RF/Microwave Circuit and System

Lecture 7

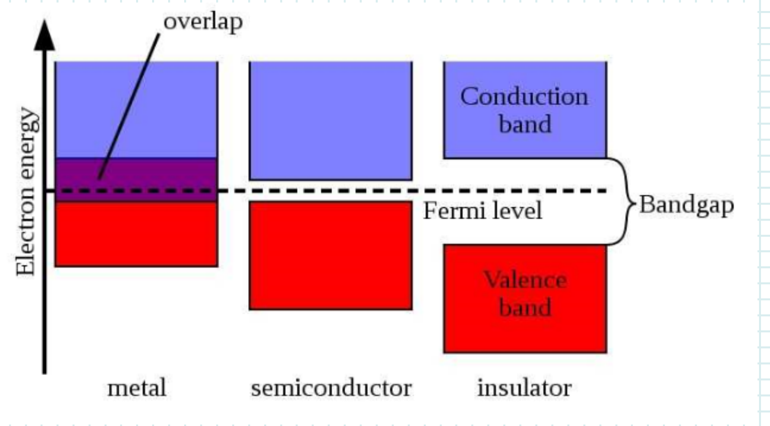
Active components

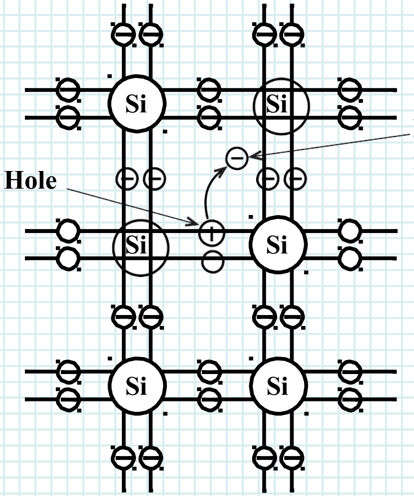
http://v.youku.com/v_show/id_XMTQ1NzM5MDU5Ng==.html#paction

Active RF Components

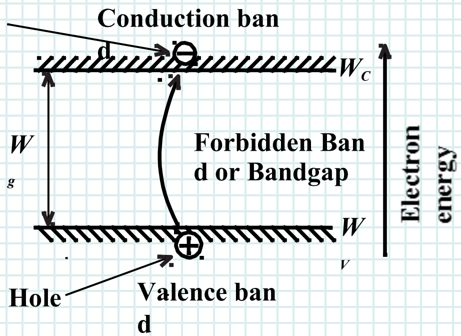
- Semiconductor Basics
- PN-Junction
- Schottky Contact
- Schottky Diode
- PIN Doide
- Varactor Diode
- IMPATT Diode
- Tunnel Diode
- Biopload Transistor
- RF Field Effect Transistor

- **Semiconductor Basics**



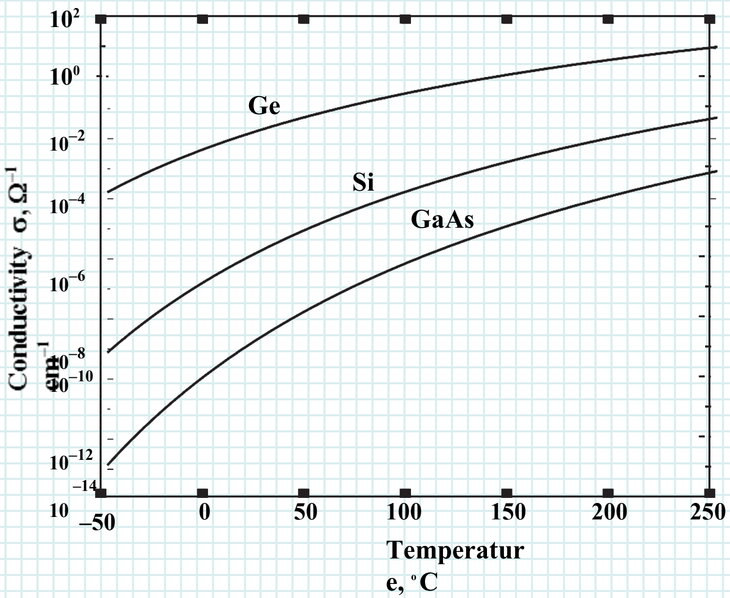


(a) Planar representation of covalent bonds

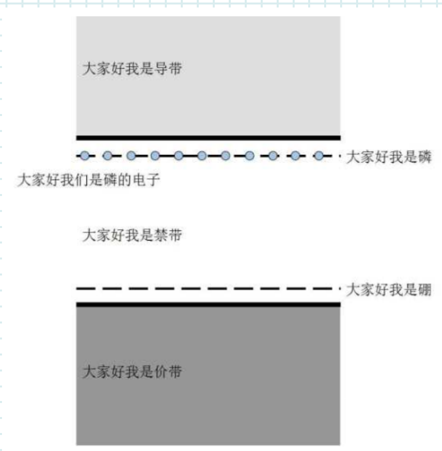


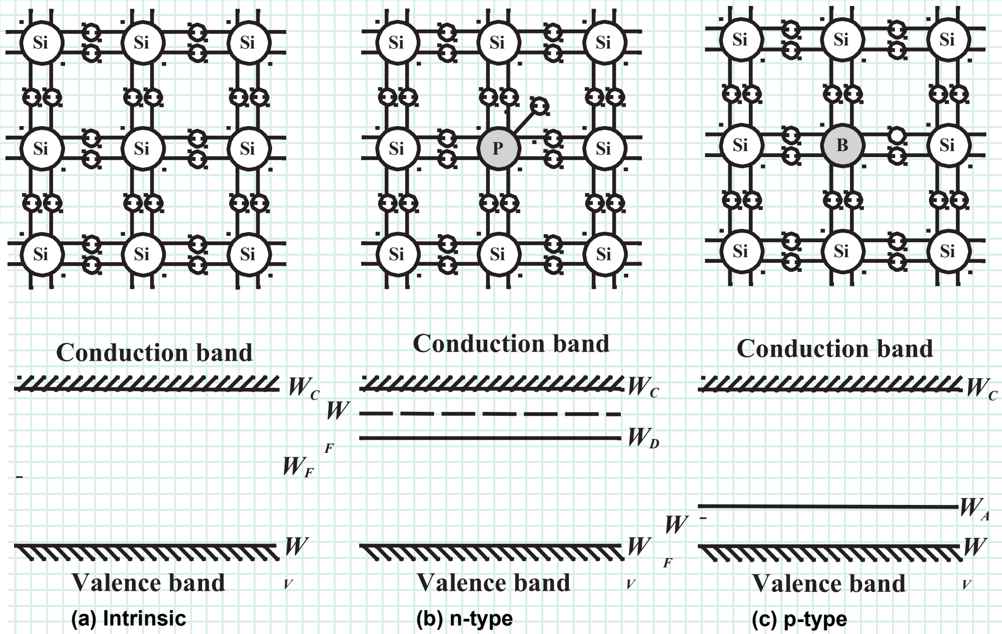
(b) Energy band levels

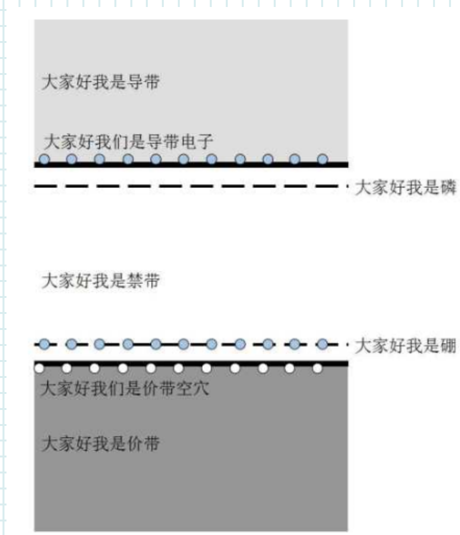
$$\sigma = q n_i(\mu_n + \mu_p) = q\sqrt{N_C N_V}\exp\left[-\frac{W_g}{2kT}\right](\mu_n + \mu_p)$$



Conductivity of Si, Ge, GaAs in the range from –50°C to 250°C.

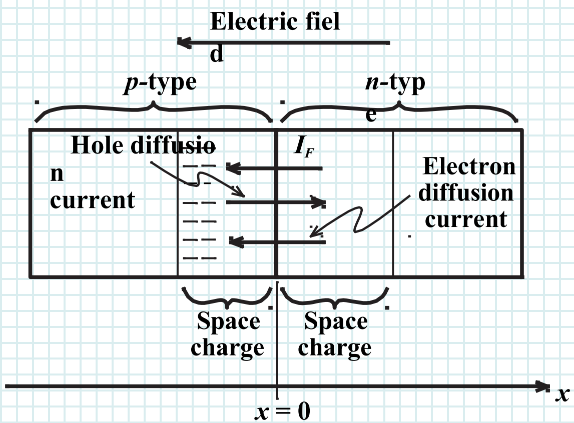




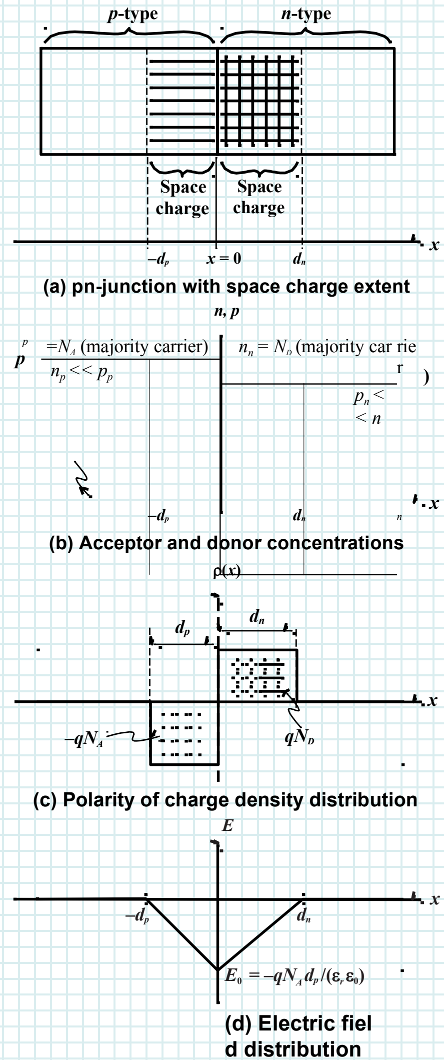


Lattice structure and energy band model for (a) intrinsic, (b) n-type, and (c) p-type semiconductors at no thermal energy. W_D and W_A are donor and acceptor energy levels.

