Analog Electronics

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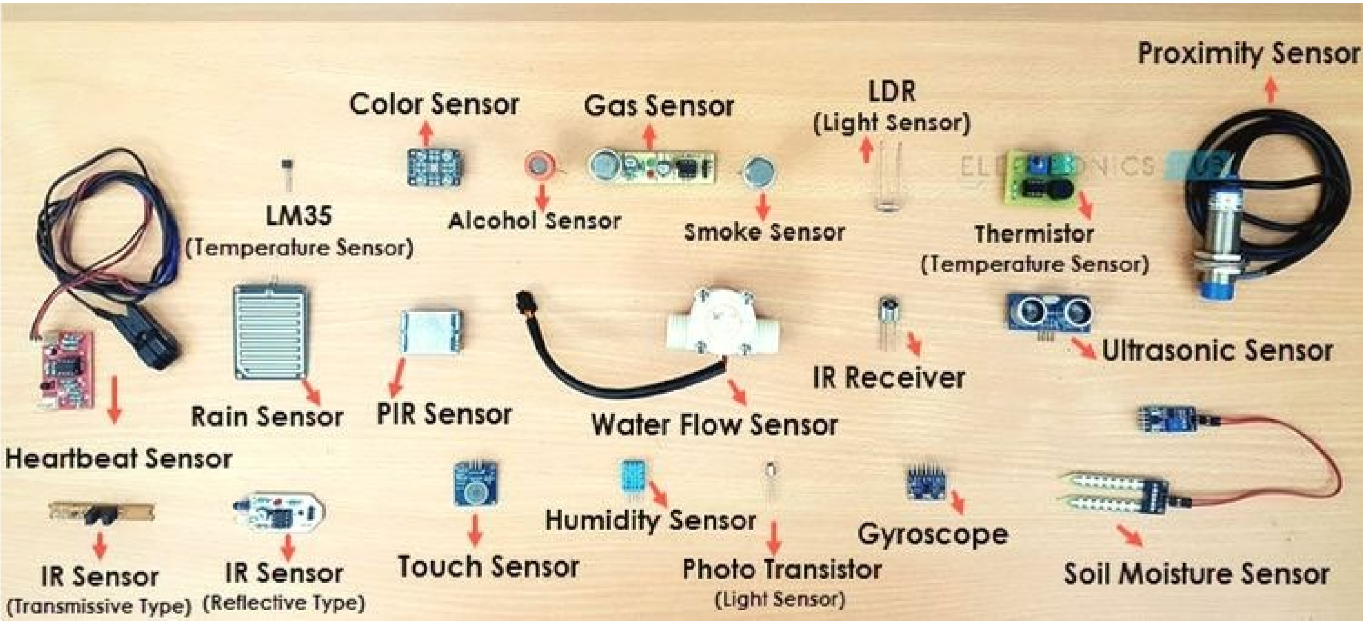
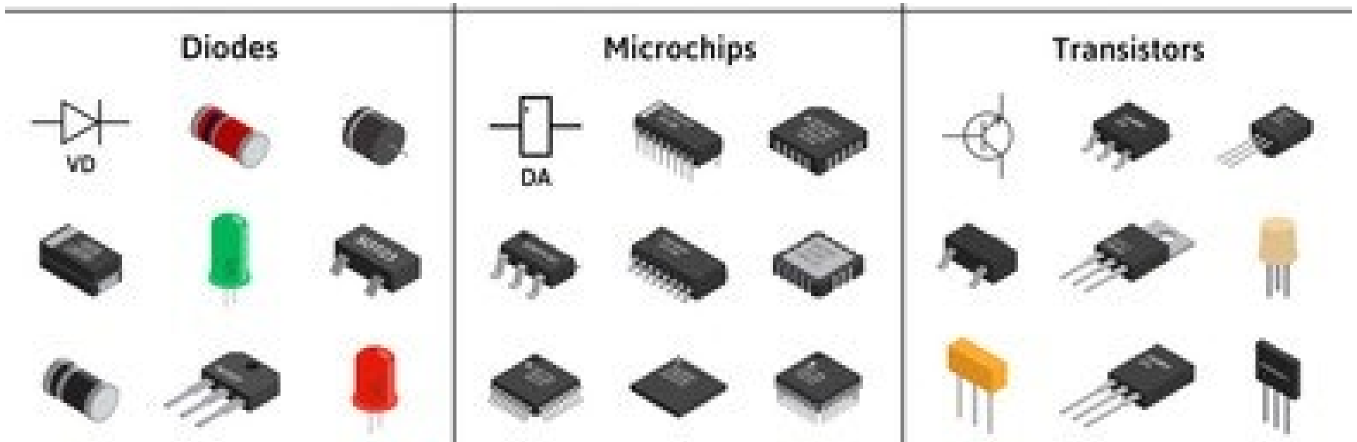
Agenda

- Introduction to analog electronics
- Course overview
  - Contents
  - Exam
  - Course execution
- Semiconductor & PN junction
- Diode
  - Models
  - I-V, input-output characteristics

What is Analog electronics?

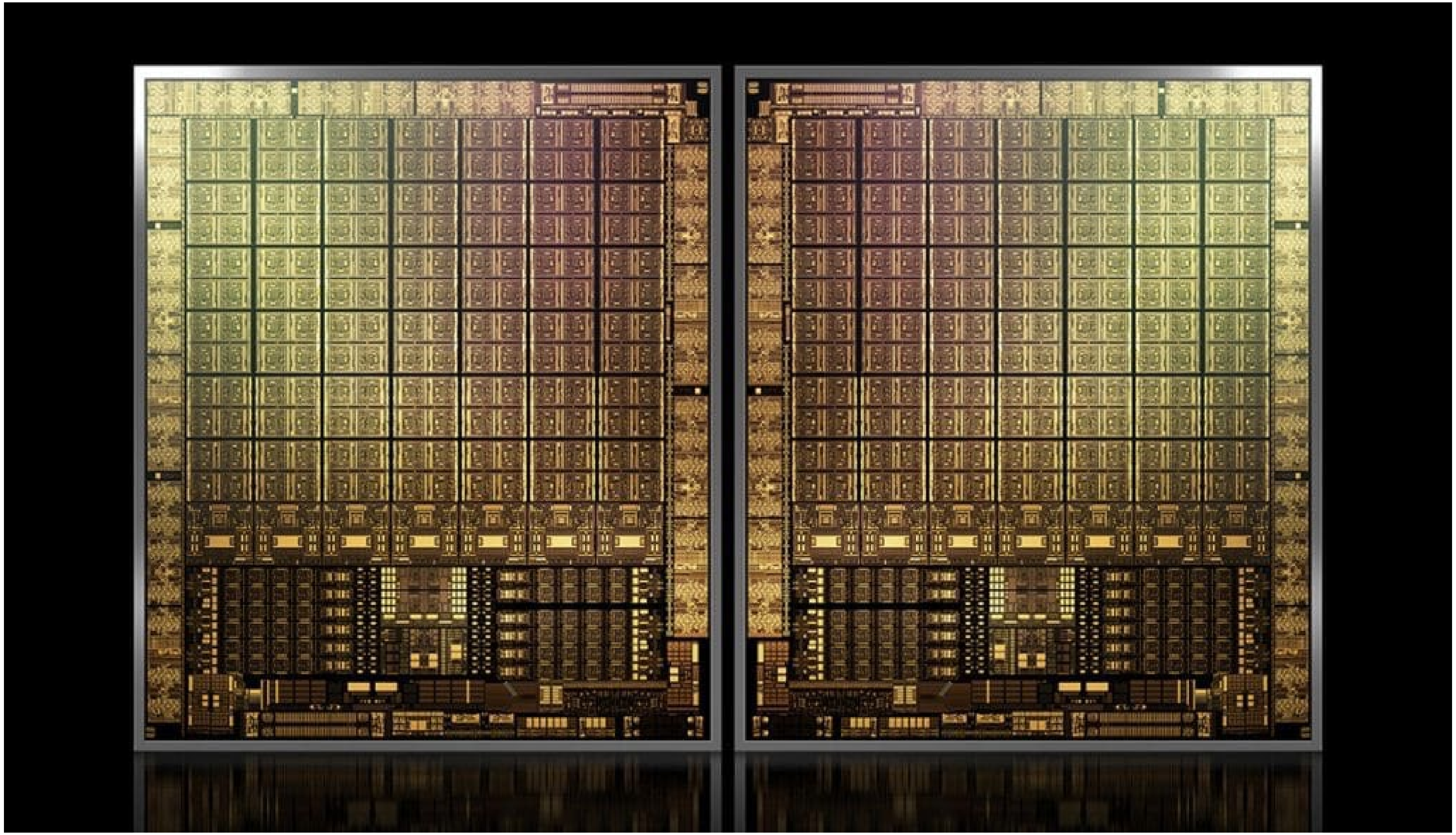
- Deal with continuous signals
  - Capture, process and transmit real-world information
- Basis of many digital components in modern system design





