrete switching action, remove the negative sign, but this is not an exact equivalent change.
 - For VON < VOFF
 - VT and VH : Same as above
 - Swap ROFF and RON

S. Switch Model Params : (VON, VOFF) vs (VT, VH)

Qspice : Switch - VH neg formula.qsch

- Formula in Smooth Transition Region

- $L_m = \ln(\sqrt{R_{ON} \times R_{OFF}})$, $L_r = \ln\left(\frac{R_{ON}}{R_{OFF}}\right)$, $V_m = \frac{V_{ON}+V_{OFF}}{2}$, $V_d = V_{ON} - V_{OFF}$
- For $V_{ON} > V_{OFF}$: $R_s = e^{L_m + \frac{3 L_r (V_c - V_m)}{2 V_d} - 2 L_r \left(\frac{V_c - V_m}{V_d}\right)^3}$
- For $V_{ON} < V_{OFF}$: $R_s = e^{L_m - \frac{3 L_r (V_c - V_m)}{2 V_d} + 2 L_r \left(\frac{V_c - V_m}{V_d}\right)^3}$



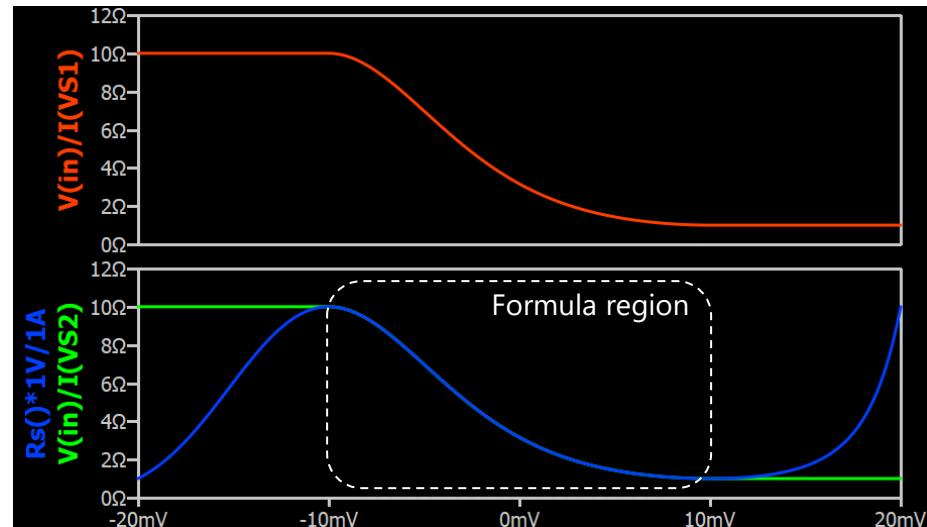
```

.plot V(in)/I(VS2) Rs()*1V/1A
.plot V(in)/I(VS1)
.param Roff=10
.param Ron=1
.param Voff=-10m
.param Von=10m
.param Vt=(Von+Voff)/2
.param Vh=abs(Von-Voff)/2*-1

.model SW1 SW ROFF=10 RON=1 Vt=Vt Vh=Vh
.model SW2 SW ROFF=Roff RON=Ron VOFF=Voff VON=Von
.dc V2 -20m 20m 0.1m

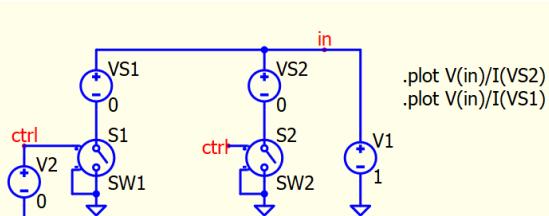
.func Lm() ln(sqrt(Ron*Roff))
.func Lr() ln(Ron/Roff)
.funcVm() (Von+Voff)/2
.funcVd() (Von-Voff)
.funcRs() exp(Lm() + 3*Lr()*(V(ctrl)-Vm())/(2*Vd()) - 2*Lr()*((V(ctrl)-Vm())/Vd())^3)

```



S. Switch Model Params : (VON, VOFF) vs (VT, VH)

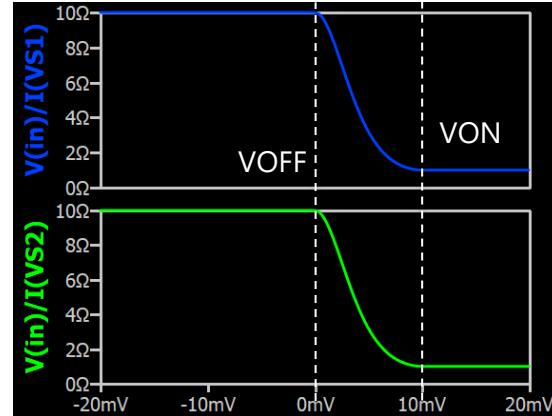
Qspice : Switch - Von Voff VT VH.qsch



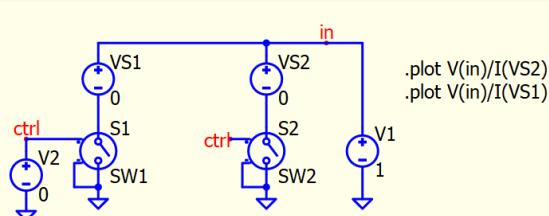
```
.model SW1 SW ROFF=10 RON=1 Vt=5m Vh=-5m
.model SW2 SW ROFF=10 RON=1 VOFF=0 VON=10m

.model SW1 SW ROFF=1E12 RON=10m Vt=5m Vh=-5m
.model SW2 SW ROFF=1E12 RON=10m VOFF=0 VON=10m

.dc V2 -20m 20m 0.1m
```



- Two examples

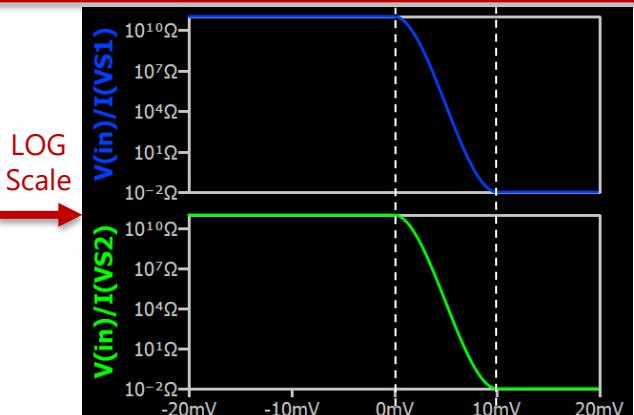
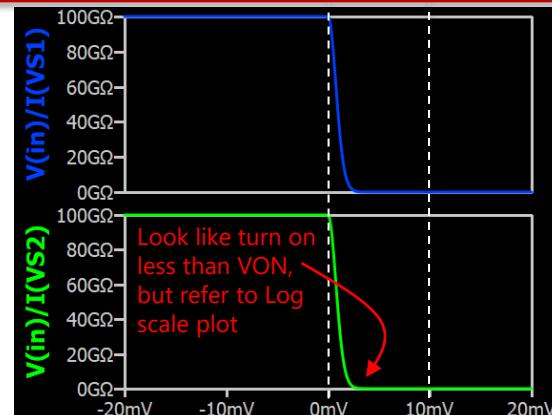


```
.model SW1 SW ROFF=10 RON=1 Vt=5m Vh=-5m
.model SW2 SW ROFF=10 RON=1 VOFF=0 VON=10m

.model SW1 SW ROFF=1E12 RON=10m Vt=5m Vh=-5m
.model SW2 SW ROFF=1E12 RON=10m VOFF=0 VON=10m

.dc V2 -20m 20m 0.1m
```

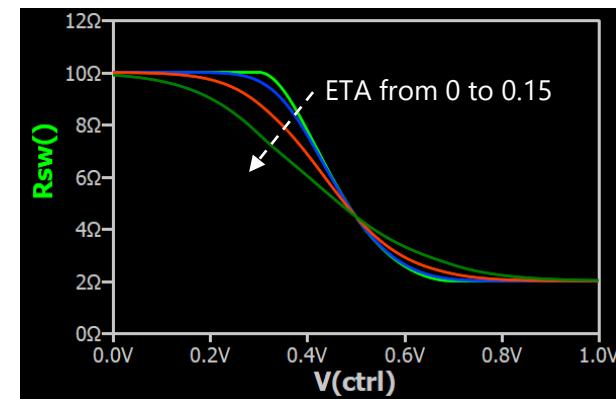
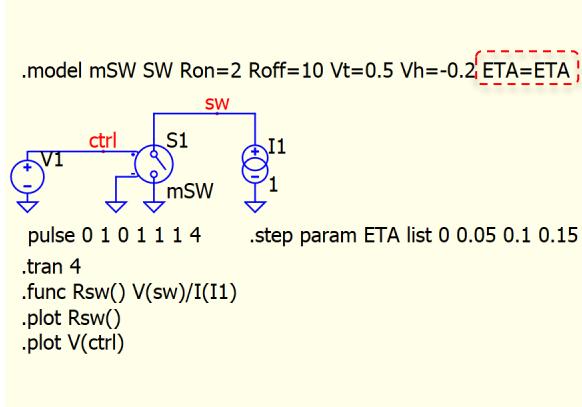
ROFF and RON is extreme



S. Switch Model Params : ETA

Qspice : Switch - ETA.qsch

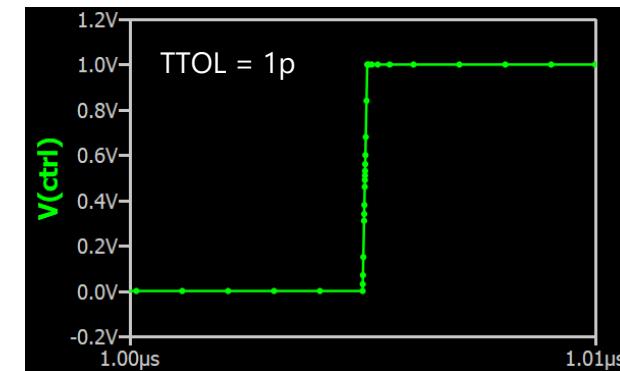
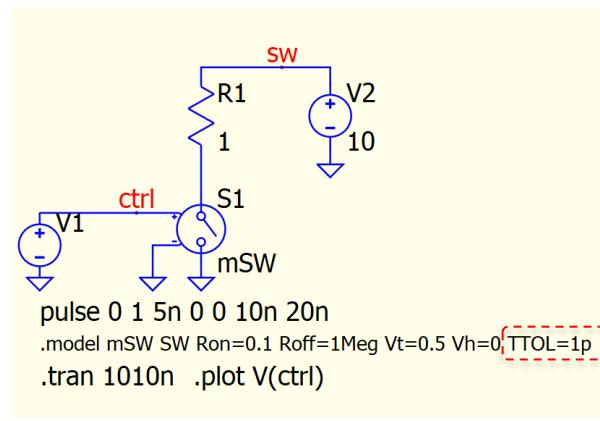
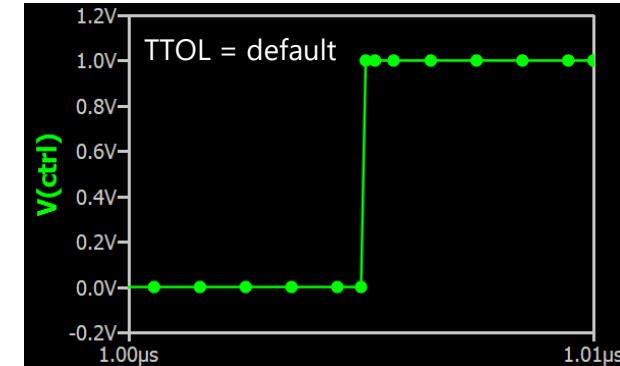
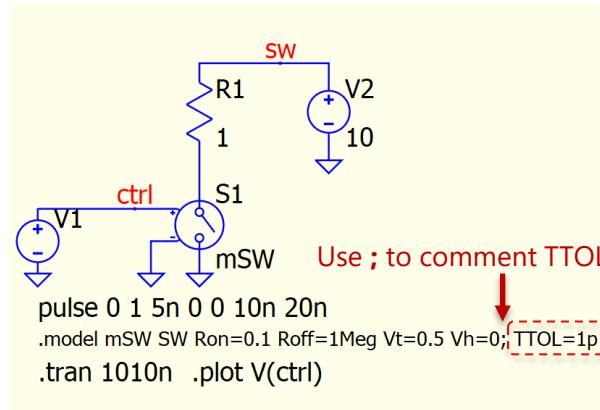
- **ETA**
 - ETA : Sub-/over- Threshold conduction
 - **Default ETA=0**
 - Prevents the control voltage Jacobian from vanishing
 - Only effective in smoothly transitions cases
 - V_t is negative
 - V_{on} / V_{off} are used without V_t and V_h



S. Switch Model Params : TTOL

Qspice : Switch - TTOL.qsch

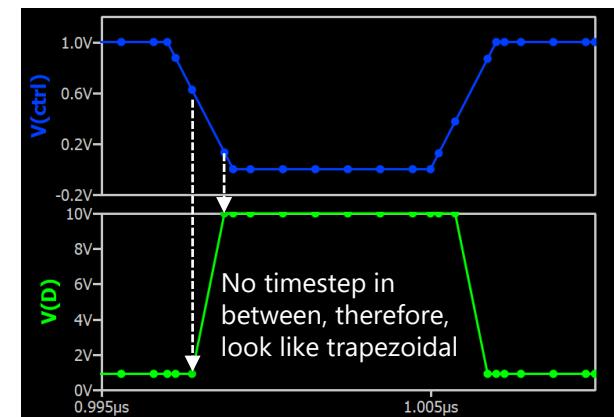
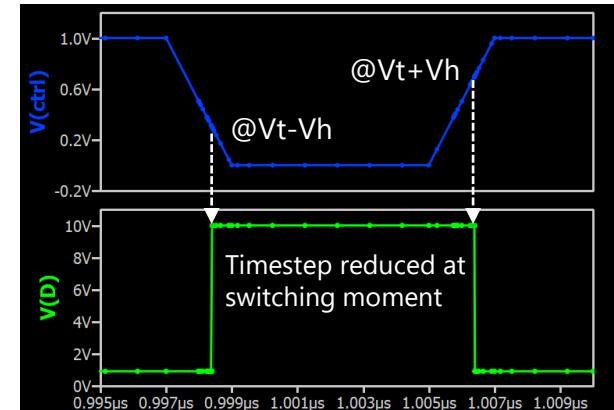
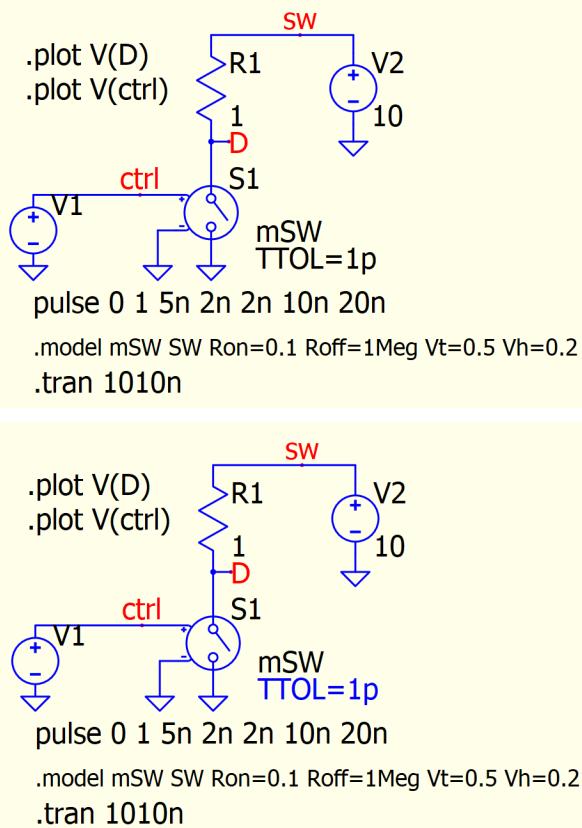
- TTOL
 - Ttol : Temporal tolerance
 - **Default TTOL=1e308s**
- Usage
 - TTOL allows one to determine how accurately the switch time should be found
 - It only affect timestep at switch time, which maintain simulation speed but improve accuracy at switching or logic action



S. Switch Model Params : TTOL (with VH hysteresis)

Qspice : Switch - TTOL with VH.qsch

- TTOL
 - Ttol : Temporal tolerance
 - **Default TTOL=1e308s**
- With Vh hysteresis
 - Extra timestep occurs according to switching action with hysteresis
 - ** TTOL may not response to negative Vh (-Vh) as switch is defined as smoothly transit instead of discrete state



T. Lossless Transmission Line

T. Lossless Transmission Line Instance Parameters

- T. Lossless Transmission Line
 - Syntax: Tnnn L+ L- R+ R- Zo=<value> Td=<value>

Lossless Transmission Line Instance Parameters

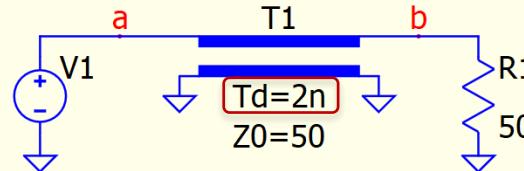
| Name | Description | Units | Default |
|-----------------|--------------------------------------|-------------|---------|
| F ¹ | Frequency | Hertz | 1GHz |
| NL ¹ | Normalized length at frequency given | wavelengths | 1/4 |
| TD | Transmission delay | sec | |
| Z0 | Characteristic impedance(aka ZO) | Ω | 50Ω |

T. Instance Params : TD, F and NL

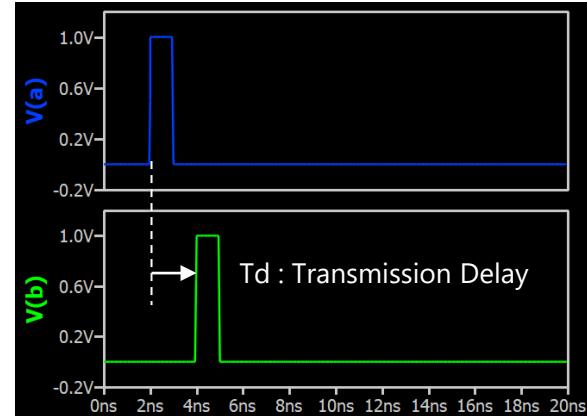
Qspice : Tline - Td.qsch ; Tline - F NL.qsch

- TD and Z0

- Td : Transmission delay
- Z0 : Characteristic Impedance
- **Default TD is not set**
- **Default Z0=50Ω**
- This simulation terminate transmission line with characteristic impedance Z0, no reflection of signal
- If TD is given, F and NL are ignored



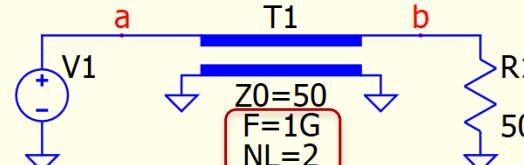
```
pulse 0 1 2n 0 0 1n 1 1  
.options MAXSTEP=1p  
.tran 20n  
.plot V(b)  
.plot V(a)
```



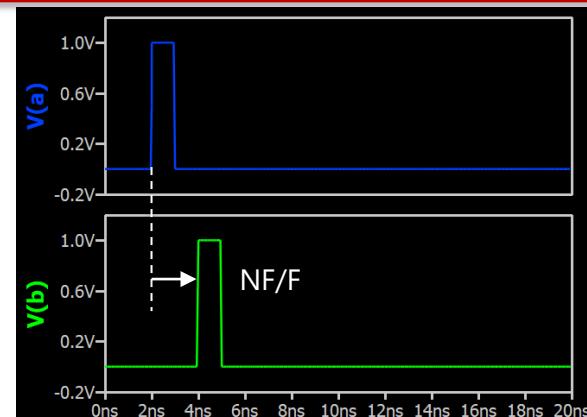
- F and NL

- F : Frequency
- NL : Normalized length at frequency given
- **Default F=1GHz**
- **Default NL=1/4**
- Equation

$$\begin{aligned} NL &= \frac{\text{Length}}{\text{Wavelength}} = \frac{\text{Length}}{\lambda} \\ \text{Period per } \lambda &: T = \frac{1}{F} \\ \text{Delay } T_d &= T \times \frac{\text{Length}}{\lambda} = \frac{NL}{F} \end{aligned}$$



```
pulse 0 1 2n 0 0 1n 1 1  
.options MAXSTEP=1p  
.tran 20n  
.plot V(b)  
.plot V(a)
```



V. Voltage Source

V. Voltage Source - Instance Params

- V. Voltage Source
 - Syntax: Vnnn N+ N- <voltage> [Additional Instance Parameters]

| Voltage Source Instance Parameters | | | | |
|------------------------------------|--|--------|-----------|--|
| Name | Description | Units | Default | |
| AC | AC magnitude, optionally followed by phase angle | V, ° | 0. | |
| ACMAG | AC Magnitude | V | 0. | |
| ACPHASE | AC Phase | ° | 0. | |
| DC | DC source value | V | 0. | |
| EXP | Exponential source description | | | |
| LOG | Interpolate between PWL and CHIRP points | | (not set) | |
| PULSE | Pulse description | | | |
| PWL | Piecewise linear description | | | |
| RSER | Internal series resistance | | | |
| SFFM | Single frequency FM description | | | |
| SINE | Sinusoidal source description(aka SIN) | | | |
| TIMECTRL | Time step control, one of NONE, LIMITS ¹ , BREAKS ² , BOTH | String | LIMITS | |
| TIME_SCALE_FACTOR | Multiplies times, divides frequencies | | 1. | |
| VALUE_SCALE_FACTOR | Multiplies voltages | | 1. | |
| XTRAP | Extrapolate beyond PWL and CHIRP points | | (not set) | |

V. Voltage Source (Instance Params) : DC

- DC
 - DC source value
 - This DC value is used in .dc analysis
 - Special Usage
 - For pulse in .tran, DC value can define voltage before Tdelay or at 0s
 - Without DC, this voltage equals <value1> in pulse

```
.tran 3  
.param Td=1  
.plot V(pulse-WithDC)  
.plot V(pulse-WithoutDC)
```

pulse-WithoutDC **Special Usage in Pulse**

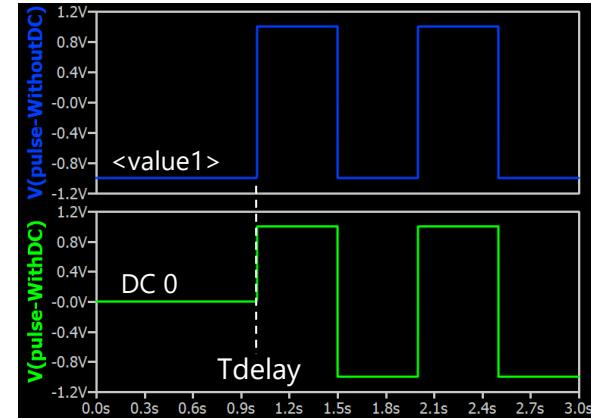


pulse -1 1 Td 0 0 0.5 1

pulse-WithDC



DC 0

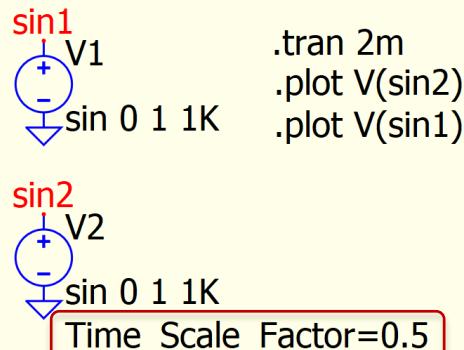


V. Voltage Source (Instance Params) : Time/Value_Scale_Factor

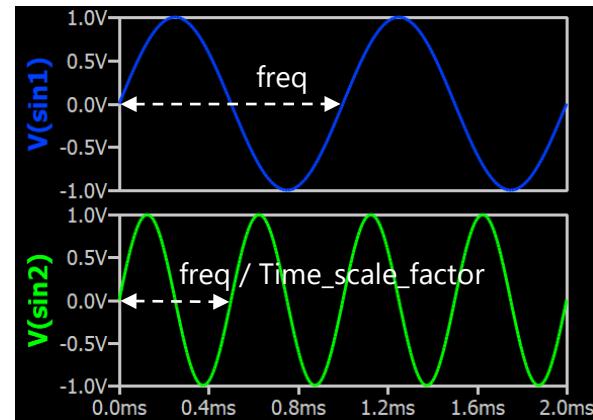
Qspice : Vsource - Time_Scale_Factor.qsch / Vsource - Value_Scale_Factor.qsch

- TIME_SCALE_FACTOR

- Time_Scale_Factor : multiples times, divides frequency
- Default Time_Scale_Factor=1

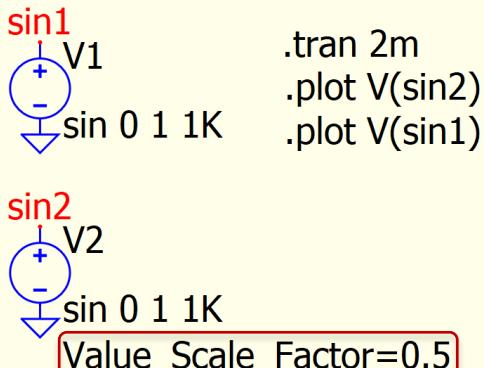


```
.tran 2m  
.plot V(sin2)  
.plot V(sin1)
```

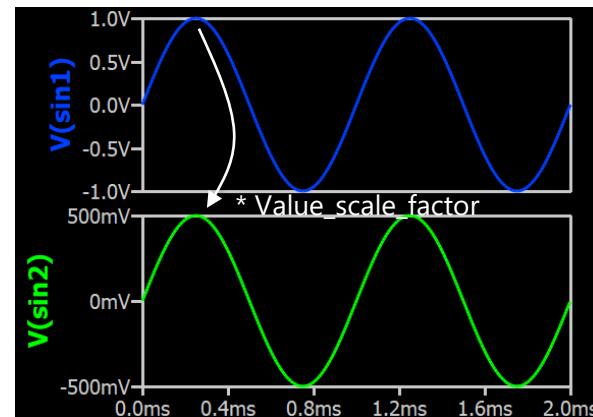


- VALUE_SCALE_FACTOR

- Value_Scale_Factor : multiples voltages
- Default Value_Scale_Factor=1



```
.tran 2m  
.plot V(sin2)  
.plot V(sin1)
```

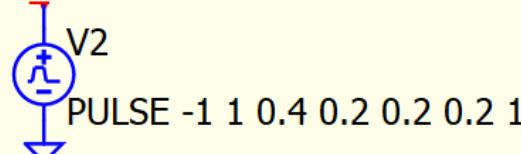


V. Voltage Source : PULSE (Pulse)

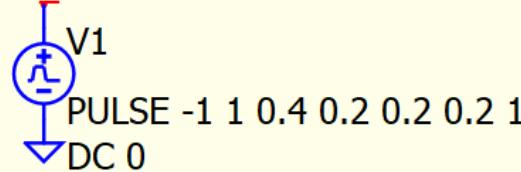
Qspice : Vsource PULSE.qsch

Syntax : PULSE V1 V2 Td Trise Tfall Ton Tperiod

pulse_woDC

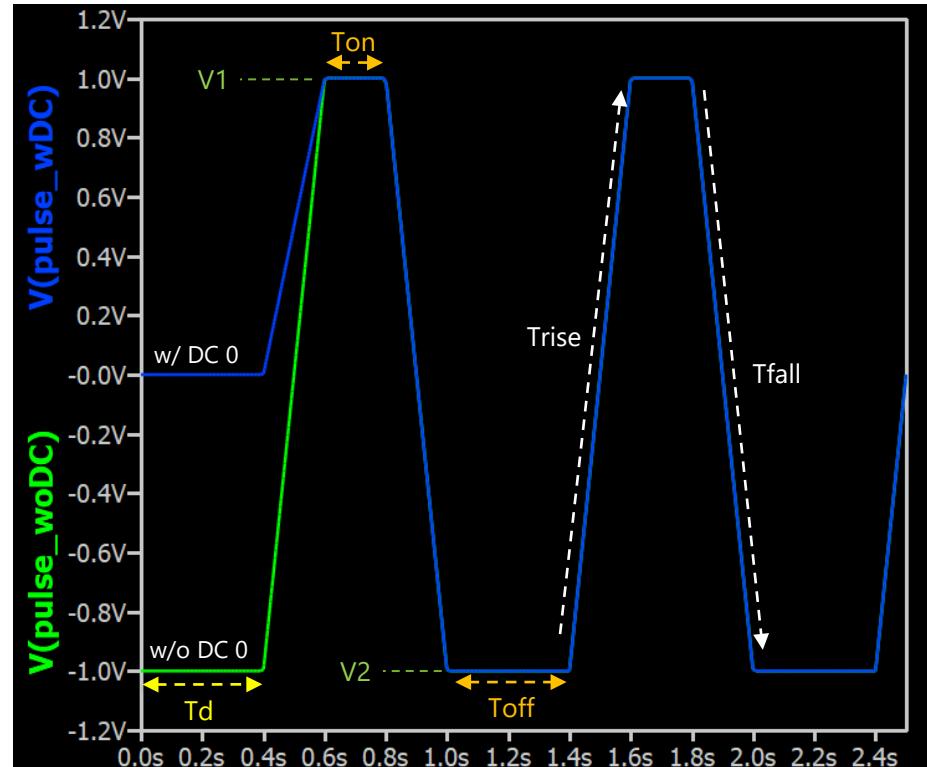


pulse_wDC



.tran 2.5

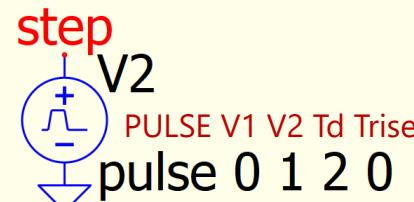
.plot V(pulse_woDC) V(pulse_wDC)



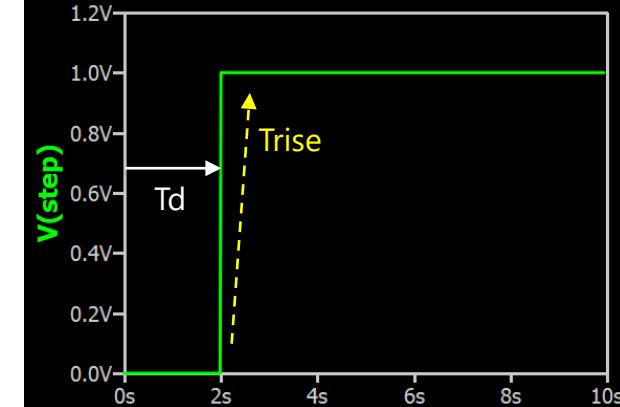
V. Voltage Source : PULSE (Pulse) : Usage

Qspice : Vsource PULSE-Step.qsch / Vsource PULSE-SinglePulse.qsch

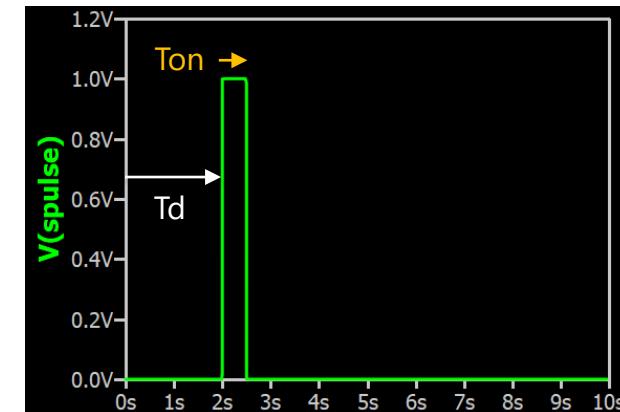
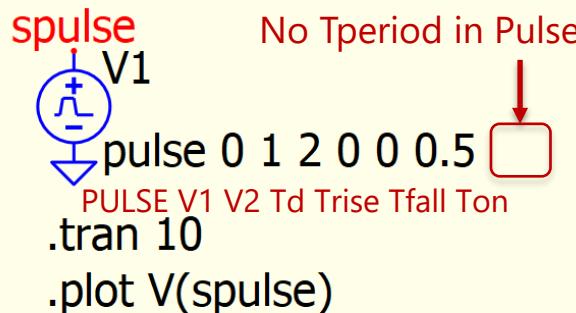
- Step with PULSE
 - To generate a step, only input value to **Trise**



.tran 10
.plot V(step)



- Single Pulse with PULSE
 - To generate a single non-repeating pulse, does not specify **Tperiod** in pulse statement

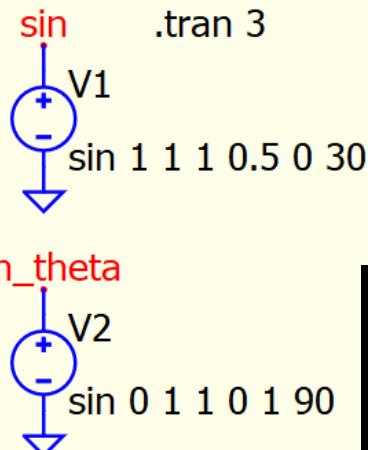


V. Voltage Source : SIN (Sine Wave)

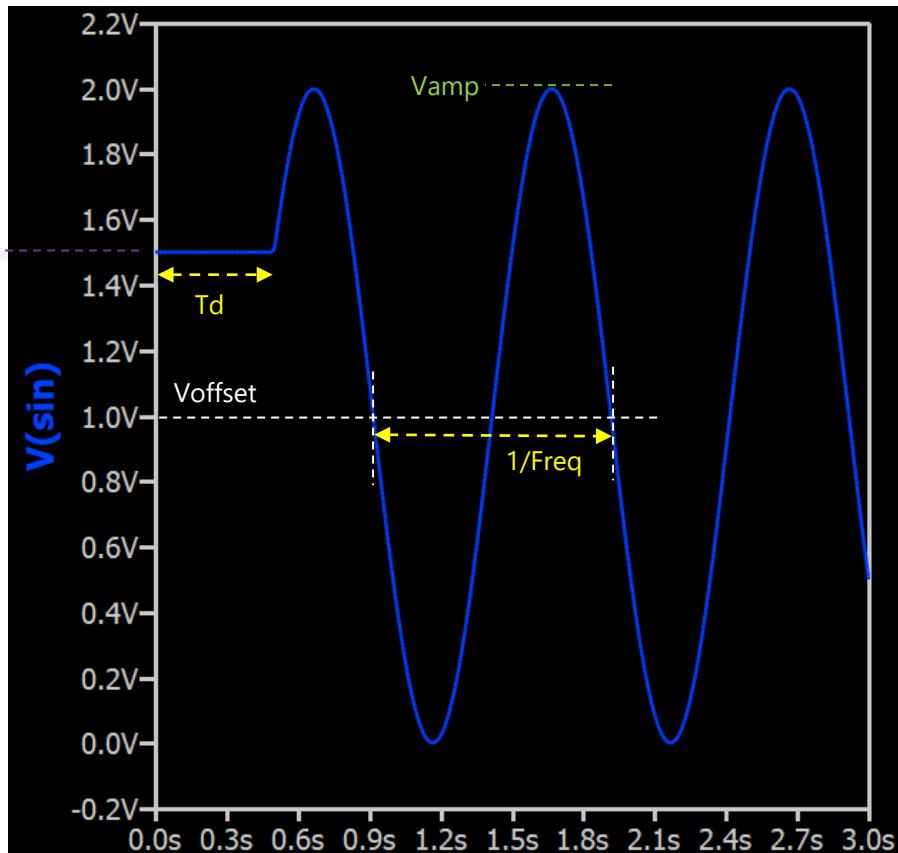
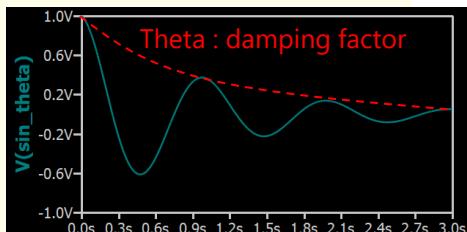
Qspice : Vsource SIN.qsch