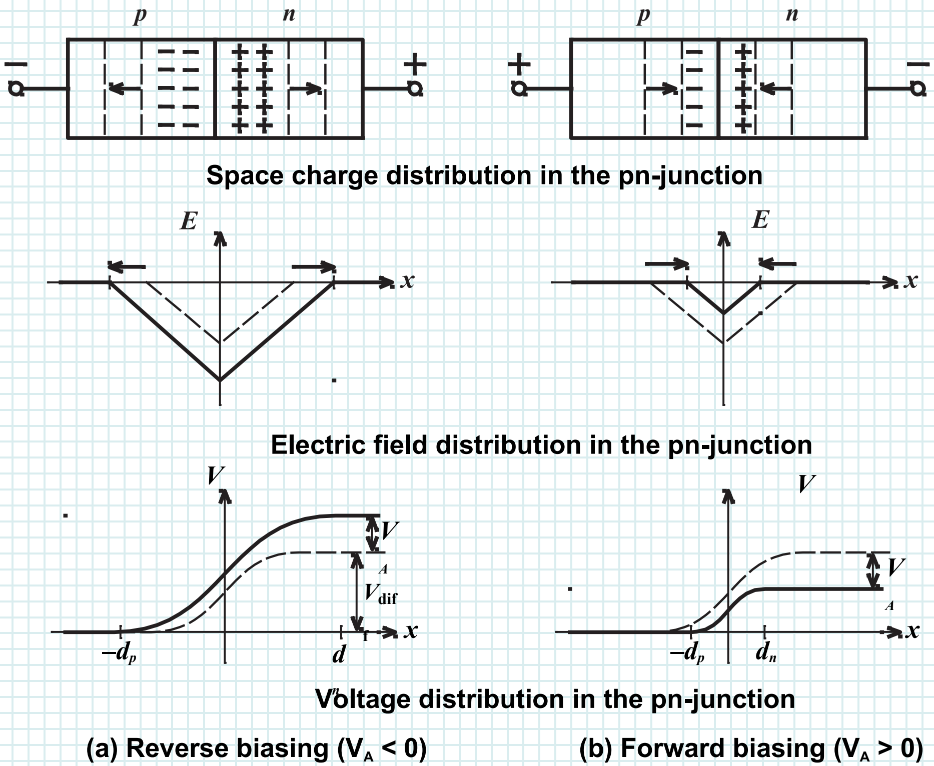
PN-Junction



$$C = A\left\{\frac{q\varepsilon}{2V_{\mathrm{diff}}}\frac{N_A N_D}{N_A + N_D}\right\}^{1/2}$$

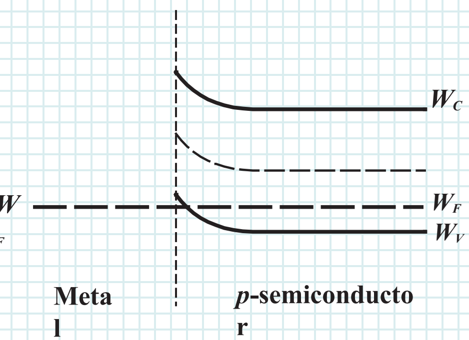


The pn-junction with abrupt charge carrier transition in the absence of an externally applied voltage.

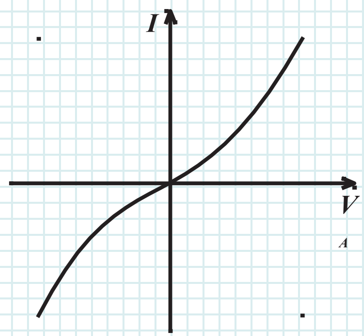


External voltage applied to the pn-junction in reverse and forward directions.

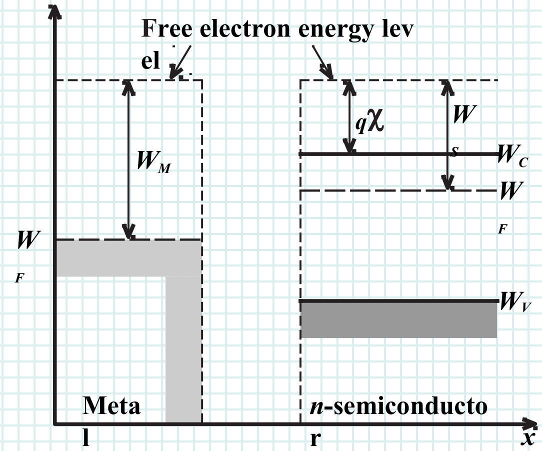
Schottky Contact



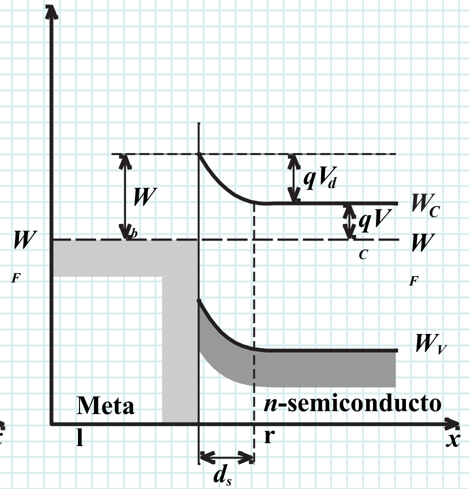
(a) Energy band model



(b) Voltage-current characteristic



(a) Metal and semiconductor do not interact



(b) Metal-semiconductor contact

Energy-band diagram of Schottky contact, (a) before and (b) after contact.

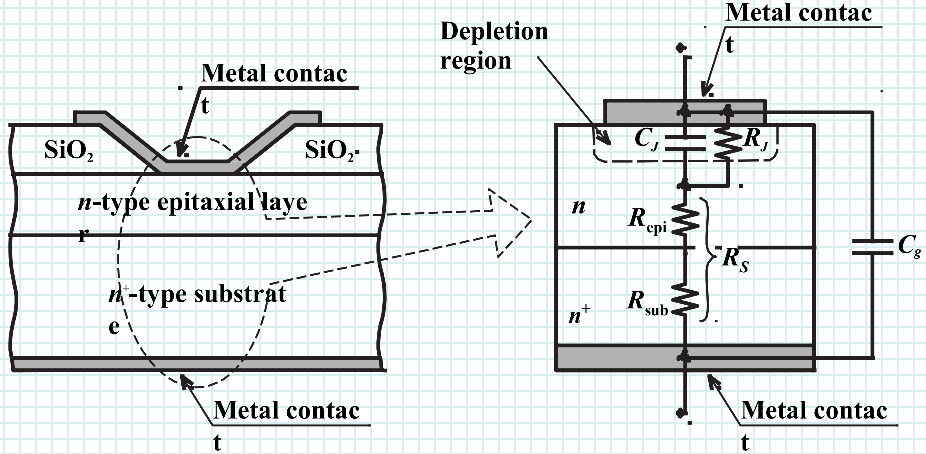
Metal electrode in contact with p-semiconductor.

Work function potentials of some metals

Material	Work function potential, V_M
Silver (Ag)	4.26 V
Aluminum (Al)	4.28 V
Gold (Au)	5.1 V
Chromium (Cr)	4.5 V
Molybdenum (Mo)	4.6 V
Nickel (Ni)	5.15 V
Palladium (Pd)	5.12 V
Platinum (Pt)	5.65 V
Titanium (Ti)	4.33 V

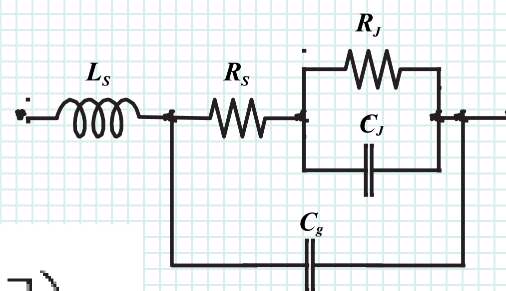
$$C_J = A\frac{\varepsilon}{d_S} = A\left\{\frac{q\varepsilon}{2(V_d - V_A)}N_D\right\}^{\frac{1}{2}}$$

Schottky Diode



Cross-sectional view of Si Schottky diode.

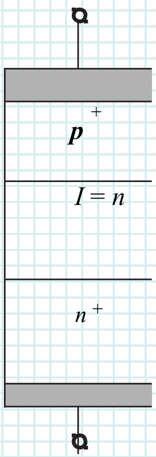
$$I = I_S(e^{(V_A - IR_S)} - 1)$$



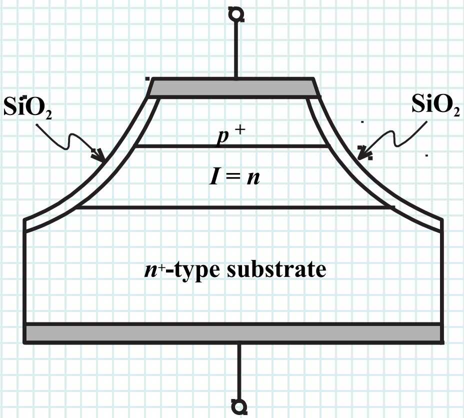
Reverse-saturation current

$$I_S = A\left(R^* T^2 \exp\left[\frac{-qV_b}{kT}\right]\right)$$

PIN Doide

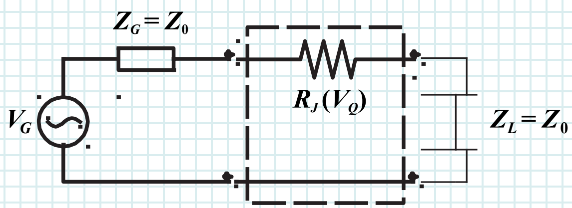


(a) Simplified structure of a PIN dio
de

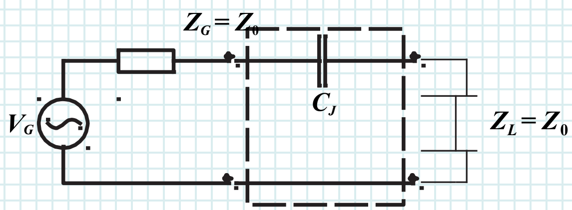


(b) Fabrication in mesa processing technol
ogy

$$I = A\left(\frac{qn_iW}{\tau_p}\right)\left(e^{V_A/(2V_T)} - 1\right)$$

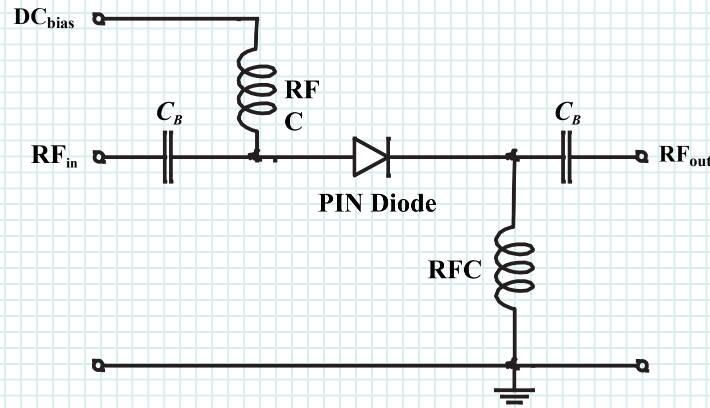


(a) Forward bias

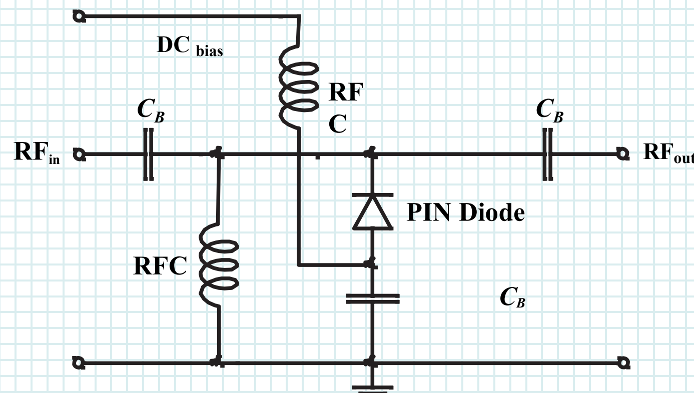


(b) Reverse bias (isolation)

PIN diode in series connection.