Semiconductor devices

The two graphic processing unit (GPU) chips host 28.3 billion transistors each



Provisional course plan

- Module 1: semiconductor, PN junction and diode
  - 1.1 Course introduction, semiconductors, PN junction, diode models
  - 1.2 Diode circuit principle, practical diode circuits
  - 1.3 Practical diode circuits, small signal model
  - 1.4 Measurement 1
- Module 2: Bipolar Junction Transistor (BJT)
  - 2.1 Structure and operation, properties in various regions, bias, large-signal & small-signal model, early effect
  - 2.2 Common-emitter stage w/o and w/ degeneration, biassing techniques
  - 2.3 Common-base stage, emitter followers
  - 2.4 Hybrid pi model
  - 2.5 Measurement 2

Provisional course plan

- Module 3: Metal-Oxide-Semiconductor Field-Effect Transistor(MOSFET)
  - 3.1 Introduction to MOSFETs, biasing, transconductance
  - 3.2 Large-signal & small-signal operation, NMOS & PMOS
  - 3.3 Common-source stage w/o and w/ degeneration, biasing techniques
  - 3.4 Time harmonic distortion
  - 3.5 Measurement 3

Exam

- Assessment : 7-step scale
- Written exam in June
  - Based on assignments
  - 6 tasks, 2 for each module

Course execution

- Traditional lectures and assignments in groups:
  - Preferably calculate tasks together on the board, bring a notebook and pen.
  - Quizzes during the lecture.
  - It is not important that all assignments are calculated. BUT it is important that you understand the principles!
  - Simulations: LTspice
- Lab session:
  - Measurements
  - With simulations and measurements, you must always evaluate the results - do they make sense in relation to characteristics of the circuit.

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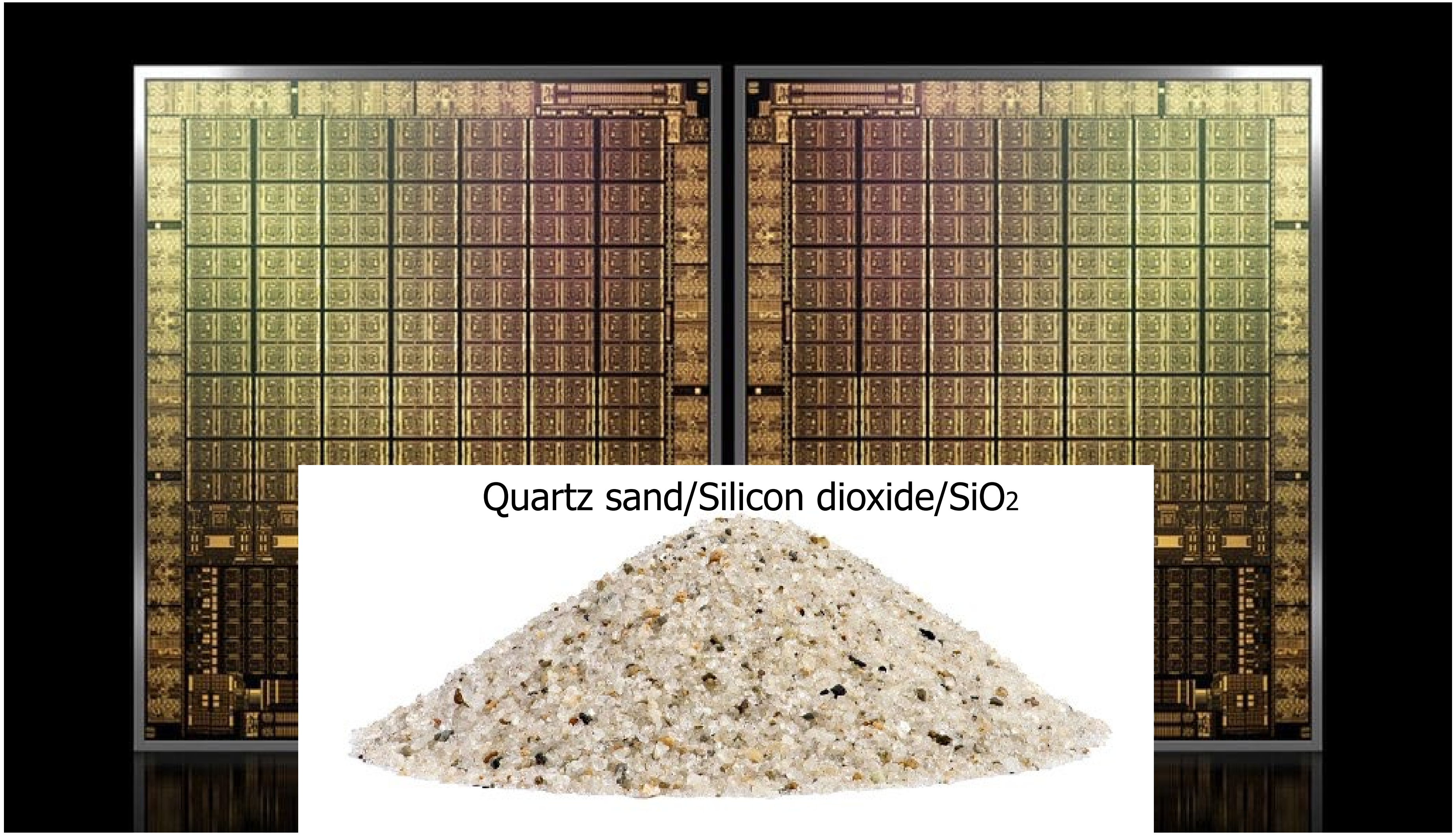
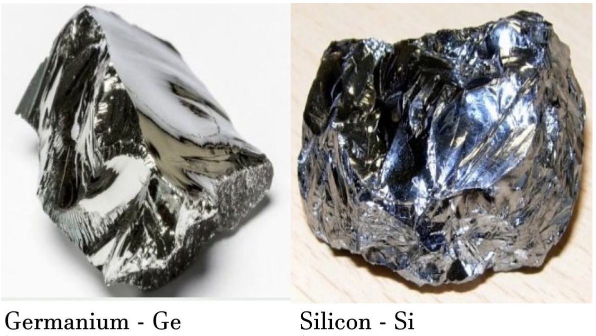
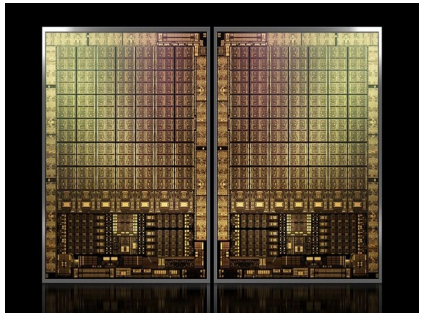
What is the raw material for the GPU chips?



Semiconductors devices



Semiconductor



Semiconductor

Conductivity: ability to allow the flow of electric current

Conductor

Germanium - Ge

Silicon - Si

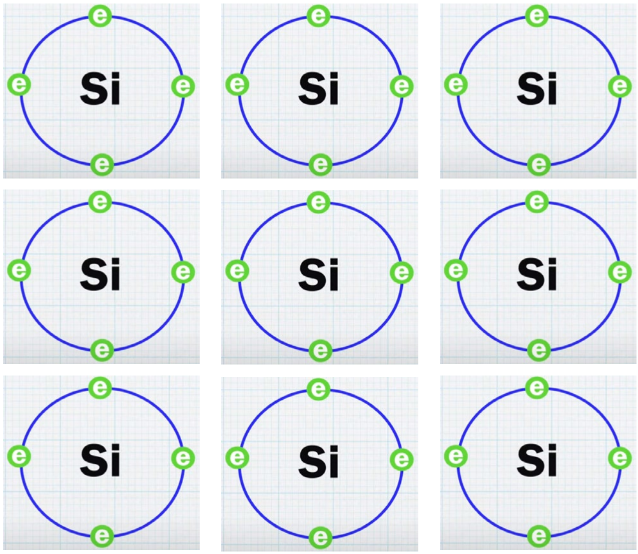
Semiconductor

rubber glass oil diamond wood

Insulators

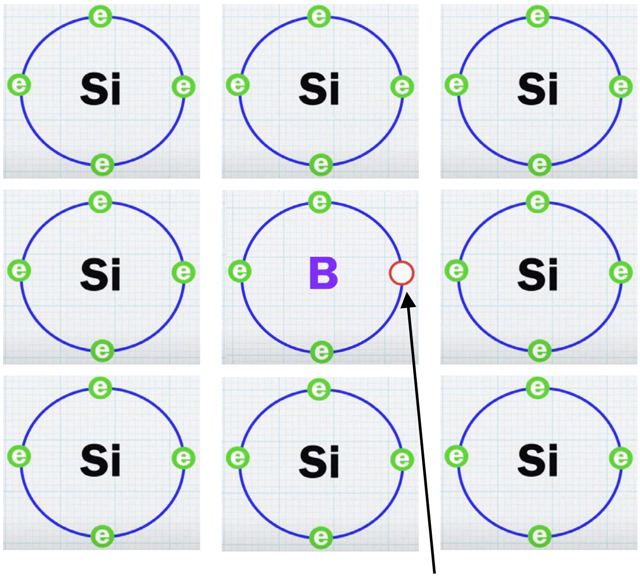
Semiconductor

Intrinsic (Undoped)