Phi : level = $V_{offset} + \sin(\Phi)$
e.g.: $=1+\sin(30^\circ) = 1.5$

Syntax : SIN Voffset Vamp Freq Td Theta Phi



Amplitude drops by
 $e^{-1} \sim 0.378$ in $1/\Theta$ seconds



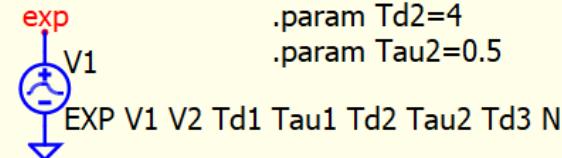
V. Voltage Source : EXP (Exponential)

Qspice : Vsource EXP.qsch

```
.plot V(expTperiod) V(exp)
```

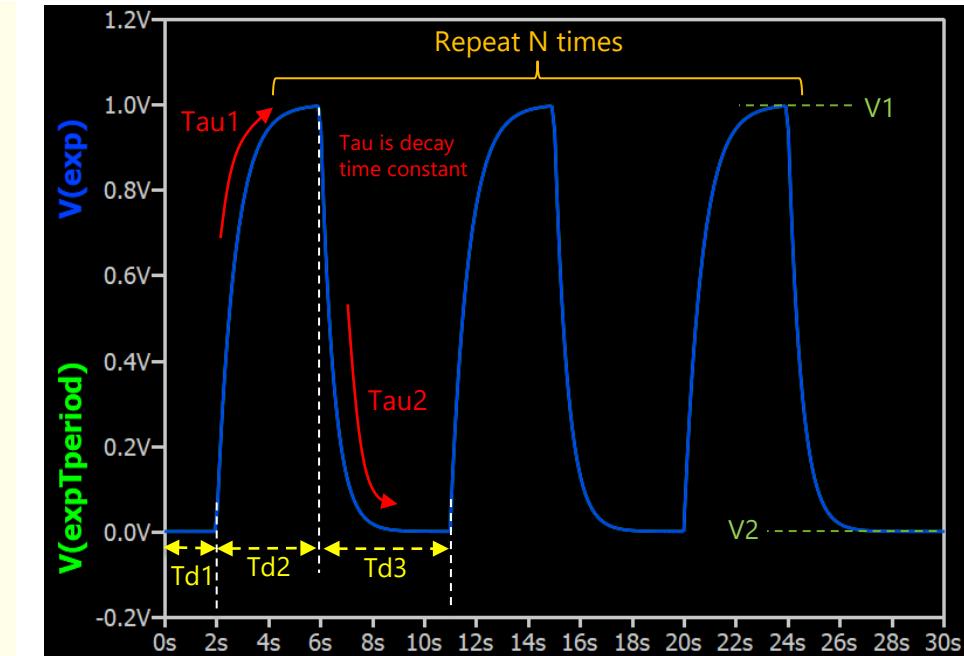
Syntax : EXP V1 V2 Td1 Tau1 Td2 Tau2 Td3 N Tperiod

```
.tran 200          .param V1=0      .param Td3=9  
                   .param V2=1      .param N=3  
                   .param Td1=2      .param Tperiod=50  
                   .param Tau1=0.7  
                   .param Td2=4  
                   .param Tau2=0.5
```



expTperiod

```
EXP V1 V2 Td1 Tau1 Td2 Tau2 Td3 N Tperiod
```



V. Voltage Source : SFFM (Single Frequency FM)

Qspice Vsource SFFM.qsch

- SFFM
 - Single Frequency FM
 - It is hard to observe FM signal in time domain waveform
 - FFT is used to explain its nature

Syntax : SFFM Voff Vamp Fcar MDI Fsig

SFFM



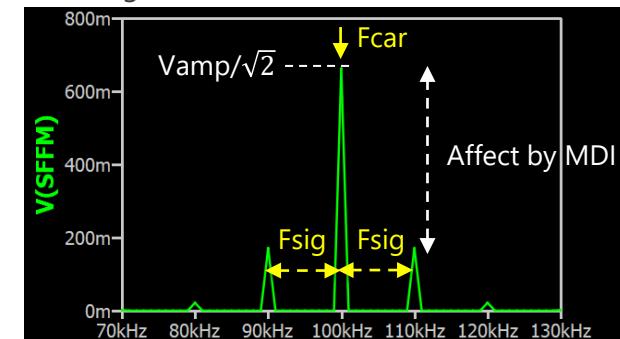
V1

SFFM 0 1 100K 0.5 10K

.tran 10/10K

.plot V(SFFM)

FFT magnitude is RMS

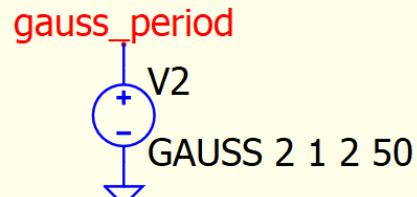
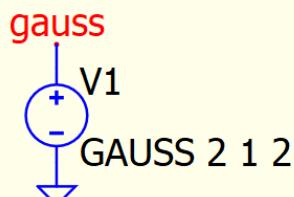


- Transient formula
 - $V_{off} + V_{amp} \cdot \sin((2\pi \cdot F_{car} \cdot time) + MDI \cdot \sin(2\pi \cdot F_{sig} \cdot time))$

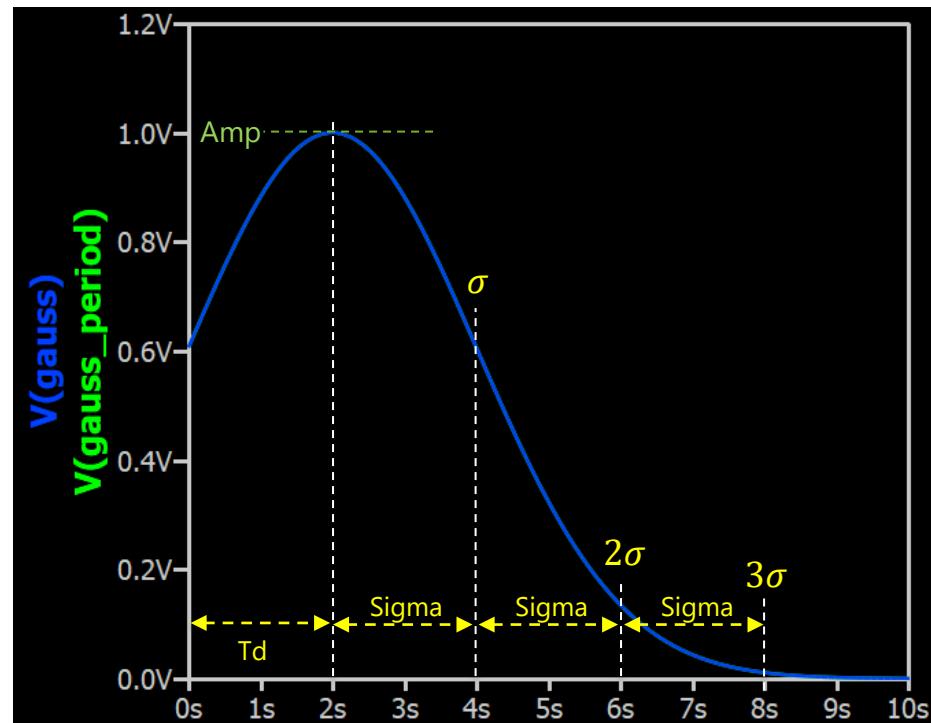
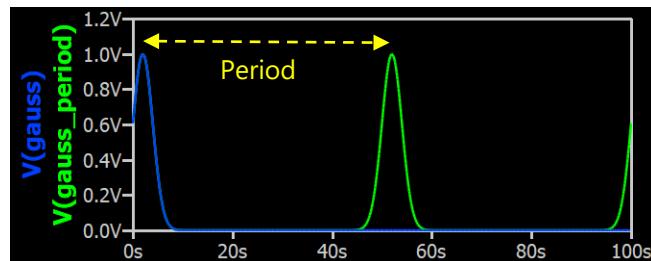
V. Voltage Source : GAUSS (Gaussian Pulse)

Qspice Vsource GAUSS.qsch

Syntax : GAUSS Td Amp Sigma [Period]



```
.plot V(gauss_period) V(gauss)
.tran 100
```

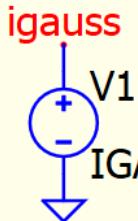


V. Voltage Source : IGAUSS (Imaginary Gaussian Pulse)

Qspice Vsource IGAUSS.qsch

Syntax : IGAUSS Td Period Sigma Amp

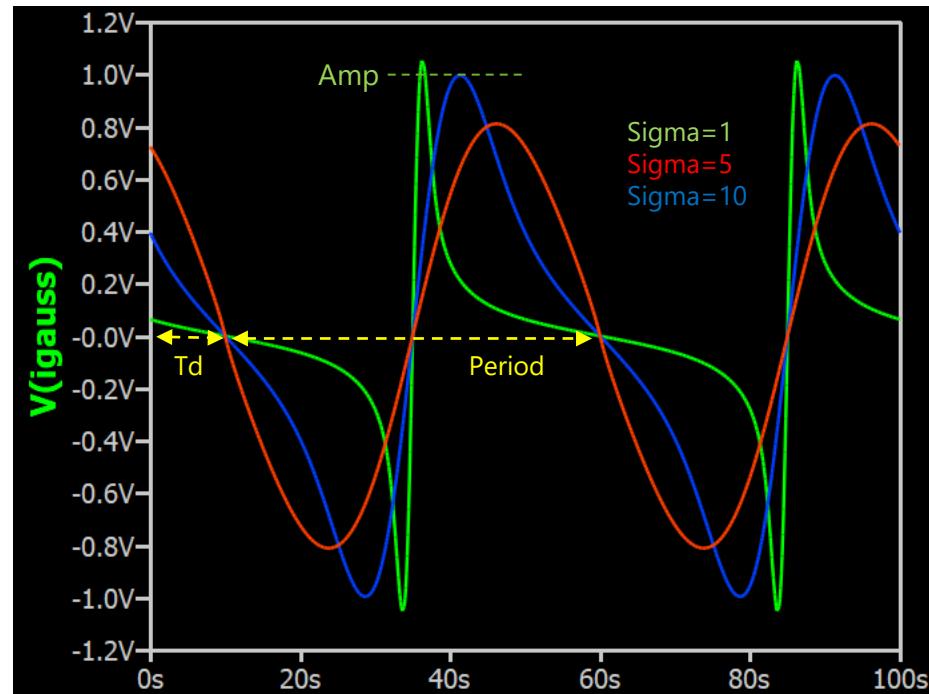
.step param Sigma list 1 5 10



IGAUSS 10 50 Sigma 1

.plot V(igauss)

.tran 100



V. Voltage Source : CHIRP (Piece-wise Linear Chirp)

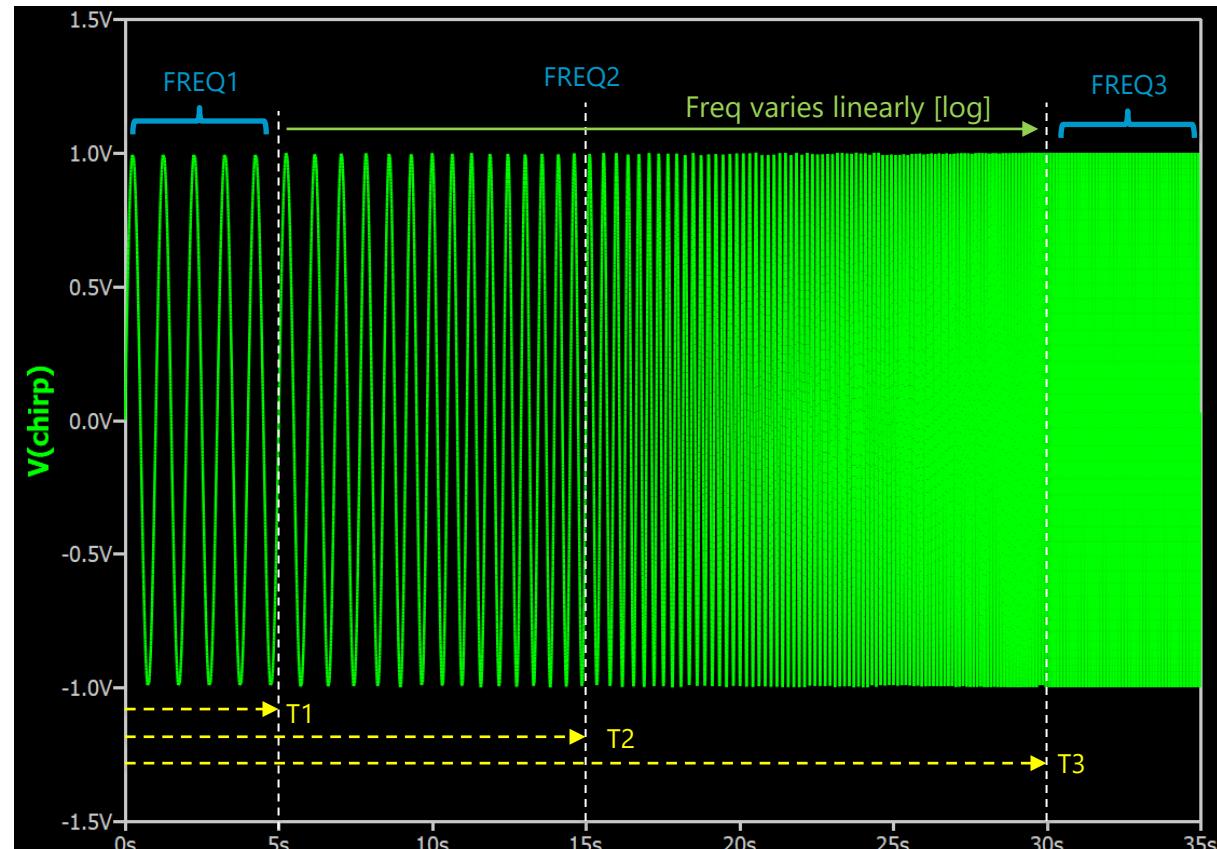
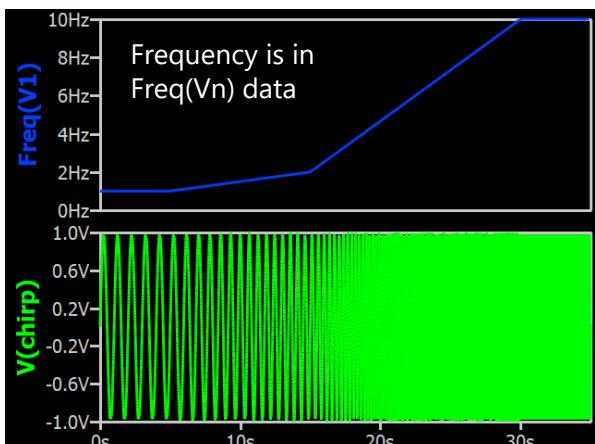
Qspice Vsource Chirp.qsch

Syntax : CHIRP(AMP T1 FREQ1 T2 FREQ2 [...]) [LOG] [XTRAP]

```
.param AMP=1  
.param T1=5  
.param FREQ1=1  
.param T2=15  
.param FREQ2=2  
.param T3=30  
.param FREQ3=10  
  
chirp  
V1  
-  
CHIRP AMP T1 FREQ1 T2 FREQ2 T3 FREQ3  
  
.
```

```
.plot V(chirp)  
.tran 35  
.options MAXSTEP=1/1000
```

XTRAP : extrapolate beyond PWL and CHIRP points



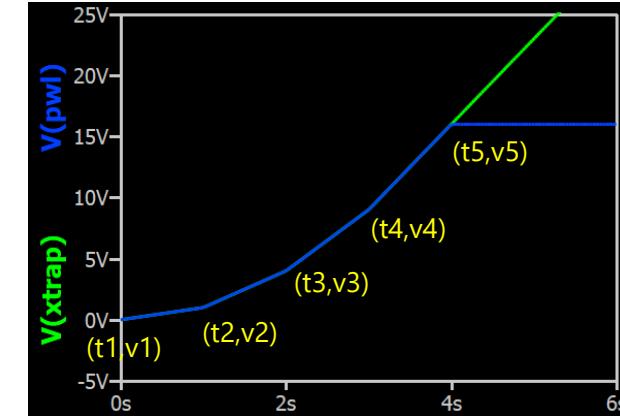
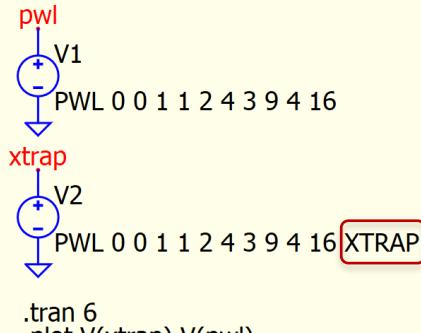
V. Voltage Source : PWL (Piece-wise Linear) – XTRAP and LOG

Qspice : Vsource PWL-Xtrap.qsch/ Vsource PWL-Log.qsch

- Basic Usage and XTRAP

- Standard
 - last value will hold
- Xtrap
 - Extrapolate beyond PWL and CHIRP points

Syntax : PWL(t1 v1 t2 v2 t3 v3...) [LOG] [XTRAP]

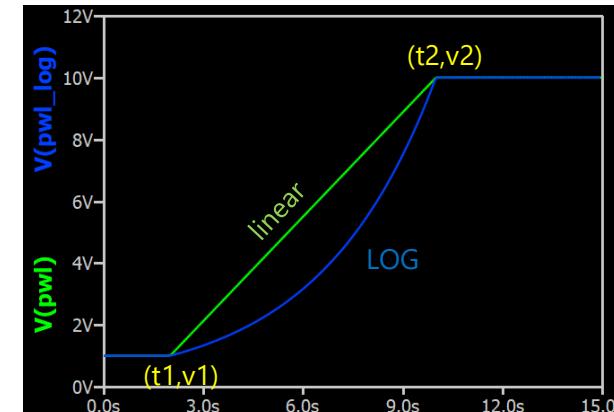
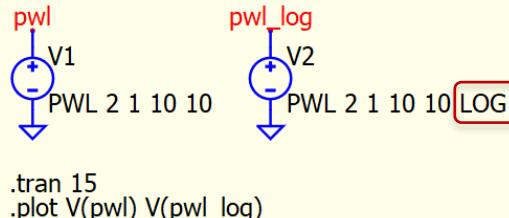


- LOG

- Log

- Interpolate between PWL and CHIRP points with log function

Syntax : PWL(t1 v1 t2 v2 t3 v3...) [LOG] [XTRAP]



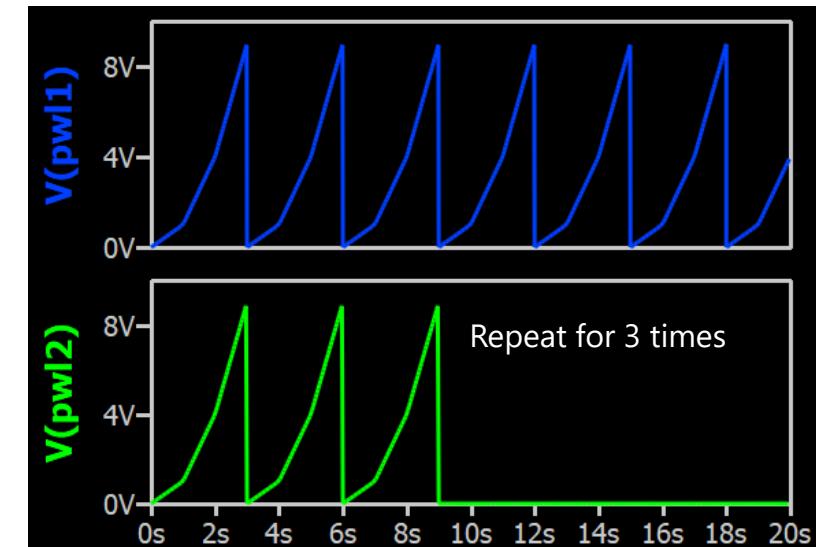
V. Voltage Source : PWL (Piece-wise Linear) – REPEAT

Qspice : Vsource PWL-Repeat.qsch

- PWL Repeat Syntax

- Vnnn N+ N- PWL **REPEAT FOREVER** t1 v1 t2 v2 t3 v3... **ENDREPEAT**
- Vnnn N+ N- PWL **REPEAT FOR N** t1 v1 t2 v2 t3 v3... **ENDREPEAT**
 - N is number of times
 - ** last voltage value of a repeated PWL will be ignored and forced to be equal to the first value**

```
Syntax : PWL FOR[EVER] [times] (t1 v1 t2 v2 t3 v3...) Endrepeat  
pwl1  
V1  
PWL REPEAT FOREVER (0 0 1 1 2 4 3 9 3+1p 0) Endrepeat  
  
pwl2  
V2  
PWL REPEAT FOR 3 (0 0 1 1 2 4 3 9 3+1p 0) Endrepeat  
  
.tran 20  
.plot V(pwl2)  
.plot V(pwl1)
```

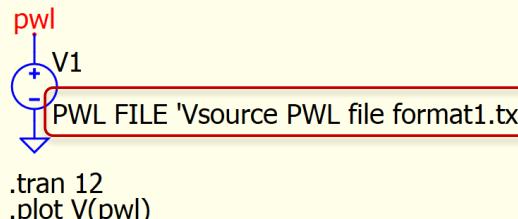


V. Voltage Source : PWL (Piece-wise Linear) – Load from file

Qspice : Vsource PWL file.qsch / Vsource PWL-Repeat-File.qsch

- PWL : load from file
 - Filename is quoted with single ('filename') or double ("filename") quotation
 - Delimiter can be space [] or comma [,]
 - To load from file, syntax is
 - FILE filename
 - Support repeat syntax, but remember last value in repeated PWL is ignored and forced to be equal to first value

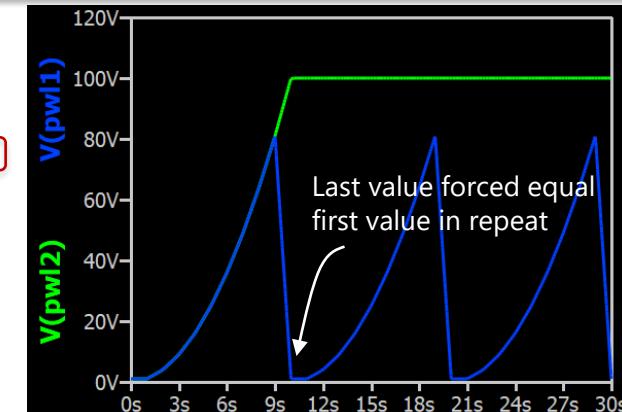
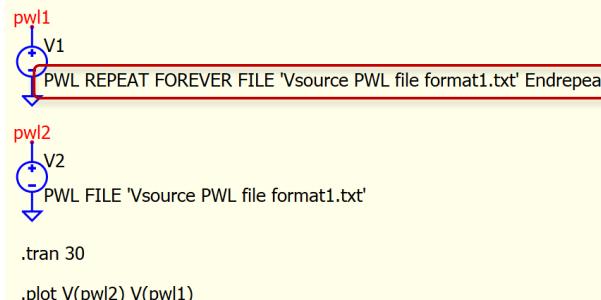
Syntax : PWL FILE file.txt [LOG] [XTRAP]



| 1 | 1 | 1 |
|----|----|-----|
| 2 | 2 | 4 |
| 3 | 3 | 9 |
| 4 | 4 | 16 |
| 5 | 5 | 25 |
| 6 | 6 | 36 |
| 7 | 7 | 49 |
| 8 | 8 | 64 |
| 9 | 9 | 81 |
| 10 | 10 | 100 |

| 1 | 1,1 |
|----|--------|
| 2 | 2,4 |
| 3 | 3,9 |
| 4 | 4,16 |
| 5 | 5,25 |
| 6 | 6,36 |
| 7 | 7,49 |
| 8 | 8,64 |
| 9 | 9,81 |
| 10 | 10,100 |

Syntax : PWL FOR[EVER] [times] FILE 'filename' Endrepeat



V. Voltage Source : PWL (Piece-wise Linear) – Usage

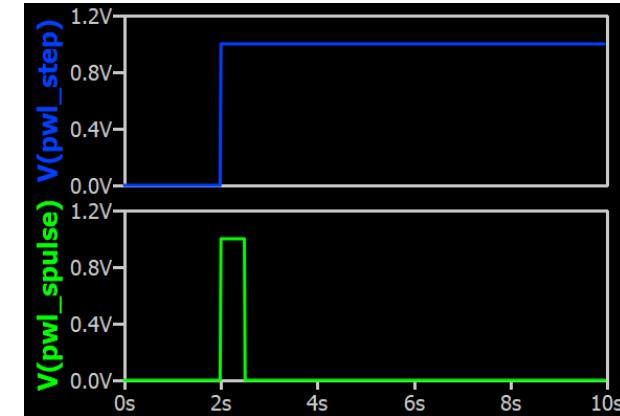
Qspice : Vsource PWL-SinglePulse.qsch

- Step and Single Pulse
 - To create step or single pulse with PWL, a datapoint to maintain voltage level before change is required
 - For example, if change occurs at 2s, define an extra datapoint at 1.999s or (2-1p)

pwl_step
V1
pwl 0 0, 2-1p 0, 2 1

pwl_spulse
V2
pwl 0 0, 2-1p 0, 2 1, 2.5-1p 1, 2.5 0

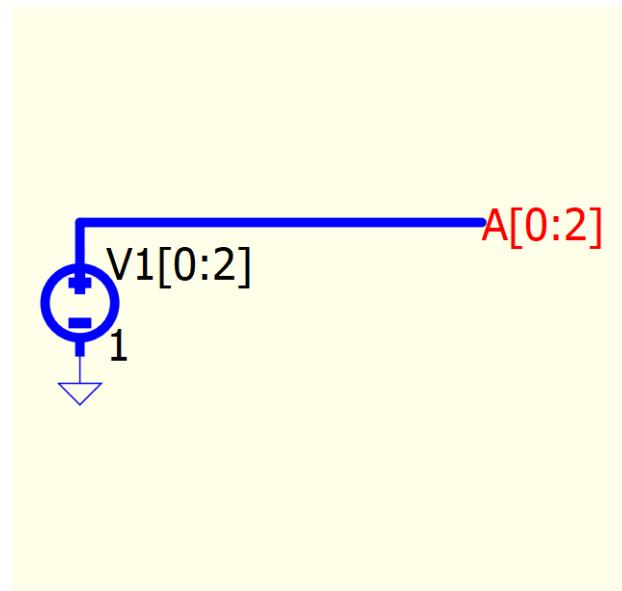
.tran 10
.plot V(pwl_spulse)
.plot V(pwl_step)



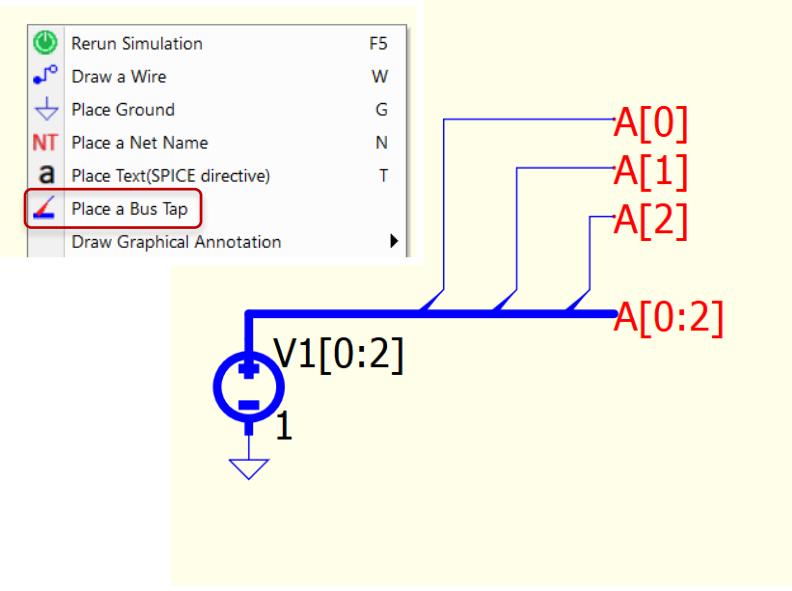
W. Wire and BUS

W. Wire and Bus : Introduction

- [1] Place a voltage source and draw wire
- [2] Rename voltage source to V1[0:2]
- [3] Place net name as A[0:2]
- [4] Now, the wire becomes a bus, in this example, A[m] is voltage of V1[m]

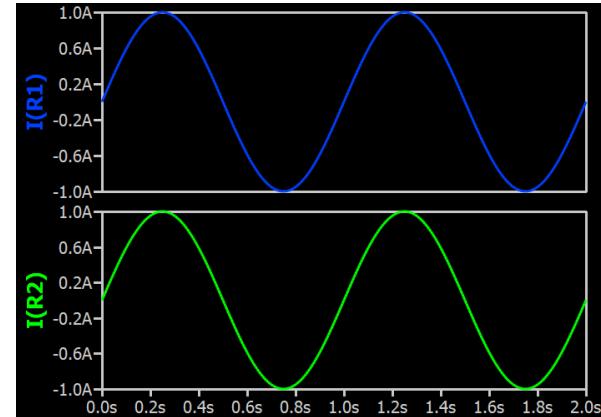
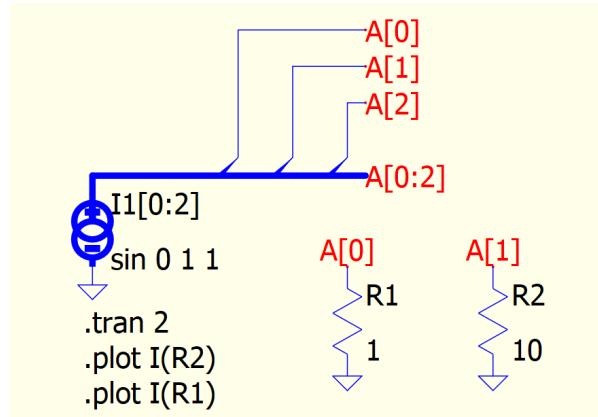


- [5] Right click and select "Place a Bus Tap"
- [6] Place net name to bus tap wire



W. Wire and Bus : Bus for V/I-source

- Identical I-source
 - File : BUS - Isrc.qsch
 - Bus can replicate current or voltage source for multiple nodes usage
 - In netlist
 - $I1[0] 0 A[0] \sin 0 1 1$
 - $I1[1] 0 A[1] \sin 0 1 1$
 - $I1[2] 0 A[2] \sin 0 1 1$
 - ** .dc for $I1$ won't work as three I-sources $I1[0]$, $I1[1]$ and $I1[2]$ in this format



W. Wire and Bus : Bus for Ø-Device

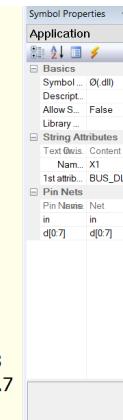
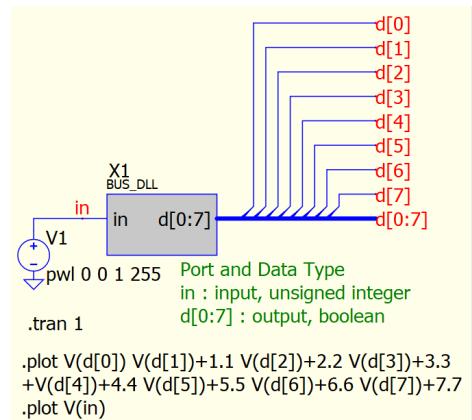
- Bus for Ø-Device

- Files

- BUS_DLL.qsch
- bus_dll.cpp
- bus_dll.dll

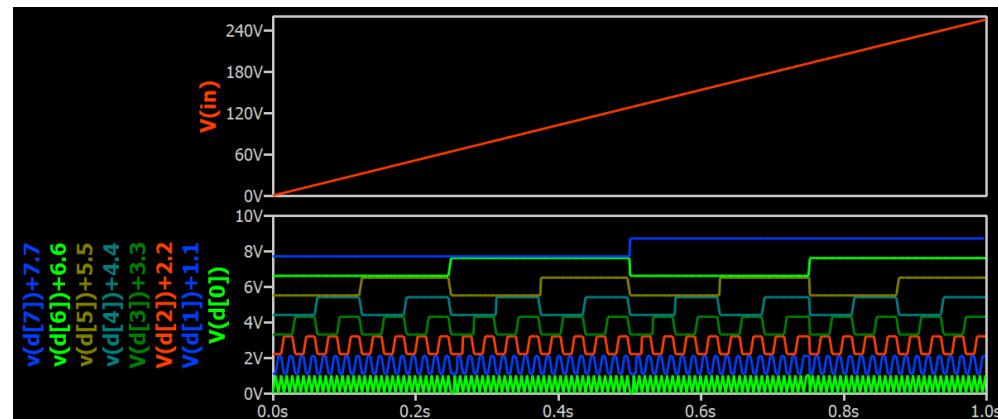
- Procedure

- For Ø-Device, defines an output port with label name with net[0:7] array
- To output bit, data type should be boolean
- In template generation, it creates variable name as `net_0_` for bit 0 and `net_7_` for bit 7



```
extern "C" __declspec(dllexport) void bus_dll
{
    unsigned int in = data[0].ui; // input
    bool &d_0 = data[1].b; // output
    bool &d_1 = data[2].b; // output
    bool &d_2 = data[3].b; // output
    bool &d_3 = data[4].b; // output
    bool &d_4 = data[5].b; // output
    bool &d_5 = data[6].b; // output
    bool &d_6 = data[7].b; // output
    bool &d_7 = data[8].b; // output

    // Implement module evaluation code here:
    d_0 = in & 0x01;
    d_1 = in & 0x02;
    d_2 = in & 0x04;
    d_3 = in & 0x08;
    d_4 = in & 0x10;
    d_5 = in & 0x20;
    d_6 = in & 0x40;
    d_7 = in & 0x80;
}
```