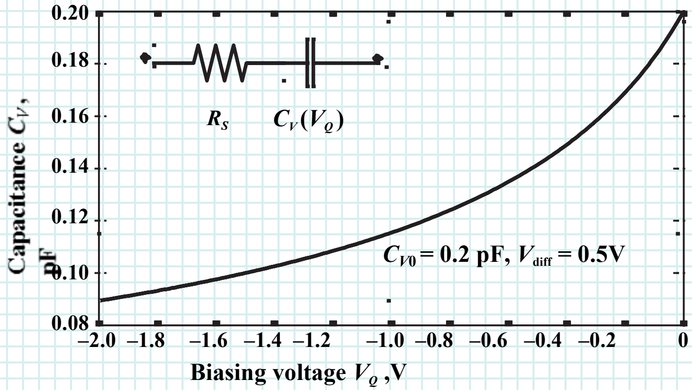
(a) Series connection of PIN diod
e



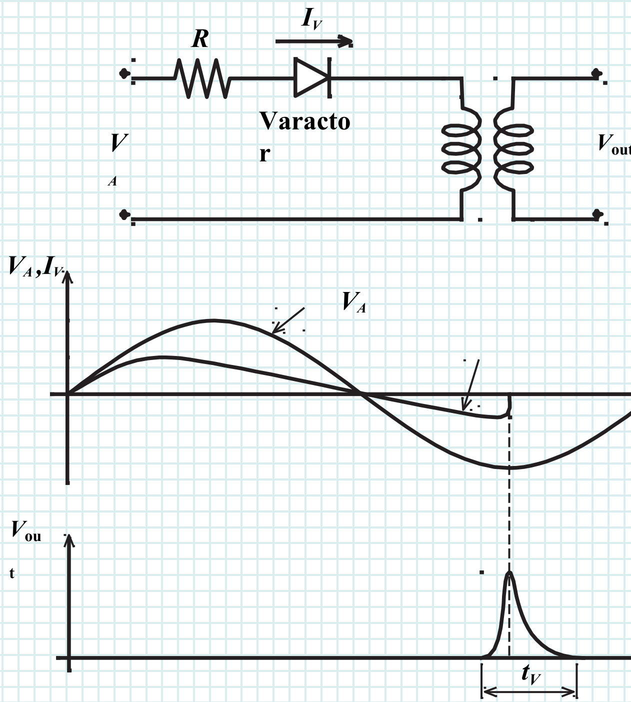
(b) Shunt connection of PIN dio
de

Attenuator circuit with biased PIN diode in series and shunt configurations.

Varactor Diode

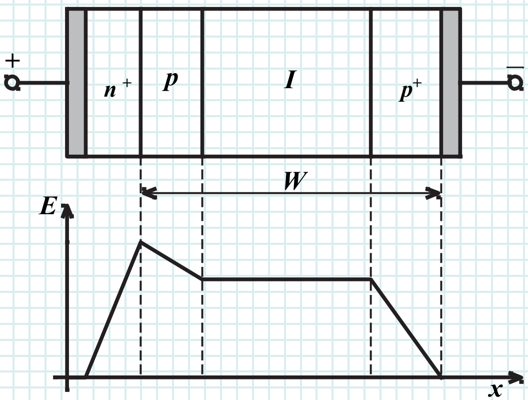


Simplified electric circuit model and capacitance behavior of varactor diode.

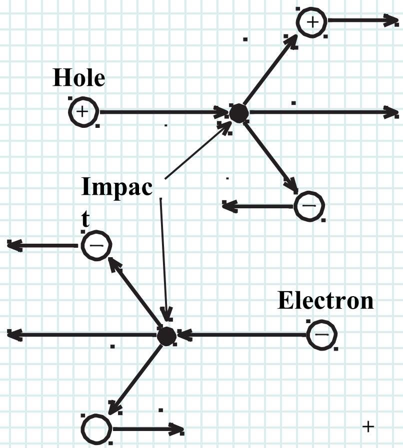


Pulse generation with a varactor diode.

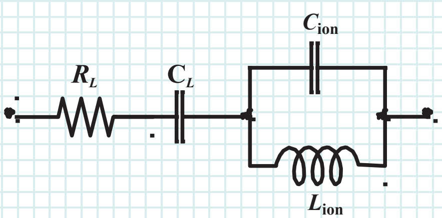
IMPATT Diode

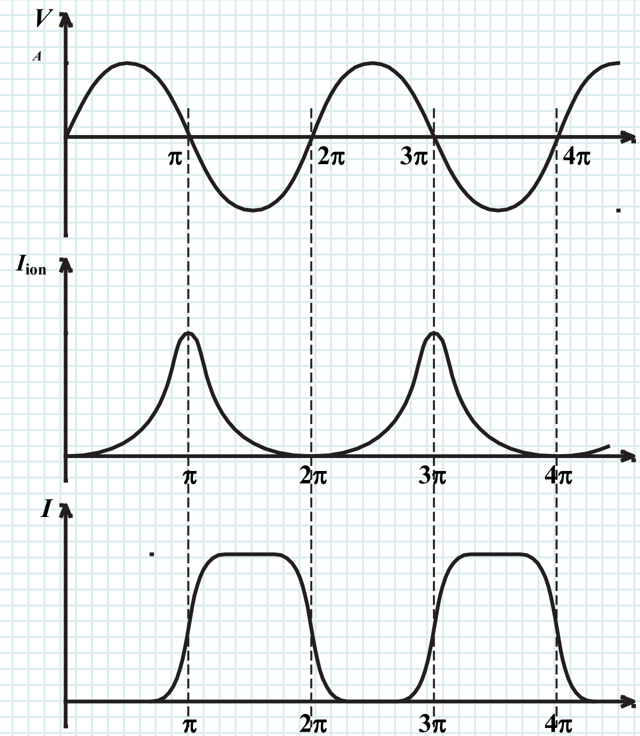


(a) Layer structure and electric field pro file



(b) Impact ionizatio n

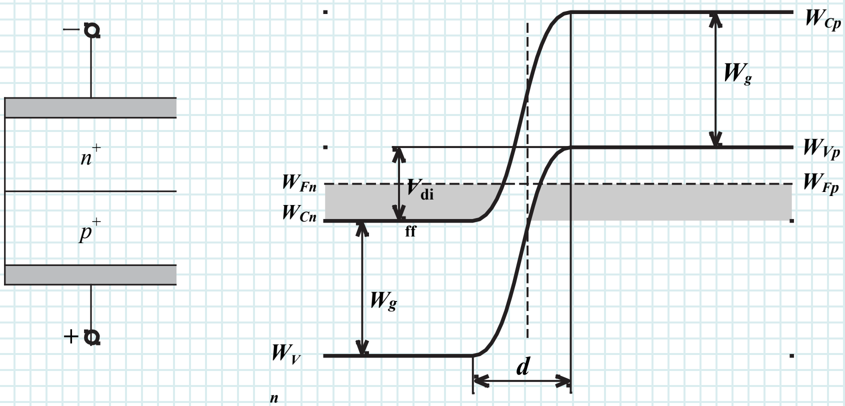




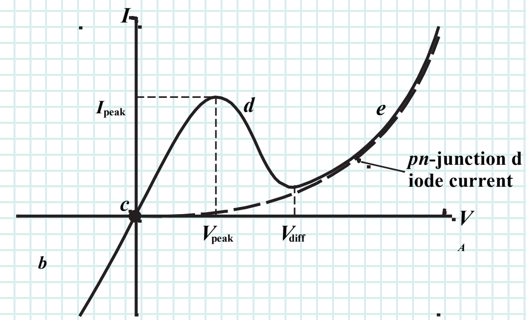
Applied voltage, ionization current, and total current of an IMPATT diode.

$$f_0 = \frac{1}{2\pi}\sqrt{2I_Q\frac{v_{d\max}}{\varepsilon}\alpha'}$$

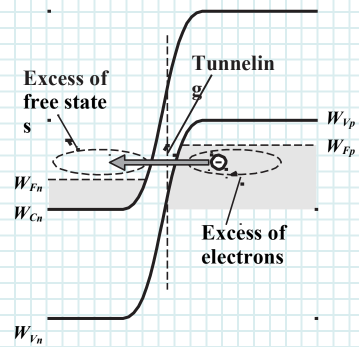
Tunnel Diode



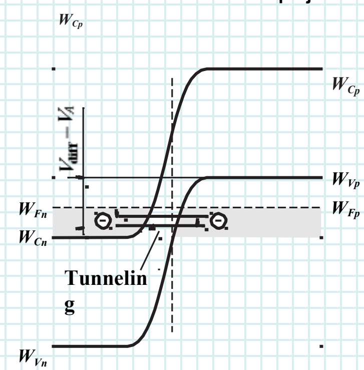
Tunnel diode and its band energy representation.



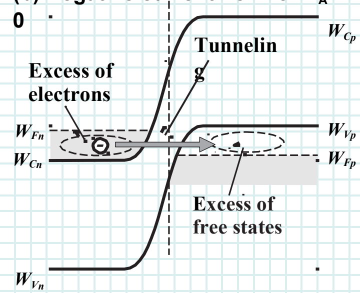
(a) I-V curve of tunnel diode. At high positive biasing voltages the corresponding current of the tunnel diode approaches the current of the conventional pn-junction diode



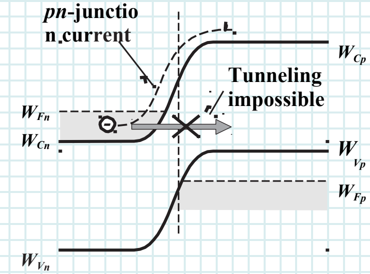
(b) Negative current flow for $V_A < 0$



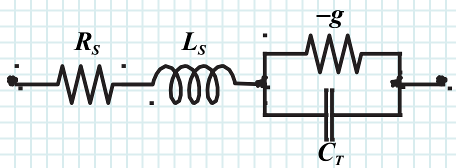
(c) No current flow for $V_A = 0$



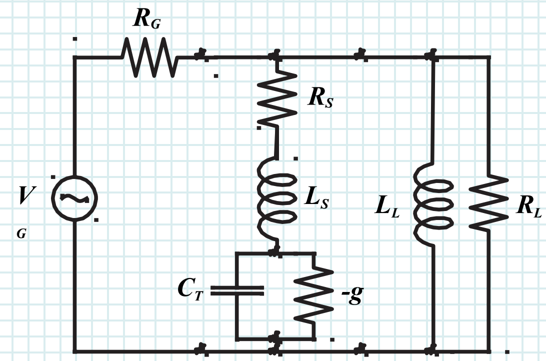
(d) Positive tunneling current, $0 < V_A < V_{diff}$



(e) Positive current flow for $V_A > V_{diff}$

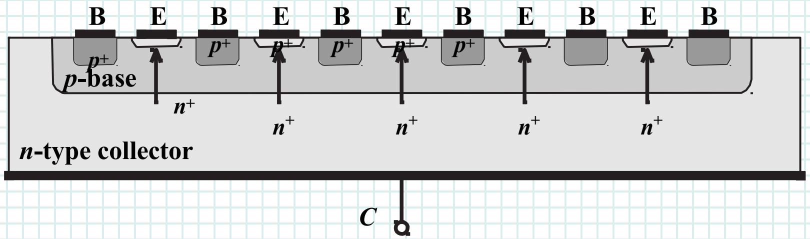


$$|G_T| = \frac{4}{R_L}\,\frac{1}{R_G(1/R_L + 1/R_G - g)^2}$$

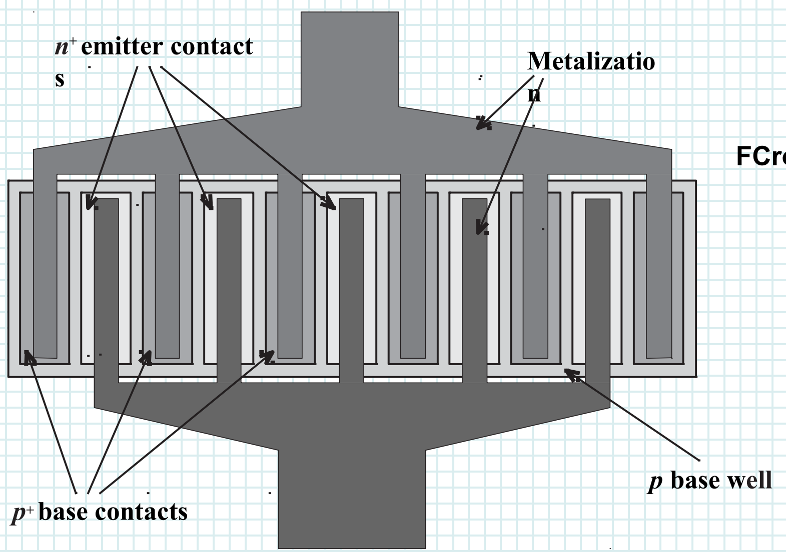


Tunnel diode circuit for amplification/oscillation behavior.