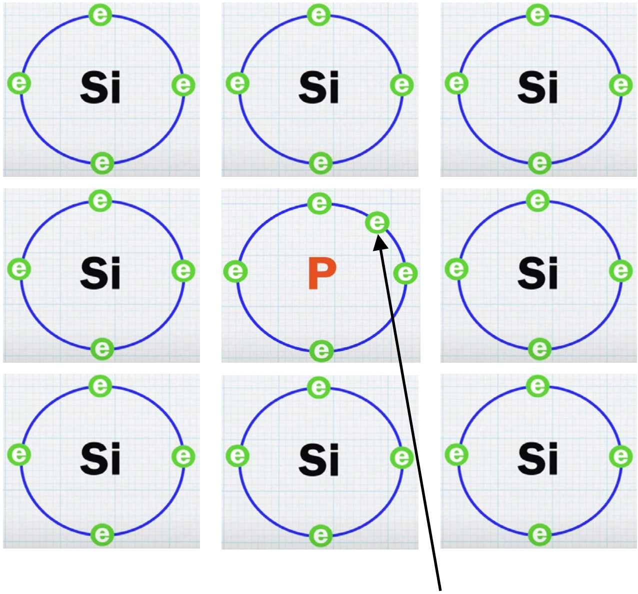
Extrinsic (Doped)

P-Type



B: Boron extra hole

N-Type

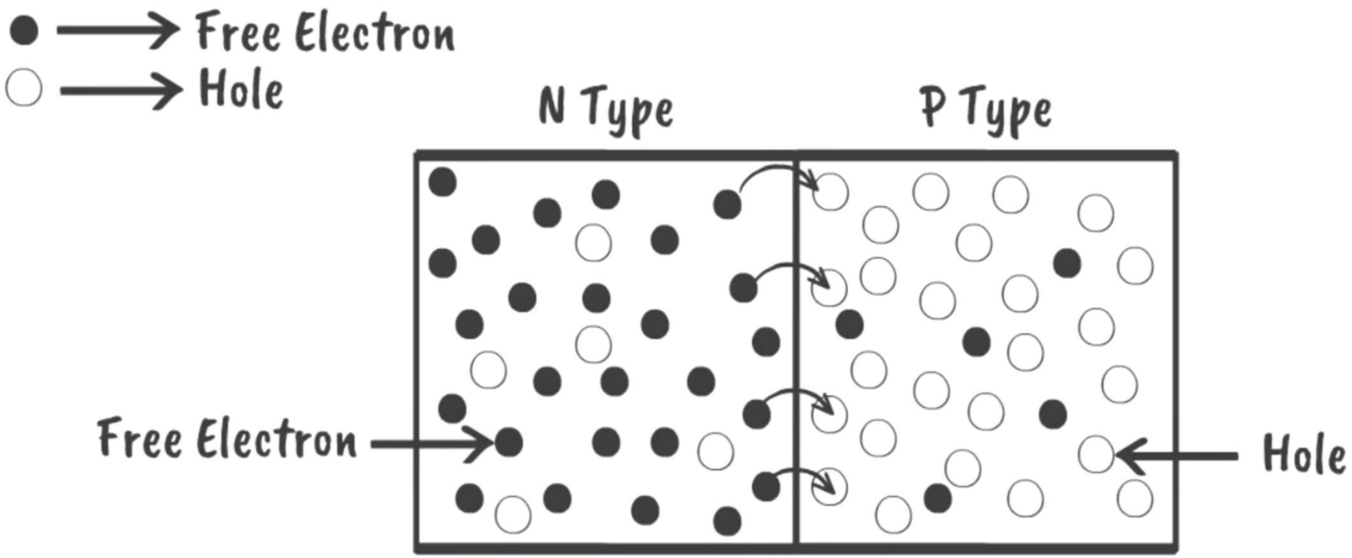


P: Phosphorus extra electron

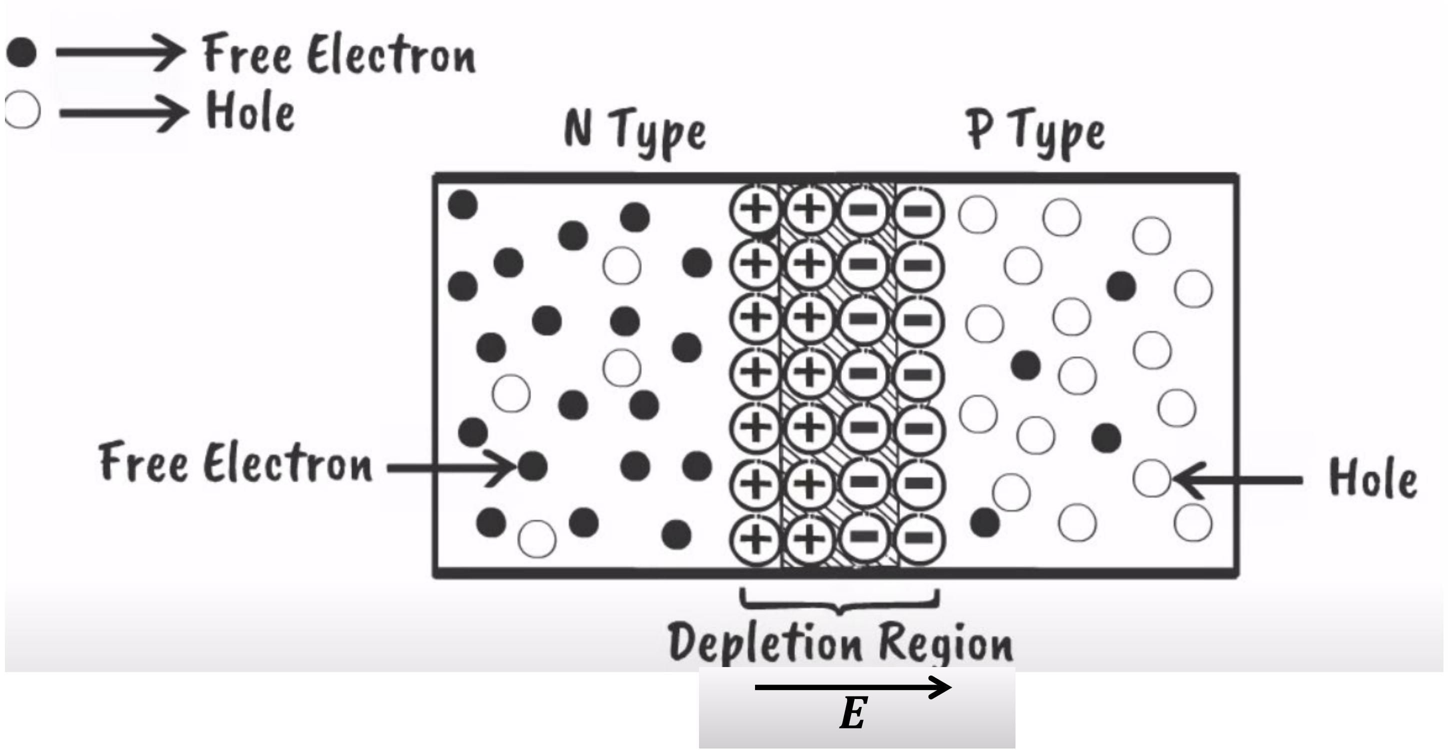
Free electrons / holes : 10^{10}~10^{12} $/cm^3$ $VS.$ 10^{15} ~ $10^{20}/cm^3$ in room temperature.

Both n-type and p-type silicon are more electrically conductive than intrinsic silicon.