Y. Piezoelectric Crystal

Y. Piezoelectric Crystal : Instance Parameters

- Y. Piezoelectric Crystal
 - Syntax: Ynnn N+ N- <frequency1> dF=<value> Ctot=<value> [Q=<value>]

Piezoelectric Crystal Instance Parameters

| Name | Description | Units | Default |
|------------------------|---|-------|----------------------------------|
| CTOT | Total capacitance as measured at DC | F | |
| DF ¹ | Difference between series and parallel resonant frequencies | Hz | |
| FREQUENCY ¹ | Resonant frequency | Hz | |
| IC | Initial internal current(Used with UIC on the .tran) | A | 0.0 |
| M | Number of parallel devices | | 1.0 |
| RSER | Series resistance | Ω | Determined from Q |
| Q | Quality factor | | $1.6e13 \div \text{FREQUENCY}^2$ |

$$Q = \min(1e6, \frac{1e13}{\text{FREQUENCY}^2})$$

If default equation is used

- If DF > 0 : **Series Resonant Freq = Frequency** and **Parallel Resonant Freq = Frequency + DF**
- If DF < 0 : **Series Resonant Freq = Frequency + DF** and **Parallel Resonant Freq = Frequency**

Y. Piezoelectric Crystal : Formula and Equivalent Circuit

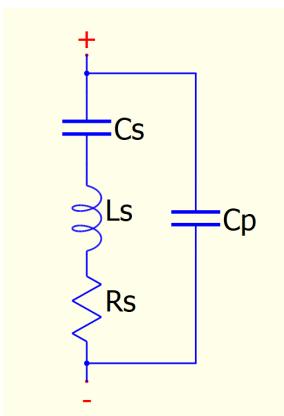
Qspice : Y Crystal - Equivalent Circuit.qsch

- Piezoelectric Crystal Equation

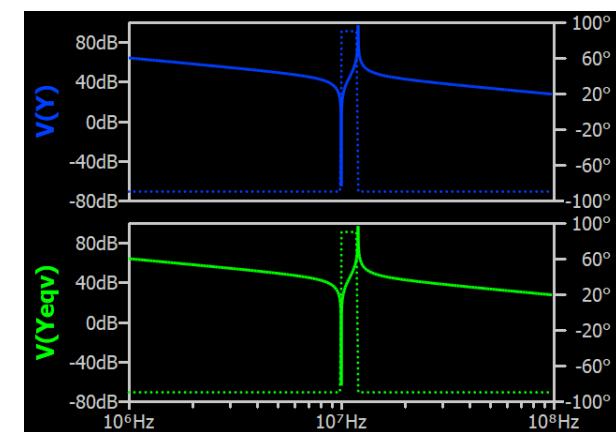
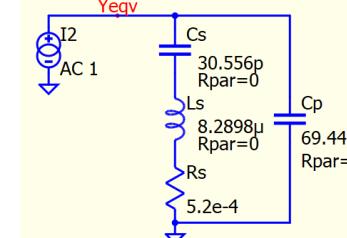
- Series Resonant Frequency : $f_s = \frac{1}{2\pi\sqrt{L_s C_s}}$
- Parallel Resonant Frequency : $f_p = \frac{1}{2\pi\sqrt{\frac{C_p C_s}{L_s C_p + C_s}}}$
- Crystal Oscillators Q-factor : $Q = \frac{X_L}{R} = \frac{2\pi f L_s}{R_s}$
- Total Capacitance : $C_{TOT} = C_p + C_s$

- Calculated Value

- $C_p = \left(\frac{f_s}{f_p}\right)^2 C_{TOT}$
- $C_s = C_{TOT} - C_p$
- $L_s = \frac{1}{(2\pi f_s)^2 C_s}$
- $R = \frac{2\pi f L}{Q}$



```
Y  
I1 AC 1  
Y1 Frequency=10Meg  
dF=2Meg  
Ctot=100p  
Q=1e6  
.ac dec 1000 1Meg 100Meg  
.plot V(Yeqv)  
.plot V(Y)
```



\tilde{A} -Device
MULTGMAMP

Ã-Device

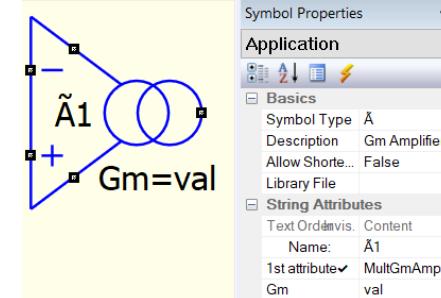
- Ä-Device
 - Syntax

~nnn VDD VSS OUT IN- IN+ MULT+ MULT- IN-- IN++ EN ##### <TYPE> [INSTANCE PARAMETERS]

- \tilde{A} -device models a highly configurable Gm block than can mimic the behavior of a complementary MOSFET output, there are two types MULTGMAMP and RROPAMP

| A-Device Types | |
|----------------|---------------------------|
| Type | Behavior |
| MULTGMAMP | Multiplying Gm Amplifier |
| RROPAMP | Rail-to-Rail Output OpAmp |

- In Symbol Properties > 1st attribute
- View > Netlist : from device syntax



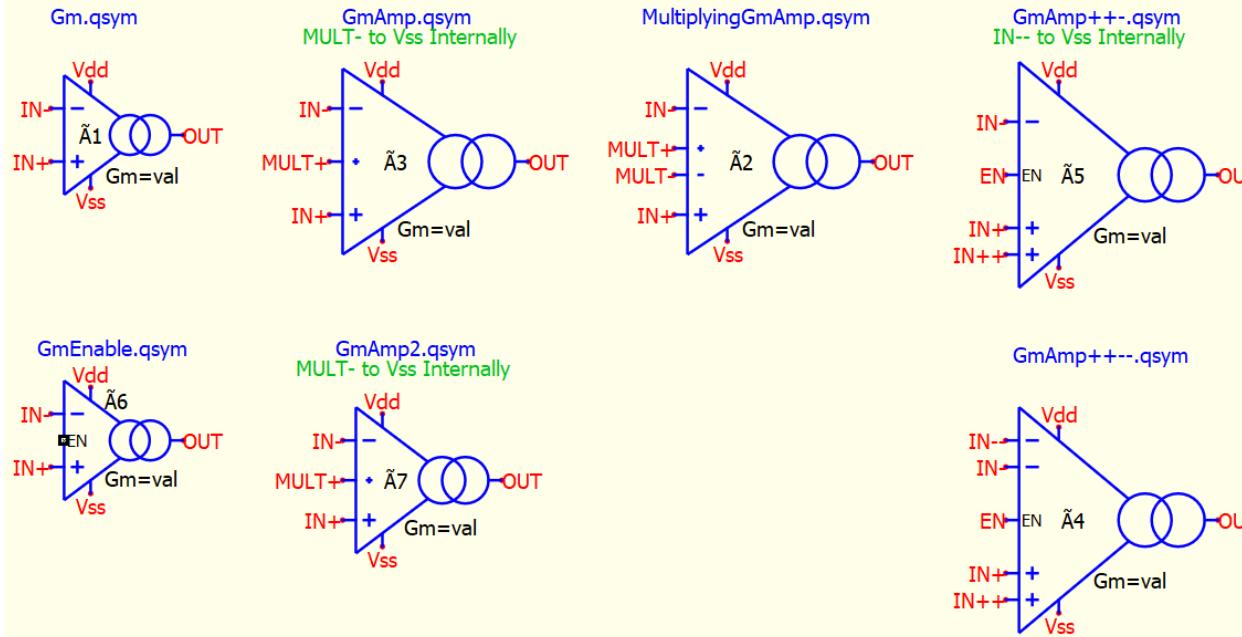
```
* C:\Users\kelvinleung\Documents\QSPICE\Untitled.qsch
A1 Y0 Y1 Y2 Y3 Y4 Y Y Y Y Y Y Y Y Y MultGmAmp Gm=val
.end
```

\tilde{A} -Device [MULTGMAMP]

- \tilde{A} -Device

- Syntax: **$\tilde{A}nnn\ VDD\ VSS\ OUT\ IN-\ IN+\ MULT+\ MULT-\ IN--\ IN++\ EN\ \#\#\#\#\#\#<TYPE>\ [INSTANCE\ PARAMETERS]$**
- Formula in Linear Region : $I_{out} = GM * V(MULT+, MULT-) * V(\min(IN+, IN++), \max(IN-, IN--))$

Symbols & IP > Behavioral > analog



Ä-Device Instance Parameters in MULTGMAMP

Ä-Device Instance Parameters

| Name | Description |
|----------|---|
| CAPINCM | Common eigenmode input capacitance |
| CAPINNM | Normal eigenmode input capacitance |
| CAPVDD | Capacitance from output to Vdd |
| CAPVSS | Capacitance from output to Vss |
| EN | Equivalent input voltage noise density |
| ENK | EN corner frequency |
| FT | 3dB bandwidth of transconductance with no voltages slewing |
| GM | Ideal transconductance |
| IC | Initial condition of $V_{in} \times V_{mult}$ |
| IN | Equivalent input current noise density |
| INF | Common mode input current noise density proportional to frequency |
| INK | IN corner frequency |
| IOUT | Maximum sourcing current |
| ISNK | Maximum sinking current |
| ISNKKNEE | Sharpness of Maximum sinking current limit |
| ISRC | Maximum sourcing current |
| ISRCKNEE | Sharpness of max sourcing current limit |
| M | Number of parallel devices |

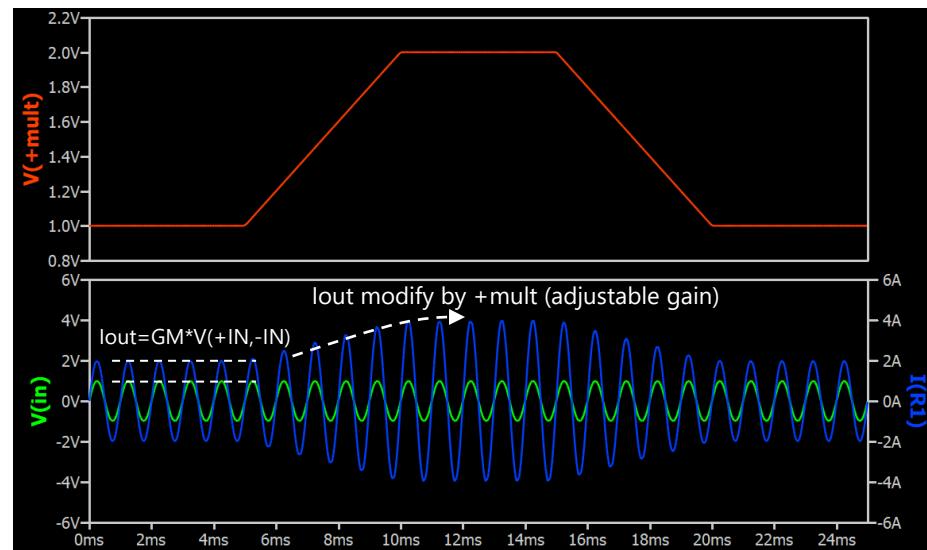
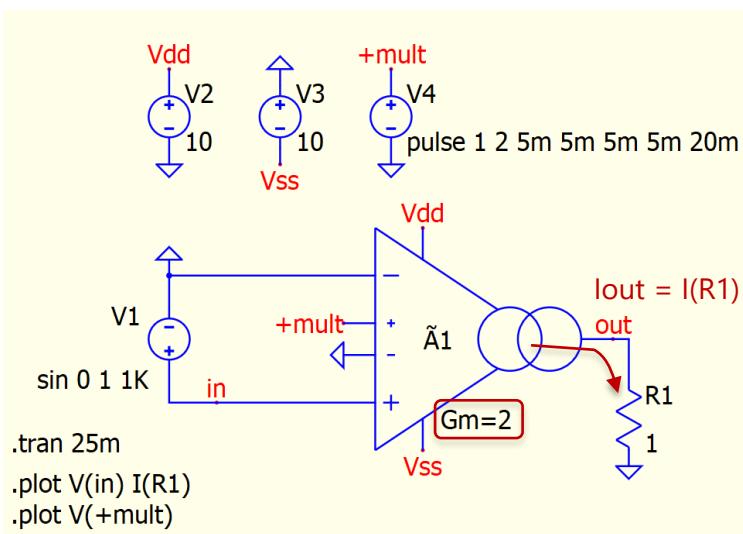
| REF | Logic threshold for enable(from Vss) |
|-------------|--|
| ROUT | Additional impedance added to output(2*R to Vdd, 2*R to Vss) |
| TEMP | Instance temperature |
| TTOL | Temporal tolerance for enable & UVLO |
| UVLO | Minimum supply voltage |
| VCROSS | Cross conduction voltage range |
| VDSAT | Voltage where gm starts to switch over to a resistance |
| VDSAT1 | Voltage where gm starts to switch over to a resistance(top FET) |
| VDSAT2 | Voltage where gm starts to switch over to a resistance(bottom FET) |
| VINHIGH | Output range measured from positive rail |
| VINHIGHKNEE | Sharpness of positive input range limit |
| VINLOW | Input range measured from negative rail |
| VINLOWKNEE | Sharpness of negative input range limit |
| VOS1 | Offset voltage for input |
| VOS2 | Offset voltage for multiplying input |
| VOUTMAX | Maximum output voltage measured from negative rail |
| VOUTMIN | Minimum output voltage measured from negative rail |

MULTGMAMP : Ideal transconductance (GM)

Qspice : Multgmamp - Gm.qsch

- Gm : Ideal transconductance

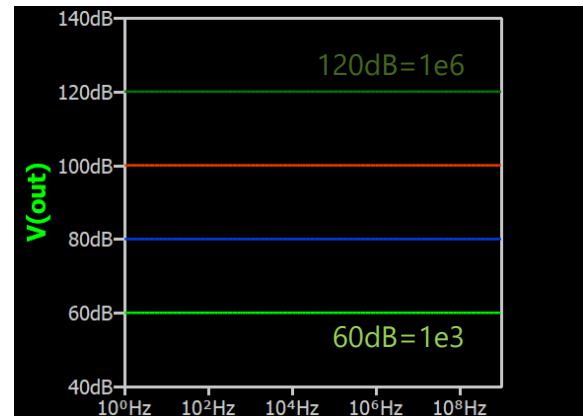
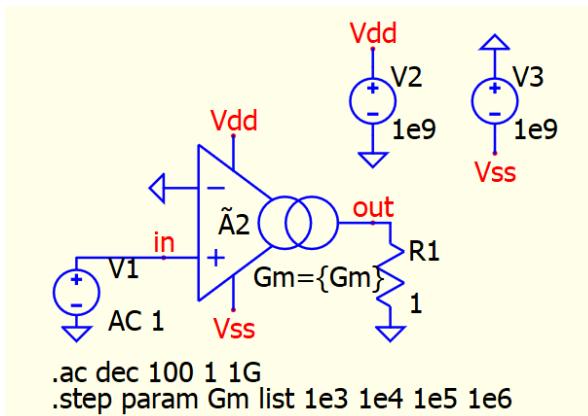
- Without $IN++$ and $IN--$, formula becomes $Iout = GM * V(MULT+, MULT-) * V(IN+, IN-)$
- For ideal operation amplifier, GM is infinity
- In Qspice, Gm cannot be set to 0



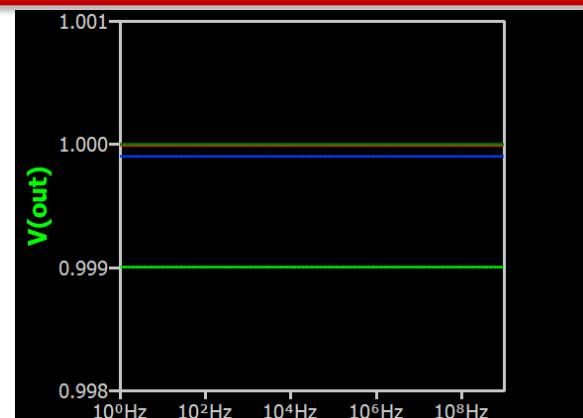
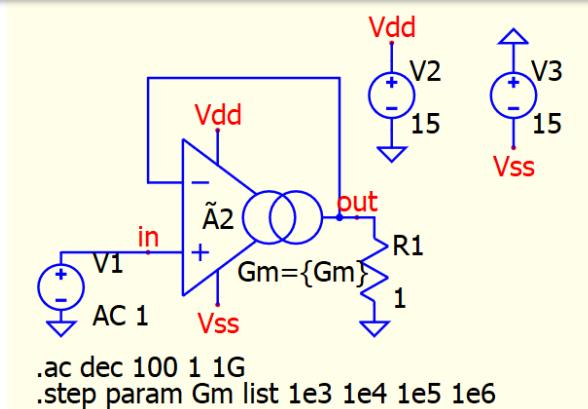
MULTGMAMP : Ideal transconductance (GM)

Qspice : Multgmamp - Gm freq response.qsch ; Multgmamp - Buffer.qsch

- Gm : Ideal transconductance
 - MULTGMAMP has ideal frequency response if without instance parameters
 - No default value of Gm, must define by user



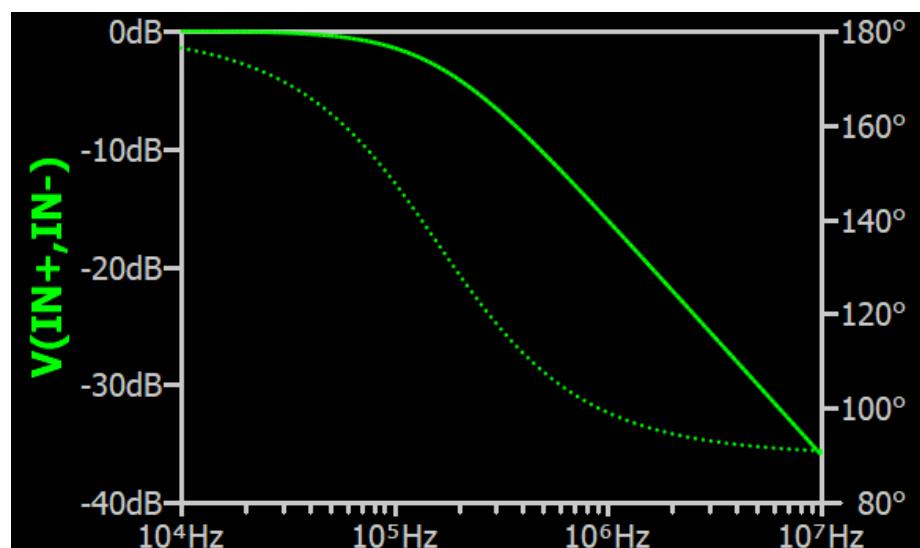
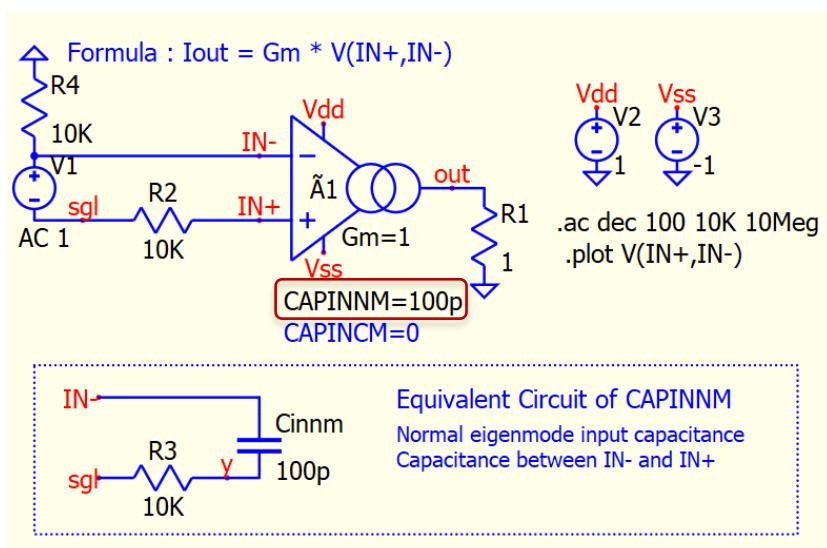
- Demo : Buffer Circuit
 - Demonstrate op-amp close loop ideal characteristic with different Gm value



MULTGMAMP : Normal eigenmode input capacitance (CAPINNM)

Qspice : Multgmamp - Capinnm.qsch

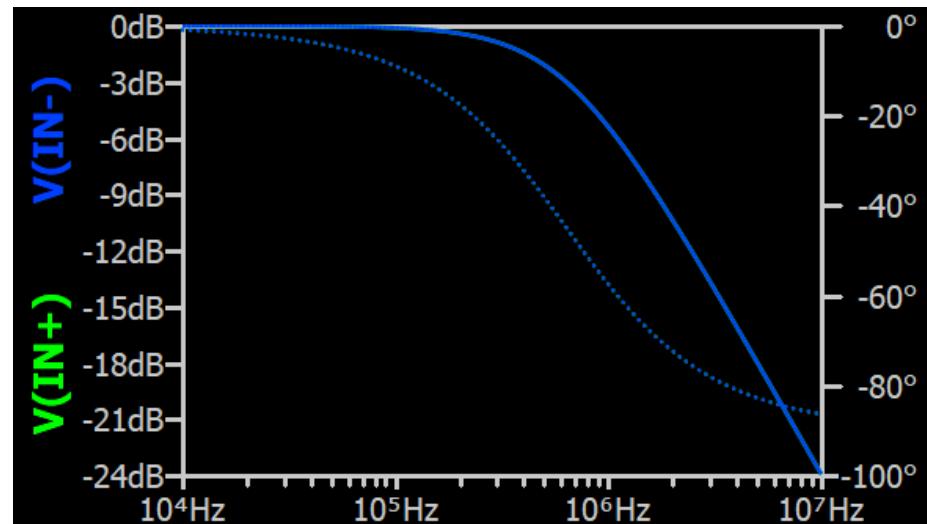
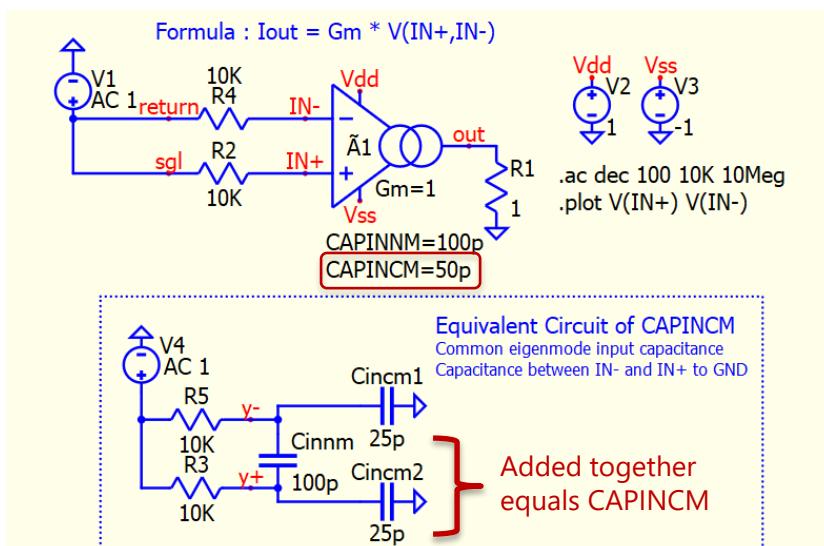
- CAPINNM : Normal eigenmode input capacitance
 - Default CAPINNM=0
 - This capacitance is equivalent between IN- and IN+



MULTGMAMP : Common eigenmode input capacitance (CAPINCM)

Qspice : Multgmamp - Capincm.qsch

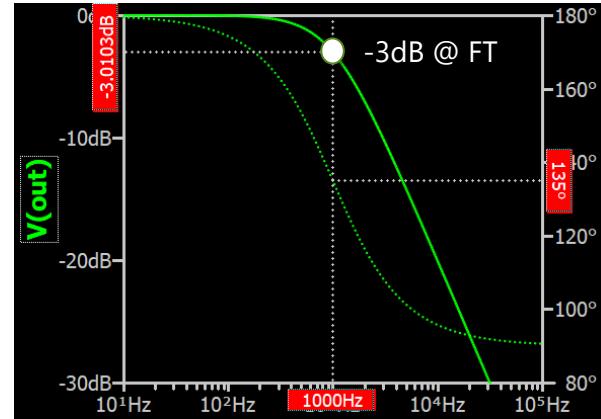
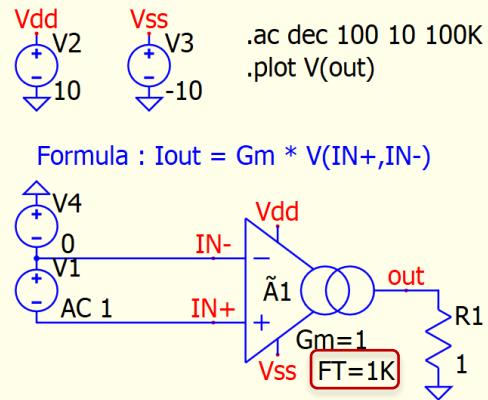
- CAPINCM : Common eigenmode input capacitance
 - Default CAPINCM=0
 - This capacitance is between IN- to GND and IN+ to GND



MULTGMAMP : FT 3dB Bandwidth

Qspice : Multgmamp - FT.qsch

- FT (3dB Bandwidth)
 - FT : 3dB bandwidth of transconductance with no voltages slewing
 - **Default FT=0** (i.e. infinite)

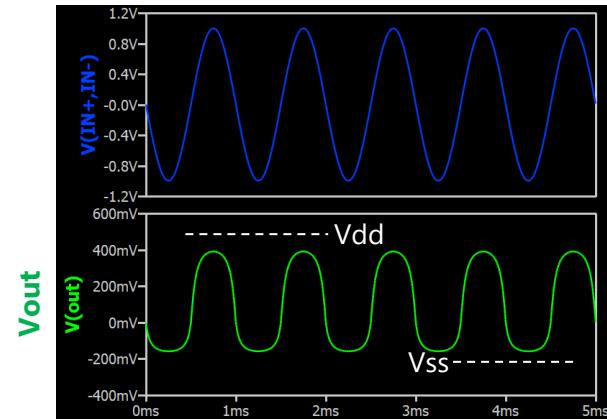
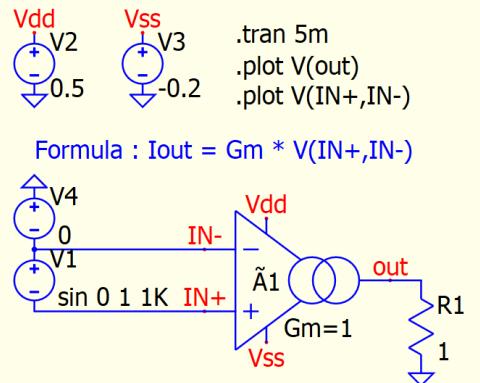


MULTGMAMP : Output Voltage Vdd, Vss and VDSAT

Qspice : Multgmamp - Vdd Vss.qsch ; Multgmamp - VDSAT.qsch

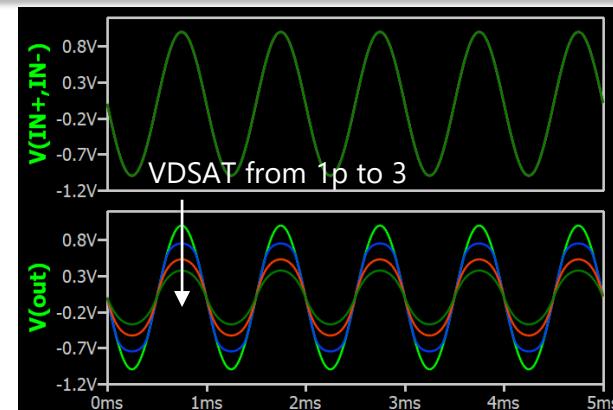
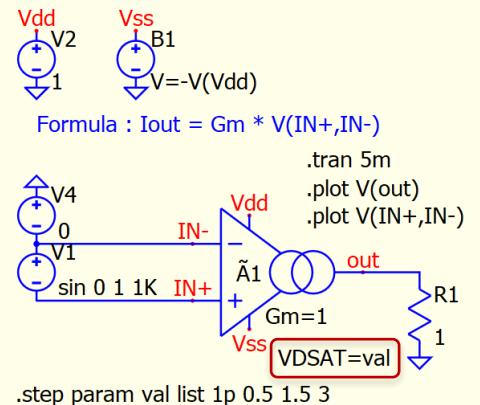
- Vdd and Vss Nets

- This is not parameters but Net 1 and Net 2 in \tilde{A} -Device
- Output voltage swing is limited by Vdd and Vss
- ** In this example, Vout cannot reach Vdd and Vss because a default VDSAT is set**



- VDSAT

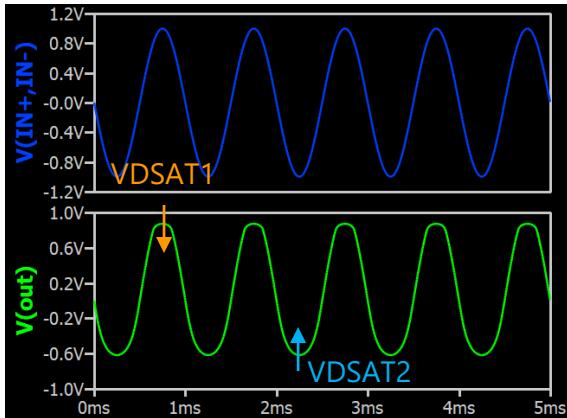
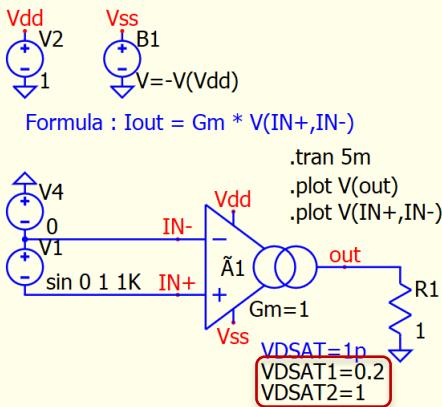
- V_{dsat} : Voltage where gm starts to switch over to a resistance
- Default VDSAT = 0.5**
- VDSAT=0** forced its to default
- VDSAT=1p** for no saturation



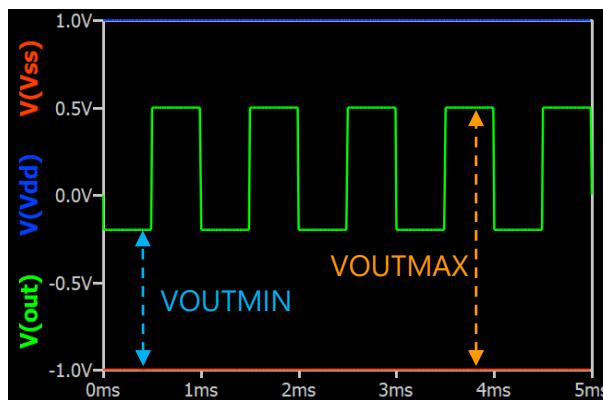
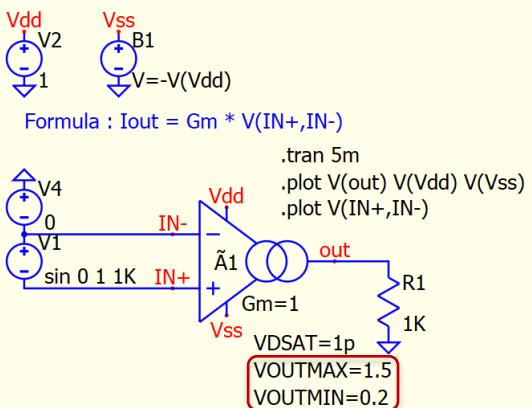
MULTGMAMP : Output Voltage VDSAT1, VDSAT2, VOUTMIN, VOUTMAX

Qspice : Multgmamp - VDSAT1 VDSAT2.qsch ; Multgmamp - VOUTMAX VOUTMIN.qsch

- VDSAT1 and VDSAT2
 - VDSAT1 : Voltage where gm starts to switch over to a resistance (top FET)
 - VDSAT2 : Voltage where gm starts to switch over to a resistance (bottom FET)
 - **Default VDSAT1=VDSAT**
 - **Default VDSAT2=VDSAT1**



- VOUTMIN and VOUTMAX
 - V_{outmin} : Minimum output voltage measured from negative rail
 - V_{outmax} : Maximum output voltage measured from negative rail

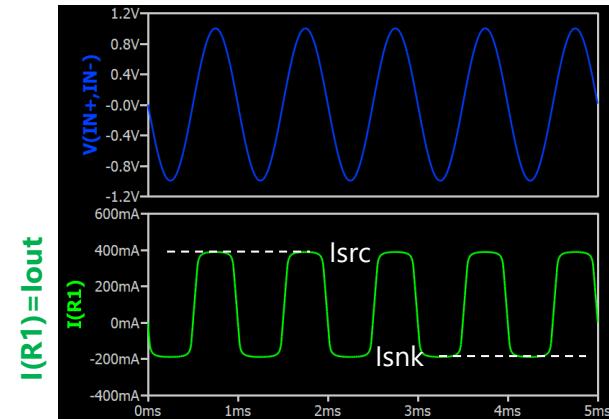
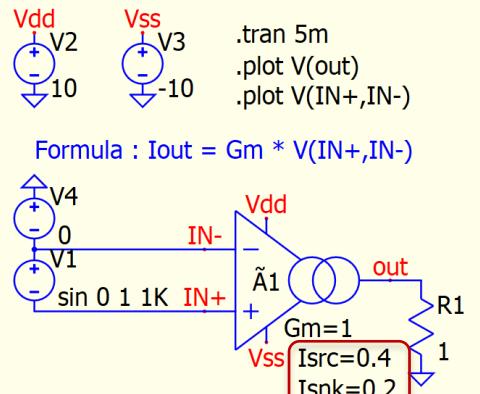


MULTGMAMP : Sink and Src Current (Iout / Isrc, Isnk)