Biopolar Transistor

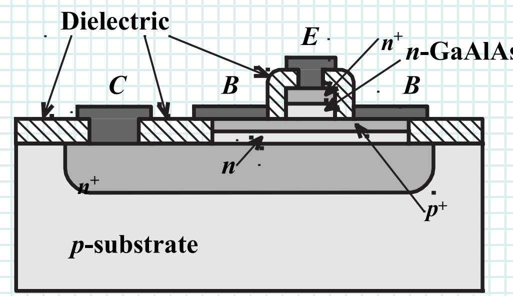


(a) Cross-sectional view of a multifinger bipolar junction transistor

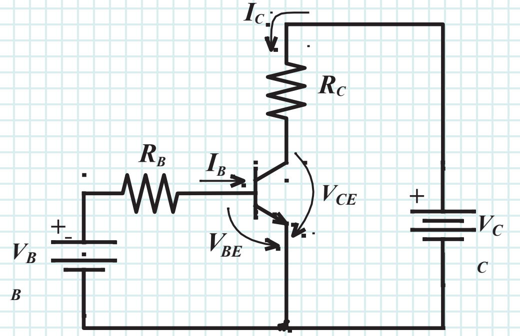


(b) Top view of a multifinger bipolar junction transistor

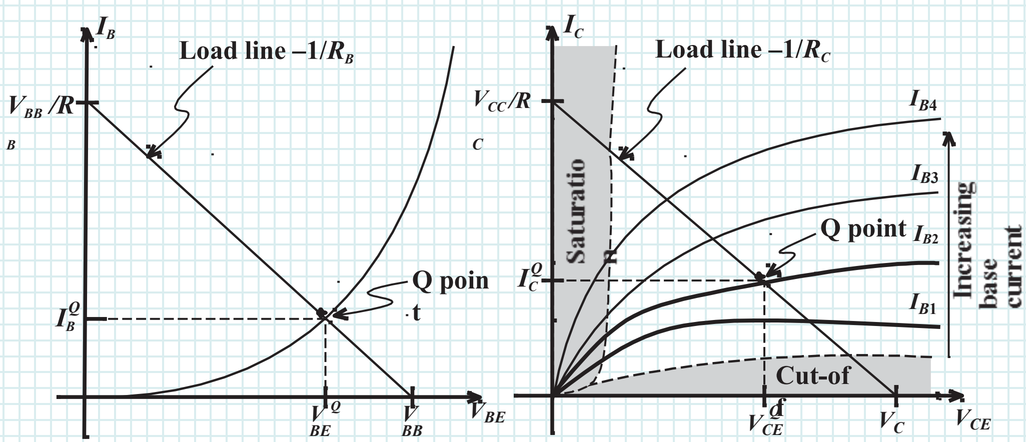
Interdigitated structure of high-frequency BJT.



FCross-sectional view of a GaAs heterojunction bipolar transistor involving a GaAlAs-GaAs interface.



(a) Biasing circuit for npn BJT in common-emitter configuration



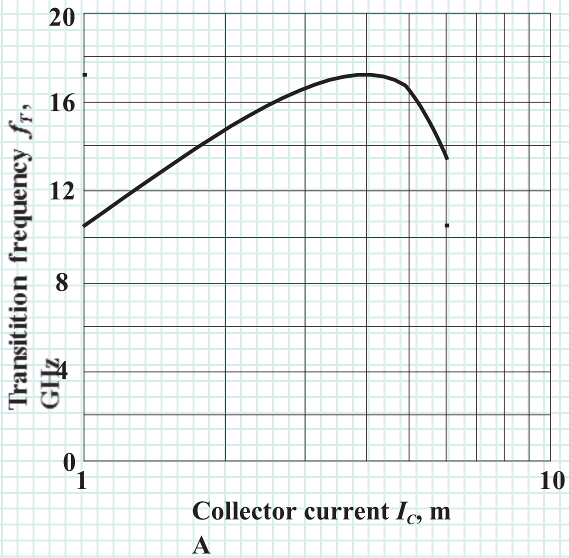
(b) Input characteristic of transistor (c) Output characteristic of transistor

Biasing and input, output characteristics of an npn BJT.

Frequency Response

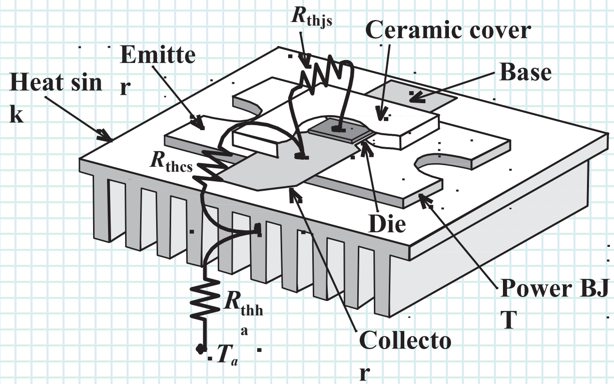
Transition frequency is related to the transit time

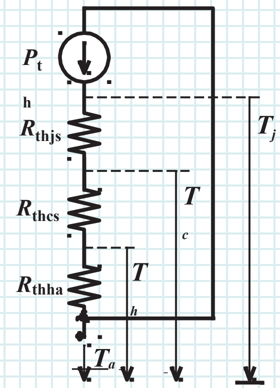
$$f_T = \frac{1}{\tau}$$



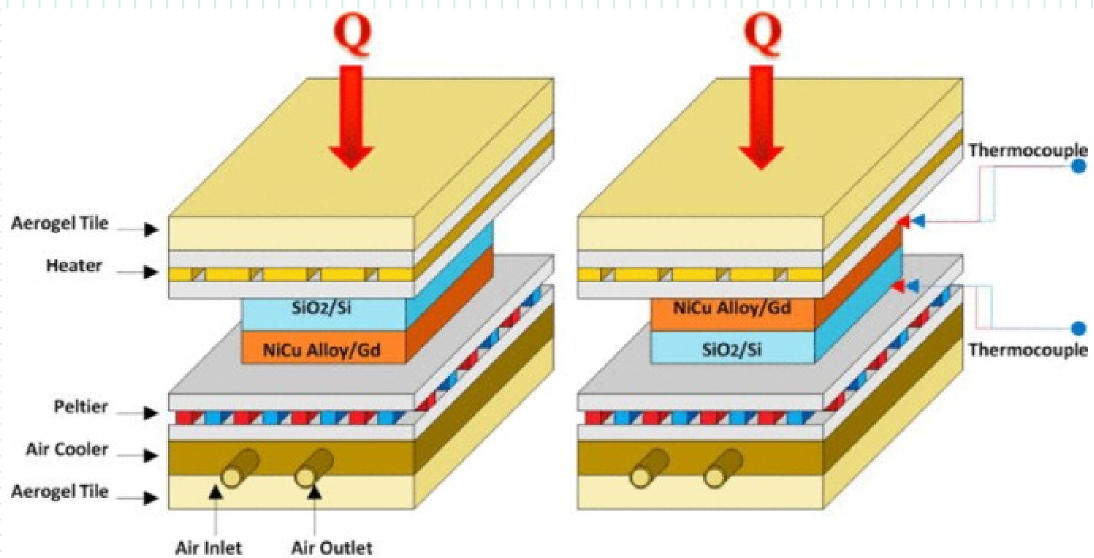
Transition frequency as a function of collector current for the 17 GHz npn wideband transistor BFG403W (courtesy of Philips Semiconductors).

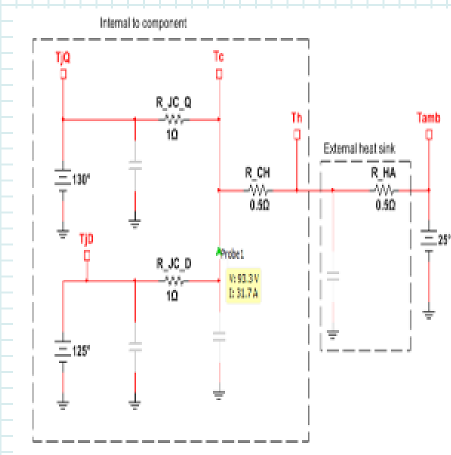
Temperature behavior



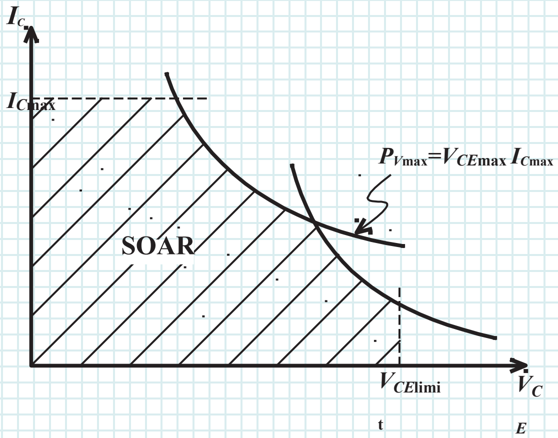


Thermal equivalent circuit of BJT.

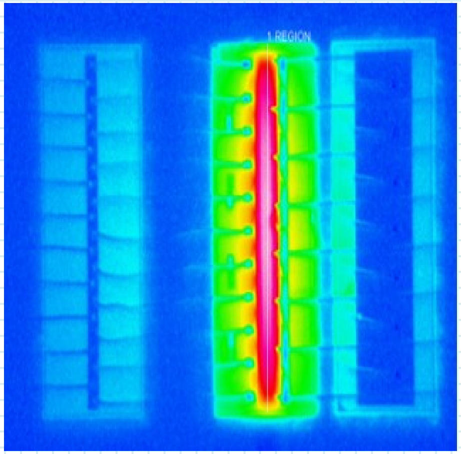


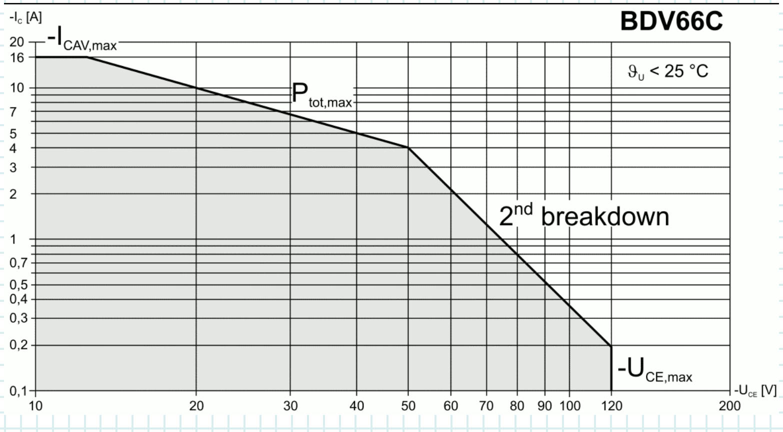


Limiting Values

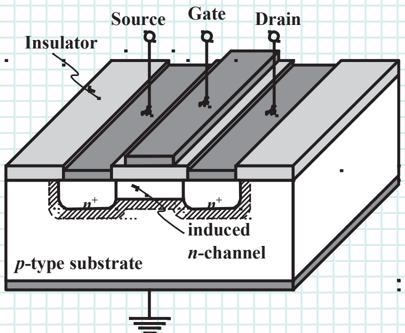


Operating domain of BJT in active mode with breakdown mechanisms.