PN junction

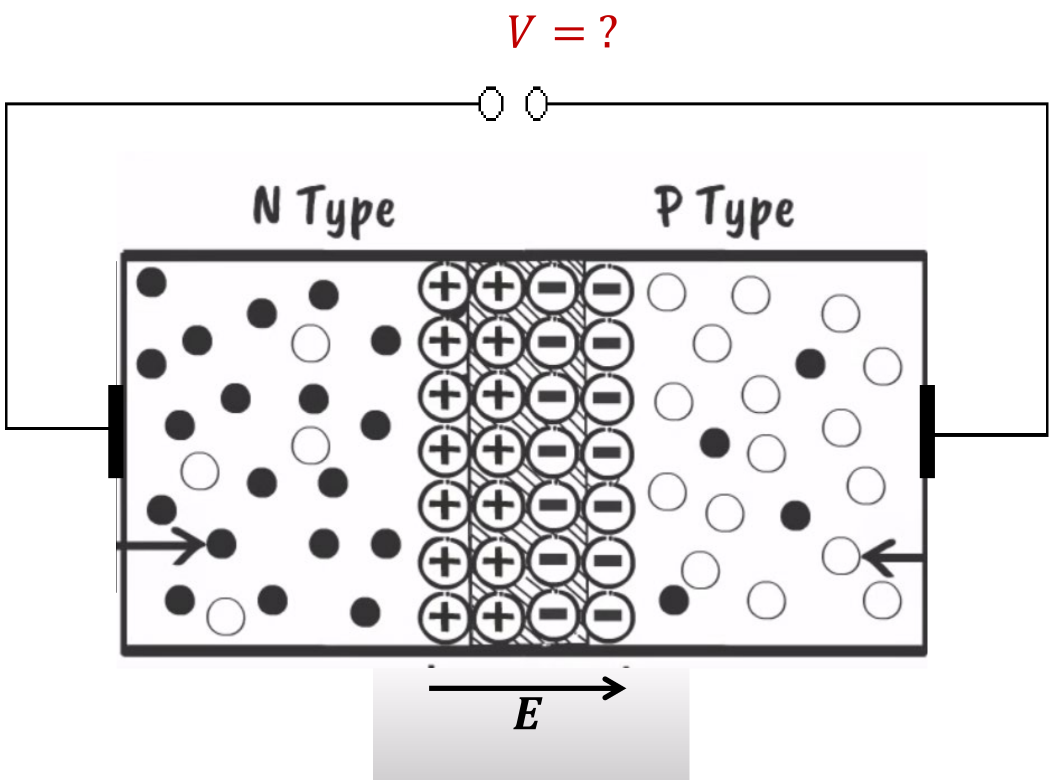


Free Electron
Hole
N Type
P Type
Free Electron
Hole



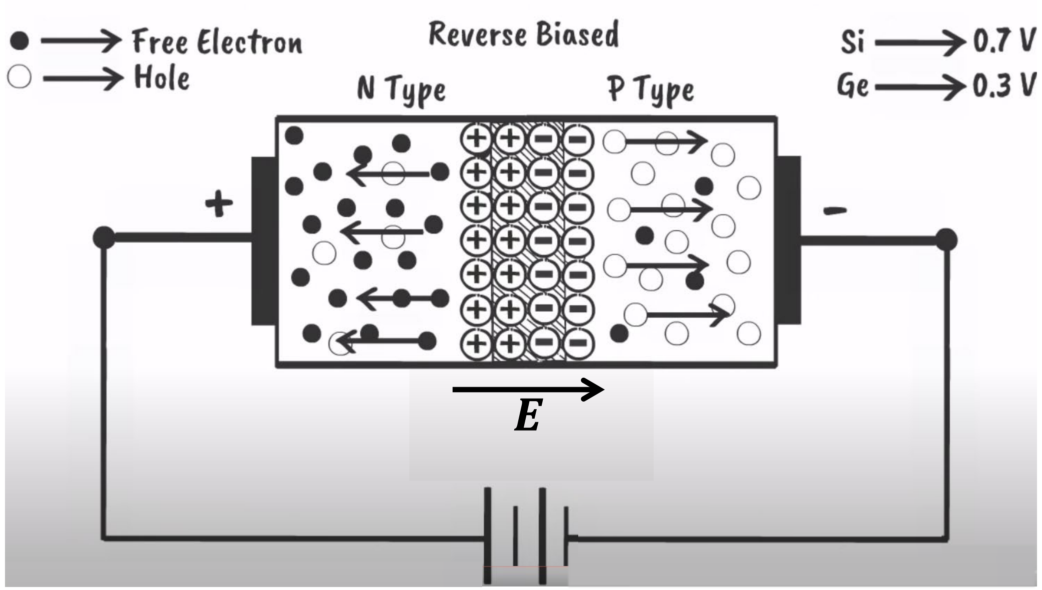
Free Electron
Hole
N Type
P Type
Free Electron
Hole
Depletion Region
E

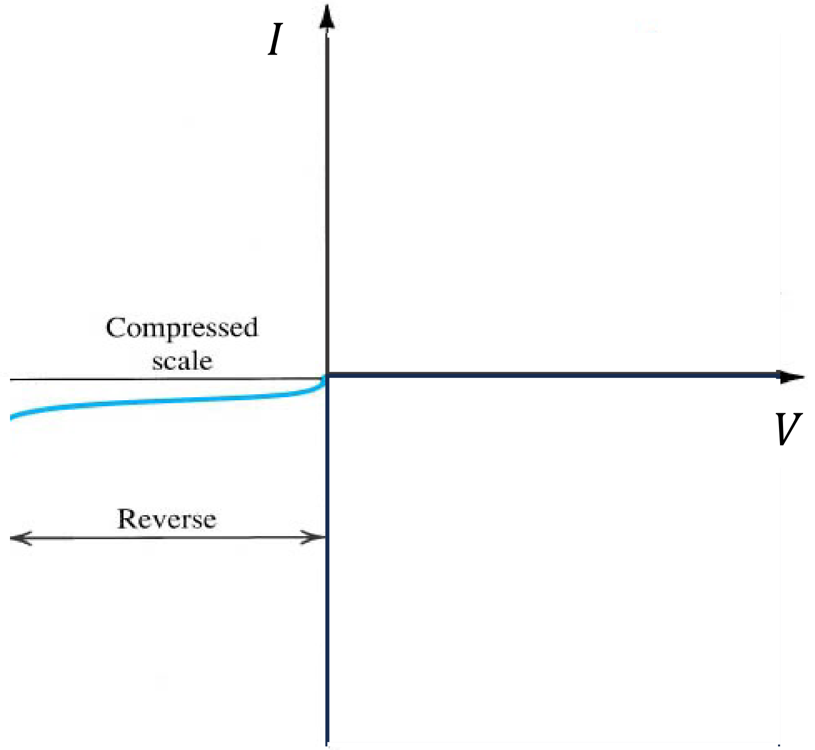
Quiz



When the PN junction terminals are left open, what will V be?

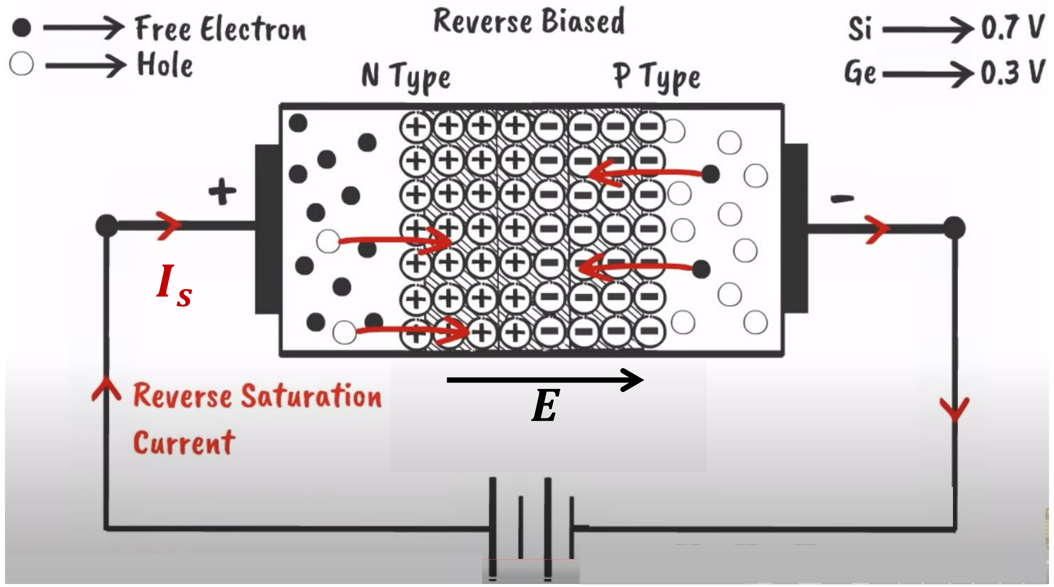
PN junction- reverse bias



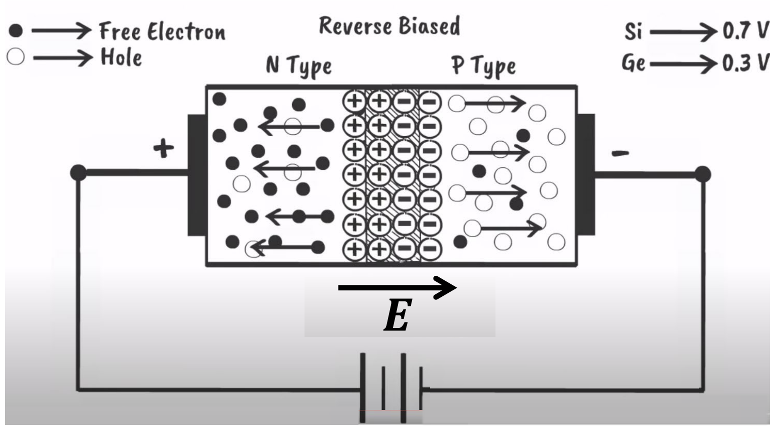


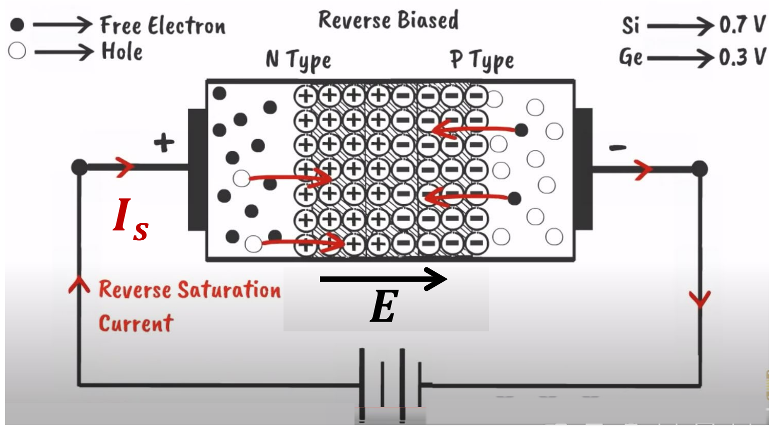
- free electrons drawn to the positive potential→ more ⊕ ions
- Holes drawn to the negative potential → more ⊖ ions