Qspice : Multgmamp - ISRC ISNK.qsch ; Multgmamp - ISRCKNEE ISNKKNEE.qsch

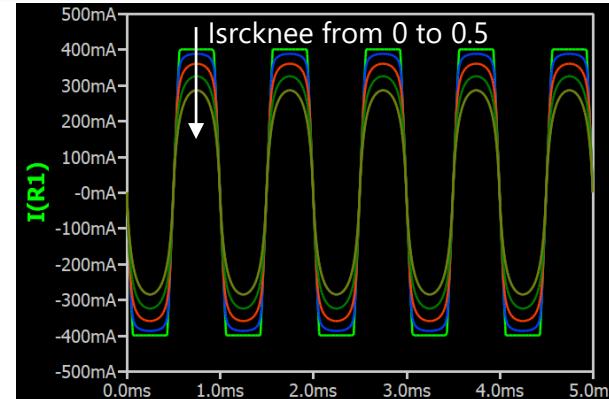
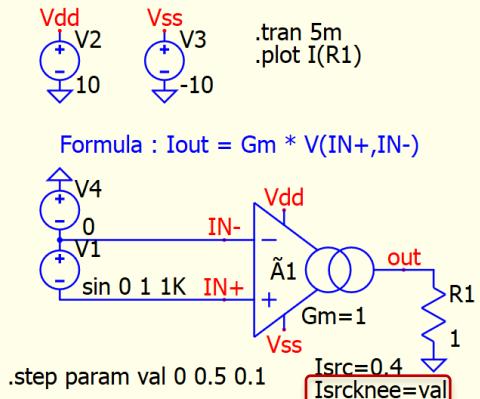
- IOUT/ISRC and ISNK

- Iout/Isrc : Maximum sourcing current (toward load)
- Isnk : Maximum sinking current (toward device)
- **Default ISRC = Infinite**
- **Default ISNK = IOUT or ISRC**
 - i.e. if ISNK not specified, ISNK equals IOUT or ISRC



- ISRCKNEE and ISNKKNEE

- $Isrcknee$: Sharpness of max sourcing current limit
- $Isnkknee$: Sharpness of Maximum sinking current limit
- **Default Isrckness = 0.1**
- **Default Isnkness = Isrcknee**



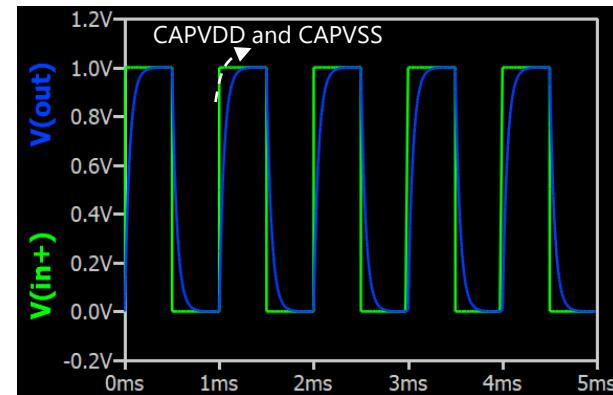
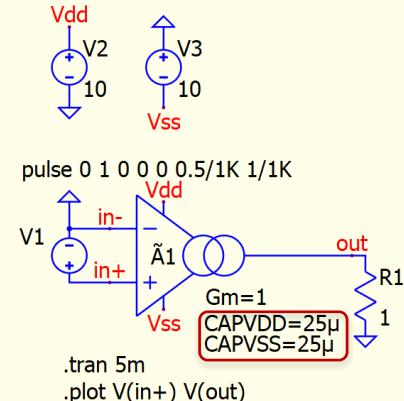
- Important Note

- To have effect, must defines ISRC or ISNK

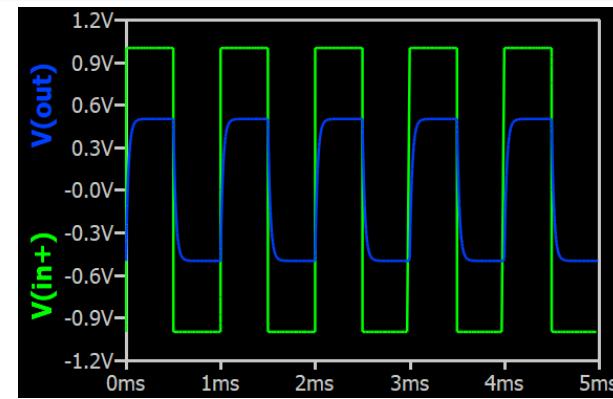
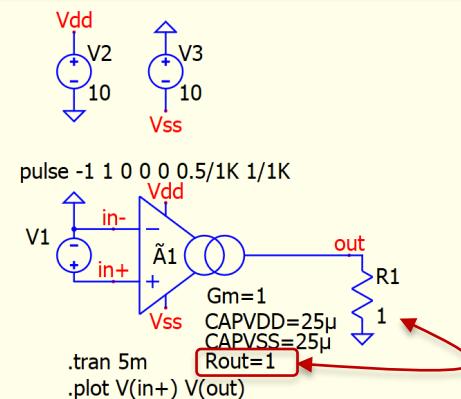
MULTGMAMP : Output Capacitance (CAPVDD, CAPVSS) and Resistance (Rout)

Qspice : Multgmamp - Capvdd Capvss.qsch ; Multgmamp - Rout.qsch

- CAPVDD and CAPVSS
 - CAPVDD : Capacitance from output to Vdd
 - Capvss : Capacitance from output to Vss



- ROUT
 - Rout : Additional impedance added to output($2 \times R$ to V_{dd} , $2 \times R$ to V_{ss})
 - In this example, Rout equal to amplifier loading, V_{out} reduced by half

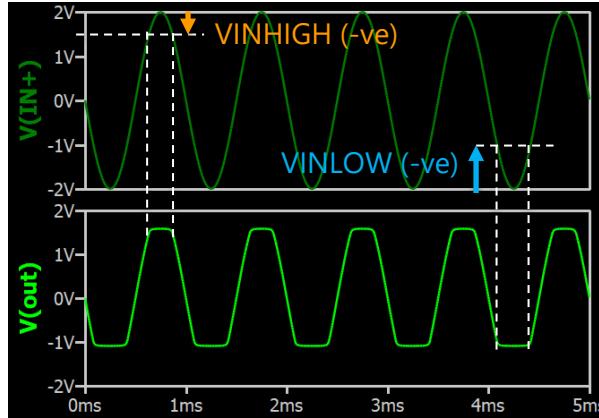
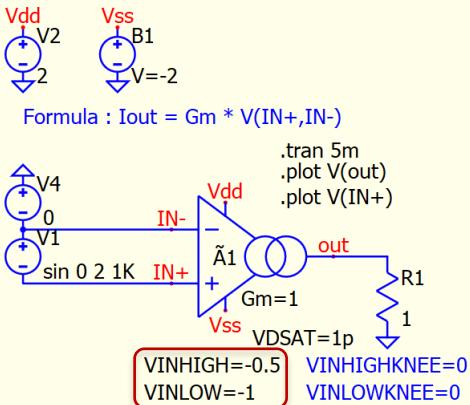


MULTGMAMP : Input Range VINLOW, VINHIGH, VINHIGHKNEE, VINLOWKNEE

Qspice : Multgmamp - VINHIGH VINLOW.qsch ; Multgmamp - VINHIGHKNEE VINLOWKNEE.qsch

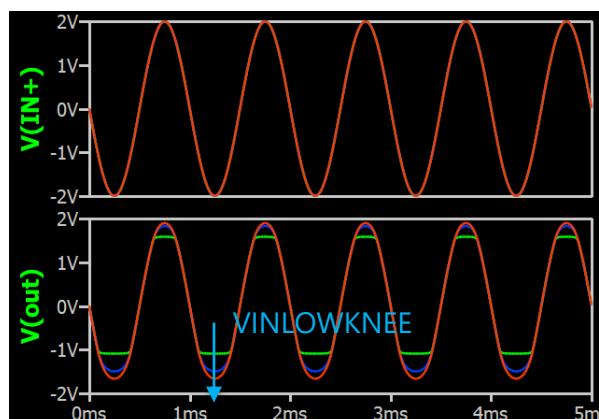
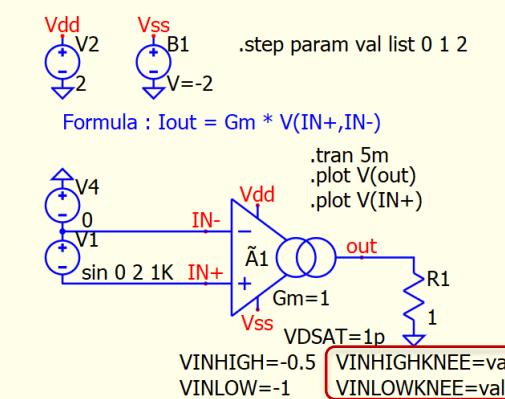
- VINLOW and VINHIGH**

- VINLOW : Input range measured from negative rail
- VINHIGH : Input range measured from positive rail
- Default VINLOW=0**
- Default VINHIGH=0**
- Value is negative**, which limit input range. For example, VINHIGH=-0.5, Input HIGH is limited to $Vdd + VINHIGH = 2 - 0.5 = 1.5$ in this example



- VINLOWKNEE**
VINHIGHKNEE

- Vinlowknee : Sharpness of negative input range limit
- Vinhightknee : Sharpness of positive input range limit
- Default VINHIGHKNEE=0**
- Default VINLOWKNEE=0**
- Increase KNEE soften the sharpness of input range, more output signal to come

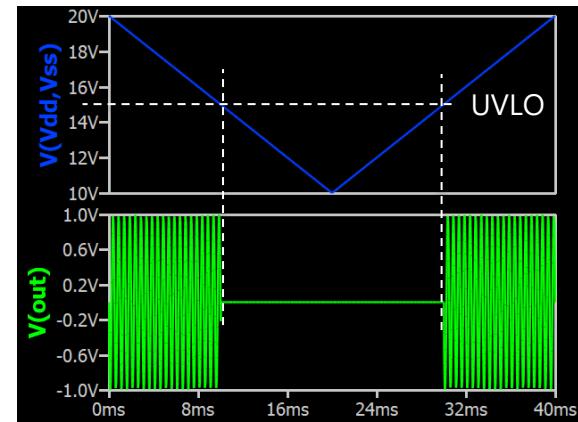
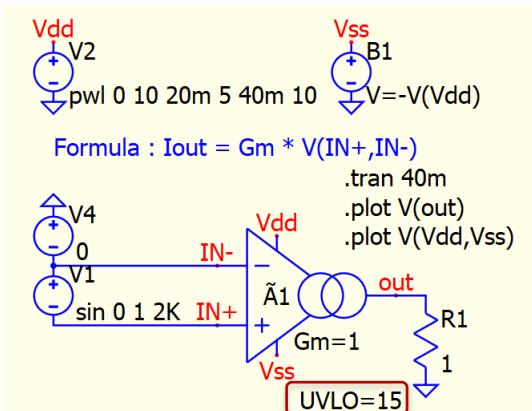


MULTGMAMP : UVLO and VOS1

Qspice : Multgmamp - UVLO.qsch ; Multgmamp - VOS1.qsch

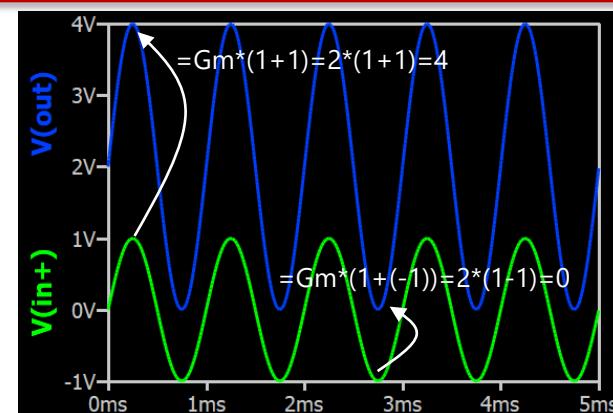
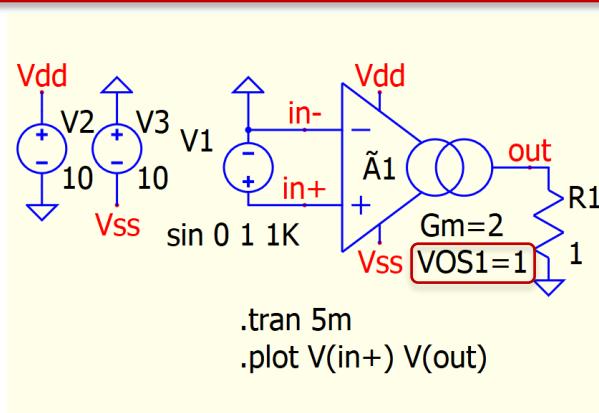
- UVLO

- UVLO : Under Voltage Lock Out - Minimum supply voltage
- Default UVLO is Infinite
- UVLO is compare to supply voltage = $V_{dd} - V_{ss}$



- VOS1

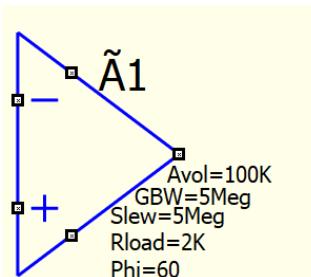
- VOS1 : Offset voltage for input
- $I_{out} = GM \cdot (VOS1 + V(IN+,IN-))$
 - This parameter is not in HELP formula, but it actually implemented
- Default VOS1 = 0



\tilde{A} -Device
RROPAMP

Ã-Device RROPAMP Amplifier

- \tilde{A} -Device RROPAMP Amplifier
 - Syntax: \tilde{A} nnn VDD VSS OUT IN- IN+ MULT+ MULT- IN-- IN++ EN ¥ ¥ ¥ ¥ ¥ ¥ ¥ RROPAMP [INSTANCE PARAMETERS]
 - A generic rail-to-rail output opamp specified by Avol, GBW, slew rate and phase margin. It is implemented with two Gm amps as above with an internal node for a Miller capacitor connected to the output.



| | |
|--------------------------|-----------------------------------|
| Symbol Type | A |
| Description | Generic Rail-to-Rail Output OpAmp |
| Allow Shorted Pins | False |
| Library File | |
| String Attributes | |
| Text Order | Invis. Content |
| Name: | Ä1 |
| 1st attribute | ✓ RRopAmp |
| Avol | 100K |
| GBW | 5Meg |
| Slew | 5Meg |
| Rload | 2K |
| Phi | 60 |

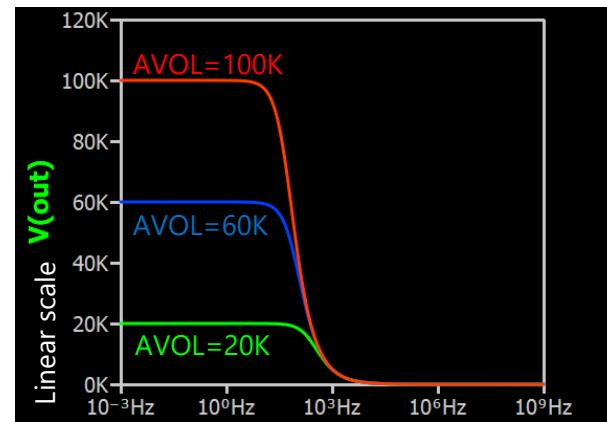
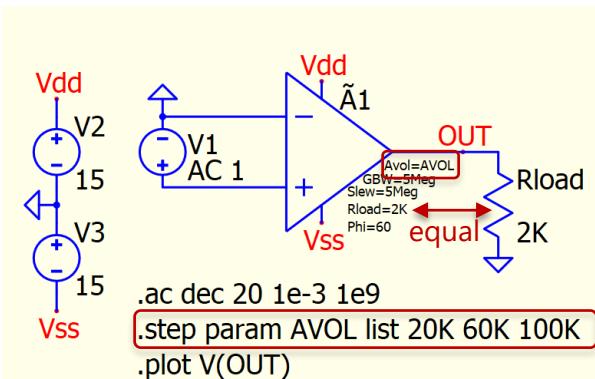
| A-Device Instance Parameters | |
|------------------------------|--|
| Name | Description |
| AVOL | Open loop voltage gain when loaded with RLOAD |
| CAPINCM | Common eigenmode input capacitance |
| CAPINNM | Normal eigenmode input capacitance |
| CAPVDD | Capacitance from output to Vdd |
| CAPVSS | Capacitance from output to Vss |
| EN | Equivalent input voltage noise density |
| ENK | EN corner frequency |
| FT | 3dB bandwidth of transconductance with no voltages slewing |
| GBW | Dominate pole gain-bandwidth |
| IC | Initial condition of Vin x Vmult |
| IN | Equivalent input current noise density |
| INF | Common mode input current noise density proportional to frequency |
| INK | IN corner frequency |
| IOUT | Maximum sourcing current |
| ISNK | Maximum sinking current |
| ISNKKNEE | Sharpness of max sinking current limit |
| ISRC | Max sourcing current |
| ISRCKNEE | Sharpness of max sourcing current limit |
| M | Number of parallel devices |
| PHI | Nominal phase margin |
| REF | Logic threshold for enable(from Vss) |
| RLOAD | Load resistance used in AVOL, GBW specification |
| ROUT | Open loop output impedance |
| SLEW | Slew rate in Volts per second |
| TEMP | Instance temperature |
| TTOL | Temporal tolerance for enable & UVLO |
| UVLO | Minimum supply voltage |
| VCROSS | Cross conduction voltage range |
| VDSAT | Voltage where gm starts to switch over to a resistance |
| VDSAT1 | Voltage where gm starts to switch over to a resistance(top FET) |
| VDSAT2 | Voltage where gm starts to switch over to a resistance(bottom FET) |
| VINHIGH | Output range measured from positive rail |
| VINHIGHKNEE | sharpness of positive input range limit |
| VINLOW | Input range measured from negative rail |
| VINLOWKNEE | Sharpness of negative input range limit |
| VOS1 | Offset voltage for input |
| VOS2 | Offset voltage for multiplying input |
| VOUTMAX | Maximum output voltage measured from negative rail |
| VOUTMIN | Minimum output voltage measured from negative rail |

RROPAMP : AVOL, GBW and RLOAD

Qspice : RROPAMP - AVOL.qsch | RROPAMP - GBW.qsch

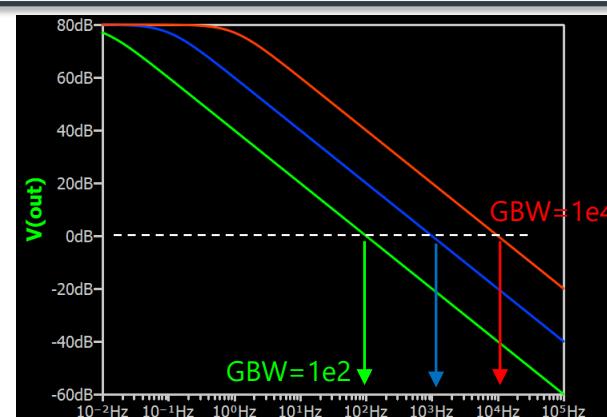
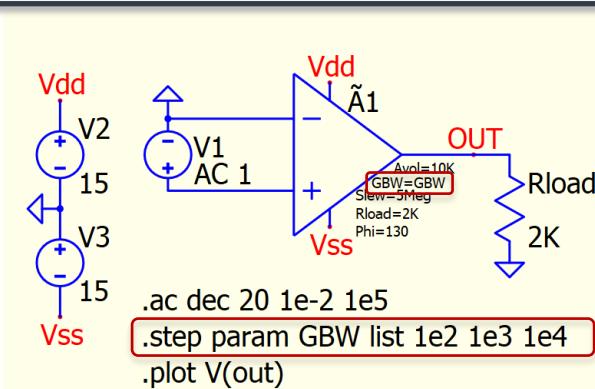
• AVOL

- Open loop voltage gain when **loaded with RLOAD**
- **Default AVOL=1000k (120dB)**
- Gain = $\frac{V_{out}}{V_+ - V_-}$
- AVOL is gain @ 0Hz when load at output equal instance parameter Rload



• GBW

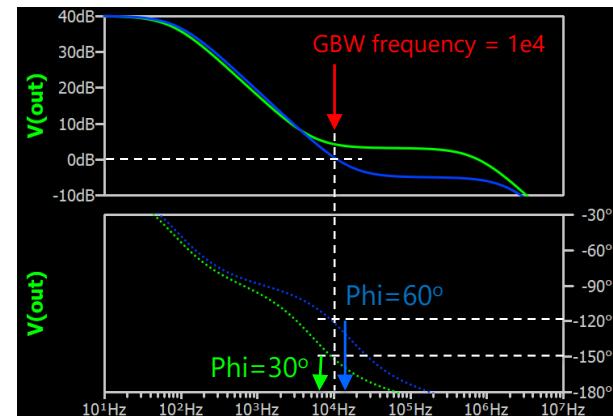
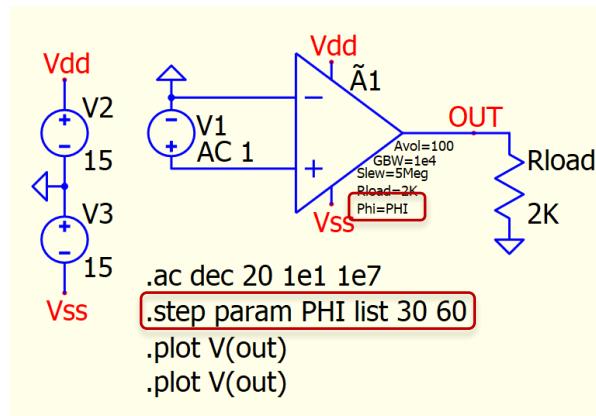
- Dominate pole gain-bandwidth
 - GBW means frequency where gain of opamp falls to unity (0dB or -1)
- **Default GBW=5Meg**



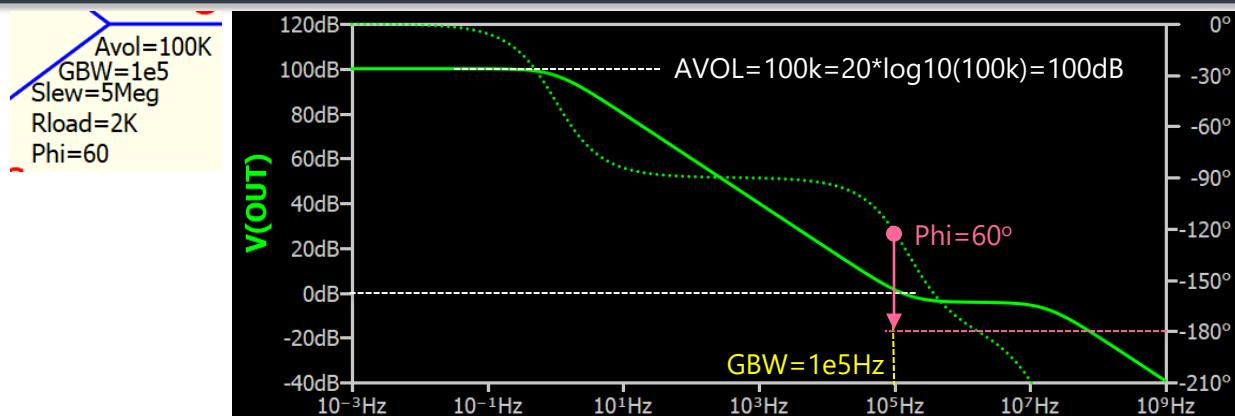
RROPAMP : PHI

Qspice : RROPAMP - PHI.qsch | RROPAMP - AVOL GBW PHI RLOAD.qsch

- PHI
 - Nominal phase margin
 - **Default PHI=60°**
 - Phase margin is measured between phase to -180° at 0dB (or at GBW frequency)



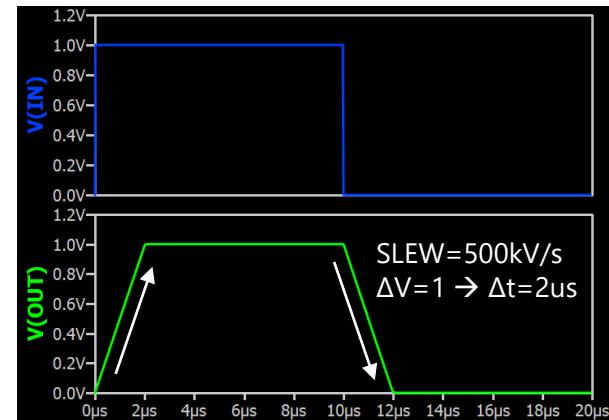
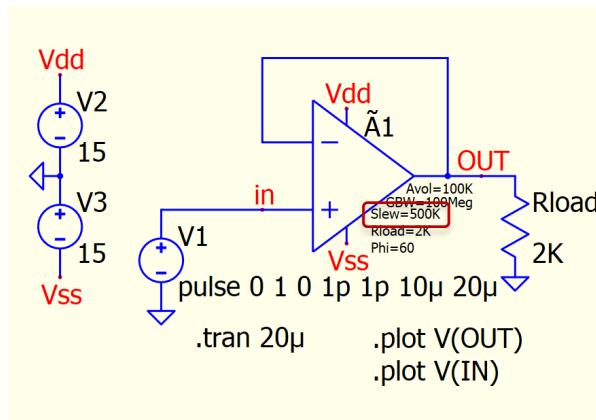
- Summary
 - AVOL, GBW, PHI are three parameters to determine open-loop frequency response of RROPAMP
 - RLOAD
 - These three parameters are specified at this Rload condition



RROPAMP : SLEW

Qspice : RROPAMP - SLEW.qsch

- SLEW
 - Slew rate in Volts per second (maximum change rate)
 - $SLEW = \frac{\Delta V_{out}}{\Delta t}$
- **Default SLEW=5Meg**



¥-Device

¥-Device

- ¥-Device
 - Syntax:

`¥nnn N1 N2 N3 N4 N5 N6 N7 N8 N9 N10 N11 N12 N13 N14 N15 N16 <TYPE> [INSTANCE PARAMETERS]`

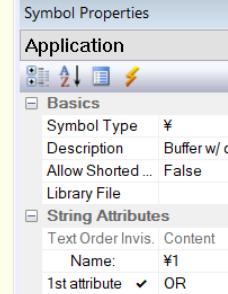
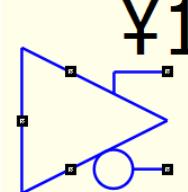
- The ¥-device supplies gate, flop, and a few other types of functional behaviors. The device expects exactly 16 pins, but not all are used. Unused pins must be specified connected to "¥".

¥-Device Types

| TYPE | Behavior |
|------------|---|
| AND | AND gate |
| CLOCKSYNC | Selects between a Sync and Clock inputs |
| D-FLOP | D-type flip-flop |
| EXTOSC | Oscillator programmed with an external resistor |
| HMITT | Schmitt trigger |
| JK-FLOP | JK-type flip-flop |
| MONOSTABLE | Retriggerable monostable |
| OR | OR gate |
| PS-FLOP | SMPS flip-flop |
| RS-FLOP | RS-type flip-flop |
| T-FLOP | Toggle flip-flop |
| XOR | XOR gate |
| Φ-DET | Phase/Frequency detector |

To Identify what <TYPE> a symbol is

- In Symbol Properties > 1st attribute
- View > Netlist : from device syntax

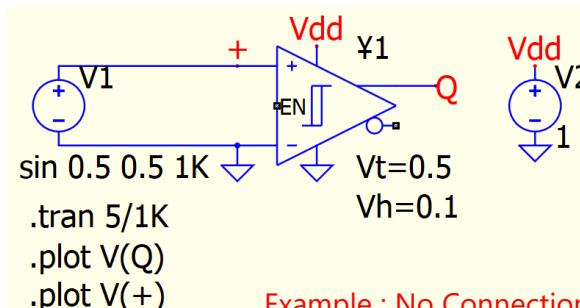


```
* C:\Users\kelvinleung\Documents\QSPICE\Unt
¥1 ¥0 ¥1 ¥2 ¥3 ¥4 ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ OR
.end
```

¥-Device : How EN pin works

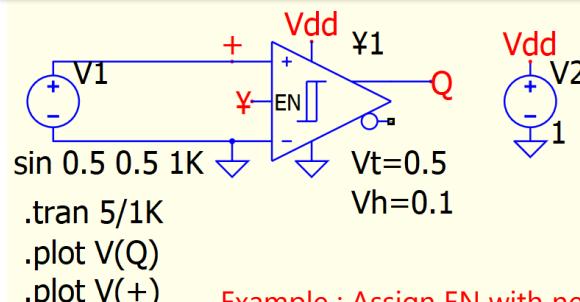
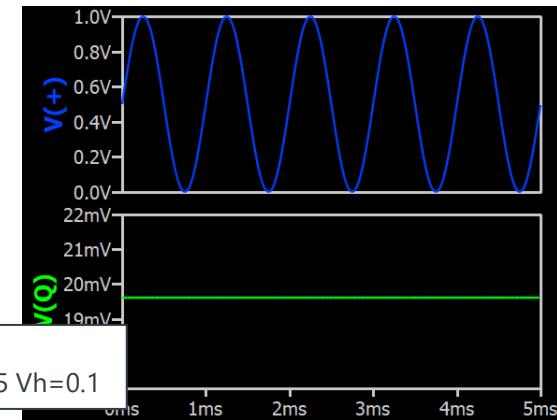
Qspice - Logic - EN.qsch

- How EN works
 - If EN is preset in symbol, normally, a signal is used to control its status. Here discuss two situations
 - #1 No connect to EN pin
 - Netlist assign ¥n as net name. EN pin is active to monitor EN signal. In this case, no output will generate
 - #2 Assign EN pin with net ¥
 - ¥ net name is equivalent to unassigned in ¥-device
 - Unassigned EN pin will be considered as Default ENABLE
 - Therefore, a symbol can be created with pin assigned to ¥ for their default



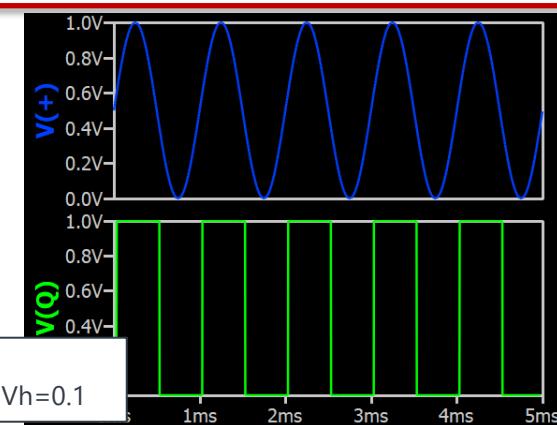
Example : No Connection

Netlist
¥1 Vdd 0 Q ¥0 + 0 ¥1 ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ HMITT Vt=0.5 Vh=0.1



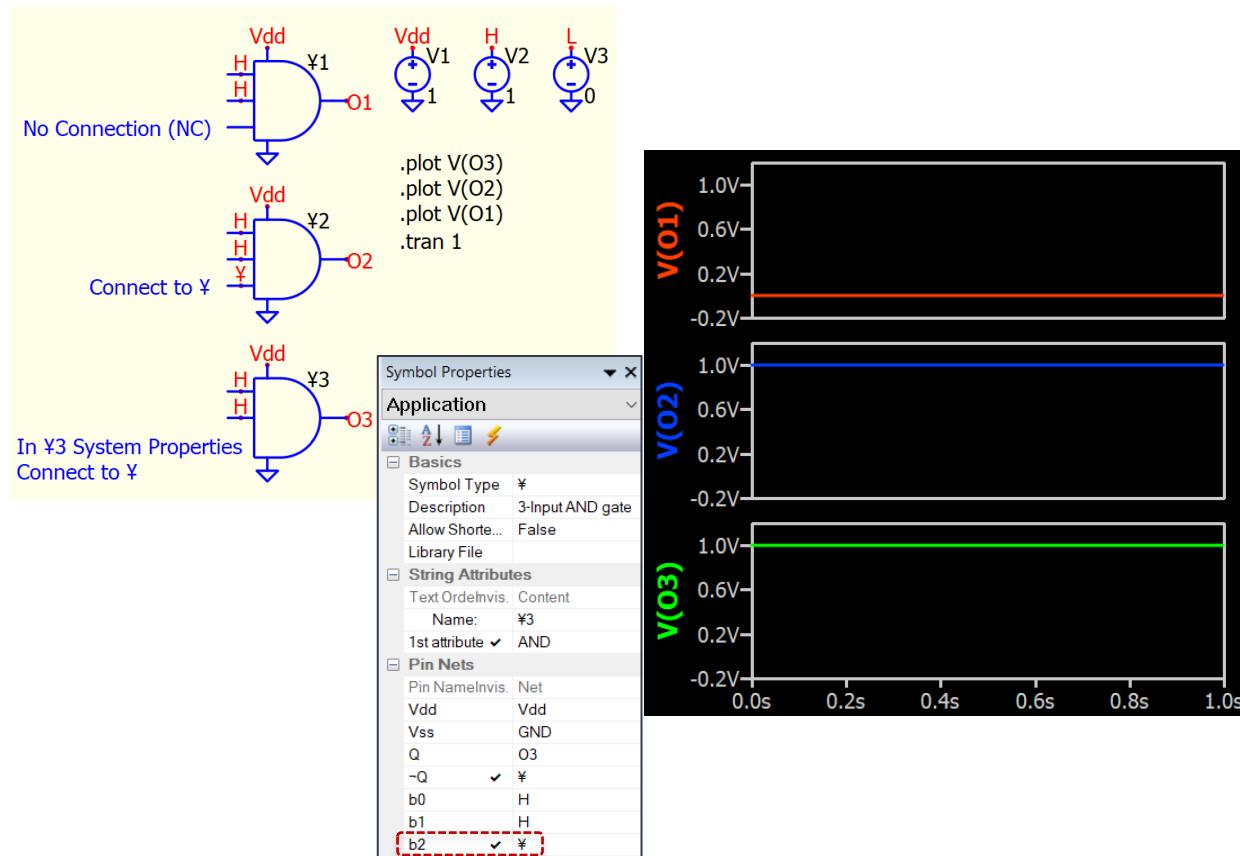
Example : Assign EN with net ¥

Netlist
¥1 Vdd 0 Q ¥0 + 0 ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ ¥ HMITT Vt=0.5 Vh=0.1



¥-Device : Net ¥

- Net ¥
 - Unconnected Pin and Pin connected to Net ¥ is different
 - Net ¥ is a special net name, in HELP of ¥-Device, it specified that unused pins must be specified connected to "¥"
 - Two methods to force a pin to ¥ if
- This is an example of AND gate
 - Device ¥1 : NC pin is equivalent to 0V and AND gate output 0
 - Device ¥2 : ¥ is assigned as Net in schematic and this input specified unused for this AND gate
 - Device ¥3 : ¥ is assigned but in System Properties, this input specified unused and become invisible in symbol