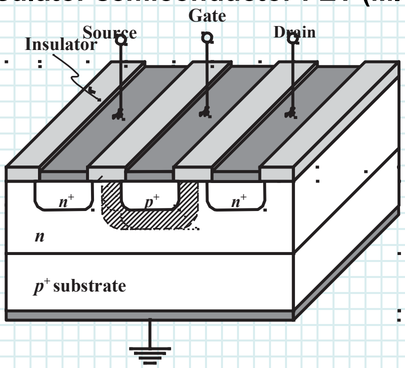




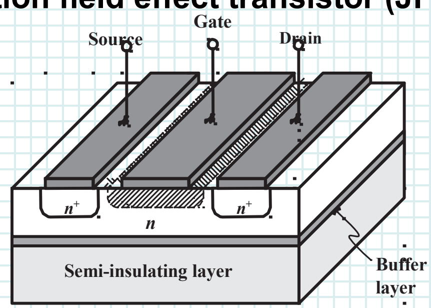
RF Field Effect Transistor



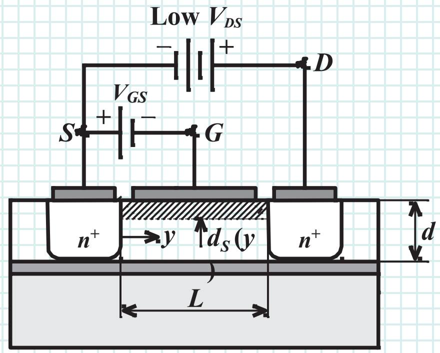
(a) Metal insulator semiconductor FET (MISFET)



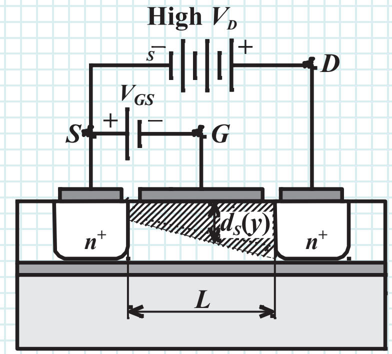
(b) Junction field effect transistor (JFET)



(c) Metal semiconductor FET (MESFET)

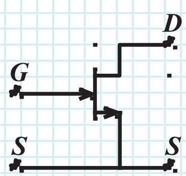


(a) Operation in the linear regio
n.

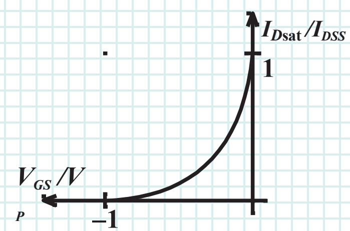


(b) Operation in the saturation
region.

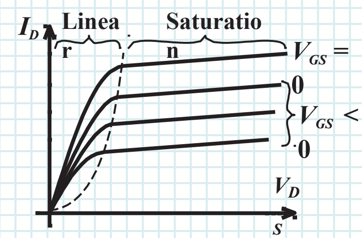
Functionality of MESFET for different drain-source voltages.



(a) Circuit symb
ol



(b) Transfer characteristi
c

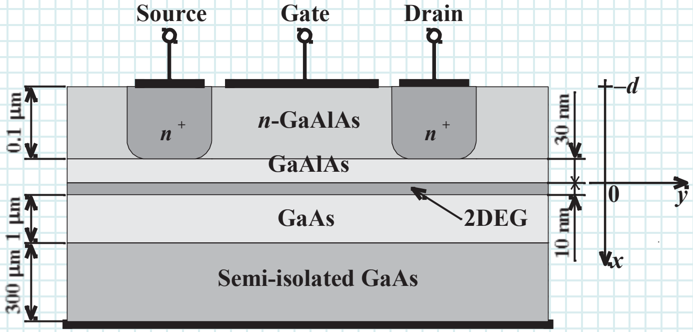


(c) Output characteristic

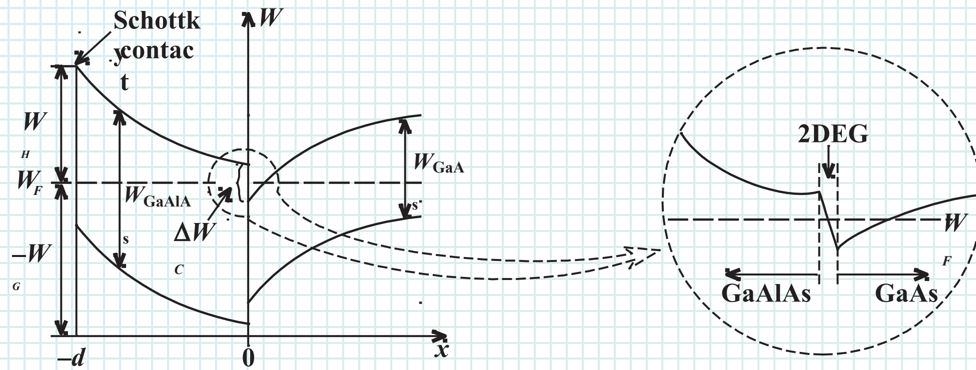
$$I_{Dsat} = I_{DSS}\left(1 - \frac{V_{GS}}{V_{T0}}\right)^2$$

$$\tau = \frac{L}{v_{sat}}$$

High Electron Mobility Transistors



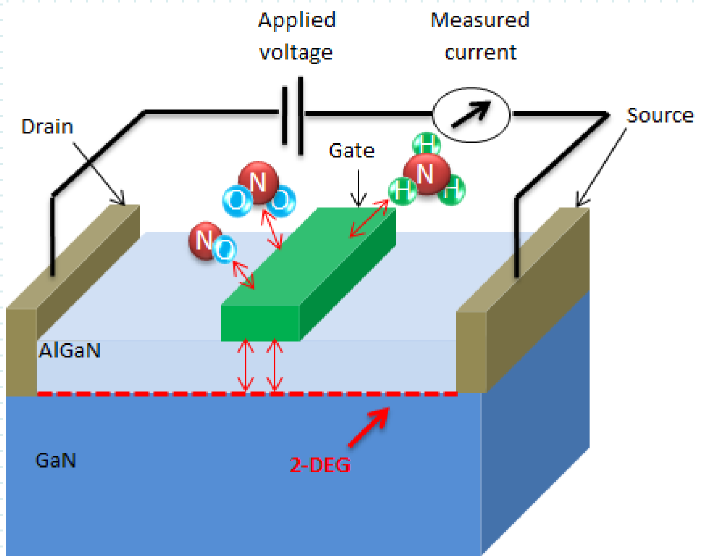
Generic heterostructure of a depletion-mode HEMT.



(a) Energy band diagram

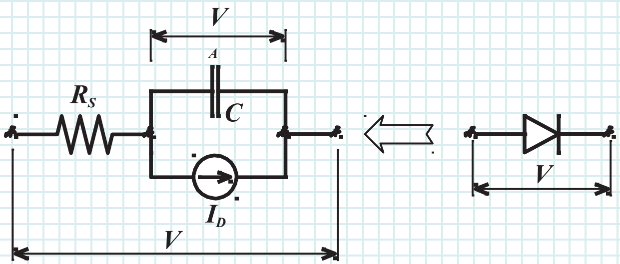
(b) Close-up view of conduction band

Energy band diagram of GaAlAs-GaAs interface for an HEMT.



Active RF Component Modeling

Diode Models



Nonlinear I-V characteristics

$$I_D = I_S\left(e^{V_A/(nV_T)} - 1\right)$$

Diode model parameters and their corresponding SPICE parameters

Symbol	SPICE	Description	Typical values
I_S	IS	saturation current	1 fA–10 μA
n	N	emission coefficient	1
τ_T	TT	transit time	5 ps–500 μs
R_S	RS	Ohmic resistance	0.1–20 Ω
V_{diff}	VJ	barrier voltage	0.6–0.8 V (*pn*) 0.5–0.6 V (Schottky)
C_{J0}	CJ0	zero-bias junction capacitance	5–50 pF (*pn*) 0.2–5 pF (Schottky)
m	M	grading coefficient	0.2–0.5
W_g	EG	bandgap energy	1.11 eV (Si) 0.69 eV (Si-Schottky)
p_t	XTI	saturation current temperature coefficient	3 (*pn*) 2 (Schottky)

SPICE parameters

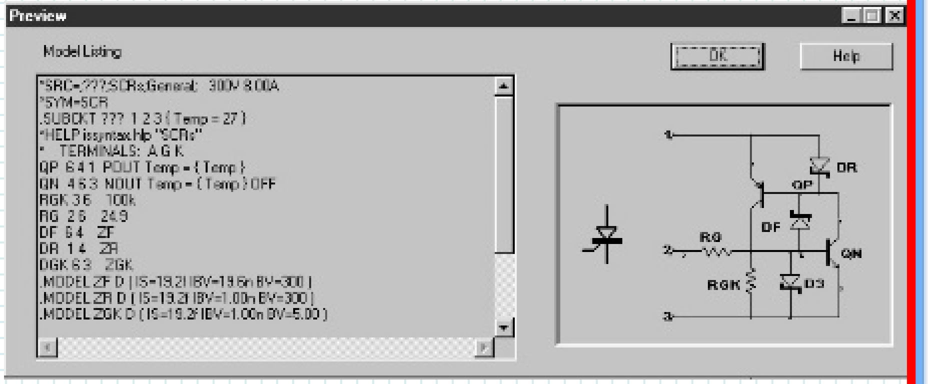
SPICE (*Simulation Program with Integrated Circuit Emphasis*)[1][2] is a general-purpose, open source analog electronic circuit simulator. It is a powerful program that is used in integrated circuit and board-level design to check the integrity of circuit designs and to predict circuit behavior.

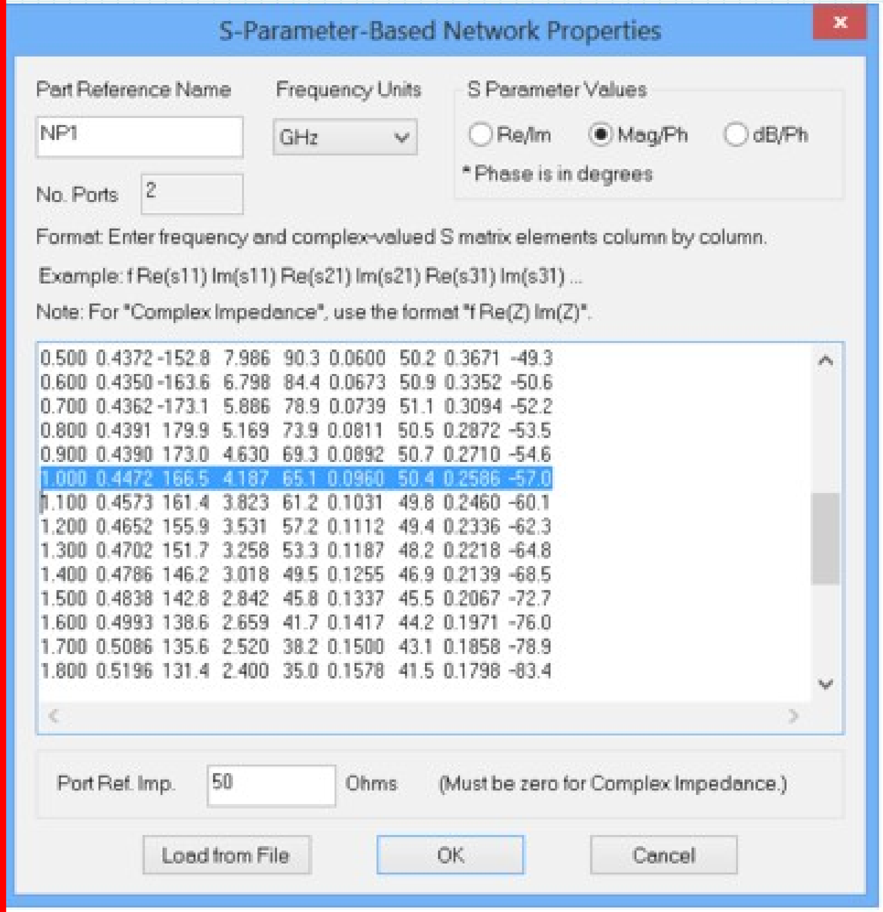
take a text netlist describing the circuit elements (transistors, resistors, capacitors, etc.) and their connections, and translate this description into equations to be solved. The general equations produced are nonlinear differential algebraic equations which are solved using implicit integration methods, Newton's method and sparse matrix techniques.