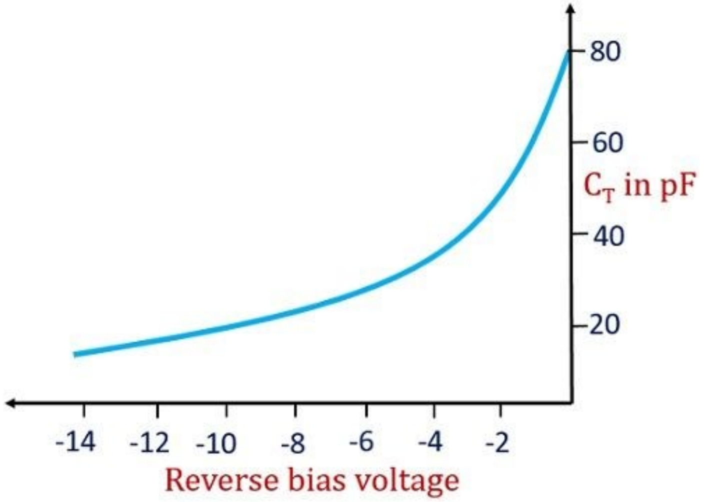
→ Wider depletion region

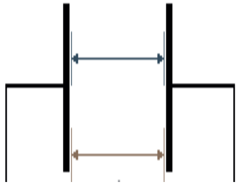


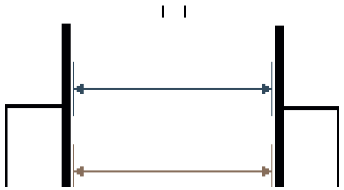
PN junction- reverse bias







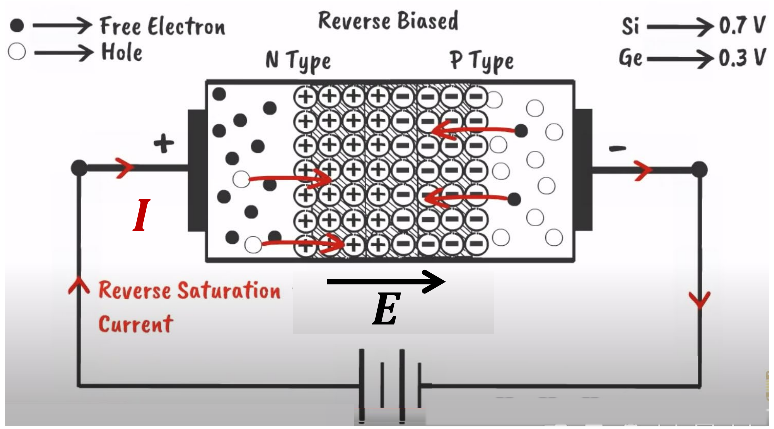


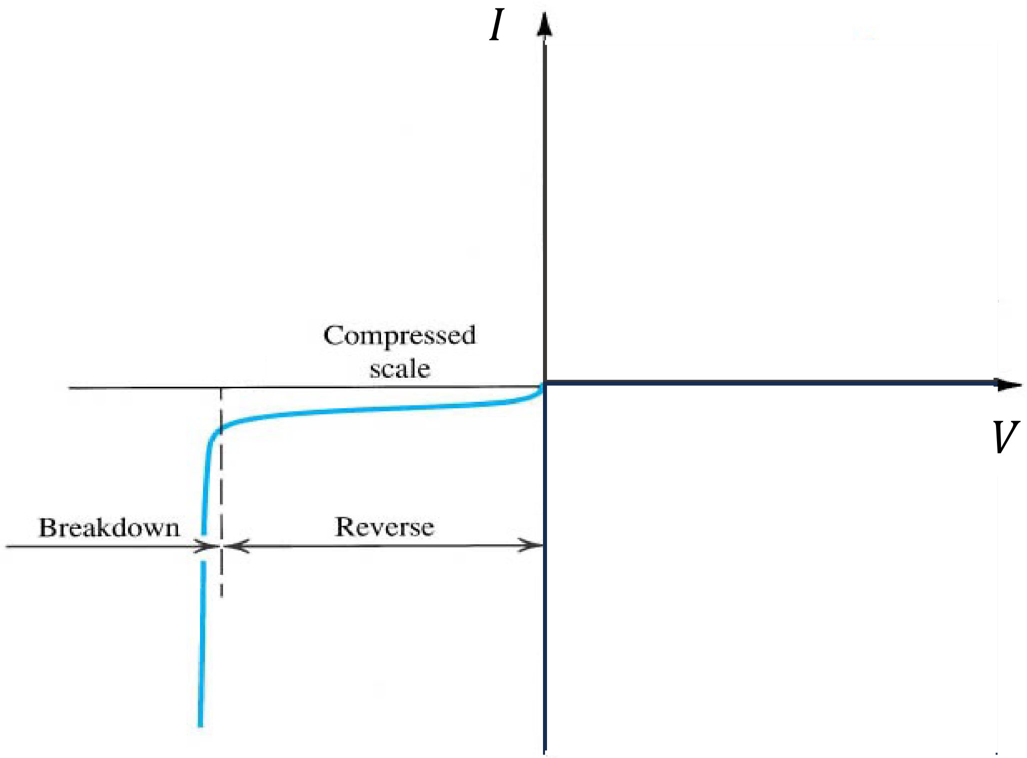


Varactor: a capacitor whose capacitance can be controlled by a voltage

Application: oscillators

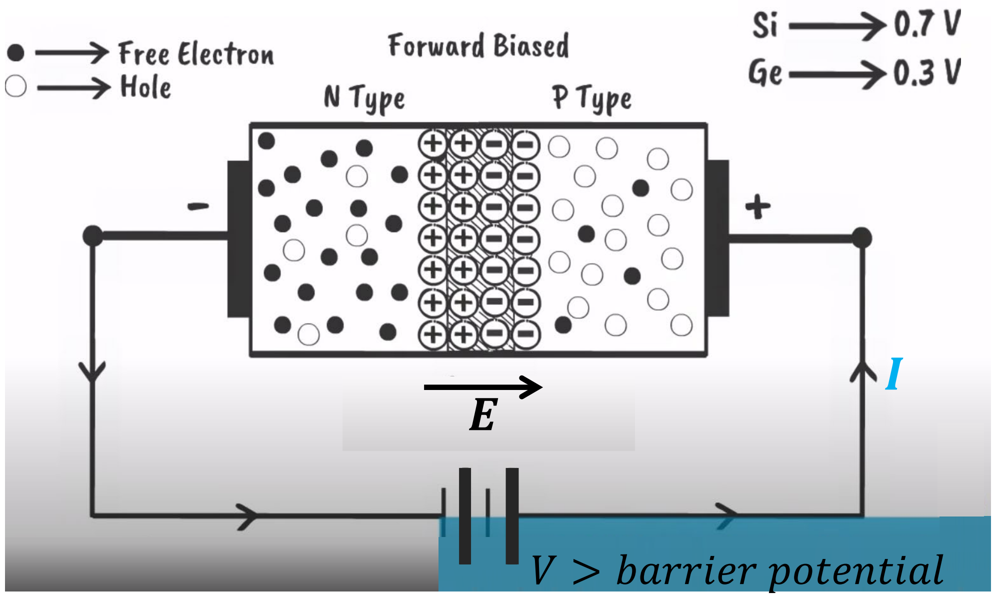
PN junction- reverse breakdown

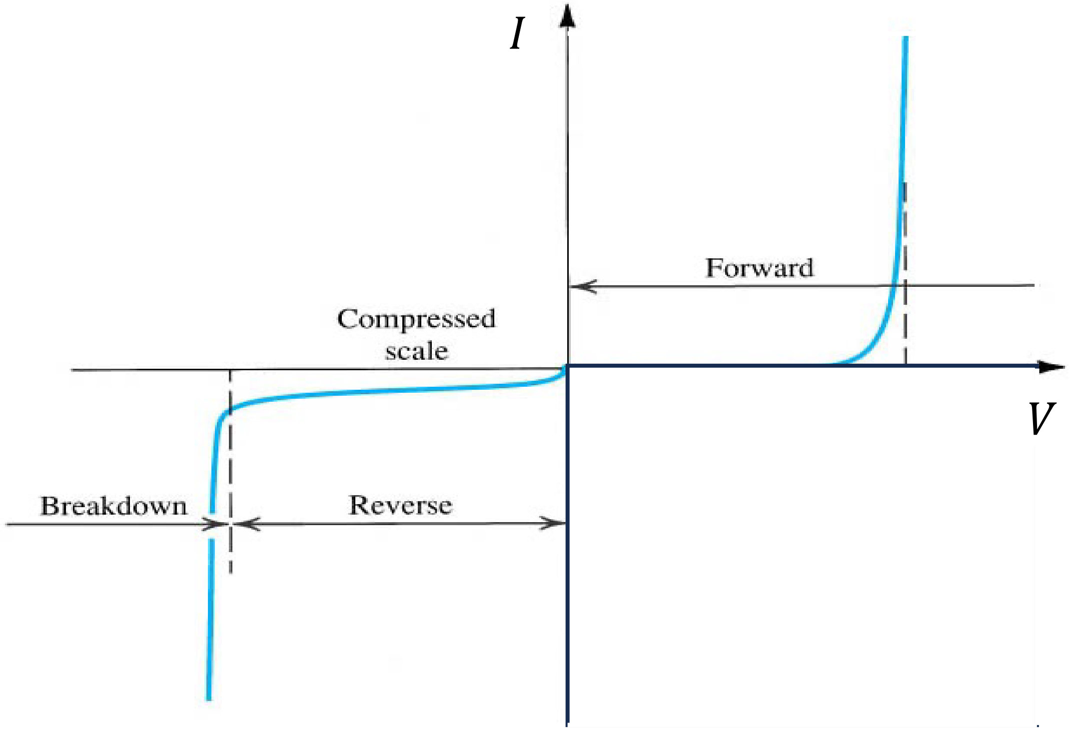




- When V becomes very negative, PN junction is broken down.
- Limit the reverse current to avoid damage
- Application: Zener diode

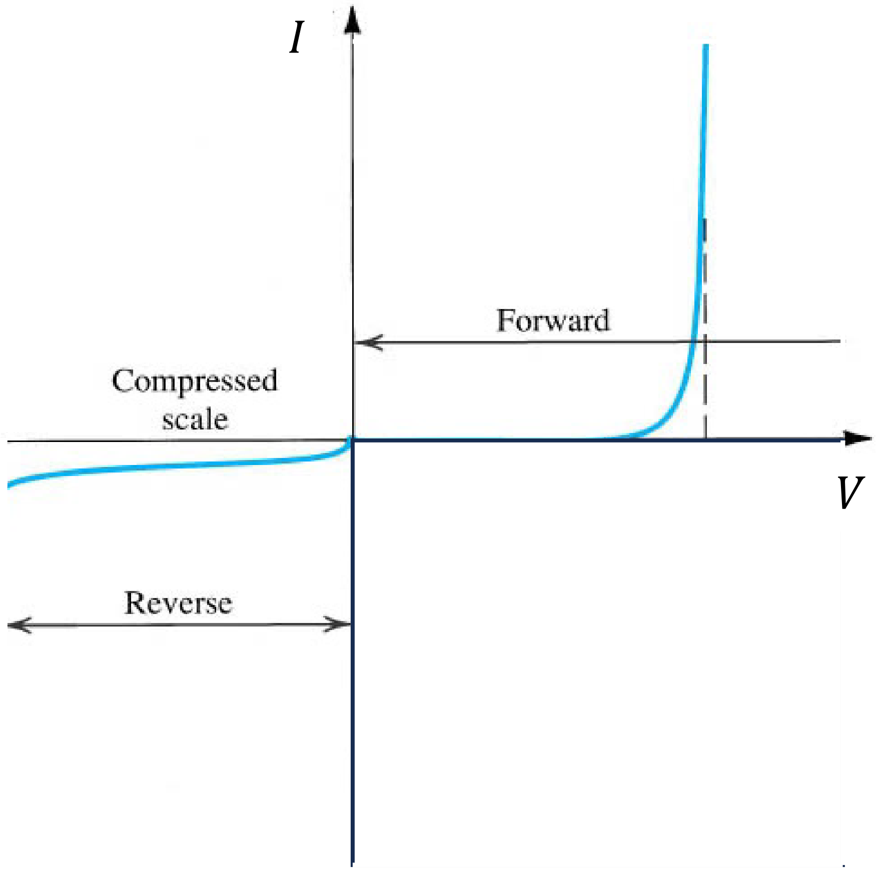
PN junction- forward bias





- Battery V pushes the free electrons (majority charge carrier) from N to P.
- As long as the battery can provide current, the current can flow from P to N.