¥-Device : HELP > Simulator > Device Reference > ¥-Device

Common Instance Parameters (example from AND Gate Instance Param)

| Name | Description | Units | Default |
|-------------|---|--------------|----------------------|
| • CAPVDD | Capacitance from an output to Vdd | F | 0. |
| • CAPVSS | Capacitance from an output to Vss | F | 0. |
| IC | Initial condition(needed, e.g., for a ring osc) | | |
| M | Number of parallel devices | | 1. |
| • REF | Logic reference voltage | V | $(Vdd + Vss) \div 2$ |
| • RSINK | Resistance to Vss when output high | Ω | RSRC |
| • RSRC | Resistance to Vdd when output low(aka ROUT) | Ω | 100. |
| • TD | Delay(aka TD1) | s | 0. |
| • TD2 | Asymmetrical delay | s | TD |
| TEMP | Instance temperature | $^{\circ}C$ | 27. |
| • TFALL | Fall time | s | 0. |
| • TRISE | Rise time | s | 0. |
| • TTOL | Temporal tolerance | s | $1\mu s$ |
| • UVLO | Minimum Vdd-Vss voltage to operate | V | 0. |
| ZMULT | Impedance multiplier when biased half way | | 1. |

¥ Instance Params : REF Logic Reference Voltage

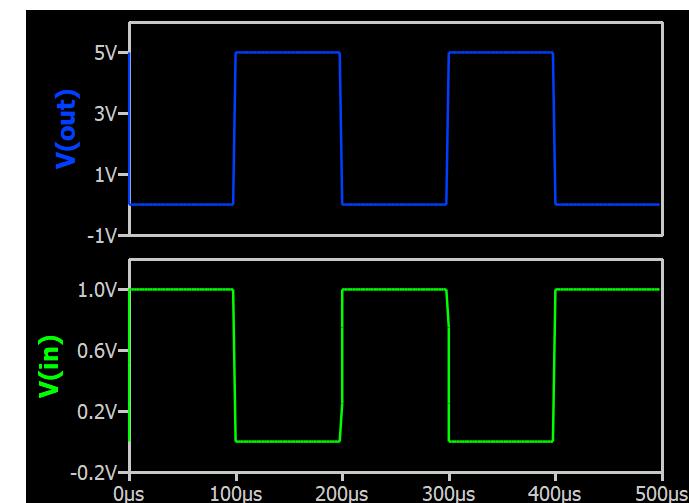
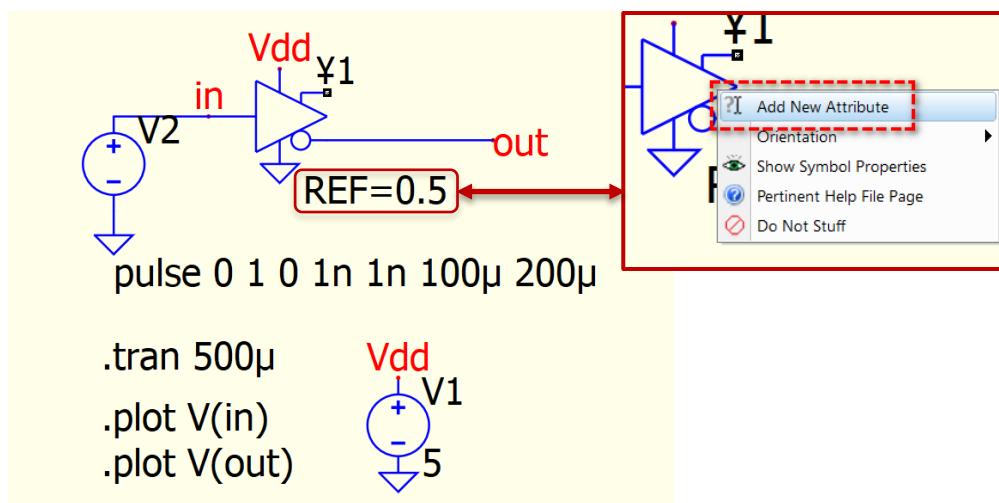
Qspice : Logic - REF.qsch

- REF : Logic reference voltage

- In default, ¥-Device logic threshold is $\frac{Vdd+Vss}{2}$

| REF | Logic reference voltage | V | $(Vdd + Vss) \div 2$ |
|-----|-------------------------|---|----------------------|
|-----|-------------------------|---|----------------------|

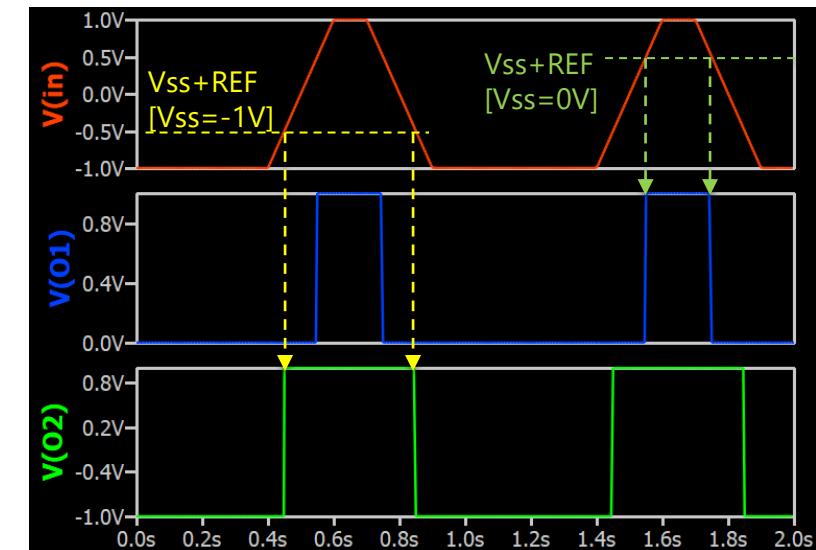
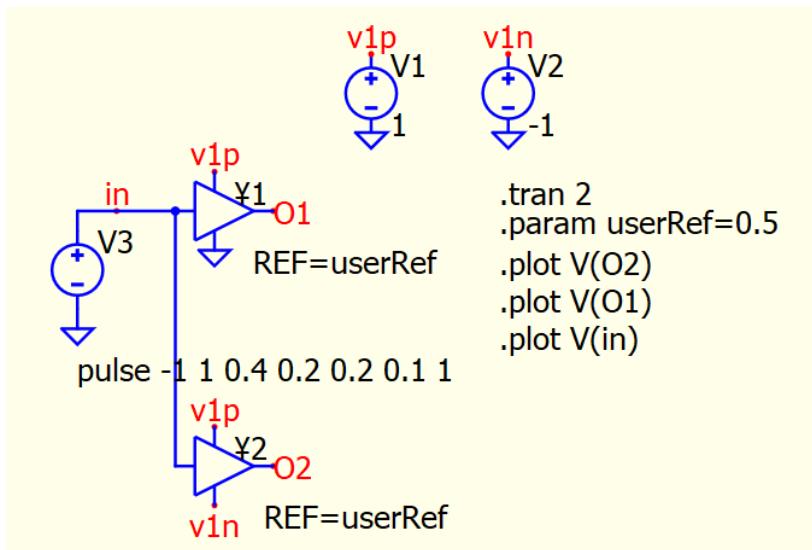
- User can change logic threshold by [right click device] > [Add New Attribute] to add `REF=<value>`
- This example show logic output follows $Vdd/0$ with logic input threshold equal 0.5V to interface with 1V input logic



¥ Instance Params : REF Logic Reference Voltage

Qspice : Logic - REF (Dual Supply).qsch

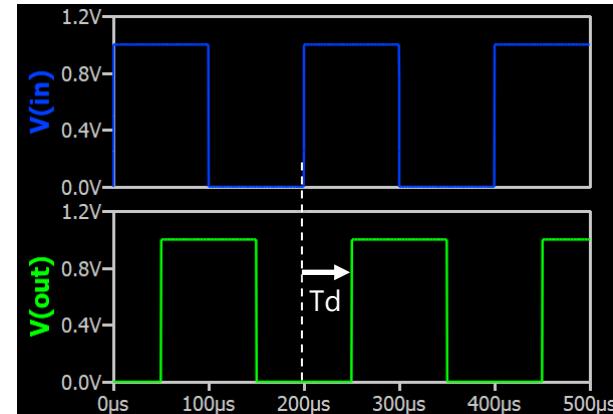
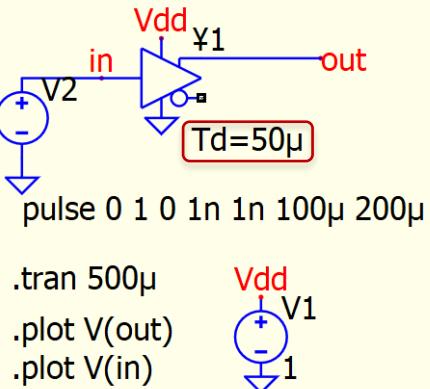
- REF : Logic Reference Voltage
 - REF is not absolute voltage to node 0, but reference to Vss node of ¥-Device
 - In this example, ¥1 and ¥2 are with same REF value, but as ¥1 Vss=0V and ¥2 Vss=-1V, their logic reference is different reference to node 0 (GND). Therefore, even their input is same, their output can be different



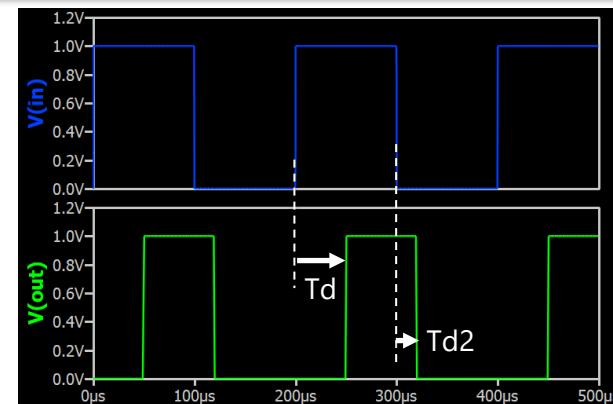
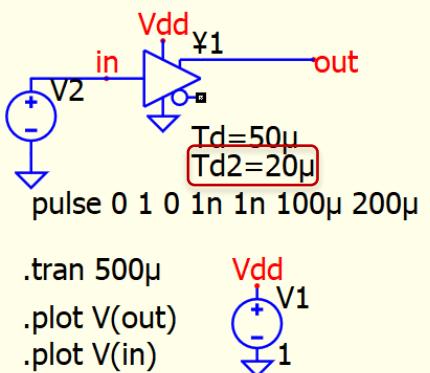
Instance Params : Delay (TD) and Asymmetrical Delay (TD2)

Qspice : Logic - Td.qsch ; Logic - Td Td2.qsch

- TD (Delay)
 - Td : Delay
 - **Default TD=0s**
 - ** If TD2 is not set, both rising and falling delay times are same
 - ** If TD > logic H duration or delay TD2 > logic L duration, output always LOW or HIGH



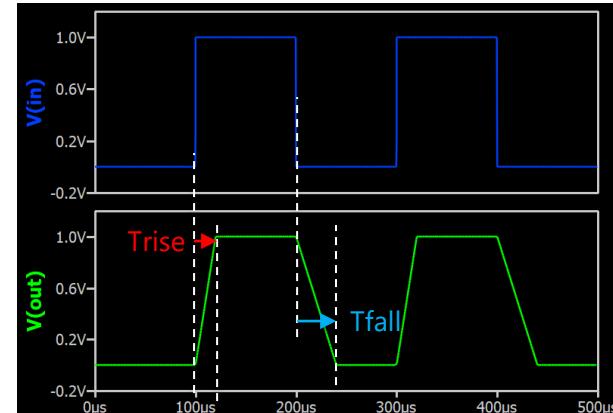
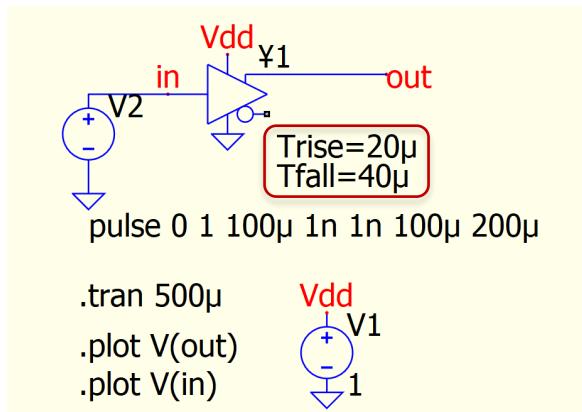
- TD2 (Asymmetrical delay)
 - TD2 : Asymmetrical delay
 - **Default TD2=TD**
 - If different delay times for rising and falling edge, set TD2 for falling edge delay time (i.e. TD only control rising edge delay time)



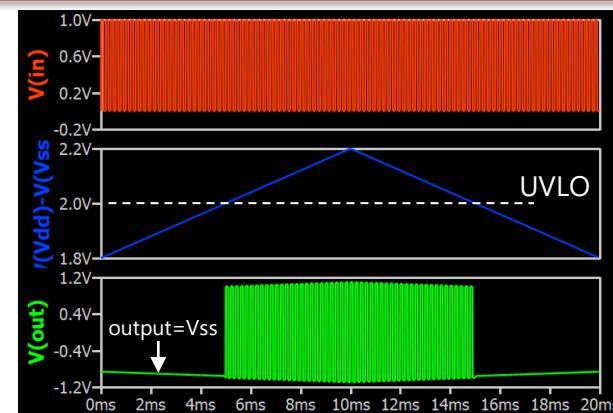
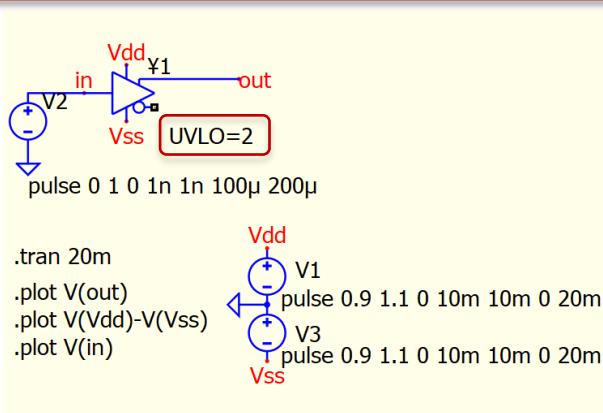
Instance Params : Rise time (Trise), Fall time (Tfall) and UVLO

Qspice : Logic - Trise Tfall.qsch

- TRISE and TFALL
 - Trise : Rise time
 - Tfall : Fall time
 - **Default TRISE=0s**
 - **Default TFALL=0s**



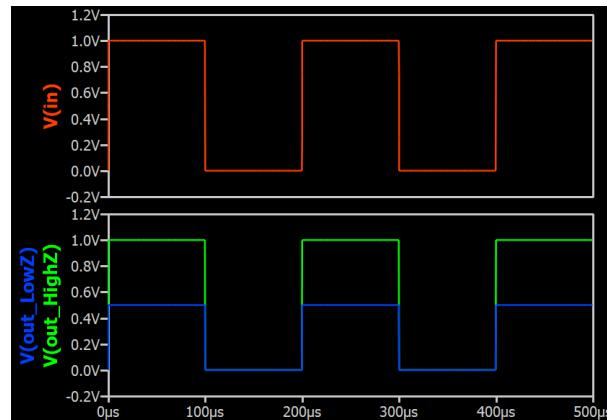
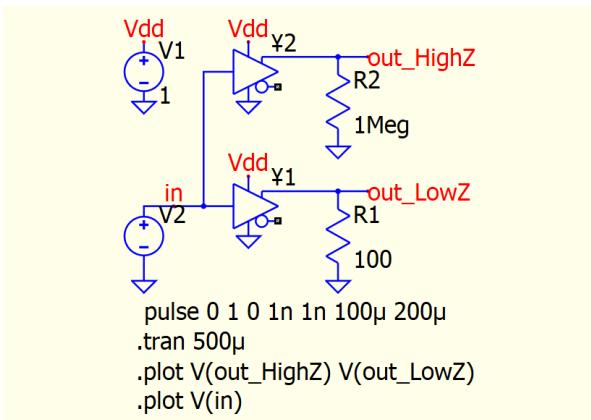
- UVLO
 - UVLO : Under Voltage Lock Out
 - **Default UVLO=0V**
 - UVLO : Minimum $V_{dd}-V_{ss}$ voltage to operate
 - Output only enabled when $V_{dd}-V_{ss} > \text{UVLO}$
 - Output equals V_{ss} when gate disable



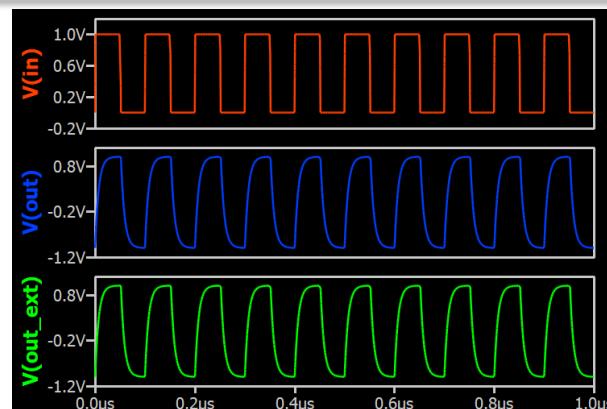
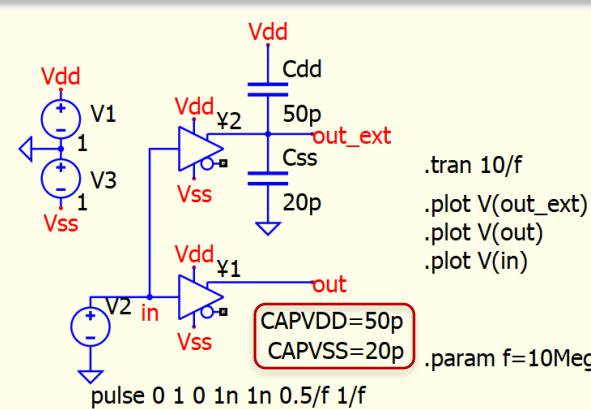
Instance Params : Output R and C (Rsink, Rsrc, Capvdd, CapVss)

Qspice : Logic - RSINK RSRC.qsch ; Logic - Capvdd Capvss.qsch

- RSINK and RSRC
 - RSINK : Res to Vss when o/p high
 - RSRC : Res to Vdd when o/p low
 - **Default RSINK=100Ω**
 - **Default RSRC=100Ω**
- Example
 - This simulation shows loading effect when output to a 100 ohms, where o/p level is reduced to half of Vdd



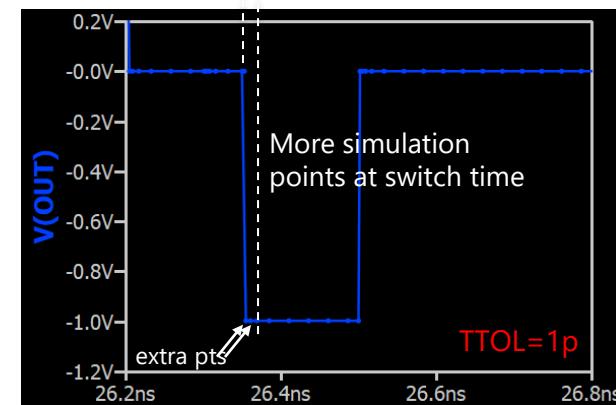
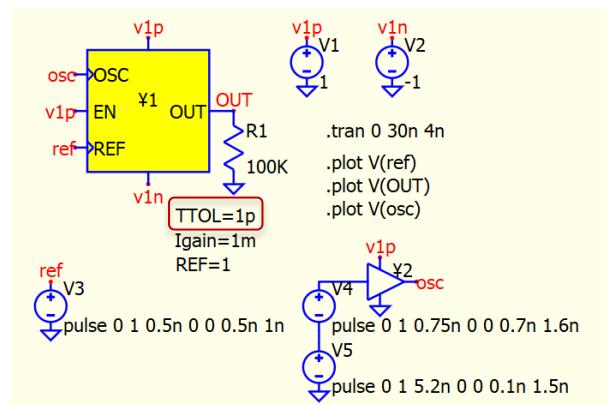
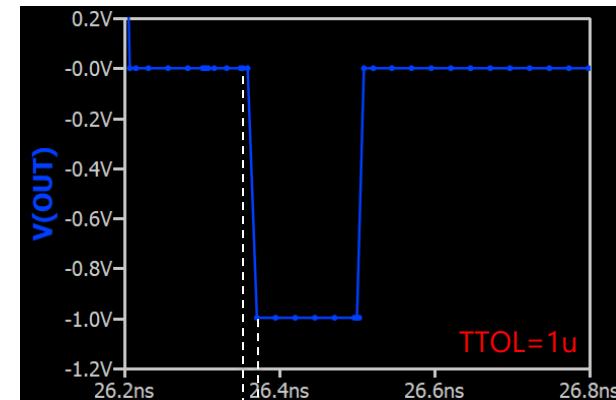
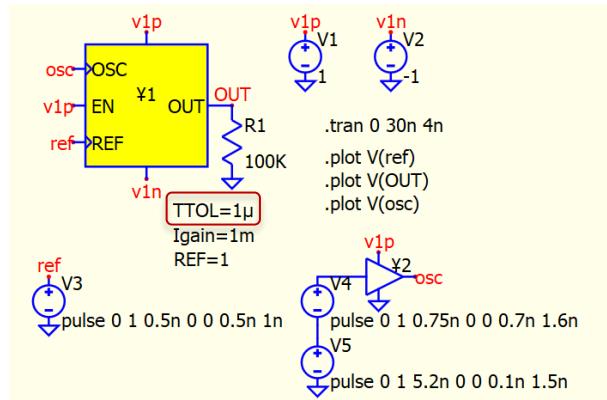
- CAPVDD, CAPVSS
 - Capvdd : Capacitance from an output to Vdd
 - Capvss : Capacitance from an output to Vss
- Explanation
 - Capacitance Capvdd/Capvss equivalent Cdd/Css this example
 - This demo can have frequency response because Rsink=Rsrc=100 internally



Instance Params : TTOL Temporal Tolerance

Qspice : Logic - TTOL.qsch

- TTOL
 - Ttol : Temporal tolerance
 - **Default TTOL=1u**
 - TTOL allows one to determine how accurately the switch time should be found

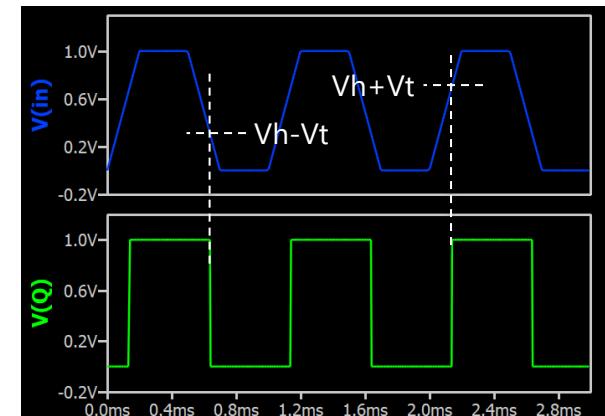
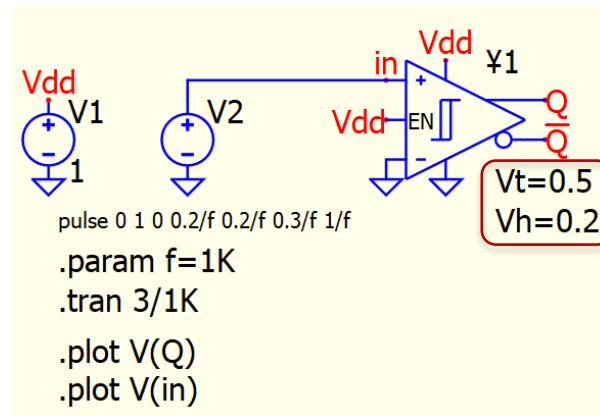


⌘ [HMITT] Instance Params : Threshold (VT) and Half Hysteresis (VH)

Qspice : HMITT - Vt VH.qsch

- VT and VH

- Vt : Threshold voltage
- VH : Half hysteresis voltage
- HMITT is schmitt trigger logic input
- low trip point is $Vt-VH$ and the high trippoint is $Vt+VH$



¥ Truth Table : AND, OR, XOR

Qspice : Truth Table of AND OR XOR.qsch

- AND

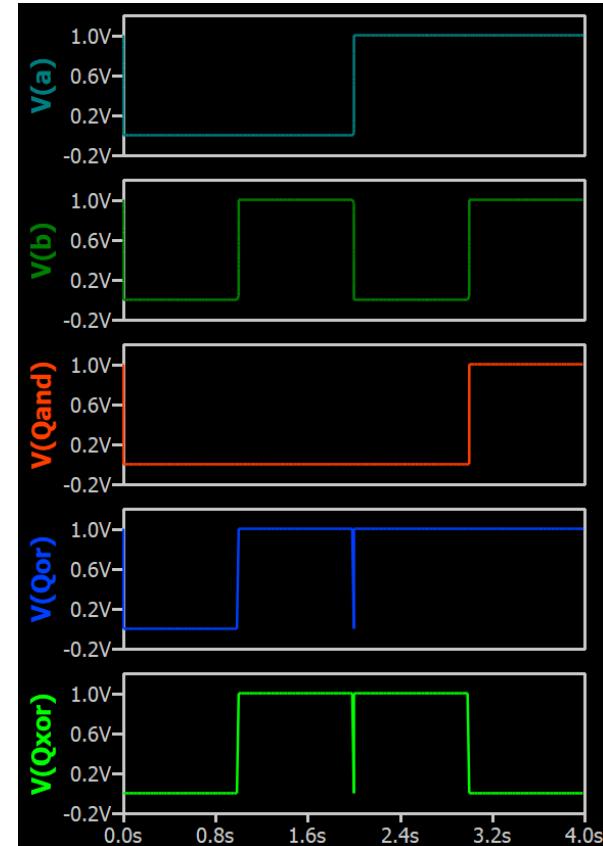
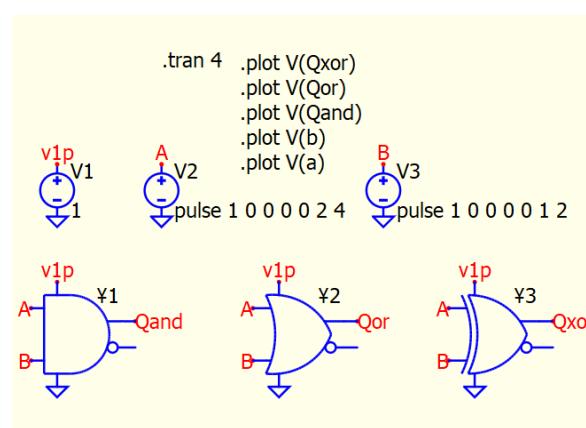
| ¥-Device AND | | | |
|--------------|---|---|----|
| A | B | Q | _Q |
| 0 | 0 | 0 | 1 |
| 0 | 1 | 0 | 1 |
| 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 0 |

- OR

| ¥-Device OR | | | |
|-------------|---|---|----|
| A | B | Q | _Q |
| 0 | 0 | 0 | 1 |
| 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 0 |
| 1 | 1 | 1 | 0 |

- XOR

| ¥-Device XOR | | | |
|--------------|---|---|----|
| A | B | Q | _Q |
| 0 | 0 | 0 | 1 |
| 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 1 |



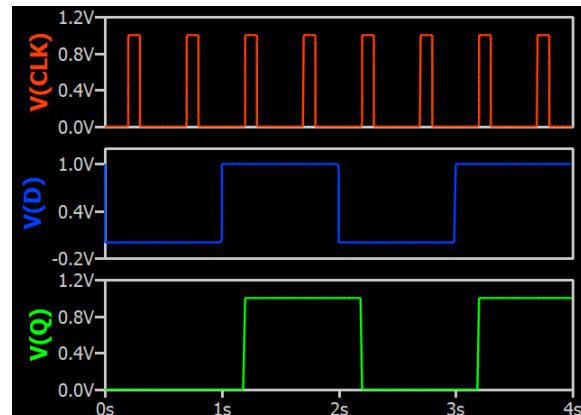
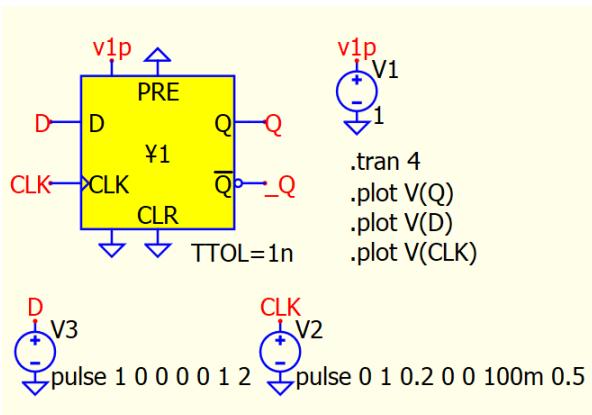
¥ Truth Table : D-FLOP and T-FLOP

Qspice : Truth Table of D-FLOP.qsch ; Truth Table of T-FLOP.qsch

- D-FLOP

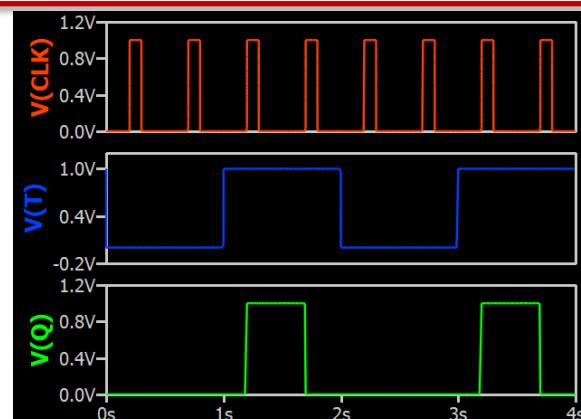
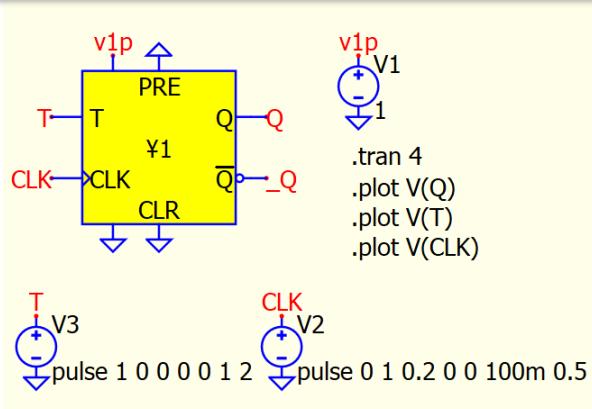
- PRE : Active High (=SET)
- CLR : Active High (=RESET)

| ¥-Device D-flop | | | | | |
|-----------------|---|-----|-----|---|-----------|
| CLK | D | PRE | CLR | Q | \bar{Q} |
| ↑ | 0 | 0 | 0 | 0 | 1 |
| ↑ | 1 | 0 | 0 | 1 | 0 |
| x | x | 0 | 0 | Q | \bar{Q} |
| x | x | 1 | 0 | 1 | 0 |
| x | x | x | 1 | 0 | 1 |



- T-FLOP

| ¥-Device T-flop | | | | |
|-----------------|---|-----|-----|-------------|
| CLK | T | PRE | CLR | Q_{n+1} |
| ↑ | 0 | 0 | 0 | 0 |
| ↑ | 1 | 0 | 0 | \bar{Q}_n |
| x | x | 0 | 0 | Q |
| x | x | 1 | 0 | 1 |
| x | x | x | 1 | 0 |

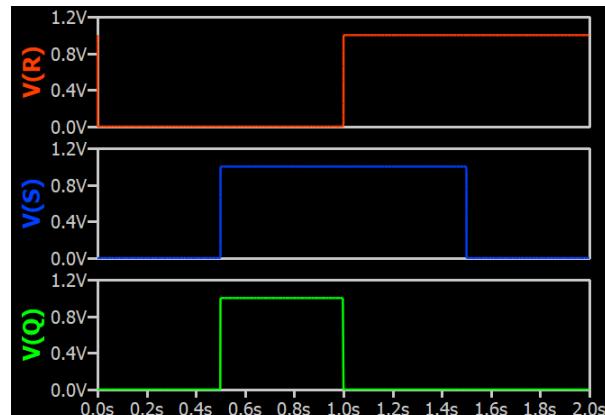
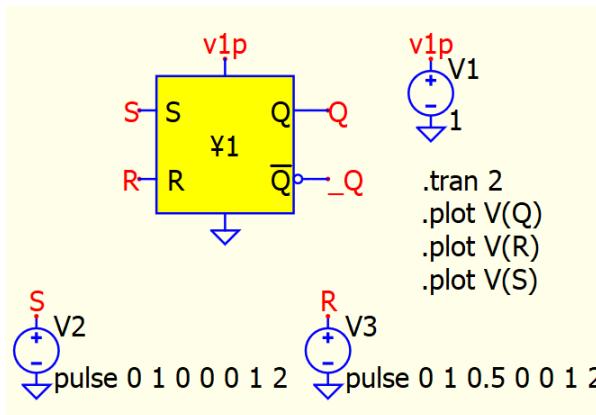


¥ Truth Table : SR-FLOP and JK-FLOP

Qspice : Truth Table of SR-FLOP.qsch ; Truth Table of JK-FLOP.qsch

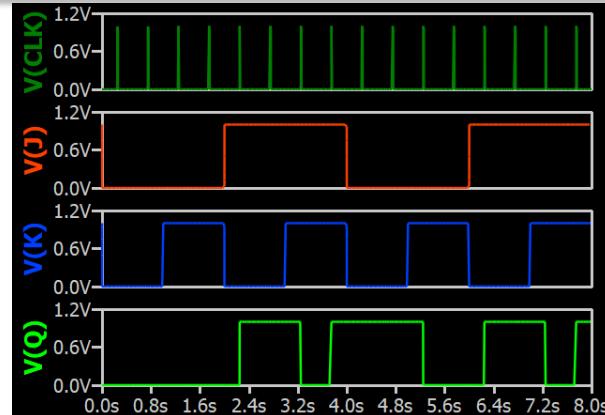
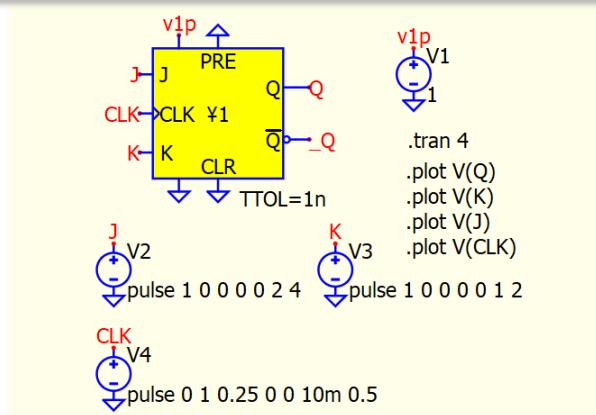
- SR-FLOP

| ¥-Device SR-flop | | Q | $_Q$ |
|------------------|---|---|-------|
| R | S | Q | $_Q$ |
| 0 | 0 | 0 | 1 |
| 0 | 1 | 1 | 0 |
| 1 | x | 0 | 1 |