SPICE parameters

Difference

S-parameters





Nonlinear spectrum shifting

multiplying the two signal can be realized by nonlinear device

$$a_2(v_1+v_2)^2 = a_2(V_{1m}\cos\omega_1 t + V_{2m}\cos\omega_2 t)^2$$

$$= \frac{a_2}{2}V_{1m}V_{2m}\left[\cos(\omega_2+\omega_1)+\cos(\omega_2-\omega_1)t\right]+\cdots$$

$$i = a_0 + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \cdots + a_N v_i^N + \cdots$$

with $v_i = v_1 + v_2$

$\left|\pm p\omega_1 \pm q\omega_2\right| \quad (p+q\geq 3)$ **are all Interference for frequency conversion**

Solutions：

（1） Feature of devices —— **square law characteristics without high-order**

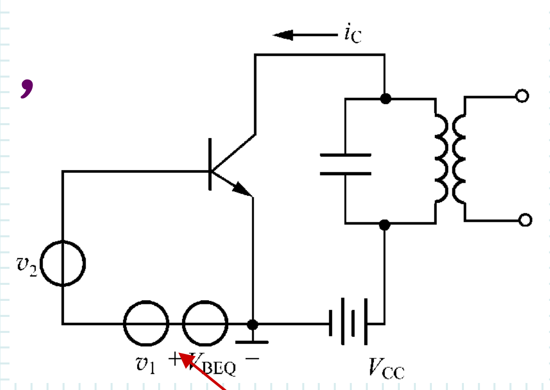
（2） Design of circuit —— **balanced circuit structure, interference cancellation**

（3） Input signals， Linear time variant

Linear time variant

Working condition： one is small signal，Another is large signal

$$v_1(t) = V_{1m}\cos\omega_1 t$$
$$v_2(t) = V_{2m}\cos\omega_2 t$$
$$V_{1m} >> V_{2m}$$



Time variant bias

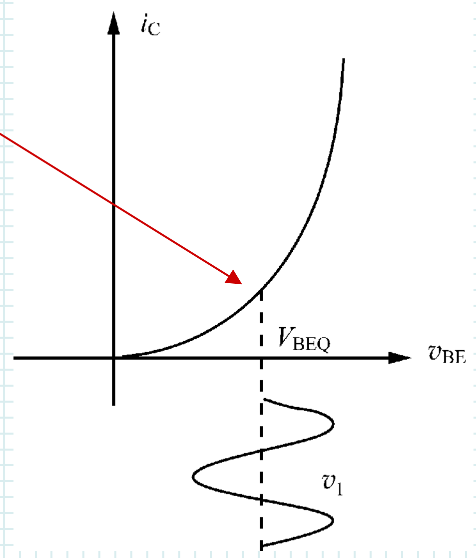
Static Bias V_{BEQ}

Large signal $v_1(t)$

→ Time variant bias

$$V_{BEQ}(t) = V_{BEQ} + v_1(t)$$

→ Time variant Work point



→ i_c In time variant work point

i_c In time variant work point

Time variant bias

Small signal

$$i_c(t) = a_0 + a_1\left(v_{be} - V_{BEQ}(t)\right) + a_2\left(v_{be} - V_{BEQ}(t)\right)^2 + a_3\left(v_{be} - V_{BEQ}(t)\right)^3 + \cdots$$

With : $v_{be} = V_{BEQ} + v_1(t) + v_2(t) = V_{BEQ}(t) + v_2(t)$

Get : $i_c(t) = a_0 + a_1 v_2 + a_2 v_2^2 + a_3 v_2^3 + \cdots$

Working point and a_i are time varying with $v_1(t)$

$$i_c(t) = a_0(t) + a_1(t)v_2 + a_2(t)v_2^2 + a_3(t)v_2^3 + \cdots$$

a_i **change with large signal**

a_i **frequency ω_1 is same with large signal $v_1(t)$**

$$a_0(t) = i_c(t)\Big|_{v_{be}=V_{BEQ}(t)} \overset{\Delta}{=} I_0(t)$$ **Time varying static current**

$$a_1(t) = \frac{di_c}{dv_{be}}\bigg|_{v_{be}=V_{BEQ}(t)} \overset{\Delta}{=} g_m(t)$$ **time-varying transcondactance**

$a_0(t)$ **and** $a_1(t)$ **are all nonlinear**

$$a_0(t) = a_{00} + a_{01}\cos\omega_1 t + a_{02}\cos 2\omega_1 t + \cdots$$

$$a_1(t) = g_m(t) = g_{m0} + g_{m1}\cos\omega_1 t + g_{m2}\cos 2\omega_1 t + \cdots$$

Frequency ω_1 **is the working frequency of large signal**

Linear is for simall signal $v_2(t)$

Out put current

$$i_c(t) = a_0(t) + a_1(t)v_2 + a_2(t)v_2^2 + a_3(t)v_2^3 + \cdots$$

$v_2(t)$ **is small enough, current can be ignored above quadratic**

$$i_c(t) \approx a_0(t) + a_1(t)v_2 = I_0(t) + g_m(t)v_2(t)$$

Only linear component $v_2(t)$

spectrum shifting

$$i_c(t) \approx a_0(t) + a_1(t)v_2 = I_0(t) + \boxed{g_m(t)v_2(t)}$$

$$a_1(t) = g_m(t) = g_{m0} + g_{m1}\cos\omega_1 t + g_{m2}\cos 2\omega_1 t + \cdots$$

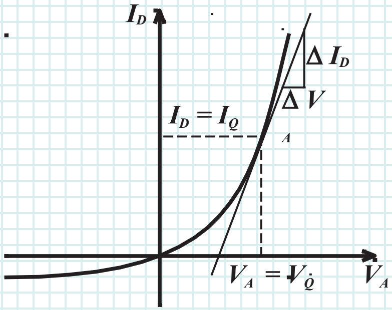
$$v_2(t) = V_{2m}\cos\omega_2 t$$

($\omega_1 + \omega_2$) ($\omega_1 - \omega_2$) **spectrum shifting**

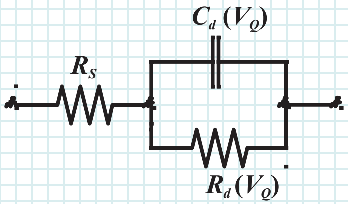
$\left|p\omega_1 \pm \omega_2\right|$ ← **Interference** → $p\omega_1$

Linear Diode Model

Small-signal diode model.



(a) tangent approximati
on at Q-point

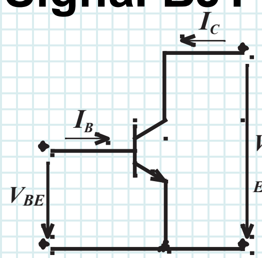


(b) linear
circuit m

$$G_d = \frac{1}{R_d} = \left.\frac{dI_D}{dV_A}\right|_{V_Q} = \frac{I_Q + I_S}{nV_T} \cong \frac{I_Q}{nV_T}$$

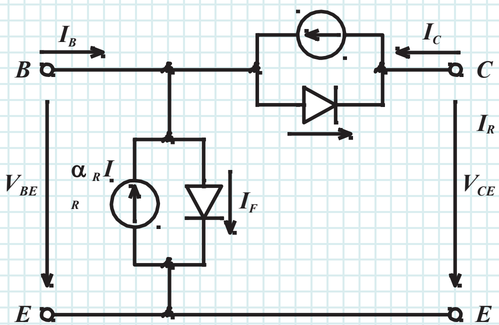
$$C_d = \frac{I_S \tau_T}{nV_T} e^{V_Q/(nV_T)}$$

Large-Signal BJT Models



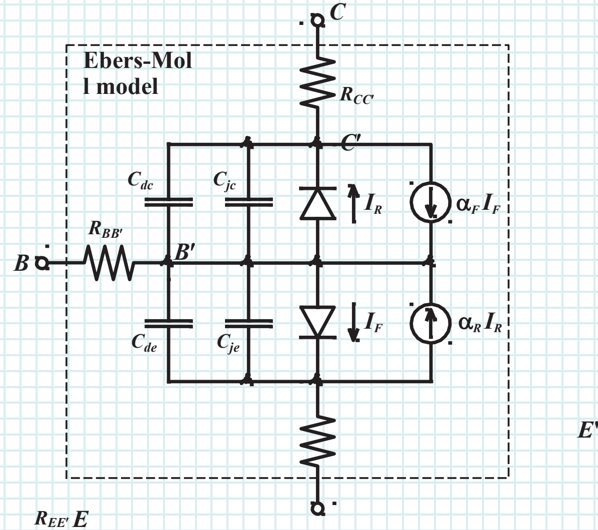
(a) Voltage and current convention for npn transistor

$\alpha_F I_F$

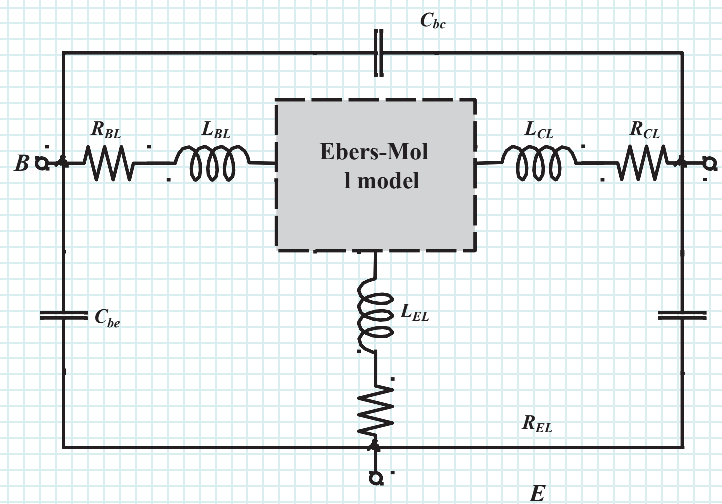


(b) Ebers-Moll circuit model

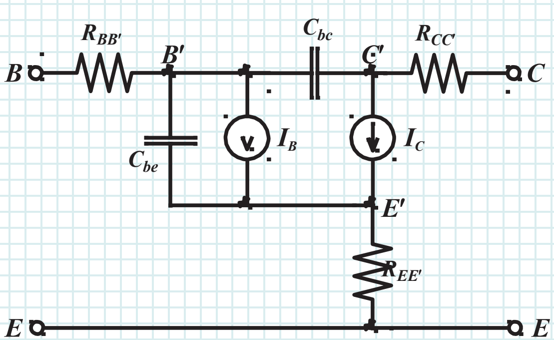
Large-signal Ebers-Moll circuit model.



(a) Dynamic Ebers-Moll chip model



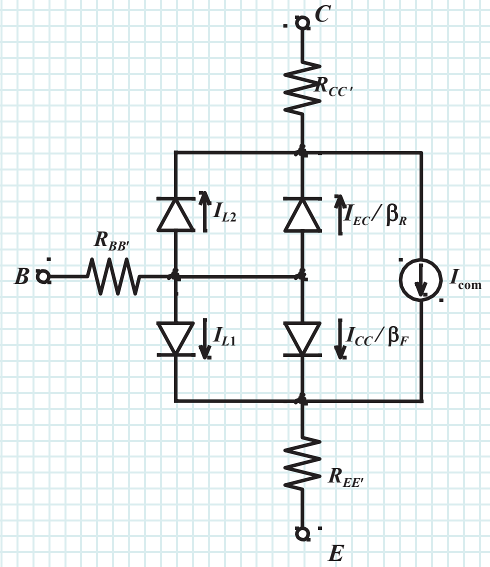
(b) RF model with parasitic terminal effects

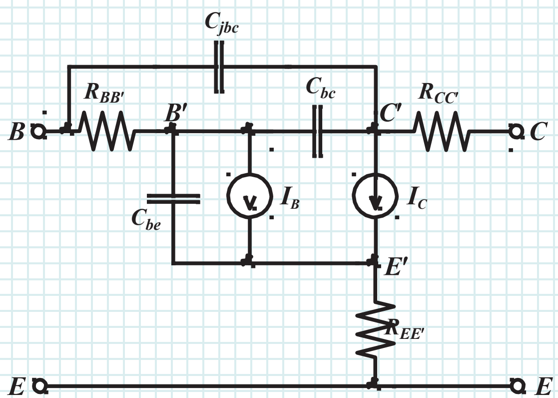


Large-signal BJT model in forward active mode.