- The current increases dramatically as V increases.
- A 'fully conducting' diode → voltage drop is 0.6 V ~0.8 V

PN junction- Shockley's equation



$$I = I_s\left(e^{\frac{V}{nV_T}} - 1\right)$$

For anything with PN junctions

I_s : reverse saturation current, given in datasheet
V: voltage across the junction
n: ideal factor, depending on the construction of the PN junction, $1 < n < 2$, $n = 1$ for ideal PN junction
V_T: thermal voltage

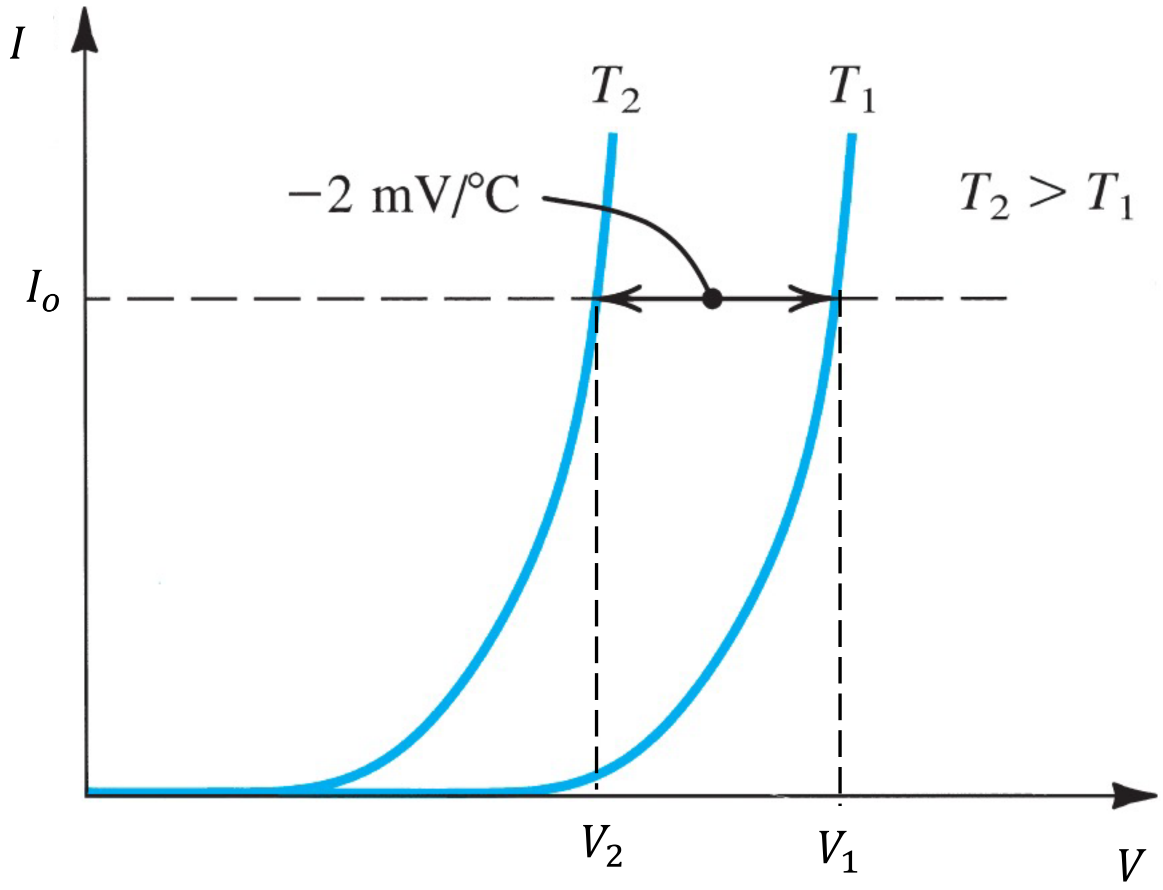
$$V_T = \frac{KT_K}{q}$$

K: Boltzmann's constant = 1.38×10^{-23} J/K
T_K: the absolute temperature in kelvins = 273 + x °C
q: the magnitude of electronic charge = 1.6×10^{-19} C
$V_T \approx$ 26 mV @ 27 °C

I_s and V_T are temperature dependent.
I_s doubles for every 5°C rise in temperature.