- JK-FLOP

| ¥-Device JK-flop | | | | | |
|------------------|---|---|-----|-----|-----------|
| CLK | J | K | PRE | CLR | Q_{n+1} |
| ↑ | 0 | 0 | 0 | 0 | Q_n |
| ↑ | 0 | 1 | 0 | 0 | 0 |
| ↑ | 1 | 0 | 0 | 0 | 1 |
| ↑ | 1 | 1 | 0 | 0 | $_Q_n$ |
| x | x | x | 0 | 0 | Q |
| x | x | x | 1 | 0 | 1 |
| x | x | x | x | 1 | 0 |

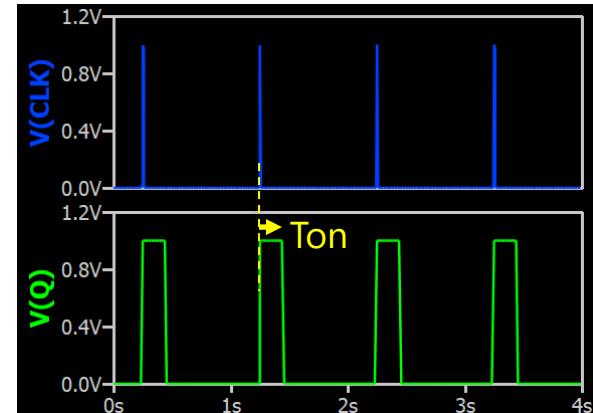
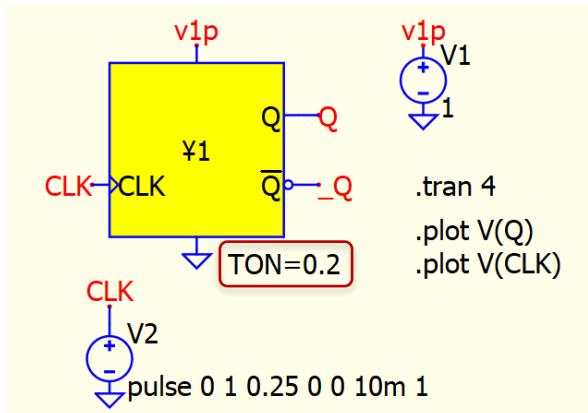


¥-Device : Monostable and Latch (Sample and Hold S&H)

Qspice : Usage - Monostable.qsch | Usage - Latch Sample and Hold.qsch

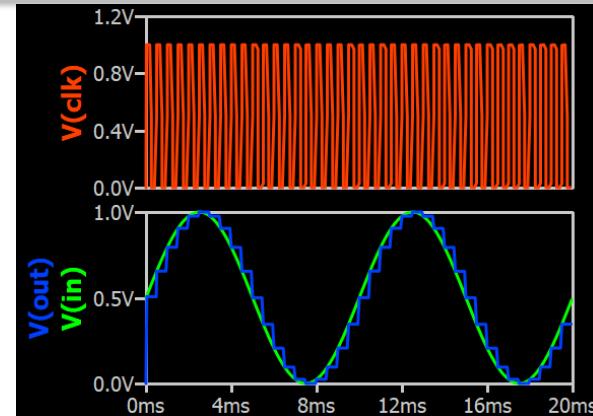
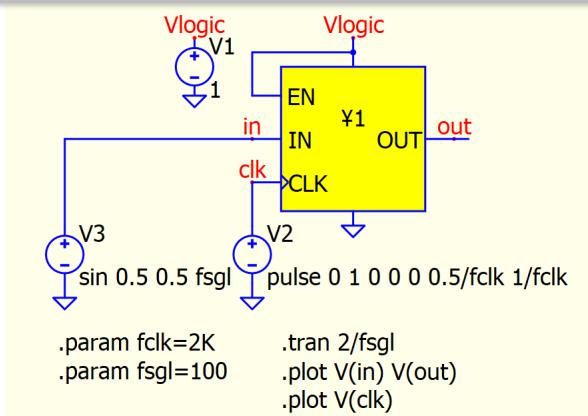
- Monostable

- TON : Monostable on time
- Default TON=0s**
- Need to add this attribute when Monostable Symbol is called to use in Qspice
- TON must be specified to use Monostable
- CLK trigger a minimum on-time pulse



- Latch

- Edge-sensitive Sample and Hold



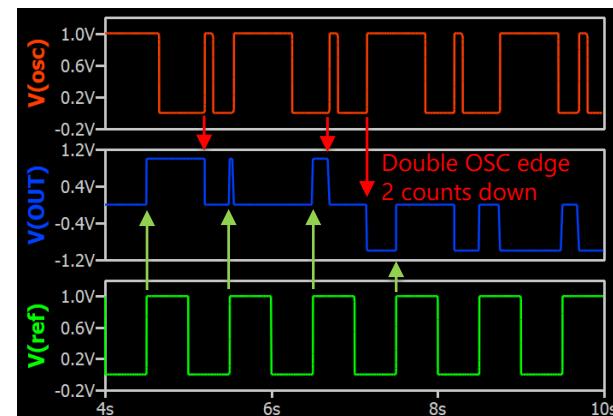
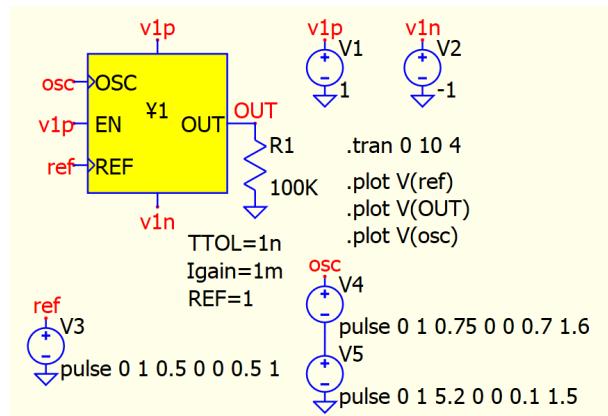
¥ Truth Table : Φ -DET (Phi-Det) [Symbol : PhaseDetector in analog]

Qspice : Truth Table of Phi-Det.qsch

- Φ -DET (Phi-Det)
 - Phase/Frequency Detector

| ¥-Device Phi-Det | | |
|------------------|-----|----------|
| REF | OSC | OUT |
| ↑ | x | Up |
| x | ↑ | Down |
| ↑ | ↑ | Unchange |

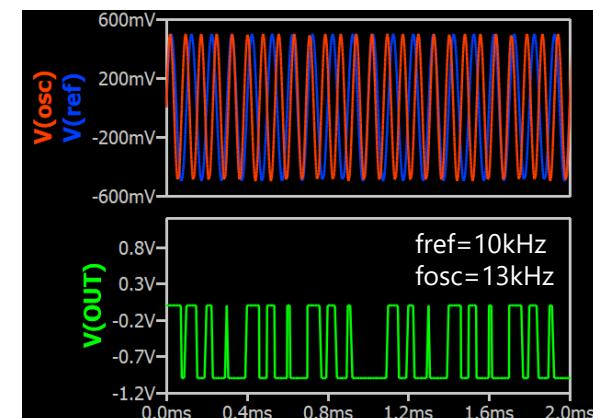
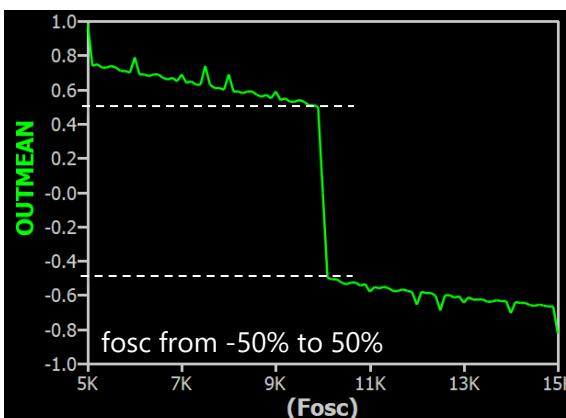
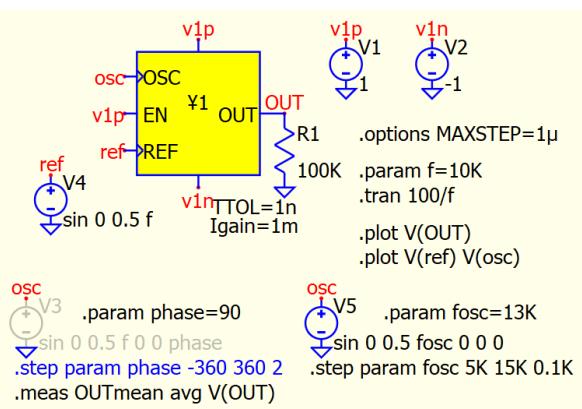
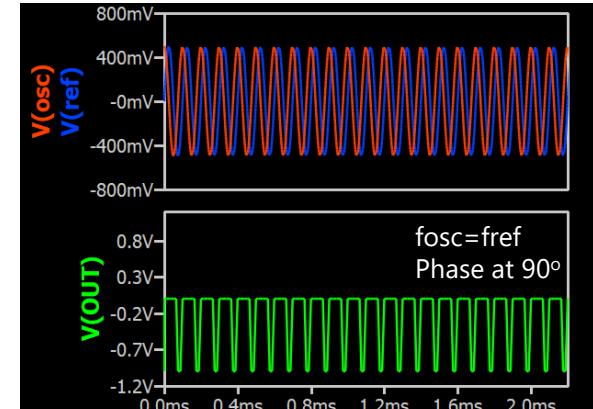
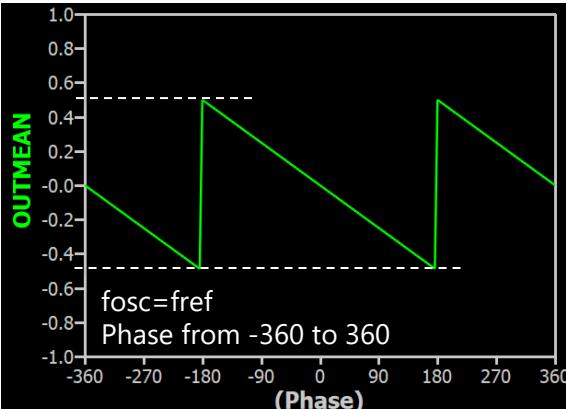
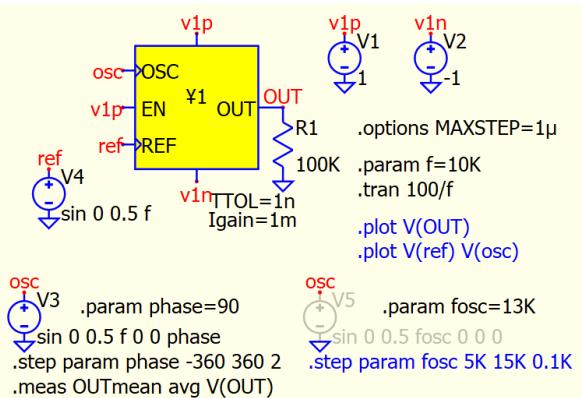
- Important
 - Output is current, not voltage
 - Suggest to set a higher Igain for OUT can reach Vdd/Vss with load (Default Igain only 10µA)
 - This device is a [Vdd, 0, Vss] 3-state counter, therefore, must operate with dual supply
 - REF edge counts up
 - OSC edge counts down



- Phase/Frequency Detection
 - Next slide is simulation results in phase change and frequency change
 - Mean of PWM output pattern can differentiate it is OSC signal phase or frequency deviate from REF signal
 - This is a key component in Phase Lock Loop (PLL)

¥-Device Φ -DET (Phi-Det) : OSC and REF Relationship with OUT

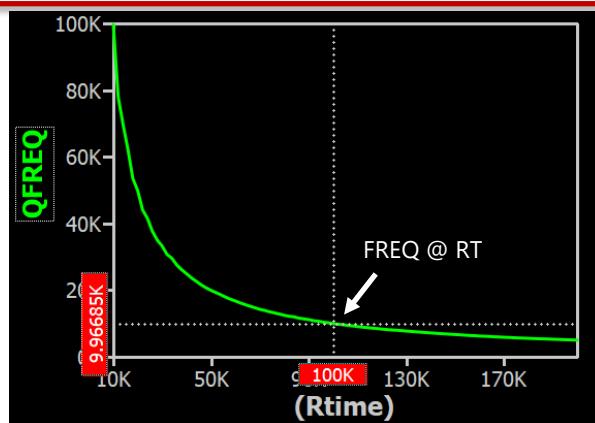
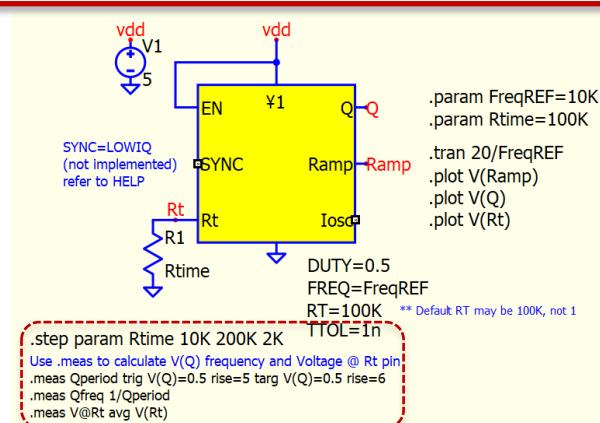
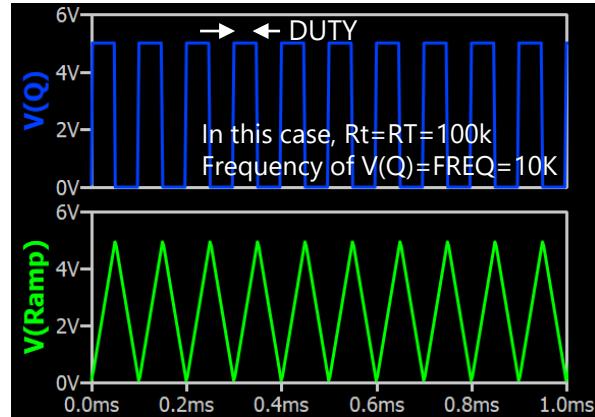
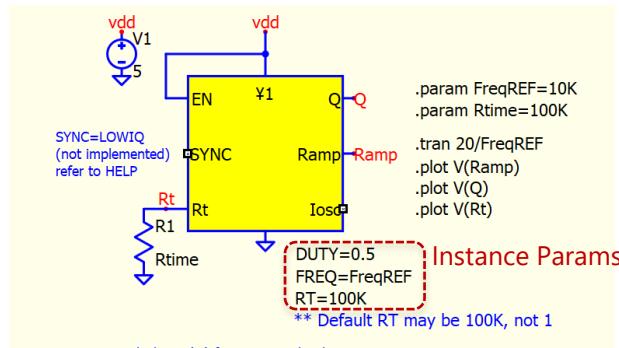
Qspice : Usage - Phi-Det (Freq and Phase).qsch



¥-Device EXTOSC : Oscillator programmed with an external resistor

Qspice : Usage - Extosc - Rtime .tran.qsch | Usage - Extosc - Rtime .step.qsch

- EXTOSC
 - Oscillator programmed with an external resistor
 - Instance Parameters
 - DUTY : Oscillated V(Q) duty [Default DUTY = 0.9]
 - FREQ : Oscillated Frequency @ RT [Default FREQ=100kHz]
 - RT : Timing Resistance (Rtime) value at FREQ [Default RT=100kohms]
 - Symbol : **ExtOsc4** in analog
 - Oscillator frequency is controlled by external resistor with this symbol as no Vres1 and Vres2 pins
- V(Q) frequency vs Rtime
 - This simulation uses .step param Rtime and .meas to plot frequency of V(Q) vs Rtime relationship
 - It can observe that V(Q) frequency has inverse relationship with Rt
 - $\text{Freq of } V(Q) = \frac{RT}{Rtime} \times \text{FREQ}$

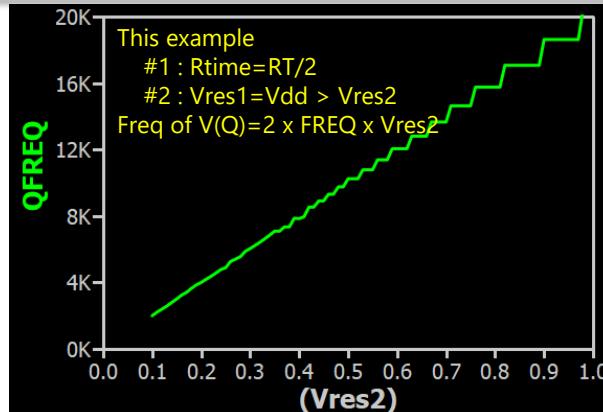
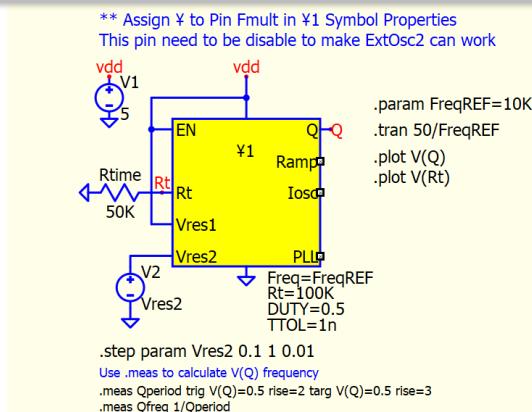
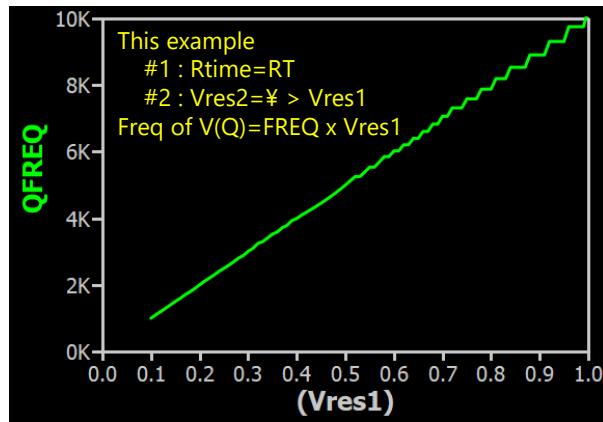
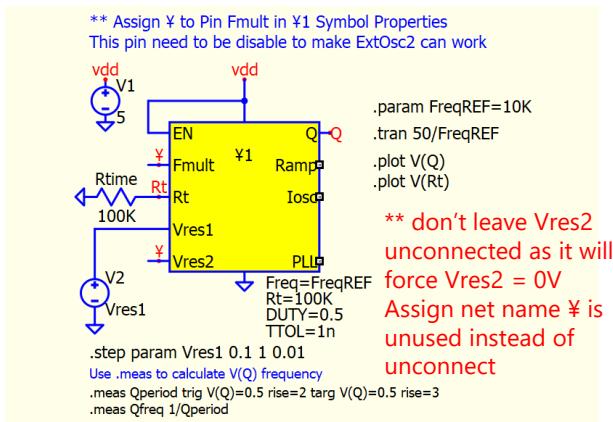


¥-Device EXTOSC : Oscillator programmed with an external resistor

Qspice : Usage - Extosc - VRES1.step.qsch | Usage - Extosc - VRES2.step.qsch

- V(Q) frequency vs Vres1/2
 - Symbol : **ExtOsc2** in analog
 - Oscillator frequency is controlled by voltage at Vres1 or Vres2 pins
 - This model with Vres1 and Vres2
 - Vres2 is not mentioned in Qspice HELP, but indeed there
 - Oscillator uses minimum value of Vres1 and Vres2 to determine output frequency
 - Instance Parameter VRT (voltage on timing resistor) can affect Frequency
 - **Freq of V(Q)**

$$= \frac{RT}{Rtime} \times FREQ \times \frac{\min(Vres1, Vres2)}{VRT}$$
- Typically, the spare one would be used for frequency foldback when the output is shorted to ground
- ** Fmult should connect to ¥ in using ExtOsc2 symbol
 - Method #1 : Connect to a Net ¥
 - Method #2 : Right Click symbol, System Properties, find Pin Name Fmult and assign Net as ¥, Fmult will be invisible and connect to ¥

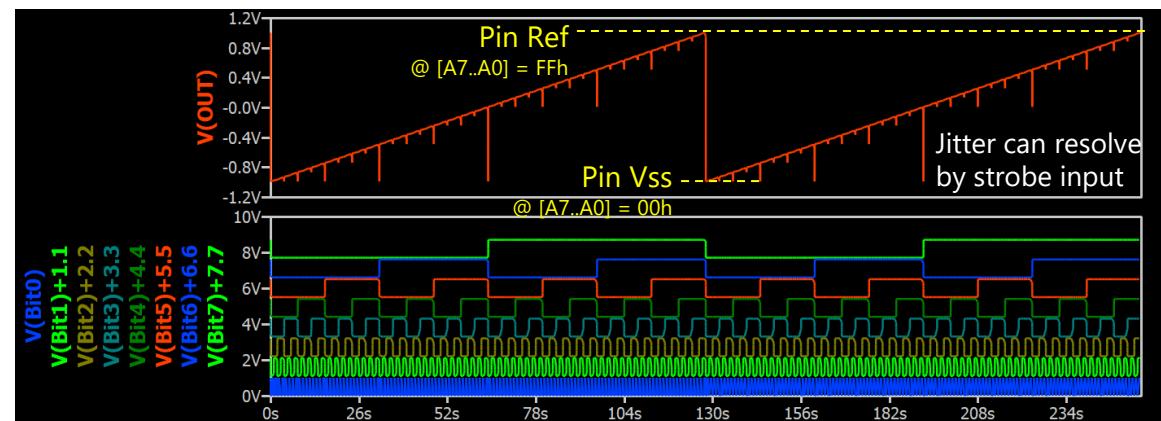
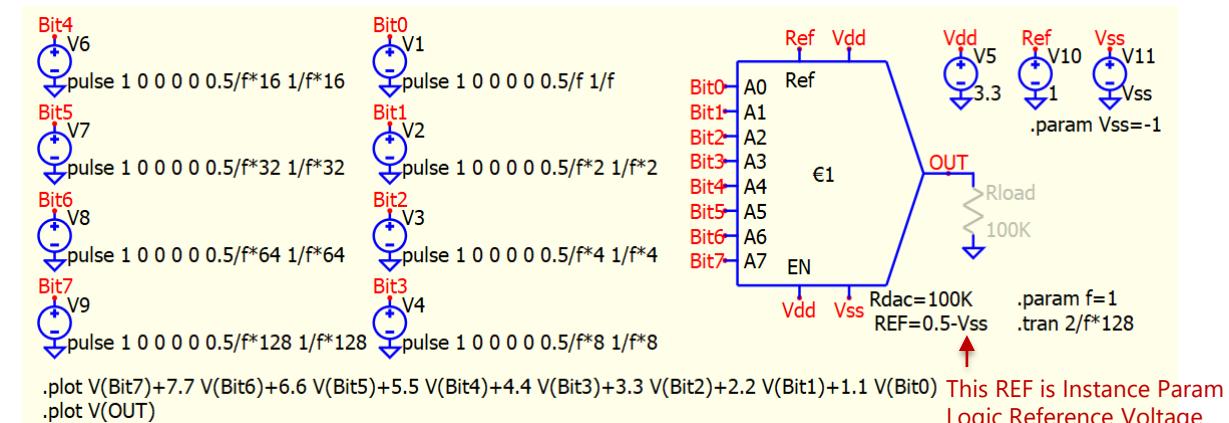


ϵ -Device

€-Device DAC : Build-in Symbol DAC8.qsym

Qspice : DAC - Basic.qsch

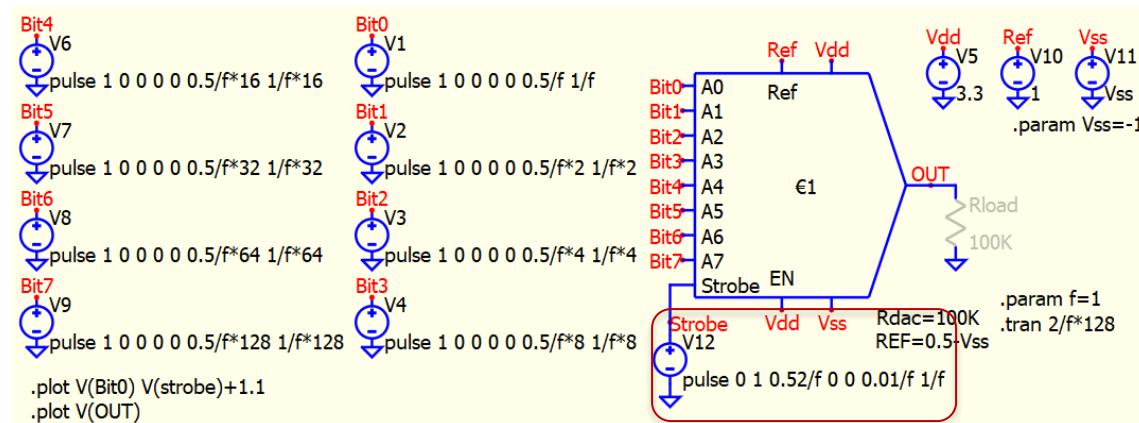
- DAC
 - DAC : Digital to Analog Converter
- Important Pins
 - Ref : the maximum voltage value that the DAC can reach
 - A7 : MSB of input word A
 - A0 : LSB of input word A
 - EN : Enable
- Instance Params
 - Common instance params can refer to €-Device section (e.g. REF)



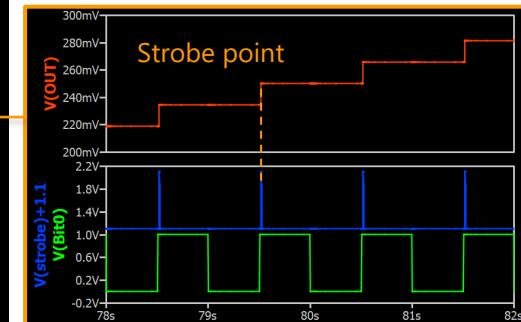
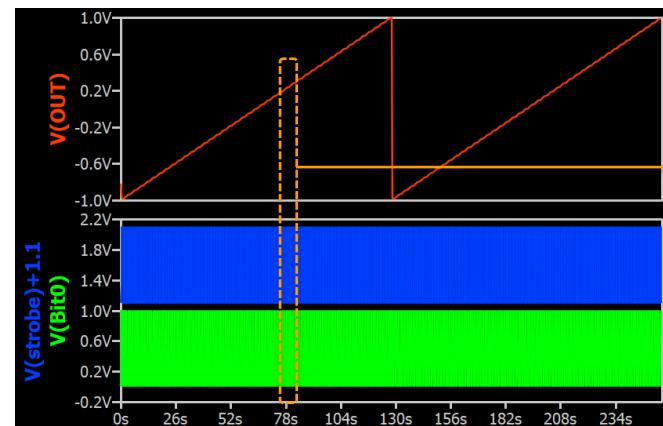
€-Device DAC : Build-in Symbol DAC8strobe.qsym

Qspice : DAC - Strobe.qsch

- Strobe
 - In practice, it named as load DAC strobe (LDAC)
 - This pin transfers all input register data to the DAC registers
 - It resolve jitter in V(out) in previous slide



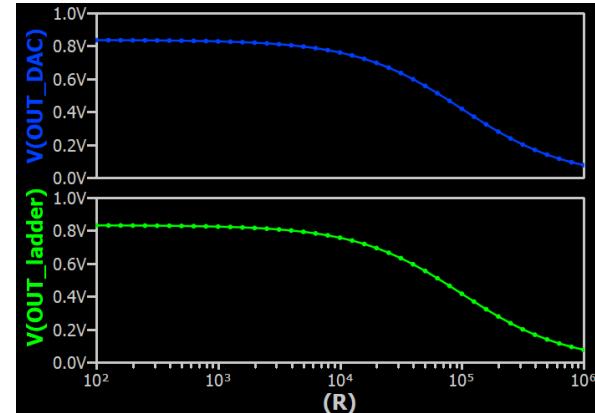
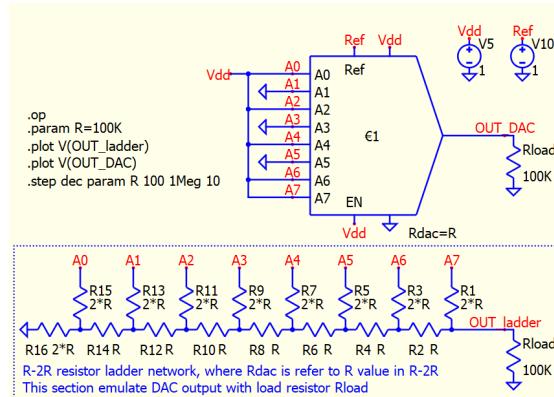
- Symbol
 - Build-in symbol with strobe is
 - DAC8strobe.qsym



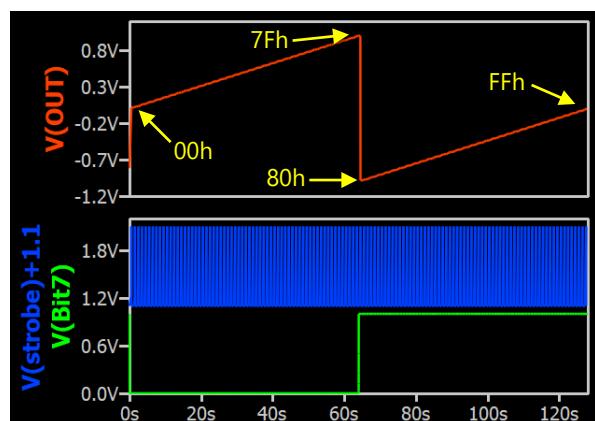
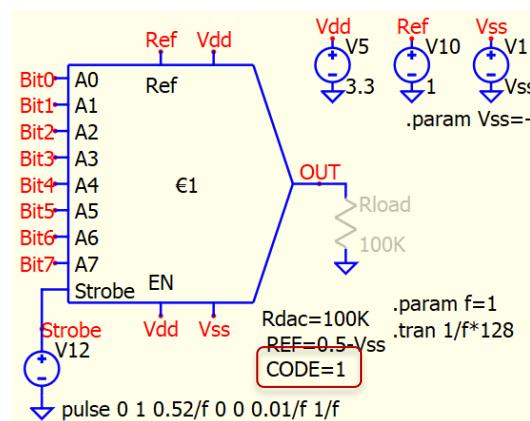
€-Device DAC Instance Params : RDAC

Qspice : DAC - RDAC.qsch ; DAC - CODE.qsch

- RDAC
 - Rdac : R of R-2R DAC
 - R-2R resistor ladder network is inexpensive solution for digital to analog conversion
 - Reference
 - https://en.wikipedia.org/wiki/Resist_ladder
 - Therefore, to prevent loading effect, a voltage buffer should be used in DAC output



- CODE
 - Code : Non-zero maps from -n to n-1 to 0 to 2n-1
 - Default CODE=0**
 - CODE=0 : Unsigned
 - CODE=1 : Signed - two's complement

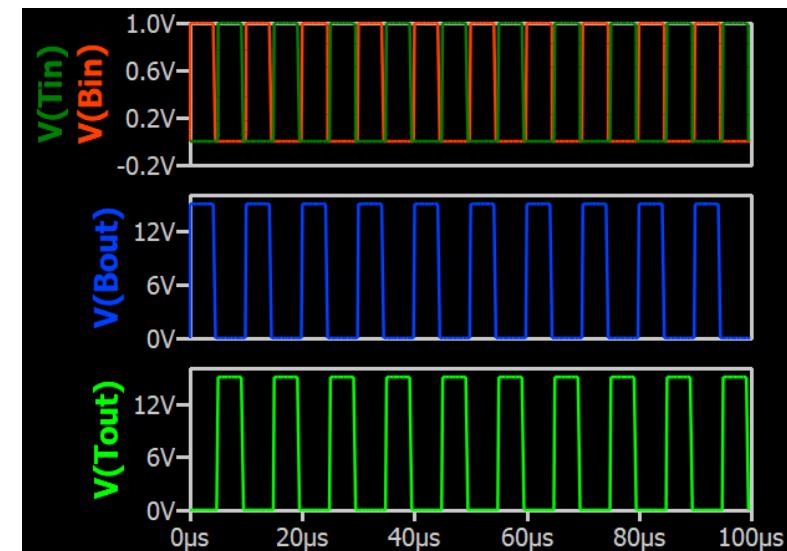
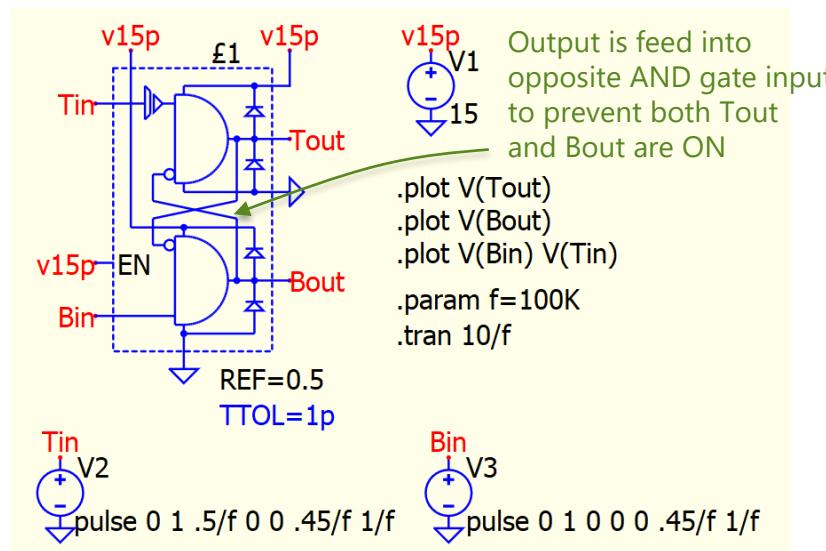


f -Device

f-Device : Dual Gate Driver

Qspice : Dual Gate Driver.qsch

- f-Device Dual Gate Driver
 - Syntax: fnnn Vdd Vss BOOST TOPGATE SW BOTGATE TCTRL BCTRL EN ¥ ¥ ¥ ... GATEDRIVER [INSTANCE PARAMETERS]
 - This behavioral device expects Top Input and Bottom Input has deadtime in between