C_{ce}

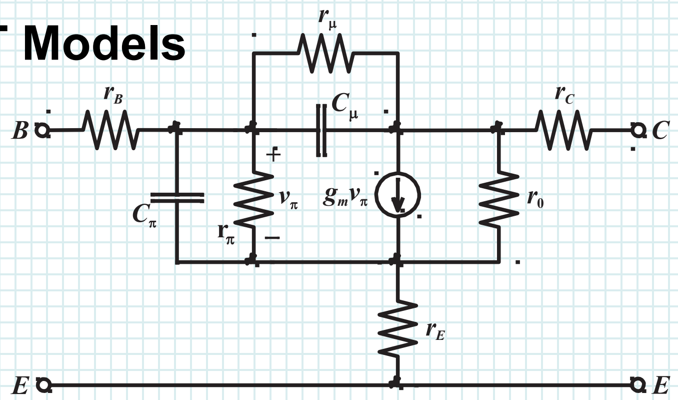
Gummel-Poon model.





Large-signal Gummel-Poon model in normal active mode.

Small-Signal BJT Models

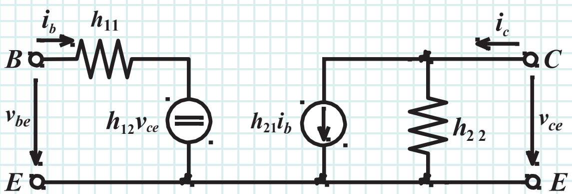


$$h_{11} = \left.\frac{v_{be}}{i_b}\right|_{v_{ce}=0}$$ input impedance

$$h_{21} = \left.\frac{i_c}{i_b}\right|_{v_{ce}=0}$$ foward current gain β_F

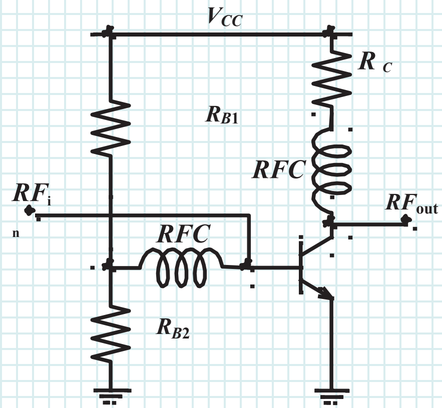
$$h_{12} = \left.\frac{v_{be}}{v_{ce}}\right|_{i_b=0}$$ reverse voltage gain

$$h_{22} = \left.\frac{i_c}{v_{ce}}\right|_{i_b=0}$$ output admittance

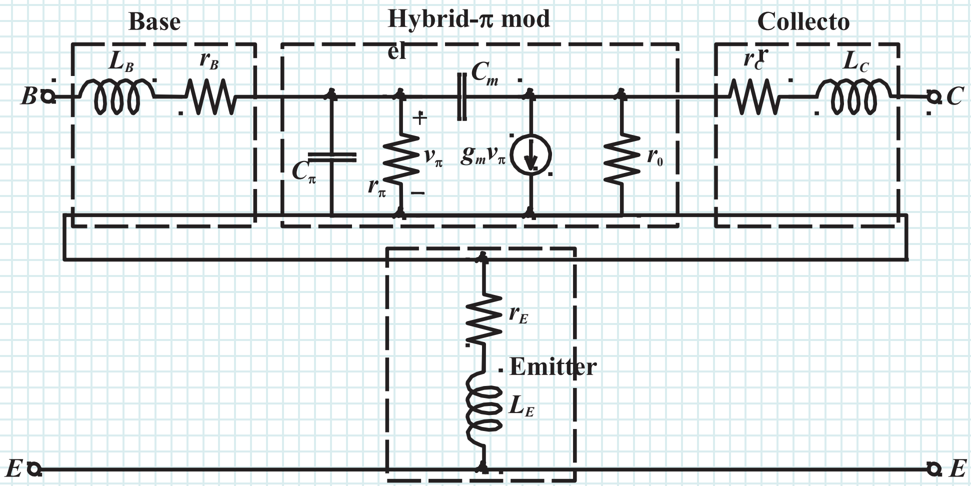


Parameters of the BJT transistor

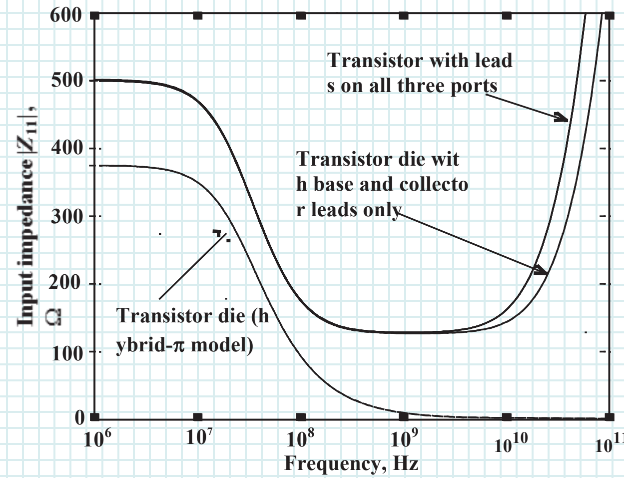
Symbol	Description	Typical value
β_F	forward current gain	145
I_S	saturation current	5.5 fA
V_{AN}	forward Early voltage	30 V
τ_F	forward transition time	4 ps
C_{JC0}	base-collector junction capacitance at zero applied junction voltage	16 fF
C_{JE0}	base-emitter junction capacitance at zero applied junction voltage	37 fF
m_C	collector capacitance grading coefficient	0.2
m_E	emitter capacitance grading coefficient	0.35
V_{BE}^{diff}	base-emitter diffusion potential	0.9 V
V_{BC}^{diff}	base-collector diffusion potential	0.6 V
r_B	base body resistance	125 Ω
r_C	collector body resistance	15 Ω
r_E	emitter body resistance	1.5 Ω
L_B	base lead inductance	1.1 nH
L_C	collector lead inductance	1.1 nH
L_E	emitter lead inductance	0.5 nH



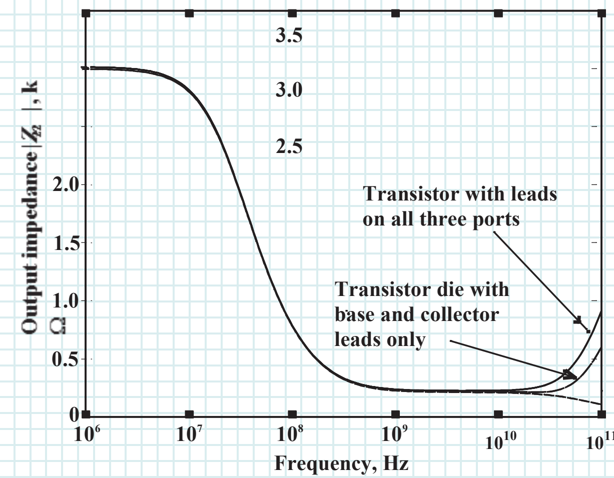
Biasing a BJT in common-emitter configuration.



Complete transistor model divided into four two-port networks.

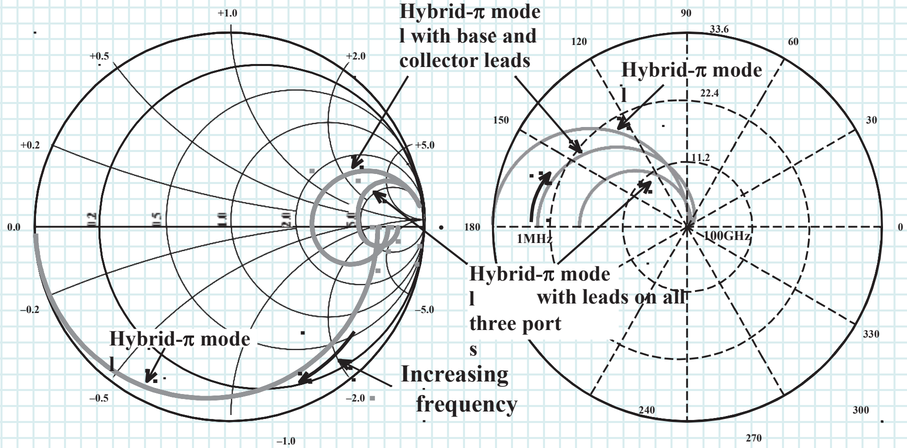


(a) Input impedance of the transistor



(b) Output impedance of the transistor

S_{11} and S_{21} responses of a BJT for various model configurations.



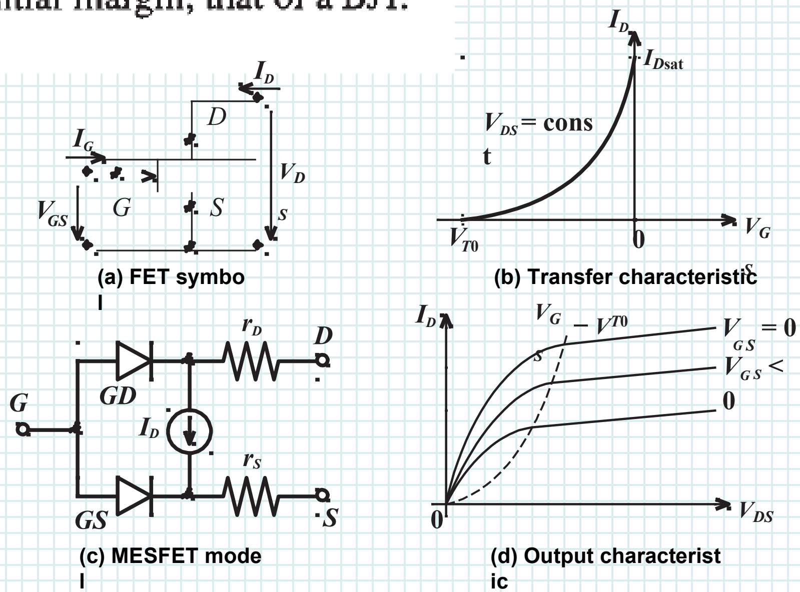
(a) Input reflection coefficient, S_{11}

(b) Gain of the transistor, S_{21}

Large-Signal FET Models

Benefits

- FETs exhibit a better temperature behavior.
- The noise performance of a FET is, in general, superior.
- The input impedance of FETs is normally very high, making them ideal for preamplification stages.
- The drain current of a FET shows a quadratic (and thus a more linear) functional behavior compared with the exponential collector current curve of a BJT.
- The upper frequency limit exceeds, often by a substantial margin, that of a BJT.
- The power consumption of a FET is smaller.



Static n-channel MESFET model.

Disadvantages

- FETs generally possess smaller gains.
- Because of the high input impedance, matching networks are more difficult to construct.
- The power handling capabilities tend to be inferior compared with BJTs.

Saturation region

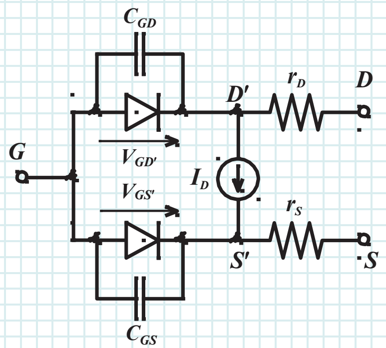
$$V_{DS} \geq V_{GS} - V_{T0} > 0$$

Linear region

$$0 < V_{DS} < V_{GS} - V_{T0}$$

Reverse saturation region

$$-V_{DS} \geq V_{GD} - V_{T0} > 0$$

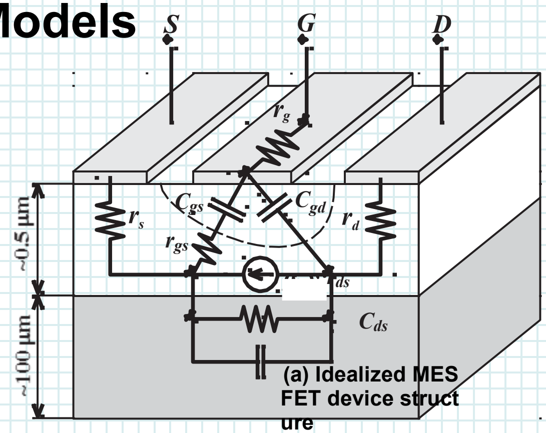


Dynamic FET model.