PN junction-temperature coefficient

$$\text{Temperature coefficient} = \left.\frac{\Delta V}{\Delta T}\right|_{I=I_o} = \left.\frac{V_2-V_1}{T_2-T_1}\right|_{I=I_o}$$



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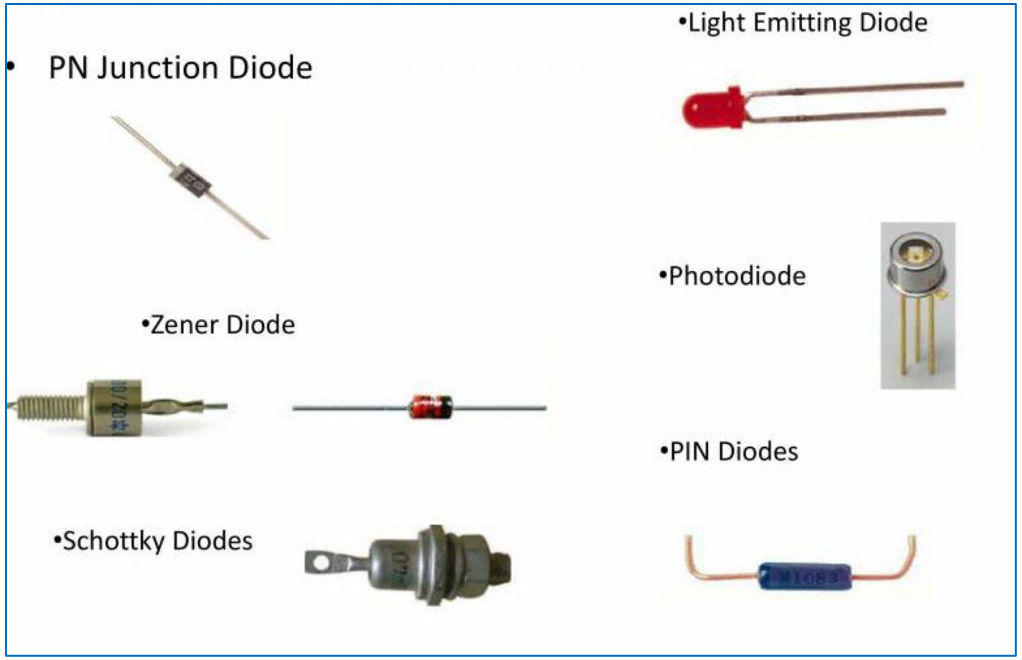
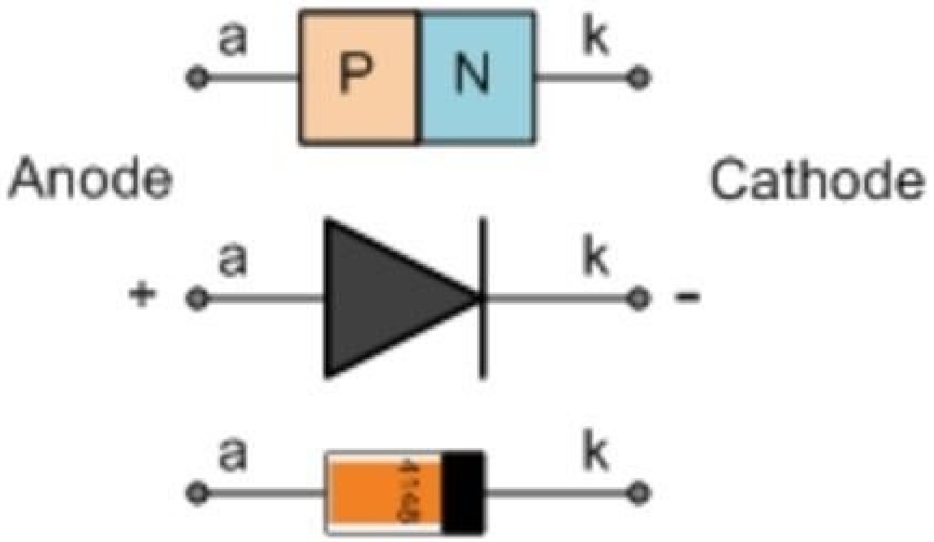
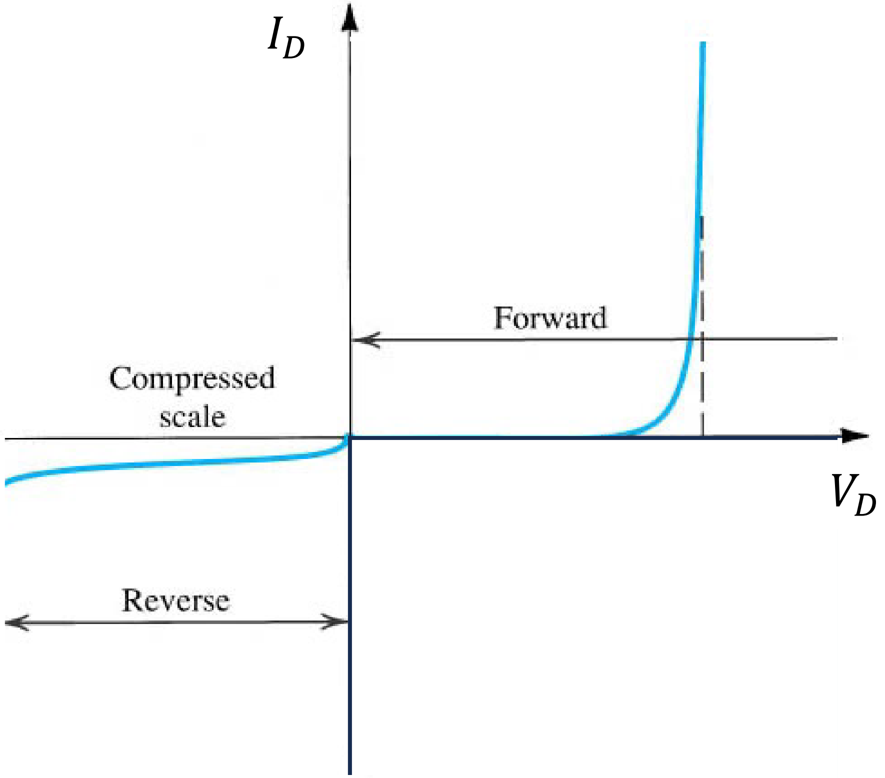
Diode

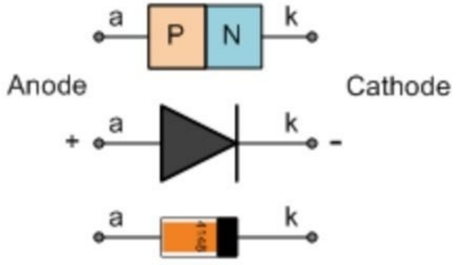
- A 2-terminal device 'passes' positive voltage & 'blocks' negative voltage
- A PN junction is a fundamental example of a diode.





PN diode





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

- I_s : reverse saturation current, given in datasheet
- V_D: voltage across the diode
- n: ideal factor, depending on the diode's construction, $1 < n < 2$, $n = 1$ for ideal diode
- V_T: thermal voltage, $V_T \approx 26$ mV @ 27 °C

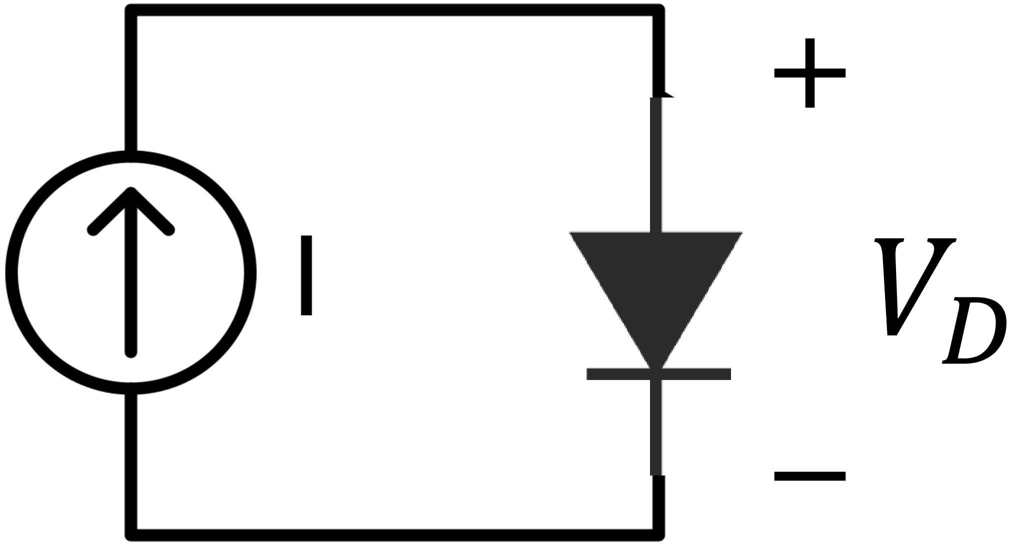
When a diode is forward-biased:

$$I_D \approx I_s\, e^{\frac{V_D}{V_T}}$$

- For $V_D \gg V_T$ ($V_D > 4V_T$ in practice), $e^4 \approx 54.5$
- $n = 1$

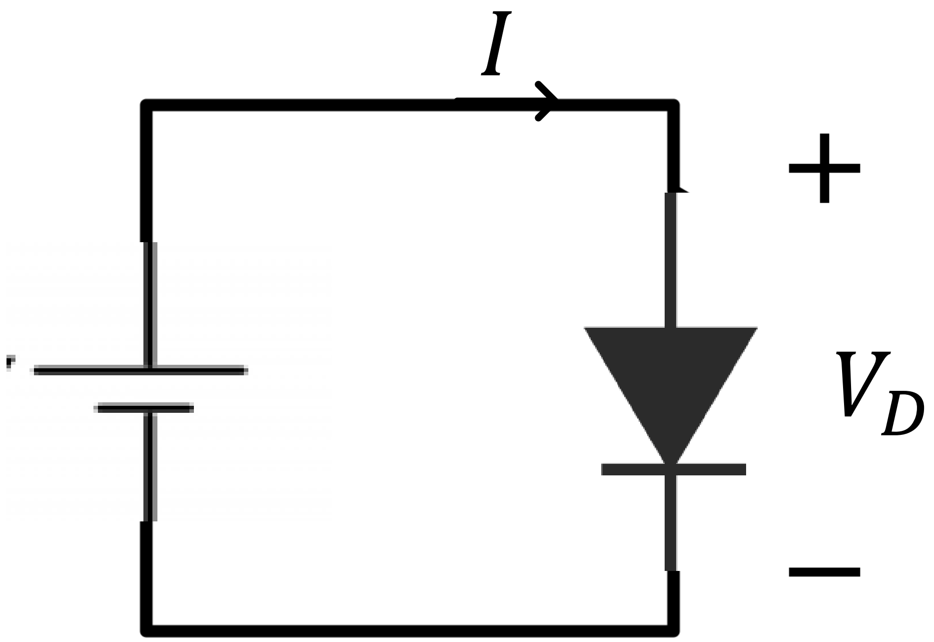
Quiz: PN diode

$I_s = 10^{-16}$A, V_T =26 mV, and $I = 1$ mA,
V_D =?