£ [Dual Gate Driver] Instance Params

Gate Driver Instance Parameters

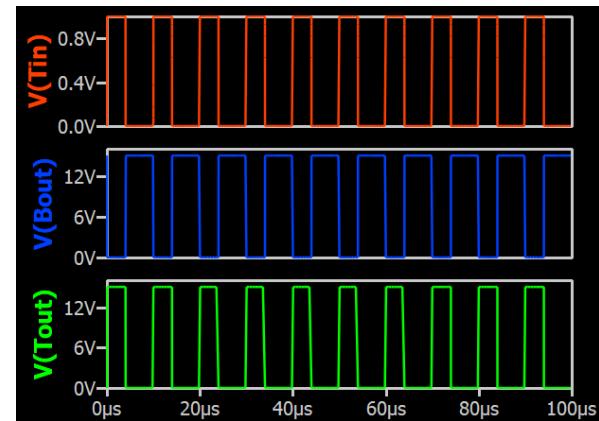
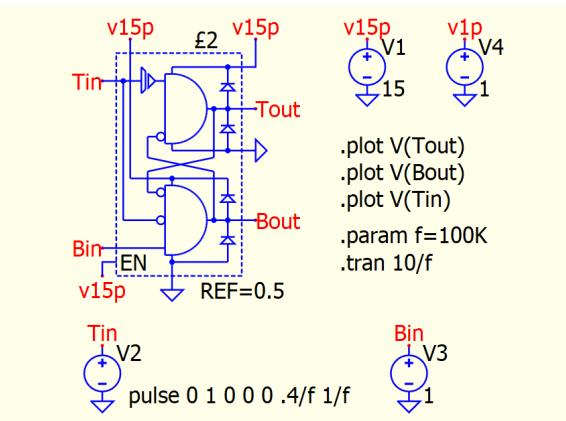
| Name | Description | Units | Default |
|----------|---|-------------|----------------------|
| BOOST | Add logic such that the top FET is off if the bottom is controlled to be on | | (not set) |
| BUCK | Add logic such that the bottom FET is off if the top is controlled to be on | | (not set) |
| CAPVDD | Capacitance from a logic output to Vdd(or BOOST) | F | 0. |
| CAPVSS | Capacitance from a logic output to Vss(or SW) | F | 0. |
| M | Number of parallel devices | | 1. |
| REF | Logic reference for enable input | V | $(Vdd + Vss) \div 2$ |
| ROFF1 | Resistance used to pull bottom FET to VSS | Ω | RON1 |
| RON1 | Resistance used to pull bottom FET to VDD | Ω | 1. |
| ROFF2 | Resistance used to pull top FET to SW | Ω | ROFF |
| RON2 | Resistance used to pull top FET to BOOST | Ω | RON1 |
| RPASSIVE | Resistance used to pull both FETs' gates low when the driver is not enabled | Ω | 1Meg |
| TEMP | Instance temperature | $^{\circ}C$ | 27. |
| TTOL | Temporal tolerance | s | |
| UVLO | Minimum Vdd-Vss voltage to operate | V | 2. |

£ [Dual Gate Driver] Instance Params - Buck and Boost

Qspice : Dual Gate Driver (Buck).qsch; Dual Gate Driver (Boost).qsch

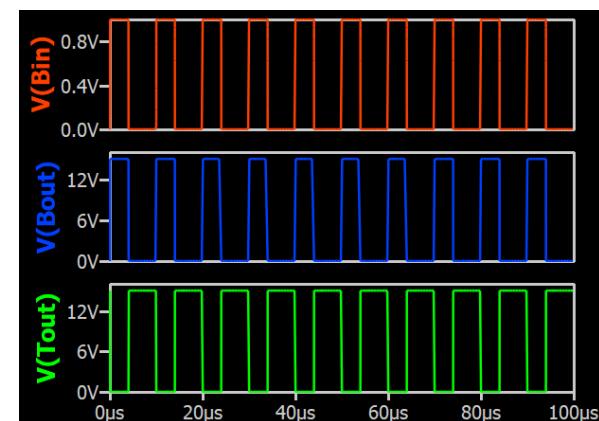
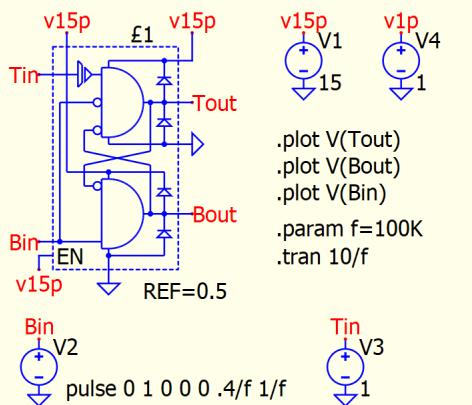
• BUCK

- Add logic such that the bottom FET is off if the top is controlled to on
- **Tin** is inverted to drive Bottom AND gate
 - Bin connects to LOW
- Switch of buck converter is generally at High Side



• BOOST

- Add logic such that the top FET is off if the bottom is controlled to be on
- **Bin** is inverted to drive Top AND gate
 - Tin connects to HIGH
- Switch of boost converter is generally at Low Side

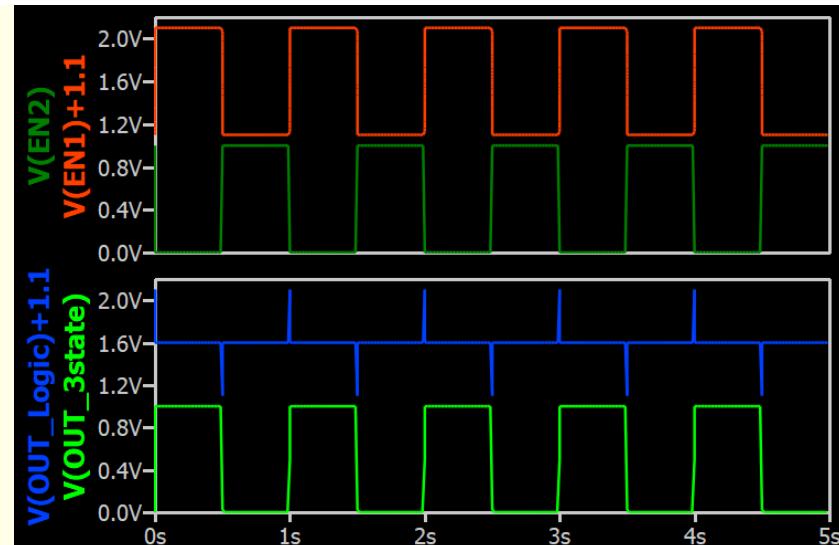
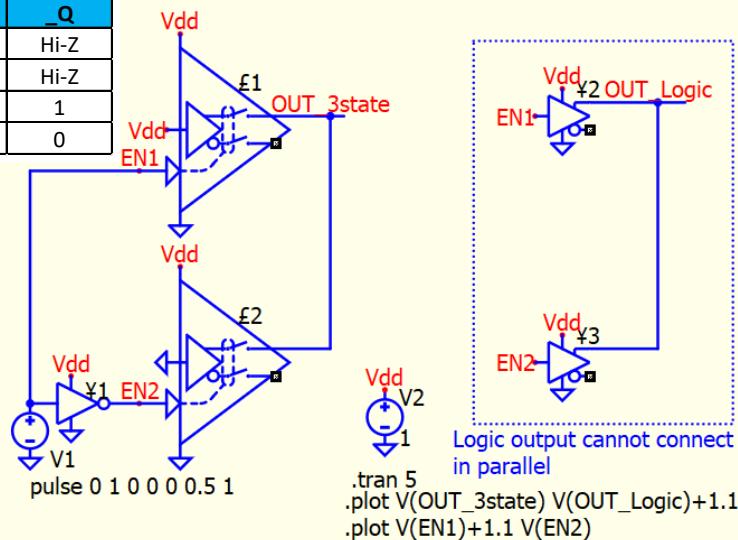


f-Device : Tri-state Buffer

- Tri-state Buffer

- Syntax: fnnn Vdd Vss Q Q̄ IN EN ¥ ¥ ¥ ... 3STATE [INSTANCE PARAMETERS]
- A tri-state output allows multiple circuits to share the same output line(s)
- Output into High-Z when disable

| f-Device Tri-state Buffer | | | |
|---------------------------|----|------|------|
| EN | IN | Q | _Q |
| 0 | 0 | Hi-Z | Hi-Z |
| 0 | 1 | Hi-Z | Hi-Z |
| 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 0 |

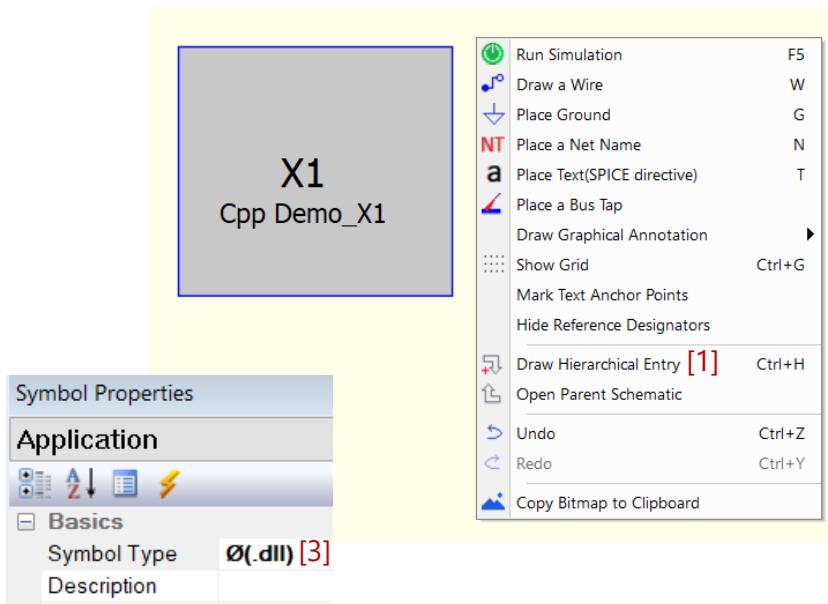


\emptyset -Device
.DLL

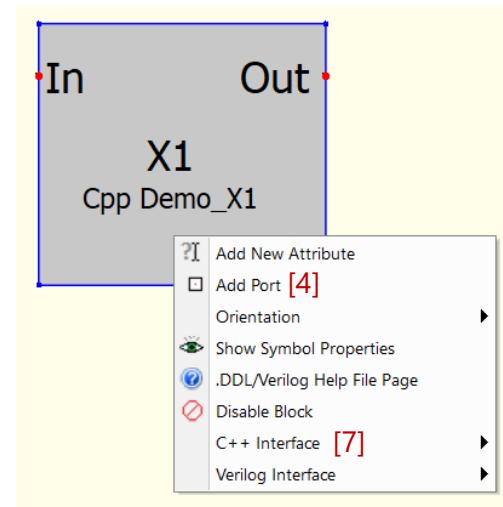
Workflow to Create .DLL C++ (\emptyset -Device)

Qspice : Cpp_Demo.qsch

- [1] In schematic, Right click > Draw Hierarchical Entry
- [2] Right click hierarchical block and Show Symbol Properties
- [3] In Symbol Type, change to \emptyset (.dll)



- [4] Right click hierarchical block > Add Port
- [5] Right click each port, select corresponding Port Type
 - For In, Port Type : Input
 - For Out, Port Type : Output
- [6] Right click each port, select corresponding Data Type
 - For In, Data Type : float (64 bit double)
 - For Out, Data Type : float (64 bit double)
- [7] Right click hierarchical block > C++ Interface
 - Create C++ Template > OK



Workflow to Create .DLL C++ (\emptyset -Device)

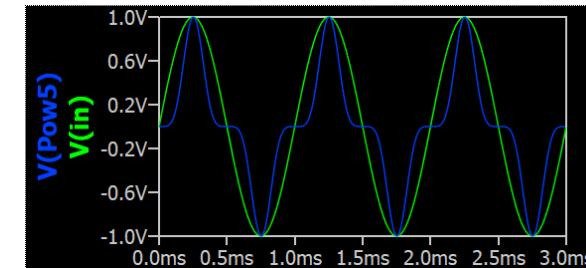
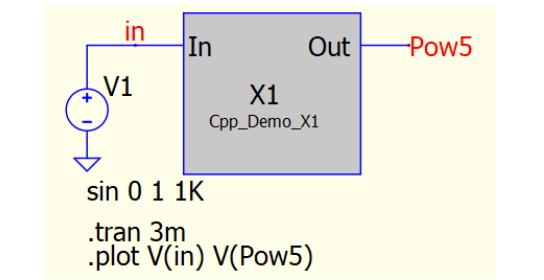
Qspice : Cpp_Demo.qsch

The screenshot shows the QSPICE software interface with the file 'Cpp_Demo.qsch' open. The code editor contains C++ code for a DLL device. Handwritten annotations with red arrows point to specific parts of the code:

- #include <cmath> ← [8]
- // Implement module evaluation code here:
Out = pow(In,5); ← [9]
- "Cpp_Demo_x1.dll" created successfully ← [10]

The status bar at the bottom also has a red arrow pointing to the message "Cpp_Demo_x1.dll" created successfully [10]. A context menu is open over the code, with the option "Compile DLL [10] F5" highlighted.

- [8] add #include<cmath> if math function is needed
- [9] Implement the function of the device below the comment
// Implement module evaluation code here
- [10] Right click > Compile DLL
 - If success, a successful statement in status bar
- [11] Run SPICE simulation that call the C++ device



Ø-Device Instance Parameters

Ø-Device Instance Parameters

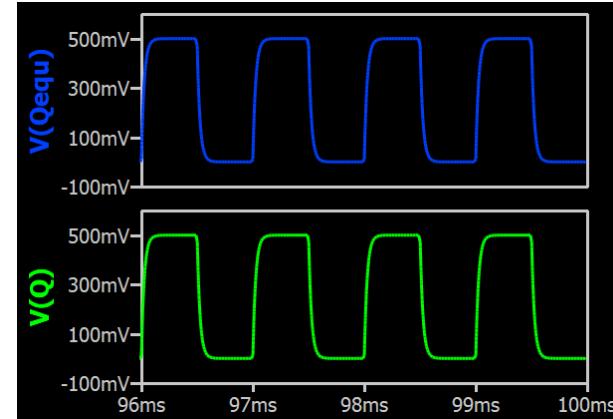
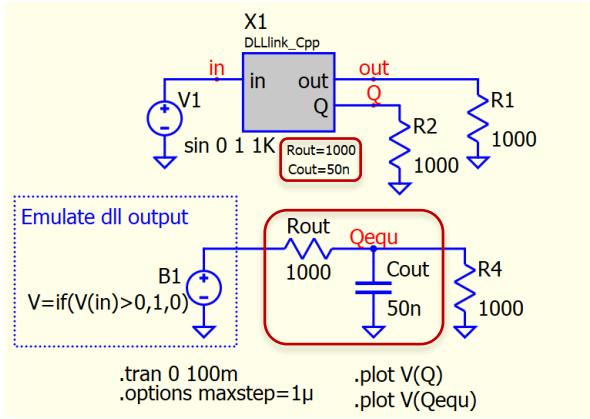
| Name | Description | Units | Default |
|-------------|---|----------|----------|
| COUT | Output capacitance | C | 0. |
| MAXTIMESTEP | Maximum time between evaluations | s | Infinite |
| REF | Logic threshold for inputs declared as boolean | V | .5 |
| ROUT | Output impedance | Ω | 1000. |
| VHIGH | Logic high level for outputs declared as boolean | V | 1. |
| VLSB | ADC and DAC incremental voltage for an LSB change for multi-bit binary data types | V | 1. |

\emptyset -Device Instance Params : Rout / Cout and Vhigh

Qspice : DLLlink - Rout Cout.qsch / DLLlink - VHIGH.qsch

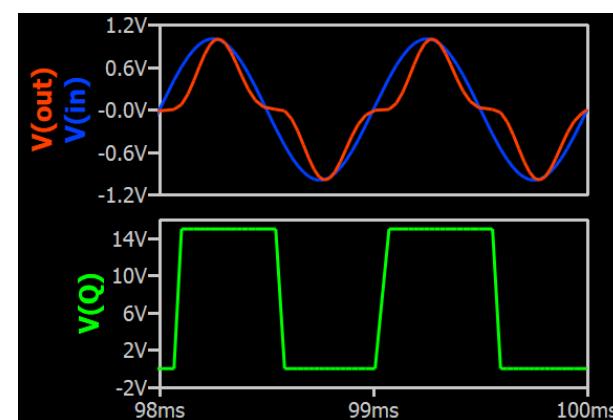
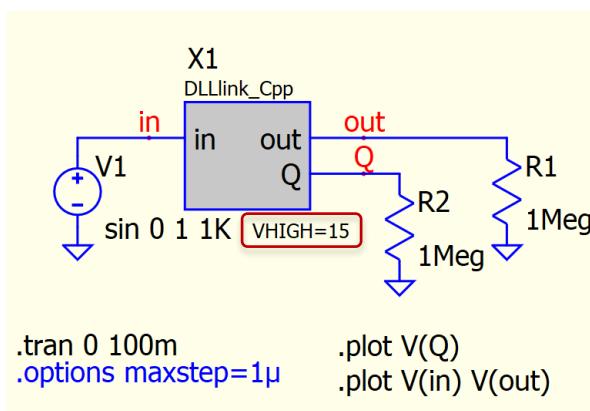
ROUT and COUT

- Rout : Output Impedance
- Cout : Output capacitance
- **Default ROUT=1000Ω**
- **Default COUT=0F**
- Example
 - In this example, it shown circuit arrangement of Rout and Cout in .dll device output



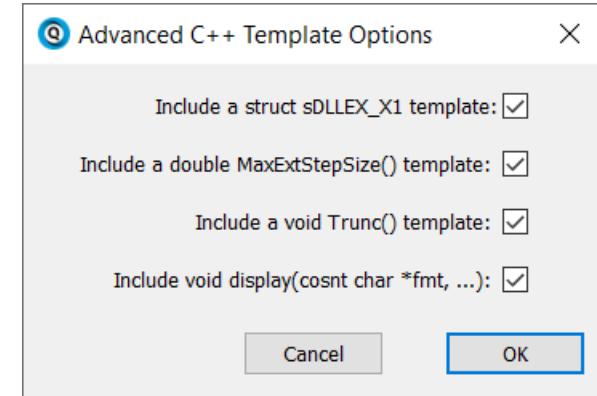
VHIGH

- Vhigh : Logic high level for outputs declared as Boolean
- **Default VHIGH=1V**



Ø-Device (Template)

- Ø-Device Advanced C++ Template Options
 - [1] Struct template
 - Declare the structure variable which can be used between functions
 - Pointer variable, e.g. inst->[variable]
 - [2] MaxExtStepSize()
 - Decide maximum time step in simulation (maxstep)
 - Special usage : Can return -1e308 to abort simulation and goes to the next step (if any)
 - [3] Trunc()
 - Limit Temporal TOLerance timestep (TTOL)
 - [4] Display()
 - For diagnostic print statements
 - To display a string in output windows during simulation



Ø-Device (Template)

Qspice : DLLex.qsch

```
// Automatically generated C++ file on Mon Nov 13 22:18:25 2023
// To build with Digital Mars C++ Compiler:
//   dmc -mn -WD dllex_x1.cpp kernel32.lib

#include <stdio.h>
#include <malloc.h>
#include <stdarg.h>
#include <time.h>

union uData
{
    bool b;
    char c;
    unsigned char uc;
    short s;
    unsigned short us;
    int i;
    unsigned int ui;
    float f;
    double d;
    long long int i64;
    unsigned long long int ui64;
    char *str;
    unsigned char *bytes;
};

// int DllMain() must exist and return 1 for a process to load the .DLL
// See https://docs.microsoft.com/en-us/windows/win32/dlls/dllmain for more information.
int __stdcall DllMain(void *module, unsigned int reason, void *reserved) { return 1; }

void display(const char *fmt, ...)
// for diagnostic print statements
{
    msleep(30);
    fflush(stdout);
    va_list args = { 0 };
    va_start(args, fmt);
    vprintf(fmt, args);
    va_end(args);
    fflush(stdout);
    msleep(30);
}

void bzero(void *ptr, unsigned int count)
{
    unsigned char *first = (unsigned char *) ptr;
    unsigned char *last = first + count;
    while(first < last)
        *first++ = '\0';
}

//
```

union uData
Define all data types

display()
To print in console
As msleep(30), can slow down simulation each time display() is called

bzero()
Reset all value in struct to zero

MaxExtStepSize() [2]
To determine maximum time step

Trunc() [3]
To determine if any next timestep

```
// #undef pin names lest they collide with names in any header file(s) you might include.
#ifndef _INCL_DLIB_CXX_ALGORITHMS
#define _INCL_DLIB_CXX_ALGORITHMS
#endif

struct sDLLEX_X1
{
    // declare the structure here
};

extern "C" __declspec(dllexport) void dllex_x1(struct sDLLEX_X1 **opaque, double t, union uData *data)
{
    double in = data[0].d; // input
    double K = data[1].d; // input parameter
    double &out = data[2].d; // output

    if(!*opaque) // if(!*opaque) only run at beginning
    {
        *opaque = (struct sDLLEX_X1 *) malloc(sizeof(struct sDLLEX_X1));
        bzero(*opaque, sizeof(struct sDLLEX_X1));
    }
    struct sDLLEX_X1 *inst = *opaque;

    // Implement module evaluation code here:
}

extern "C" __declspec(dllexport) double MaxExtStepSize(struct sDLLEX_X1 *inst)
{
    return 1e308; // implement a good choice of max timestep size that depends on struct sDLLEX_X1
}

extern "C" __declspec(dllexport) void Trunc(struct sDLLEX_X1 *inst, double t, union uData *data, double *timestep)
// limit the timestep to a tolerance if the circuit causes a change in struct sDLLEX_X1
{
    const double ttol = 1e-9;
    if(*timestep > ttol)
    {
        double &out = data[2].d; // output

        // Save output vector
        const double _out = out;

        struct sDLLEX_X1 tmp = *inst;
        dllex_x1(&(tmp), t, data);
        // if(tmp != *inst) // implement a meaningful way to detect if the state has changed
        // *timestep = ttol;

        // Restore output vector
        out = _out;
    }
}

extern "C" __declspec(dllexport) void Destroy(struct sDLLEX_X1 *inst)
{
    free(inst);
}
```

[1] Struct template

Define pointer data used throughout the code

Main

main code

destroy()

Call this function upon termination of the simulation

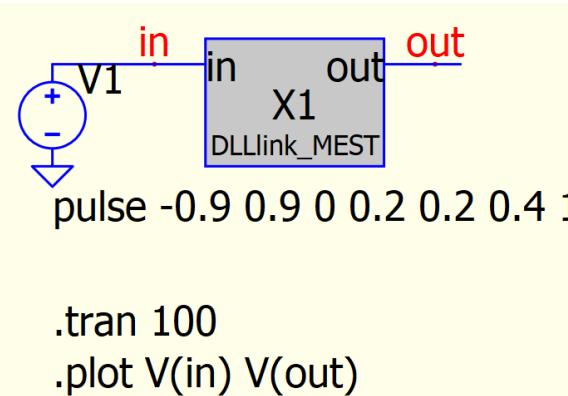
Another good reference from @physicboy

https://github.com/physicboy/QSPICE/blob/main/PWM_example_SRbuck/Three%20Complexity%20Levels%20of%20PWM%20Implementation%20for%20Digital%20Controller%20Simulation.pdf

Ø-Device (Template) : [2] MaxExtStepSize()

Qspice : DLLlink_MaxExtStepSize_Abort.qsch | dlllink_mest.cpp

- **MaxExtStepSize()**
 - Return value in `MaxExtStepSize()` determines maxstep
 - Return `1e308` equivalent maxstep is infinite (default)
 - This example demonstrates change of maxstep from infinite to 0.02 during simulation



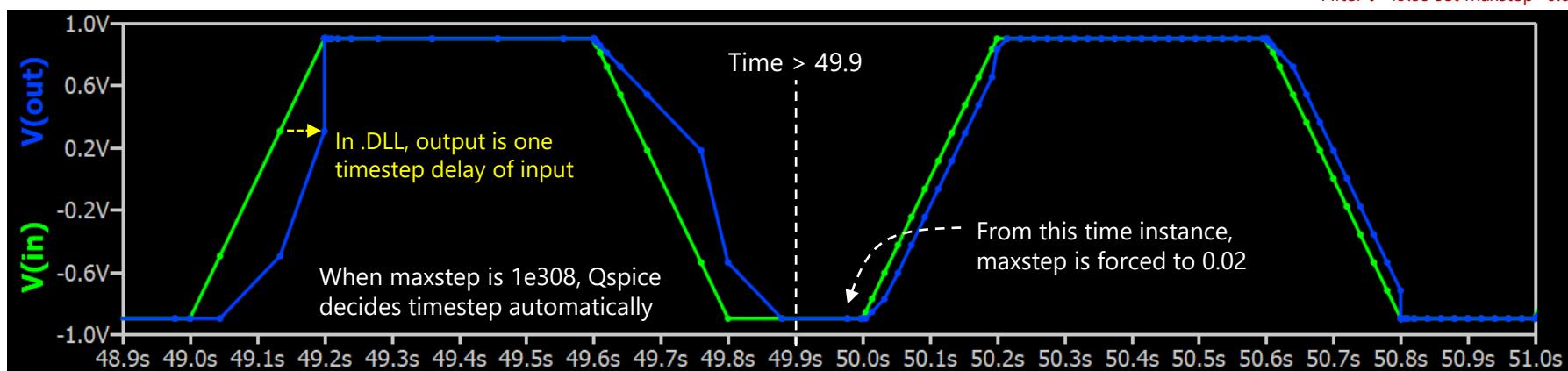
```
struct sDLLLINK_MEST
{
    // declare the structure here
    float t; ← assign an inst->t
};

extern "C" __declspec(dllexport) void dlllink_mest(struct
{
    double in = data[0].d; // input
    double out = data[1].d; // output

    if(!*opaque)
    {
        *opaque = (struct sDLLLINK_MEST *) malloc(sizeof(
            bzero(*opaque, sizeof(struct sDLLLINK_MEST));
    }
    struct sDLLLINK_MEST *inst = *opaque;

    // Implement module evaluation code here:
    out = in; ← inst->t = t as MaxExtStepSize() will
    inst->t = t; ← not accept t but only inst->t
} );
extern "C" __declspec(dllexport) double MaxExtStepSize(
{
    //return 1e308; // implement a good choice of max t
    if (inst->t > 49.9)
        return 0.2e-1;
    else
        return 1e308; ← If condition
}
```

- Before $t < 49.9s$, maxstep set to max
- After $t > 49.9s$ set maxstep=0.02

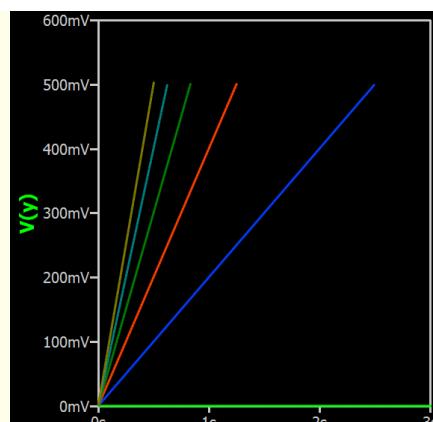
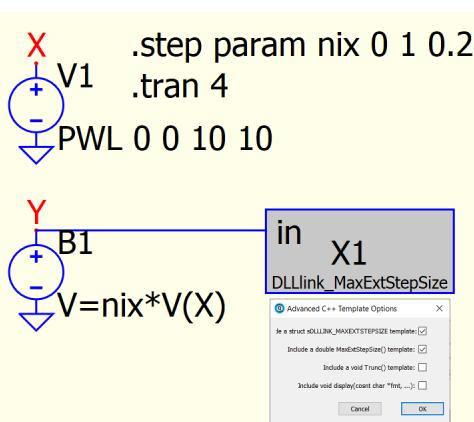


Ø-Device (Template) : [2] MaxExtStepSize()

Qspice : DLLlink_MaxExtStepSize_Abort.qsch | dlllink_maxextstepsize.cpp

- MaxExtStepSize()

- A special usage (abort simulation)
 - Have MaxExtStepSize() to return -1e308 can abort simulation and goes to the next step (if any)
 - ** Specifically -1e308, no other number



struct sDLLLINK_MAXEXTSTEPSIZE
{
 // declare the structure here
 double x; // Declare pointer inst->x
};

extern "C" __declspec(dllexport) void dlllink_maxextste
{
 double in = data[0].d; // input

 if(!*opaque)
 {
 *opaque = (struct sDLLLINK_MAXEXTSTEPSIZE *) mal
 bzero(*opaque, sizeof(struct sDLLLINK_MAXEXTSTEP
 }
 struct sDLLLINK_MAXEXTSTEPSIZE *inst = *opaque;

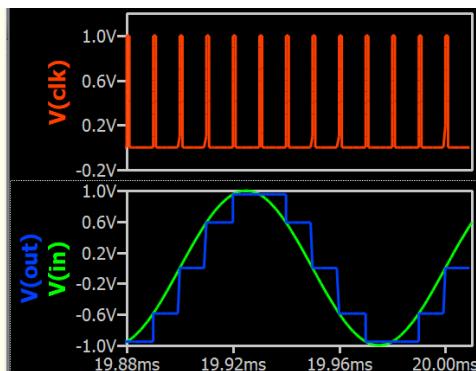
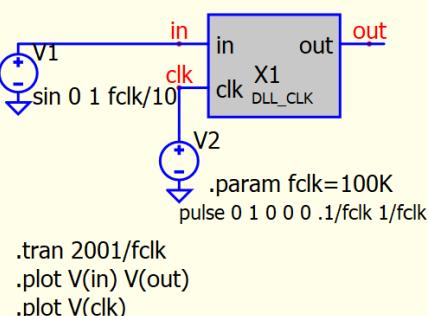
 // Implement module evaluation code here:
 inst->x = in; // Pointer is required to pass value of "in" to other
 // function, in this case, to EaxExtStepSize()
}

extern "C" __declspec(dllexport) double MaxExtStepSize(
{
 if (inst->x > 0.5) {return -1e308;}
 return 1e308; // implement a good choice of max time
}

Ø-Device (Template) : [3] Trunc(), Example#1 - Rising Edge Detection

Qspice : DLL_CLK.qsch | dll_clk.dll

- Advanced C++ Template Options
 - Include a void **Trunc() template**
 - Include a **struct** template
- Purpose of this example
 - Limit timestep with Trunc() if the circuit causes a change
 - Struct to store instance variable which only used within C++ code (pointer to pass variable between functions)
 - Demonstrate how to implement rising edge detection and sampling time calculation



```
struct sDLL_CLK
{
    // declare the structure here
    bool last_clk;
    double lastT;
};

extern "C" __declspec(dllexport) void dll_clk(struct sDLL_CLK
{
    bool clk = data[0].b; // input
    double in = data[1].d; // input
    double &out = data[2].d; // output

    if(!*opaque)
    {
        *opaque = (struct sDLL_CLK *) malloc(sizeof(struct sDLL_CLK));
        bzero(*opaque, sizeof(struct sDLL_CLK));
    }
    struct sDLL_CLK *inst = *opaque;

    // Implement module evaluation code here:
    if (clk & !inst->last_clk){
        double T = t - inst->lastT; // T : sampling period ca:
        inst->lastT = t;
        out = in;
    }
    inst->last_clk = clk;
}

extern "C" __declspec(dllexport) void Trunc(struct sDLL_CLK
{
    // limit the timestep to a tolerance if the circuit ca:
    const double ttol = 1e-9; // Line#74, next slide
    if(*timestep > ttol)
    {
        double &out = data[2].d; // output

        // Save output vector
        const double _out = out;

        struct sDLL_CLK tmp = *inst;
        dll_clk(&(tmp), t, data);
        // if(tmp != *inst) // implement a meaningful way to detect
        // *timestep = ttol;
        if((tmp.last_clk != inst->last_clk) & !inst->last_clk)
            *timestep = ttol;

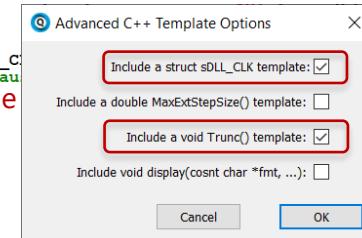
        // Restore output vector
        out = _out;
    }
}
```

[1] Declare structure variable
inst->last_clk : to store last clock
inst->last : to store last rising edge time

User code

[2] detect rising edge (last_clk=0, clk=1)

[3] Calculate time between two rising edge (T)

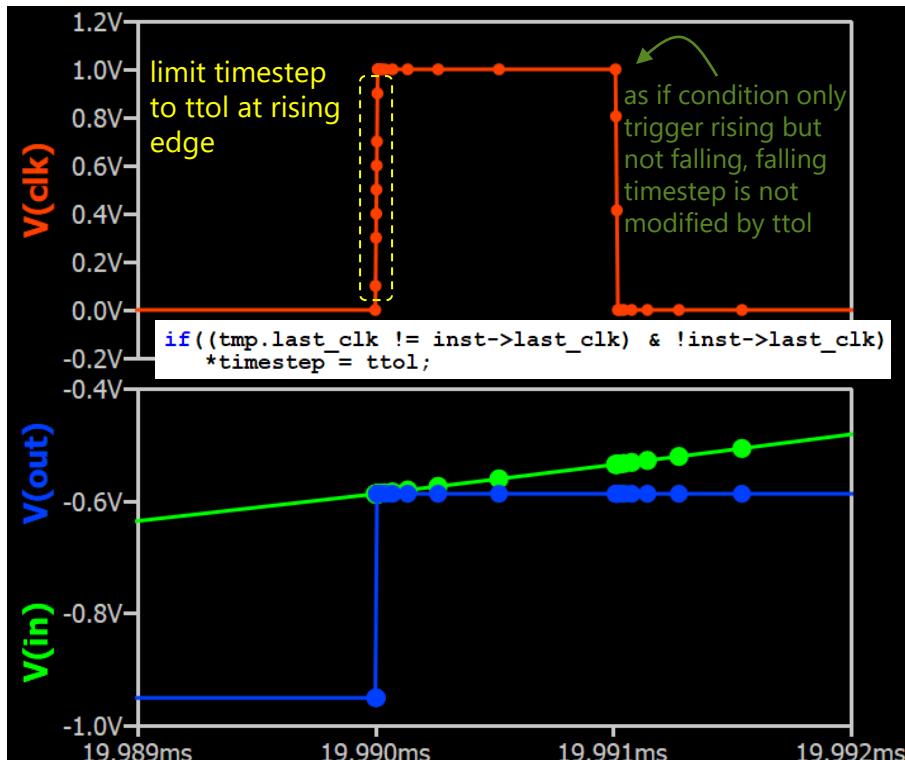


[4] if the circuit causes a change, limit the timestep to *timestep=ttol
User needs to define what the change (if condition) to force *timestep=ttol