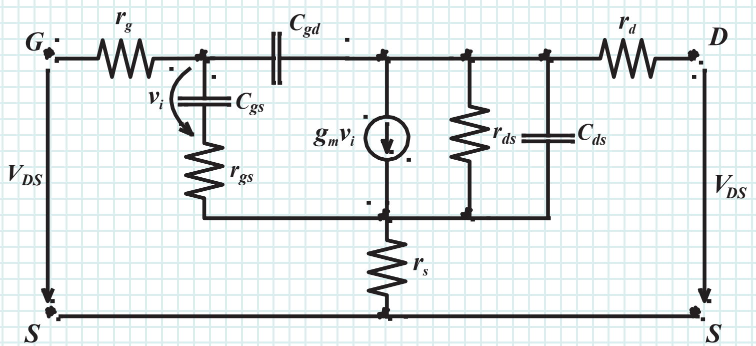
SPICE modeling parameters for a MESFET

Symbol	SPICE	Description
V_{T0}	VTO	Threshold voltage
λ	LAMBDA	Channel-length modulation coefficient
β	BETA	Conduction parameter
C_{GD}	CGD	Zero-bias gate-to-drain capacitance
C_{GS}	CGS	Zero-bias gate-to-source capacitance
r_D	RD	Drain resistance
r_S	RS	Source resistance

Small-Signal FET Models



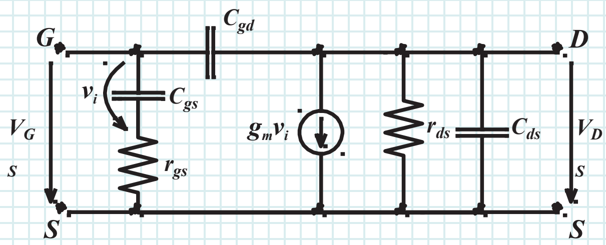
(a) Idealized MES FET device struct ure



(b) Circuit mod el

$$i_g = y_{11} v_{gs} + y_{12} v_{ds}$$

$$i_d = y_{21} v_{gs} + y_{22} v_{ds}$$



High-frequency FET model

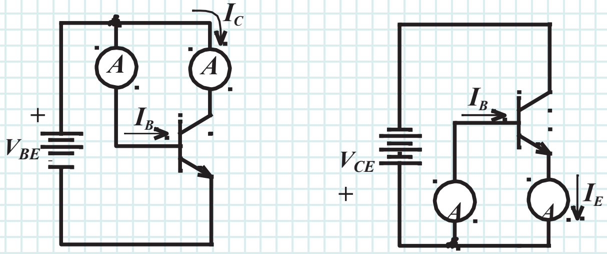
$$y_{21} = g_m = \left.\frac{dI_D}{dV_{GS}}\right|_Q = 2\beta_n(V_{GS}^Q - V_{T0})(1 + \lambda V_{DS}^Q)$$

$$y_{22} = \frac{1}{r_{ds}} = \left.\frac{dI_D}{dV_{DS}}\right|_Q = \beta_n\lambda(V_{GS}^Q - V_{T0})^2$$

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

Measurement of active devices

DC Characterization of Bipolar Transistor



(a) Forward measurement
s

(b) Reverse measurement
s

Forward and reverse measurements to determine Ebers-Moll BJT model parameters.

$$I_C = I_S(e^{V_{BE}/V_T} - 1)$$

$$I_B = \frac{I_S}{\beta_F}(e^{V_{BE}/V_T} - 1)$$

AC Parameters of Bipolar Transistor

Transconductance

$$g_m = \left.\frac{dI_C}{dV_{BE}}\right|_{V_{CE}=0} = \frac{I_C^Q}{V_T}$$

Input capacitance

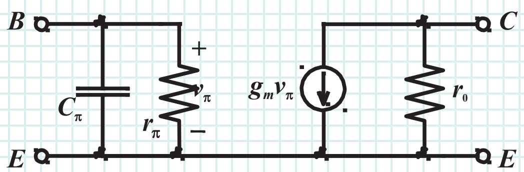
$$C_\pi = \tau_{be}\frac{I_S}{V_T}e^{V_{BE}^Q/V_T} = \tau_{be}\frac{I_C^Q}{V_T}$$

Input resistance

$$r_\pi = \left.\frac{dV_{BE}}{dI_B}\right|_{V_{CE}^Q} = \left.\frac{v_{be}}{i_b}\right|_{v_{ce}=0} = \frac{\beta_0}{g_m}$$

Output conductance

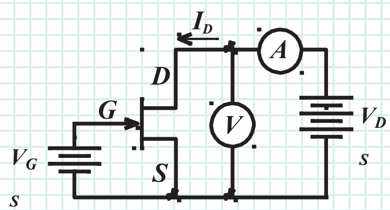
$$\frac{1}{r_0} = \left.\frac{dI_C}{dV_{CE}}\right|_{V_{BE}^Q} = \frac{I_C^Q}{V_{AN}}$$



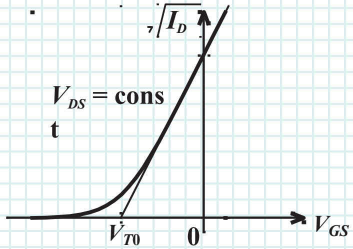
Small-signal, low-frequency h-parameter representation.

- Transconductance $g_m = I_C^Q/V_T$ for a given junction temperature
- DC current gain $\beta_0 = I_C^Q/I_B^Q$
- Input resistance $r_\pi = \beta_0/g_m$
- Output resistance $r_0 = V_{AN}/I_C^Q$
- Input impedance $Z_{in} = (1/r_\pi + j\omega C_\pi)^{-1}$ recorded at a particular angular frequency and then solved for the capacitance C_π

Measurement of Field Effect Transistor Parameters



(a) Measurement arrangeme
nt



(b) I_D versus V_{GS} transfer characteristi
c

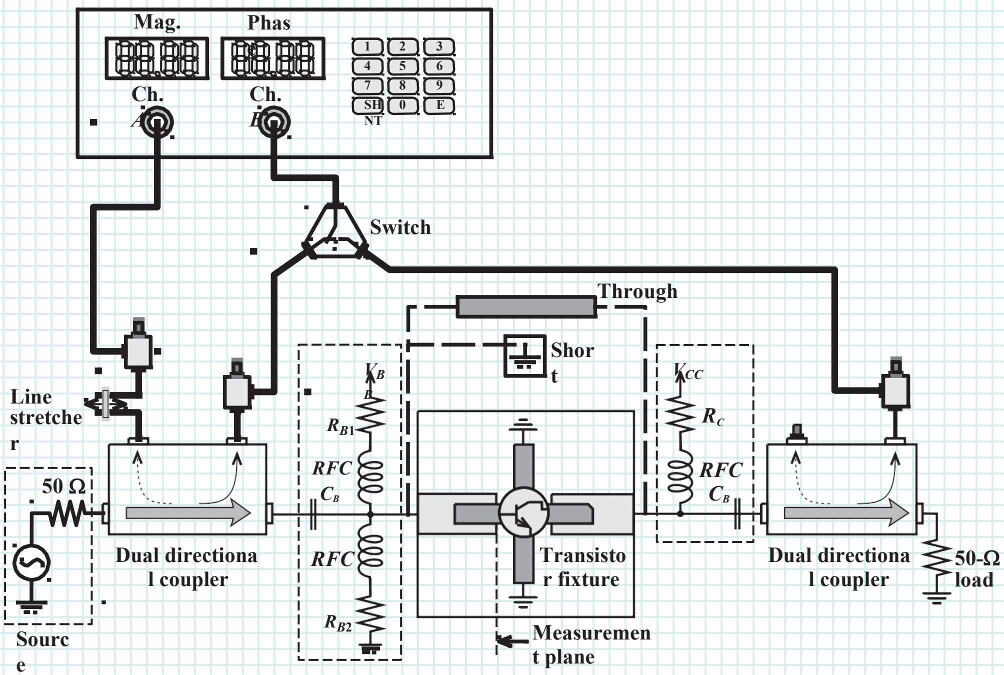
Generic measurement arrangement and transfer characteristics in saturation region.

The threshold voltage is determined indirectly by setting two different gate-source voltages V_{GS1} and V_{GS2} while maintaining a constant drain-source voltage V_{DS} = const $\geq V_{GS} - V_{T0}$ so that the transistor is operated in the saturation region. The result of these two measurements gives

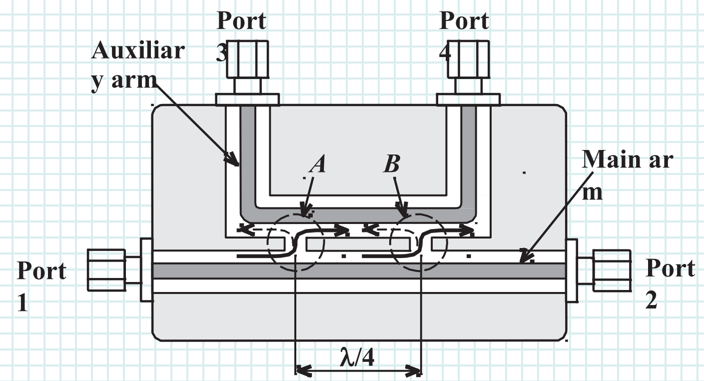
$$\sqrt{I_{D1}} = \sqrt{\beta}(V_{GS1} - V_{T0})$$

$$\sqrt{I_{D2}} = \sqrt{\beta}(V_{GS2} - V_{T0})$$

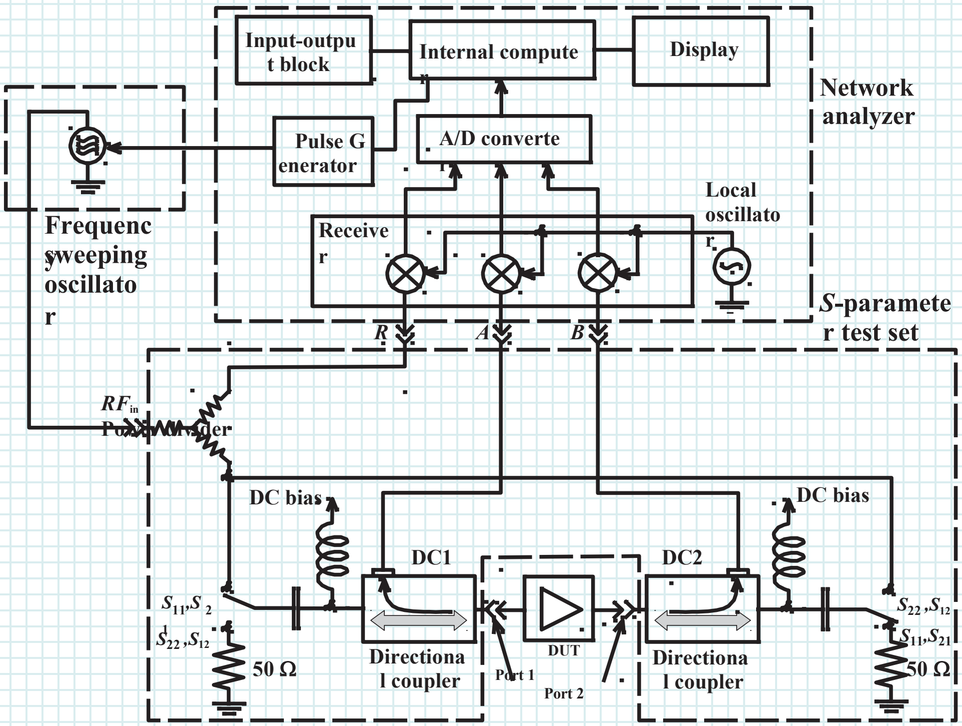
Scattering Parameters Device Characterization



Recording of S-parameters with a vector voltmeter.



Cross-sectional view of directional coupler and signal path adjustment.



Block diagram of a network analyzer with S-parameter test set.