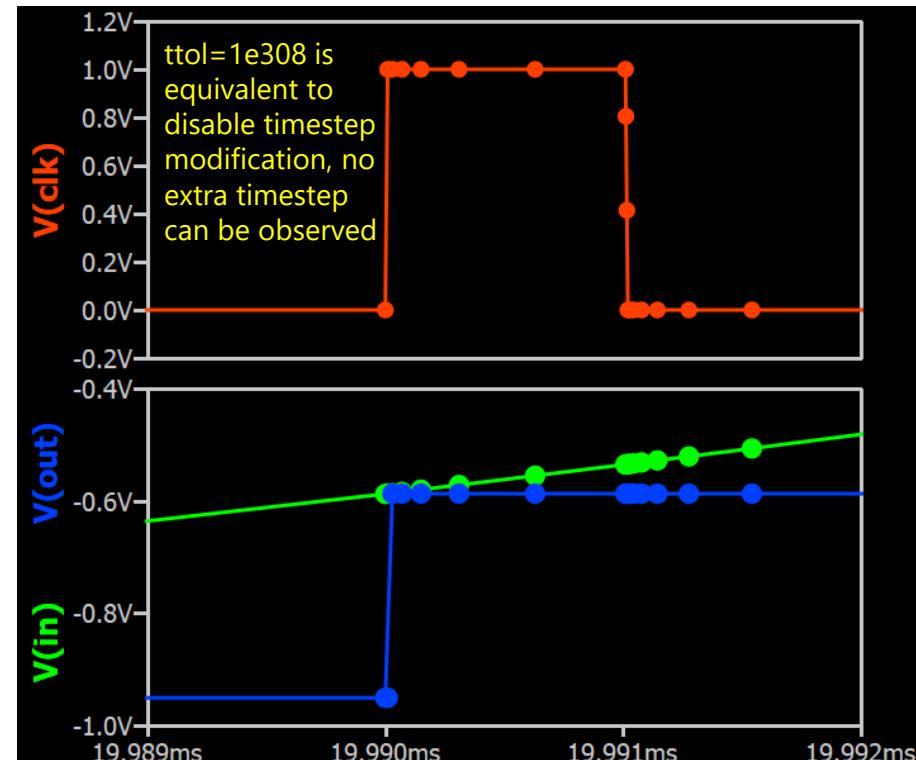
Ø-Device (Template) : [3] Trunc() and ttol

Qspice : DLL CLK.qsch | dll clk.dll

Line#74 : const double ttol=1e-9;



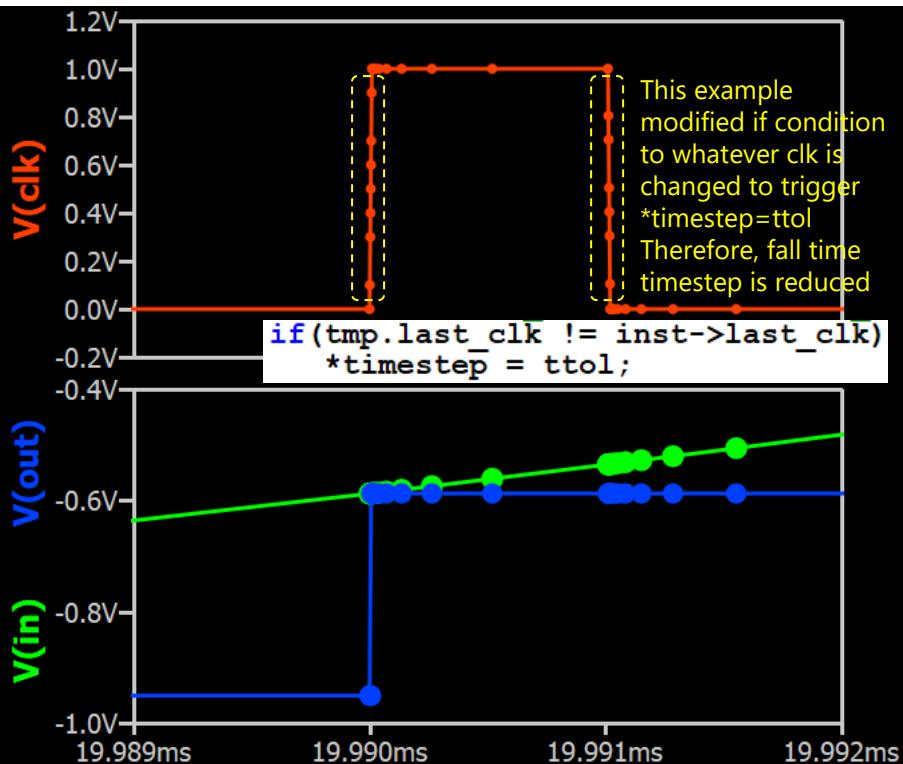
Line#74 : const double ttol=1e308;



Ø-Device (Template) : [3] Trunc() and ttol

Qspice : DLL CLK.qsch | dll clk.dll

Line#74 : const double ttol=1e-9;



Comment of Trunc() template

- Most critical in Trunc() for user to modify are these 2 lines

```
const double ttol = 1e-9;  
// if(tmp != *inst) // implement a meaningful way to detect if the state has changed  
// *timestep = ttol;
```

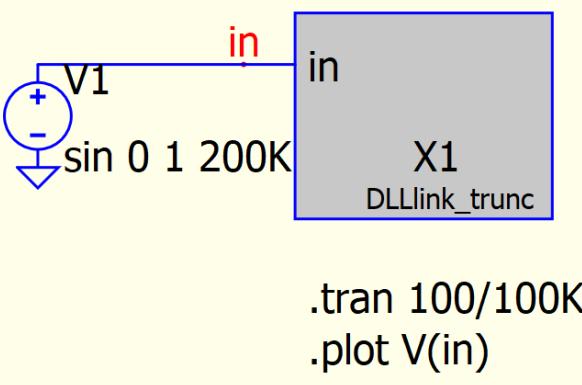
- ttol : limit Temporal tolerance timestep
- if (condition) : condition where timestep temporary force to ttol
 - In Trunc(), struct tmp is created for the purpose to compare *inst
 - User has to utilize tmp and *inst to detect if the state has changed

Ø-Device (Template) : [3] Trunc() and ttol – Example#2 Zero-crossing

Qspice : DLLlink_trunc.qsch | dlllink_trunc.cpp

- Trunc() example

- This example is to reduce simulation timestep at signal zero-crossing
- Code keynote
 - Use `inst->x = in` to pass data to `Trunc()`
 - In `Trunc()`, use if condition to force `ttol` when `tmp.x` within ± 0.1



```
struct sDLLLINK_TRUNC
{
    // declare the structure here
    double x;
};

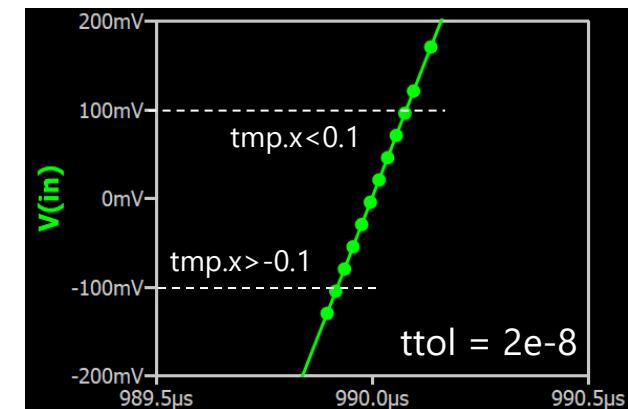
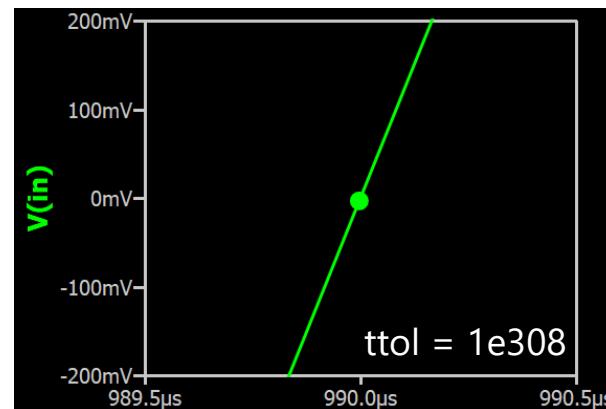
extern "C" __declspec(dllexport) void dll
{
    double in = data[0].d; // input

    if(!*opaque)
    {
        *opaque = (struct sDLLLINK_TRUNC *) bzero(*opaque, sizeof(struct sDLLLINK_TRUNC));
        struct sDLLLINK_TRUNC *inst = *opaque;
    }

    // Implement module evaluation code here:
    inst->x = in;
}
```

```
const double ttol = 2e-8;
if(*timestep > ttol)
{
    // Save output vector
    struct sDLLLINK_TRUNC tmp = *inst;
    dlllink_trunc(&tmp, t, data);
    // if(tmp != *inst) // implement a measure
    // *timestep = ttol;
    if (tmp.x < 0.1 & tmp.x > -0.1)
        *timestep = ttol;
}
```

** If use `inst->x` to replace `tmp.x`, couldn't achieve this pattern

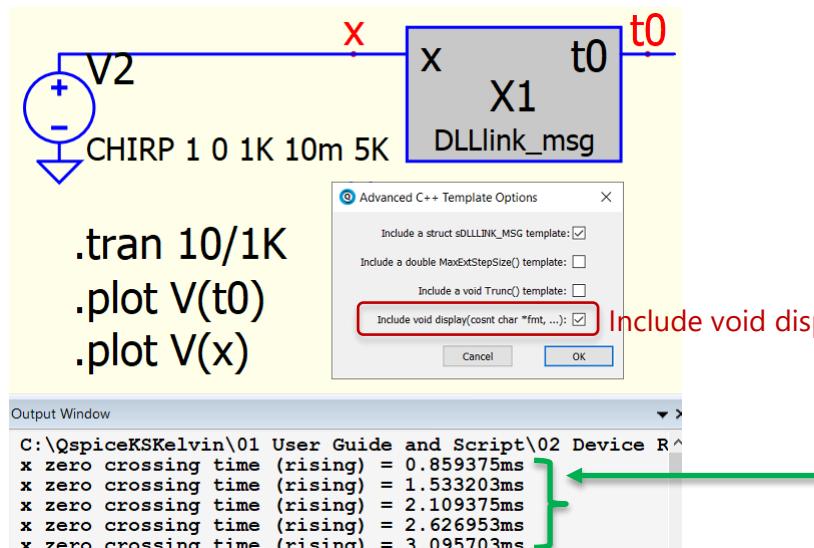


Ø-Device (Template) : [4] Display()

Qspice : DLLlink_msg.qsch | dlllink_msg.cpp

- Display() example

- Include display() can return a string in output window during simulation
- This example detect zero crossing of input x and output its time (simulation time)
- Display() is used to return this zero crossing time with a string



```
struct sDLLLINK_MSG
{
    // declare the structure here
    double last_x;
};

extern "C" __declspec(dllexport) void dlllink_msg(struct sDLLLINK
{
    double x = data[0].d; // input
    double &t0 = data[1].d; // output

    if (!*opaque)
    {
        *opaque = (struct sDLLLINK_MSG *) malloc(sizeof(struct sDLL
            bzero(*opaque, sizeof(struct sDLLLINK_MSG));
    }
    struct sDLLLINK_MSG *inst = *opaque;

    // Implement module evaluation code here:
    if (x>=0 & inst->last_x<0)
    {
        t0 = t;
        display("x zero crossing time (rising) = %fms\n",t0/1e-3);
    }
    inst->last_x = x;
}
```

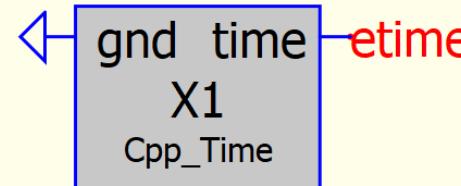
A red bracket highlights the 'Display a string' code, which is enclosed in a red box.

**Ø-Device (.DLL)
Supplementary**

Ø-Device : Simulation time and call from directory

Qspice : cpp_time.cpp

- Time
 - **t** is simulation time in C++ code



.tran 1
.plot V(etime)

```
// #undef pin names lest they collide with
// #undef time

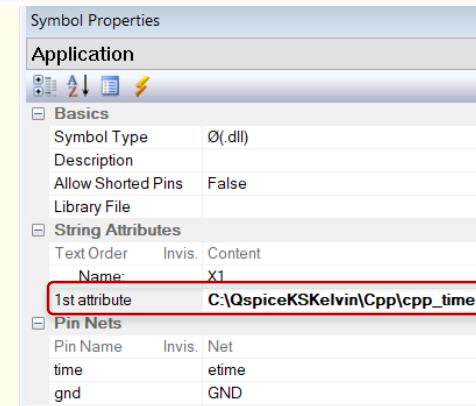
extern "C" __declspec(dllexport) void cpp_
{
    double &time = data[0].d; // output

    // Implement module evaluation code here:
    time = t;
}
```

- Dll from other directory
 - 1st attribute can accept absolute or relative path name
 - If space in directory path, add "" for string format
 - e.g. "C:\Qspice KSKelvin\Cpp\cpp_time"
 - To call for example `cpp_time.dll`, not to include .dll
 - Don't attempt to modify .cpp when path included



.tran 1
.plot V(etime)



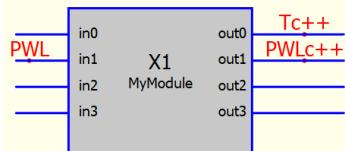
Ø-Device : Simulation time – Analog and DLL Time

Qspice : Analog and DLL Time.qsch

- Analog and DLL Time
 - Exact time "Time" is analog Newton-Raphson iteration which can be called from Behavioral source $V=Time$
 - .DLL "t" is dll time from very last timestep
- In this example
 - out0 output .DLL time "t", which is a different by a timestep to analog time "Tnewton" : Timestep = $V(Tnewton)-V(Tc++)$
 - In the same way, for out1=in1, .DLL output is last timestep data sample and therefore, out1 not exactly equal in1 at same time!

```
extern "C" __declspec(dllexport) void mym
{
    double in0 = data[0].d; // input
    double in1 = data[1].d; // input
    double in2 = data[2].d; // input
    double in3 = data[3].d; // input
    double out0 = data[4].d; // output
    double out1 = data[5].d; // output
    double out2 = data[6].d; // output
    double out3 = data[7].d; // output
}
```

```
// Implement module evaluation code here:
out0=t;
out1=in1;
```



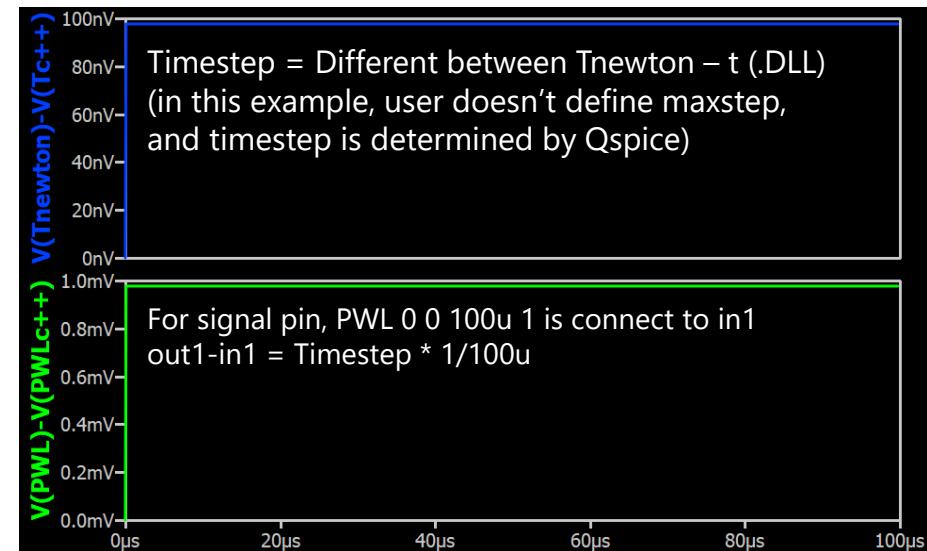
```
.tran 100u
.plot V(PWL)-V(PWLc++)
.plot V(Tnewton)-V(Tc++)
.plot V(x)
```

For verification

```
x
V1
.pulse 0 1 0 5u 5u 10u 20u
```

According to Mike Engelhardt

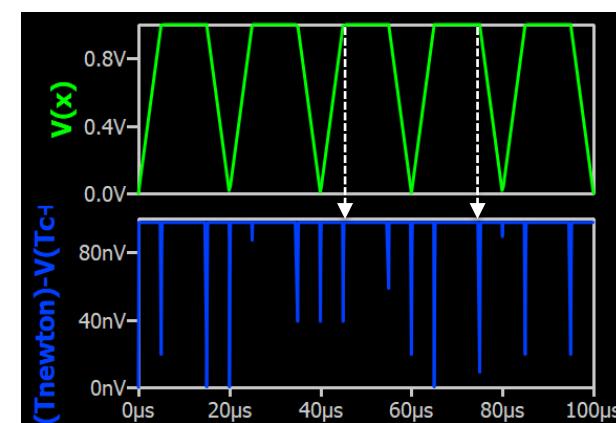
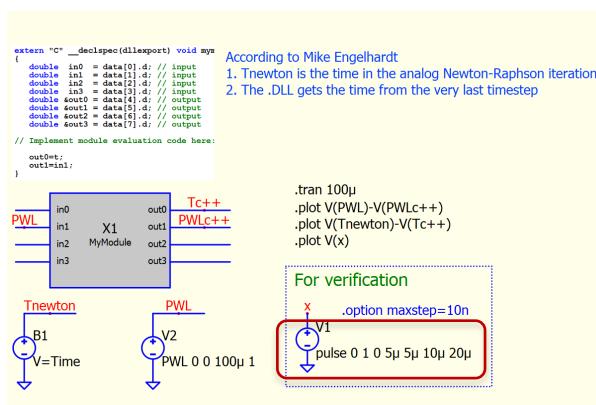
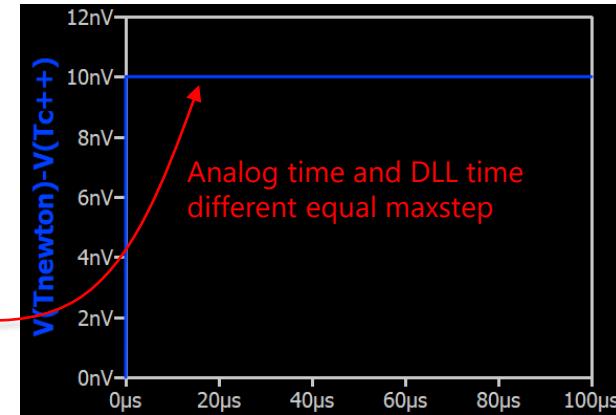
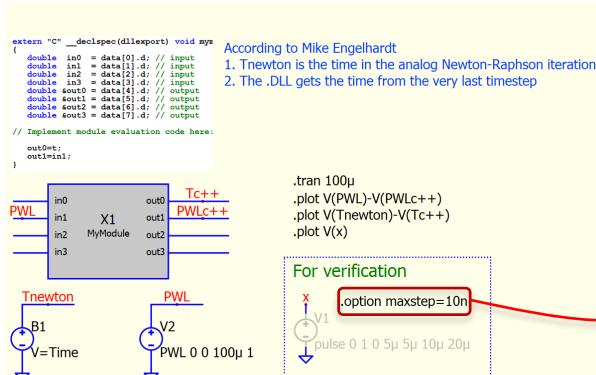
1. Tnewton is the time in the analog Newton-Raphson iteration
2. The .DLL gets the time from the very last timestep



Ø-Device : Simulation time – Analog and DLL Time

Qspice : Analog and DLL Time.qsch

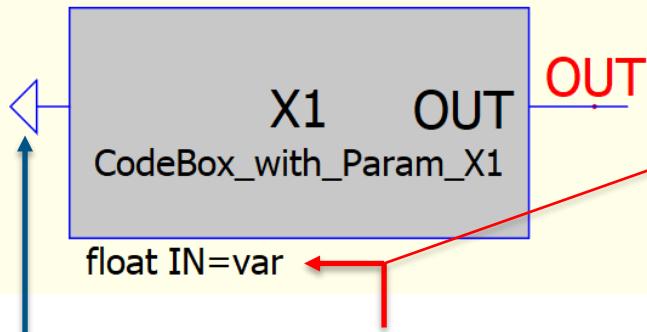
- Change of Timestep #1
 - Different between DLL t and analog time can be affected by assigning max time step with .option maxstep
 - In this example, time different is clamped to equal maxstep setting



Ø-Device with Input Parameter

Qspice : CodeBox_with_Param.qsch

```
.tran 1  
.step param var list 1 2 3
```

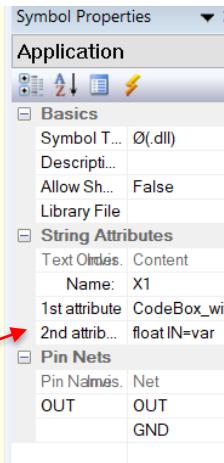


[1] For Input parameter, in creating hierarchical block

1. Right click the block > select Add attribute
2. [data type] [Input Port name] = [parameter] or <val>

As GND is needed if hierarchical doesn't have input port

- Add Port
- Right click Port > Data Type > DLL's GND



```
// #undef pin names lest they collide with names in ^  
#undef OUT  
  
extern "C" __declspec(dllexport) void codebox_with_p  
{  
    double IN = data[0].d; // input parameter  
    double &OUT = data[1].d; // output  
  
    // Implement module evaluation code here:  
    OUT = IN;  
}
```

** Important note!! Whenever you change input port, parameter or output port, you should recreate and copy code to a new C++ template, as Qspice requires particular order for index in data[]

- Right click the block > C++ Interface > Create C++ Template
- In this example, float IN=var will auto generate as input parameter
double IN = data[0].d;

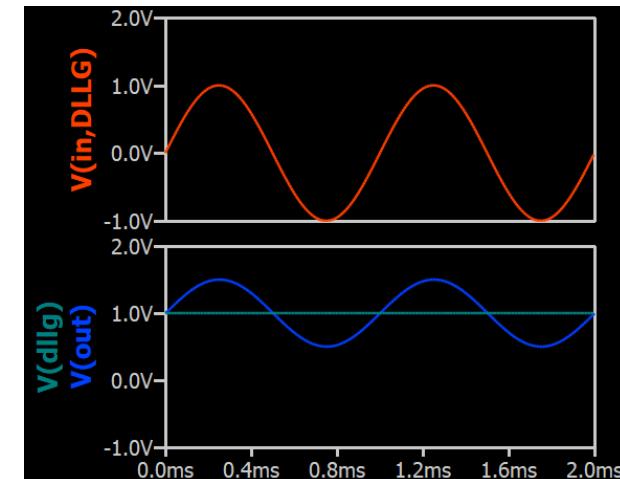
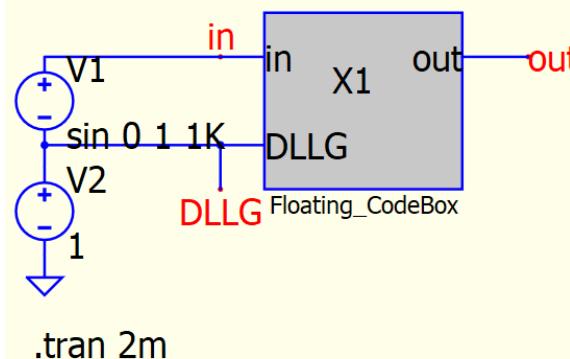
DLL's GND in Ø-Device

Qspice : Floating_CodeBox.qsch

- Two Purposes of DLL's Gnd
 - Floating operation where Ø-Device reference is not 0
 - Only output but no input port is defined (previous slide)

Example of floating ground operation

```
// Implement module evaluation code here:  
out = in * 0.5;
```



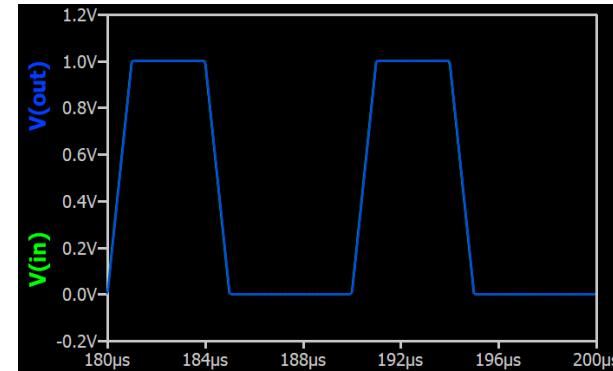
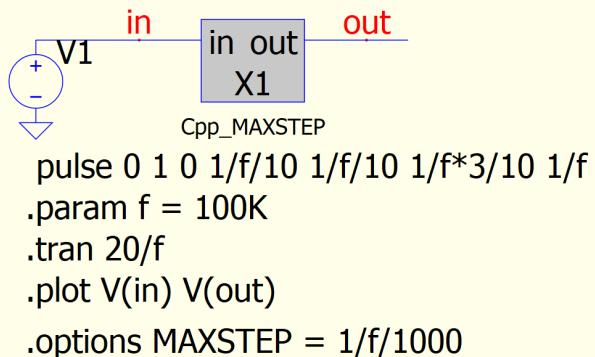
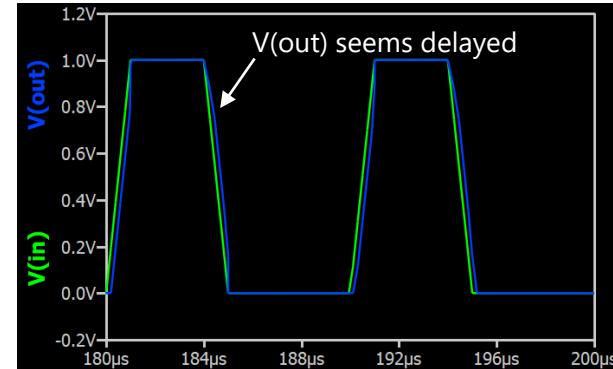
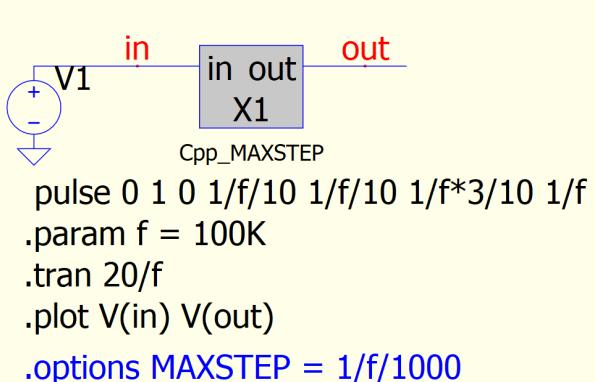
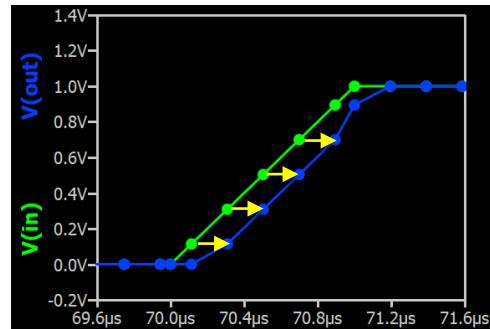
Engelhardt

The inputs and outputs of a .DLL go through a converter. If there's no DLL GND specified, the converters operate ground referenced. If you give a .DLL a GND, then inputs and output are referred to that .DLL GND port. It lets you run your logic hot decked as one might in an offline converter.

Use of MAXSTEP in C++ block (\emptyset -Device)

Qspice : Cpp_MAXSTEP.qsch

- If delay in response is observed when C++ block is used, consider to limit maximum time step by adding
 - .options MAXSTEP=<value>
 - The reason V(out) looks delayed is because output of .DLL is always one time step delay

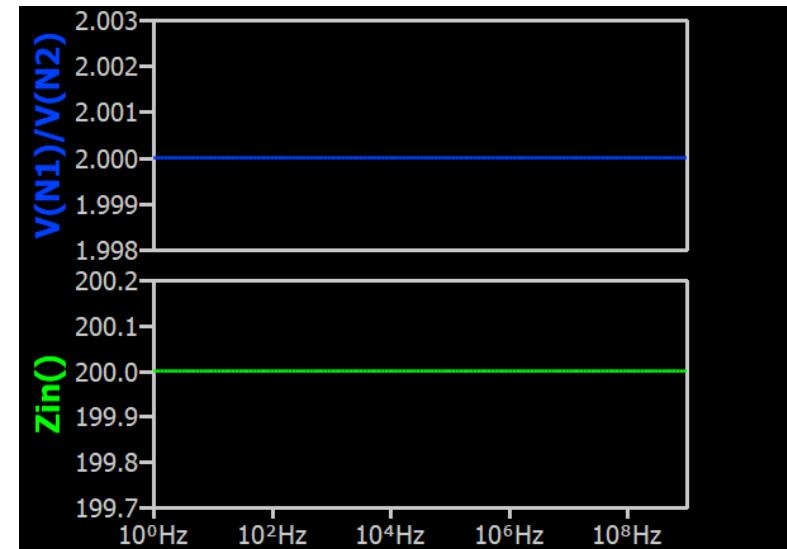
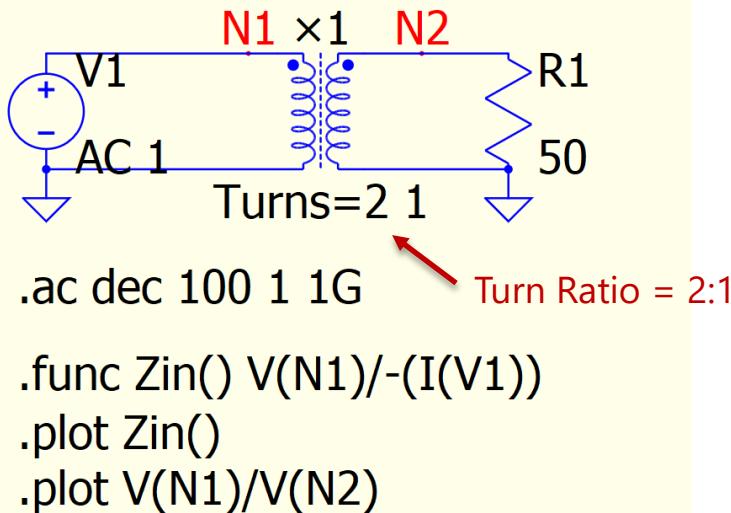


**x-Device
Transformer**

✗-Device: Transformer

Qspice : Transformer - Basic.qsch

- ✗-Device: Transformer
 - Syntax: $\times nnn \text{ «PRI+ PRI- SEC1+ SEC1- SEC2+ SEC2 [...]» } <\text{TURN}=N1 N2 N3 ...>$ [Additional Instance Parameters]
 - Ideal Transformer Equation (Inductance $\rightarrow \infty$)
 - $n = \frac{N_1}{N_2} = \frac{v_1}{v_2}$ and $Z_{N1} = n^2 Z_{N2}$



\times -Device: Transformer Instance Params

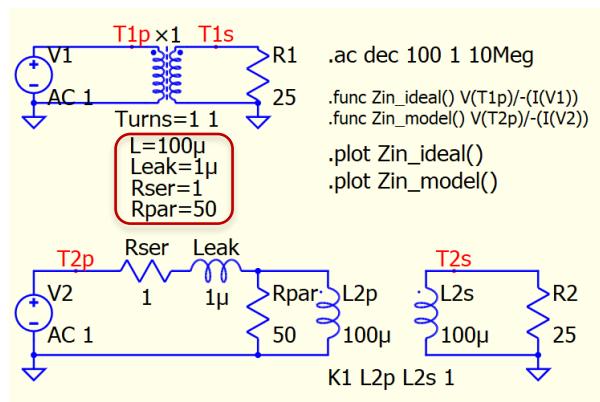
Transformer Instance Parameters

| Name | Description | Units | Default |
|----------------------|--|----------|----------|
| ISAT ¹ | Current that drops inductance to SATFRAC of zero-current value | A | Infinite |
| K ¹ | Alternate means of specifying LEAK | | 1 |
| L | Primary zero-current inductance | H | Infinite |
| LEAK | Leakage inductance | H | 0 |
| LSAT ¹ | Inductance asymptotically approached in saturation | H | 10% of L |
| RPAR ¹ | Primary parallel resistance | Ω | Infinite |
| RSER ¹ | Primary series resistance | Ω | 0.0 |
| SATFRAC ¹ | Fractional drop in L at ISAT | | 0.7 |
| TURNS | List of relative number of turns | | |

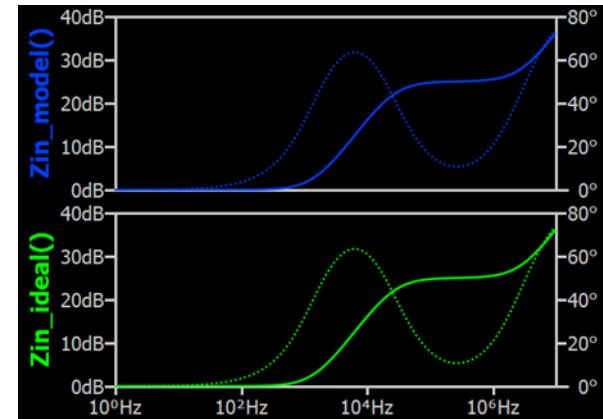
Instance Params : L, Leak, Rser, Rpar, Isat, Lsat, Satfrac

Qspice : Transformer - L Leak Rser Rpar.qsch ; Transformer - Isat Lsat Satfrac.qsch

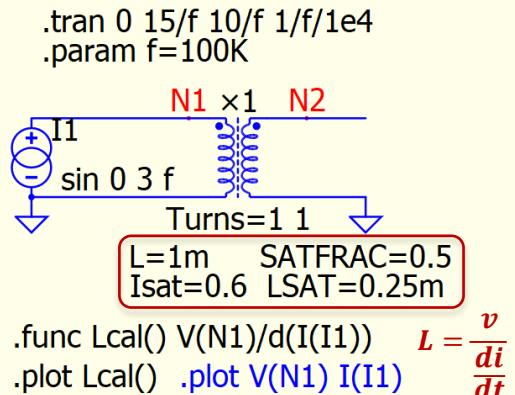
- L, Leak, Rser, Rpar
 - L : Primary Inductance
 - Leak : Leakage Inductance
 - Rser : Series Resistance
 - Rpar : Parallel Resistance
 - Equivalent model is shown in this simulation



```
.ac dec 100 1 10Meg
.func Zin_ideal() V(T1p)/-(I(V1))
.func Zin_model() V(T2p)/-(I(V2))
.plot Zin_ideal()
.plot Zin_model()
```



- ISAT, LSAT, SATFRAC
 - Isat : Current that drops inductance to SATFRAC*L
 - Satfrac : Fractional drop in L at Isat
 - Lsat : Inductance asymptotically approached in saturation
 - These parameters are ignored unless L is given



```
.tran 0 15/f 10/f 1/f/1e4
.param f=100K
```

$L=1m$ $SATFRAC=0.5$
 $Isat=0.6$ $LSAT=0.25m$

```
.func Lcal() V(N1)/d(I(I1))  $L = \frac{v}{di/dt}$ 
.plot Lcal() .plot V(N1) I(I1)
```