$I_D \approx I_s\, e^{\frac{V_D}{V_T}}$ holds for both applying a voltage source or a current source.

PN diode



$V_T \approx 26$ mV @ 27 °C

For $I = I_1$, we have $V_D = V_{D1}$.

If we want to achieve $I = I_2 = 10I_1$,
$V_{D_2} = V_{D1} + \Delta V$

ΔV = ?

Diode data sheet

1N4148

- ratings:What the manufacturer guarantees that it can withstand
- Characteristics: Properties

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)

PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
Repetitive peak reverse voltage		V_{RRM}	100	V
Reverse voltage		V_R	75	V
Peak forward surge current	t_p = 1 μs	I_{FSM}	2	A
Repetitive peak forward current		I_{FRM}	500	mA
Forward continuous current		I_F	300	mA
Average forward current	$V_R = 0$	$I_{F(AV)}$	150	mA
Power dissipation	l = 4 mm, T_L = 45 °C	P_{tot}	440	mW
	l = 4 mm, $T_L \leq$ 25 °C	P_{tot}	500	mW

$I_D V_D <$ power dissipation

THERMAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)

PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
Thermal resistance junction to ambient air	l = 4 mm, T_L = constant	R_{thJA}	350	K/W
Junction temperature		T_j	175	°C
Storage temperature range		T_{stg}	-65 to +150	°C

Diode data sheet

- Characteristics: Properties

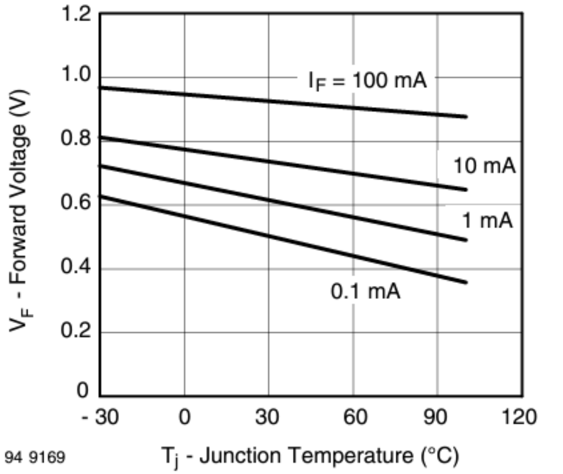


Fig. 1 - Forward Voltage vs. Junction Temperature

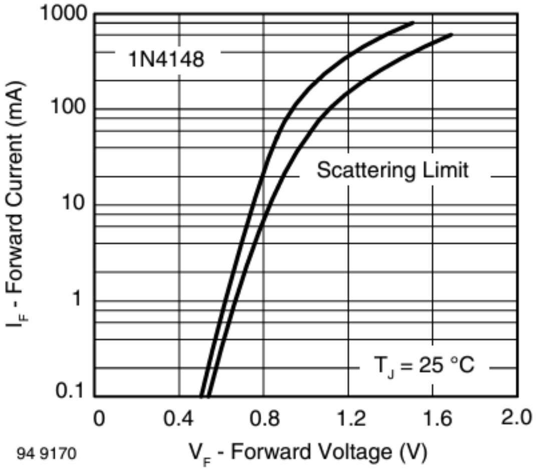


Fig. 2 - Forward Current vs. Forward Voltage

ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	**TEST CONDITION**	**SYMBOL**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
Forward voltage	I_F = 10 mA	V_F			1	V
Reverse current	V_R = 20 V	I_R			25	nA
	V_R = 20 V, T_j = 150 °C	I_R			50	µA
	V_R = 75 V	I_R			5	µA
Breakdown voltage	I_R = 100 µA, t_p/T = 0.01, t_p = 0.3 ms	$V_{(BR)}$	100			V
Diode capacitance	V_R = 0 V, f = 1 MHz, V_{HF} = 50 mV	C_D			4	pF
Rectification efficiency	V_{HF} = 2 V, f = 100 MHz	η_r	45			%
Reverse recovery time	$I_F = I_R$ = 10 mA, i_R = 1 mA	t_{rr}			8	ns
	I_F = 10 mA, V_R = 6 V, $i_R = 0.1 \times I_R$, R_L = 100 Ω	t_{rr}			4	ns

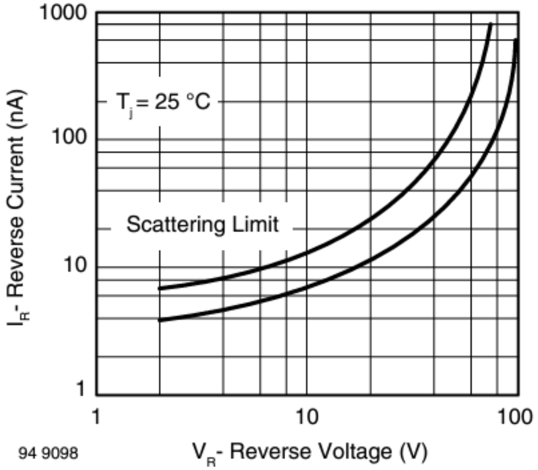
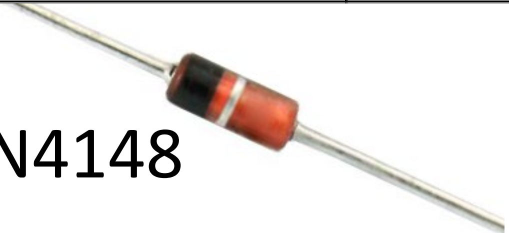


Fig. 3 - Reverse Current vs. Reverse Voltage



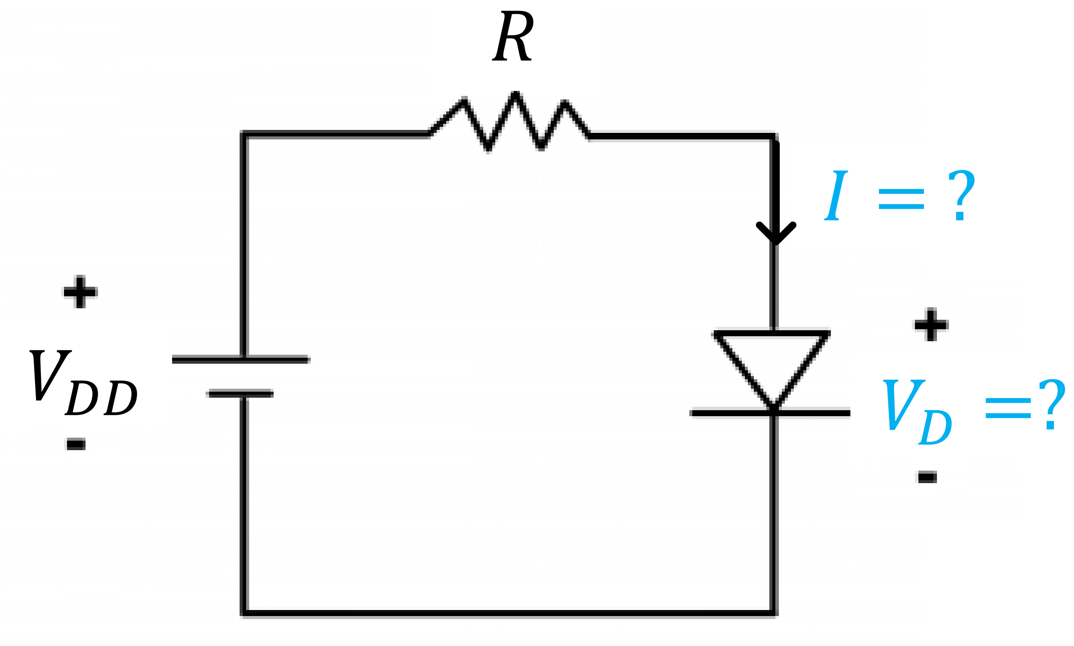
1N4148

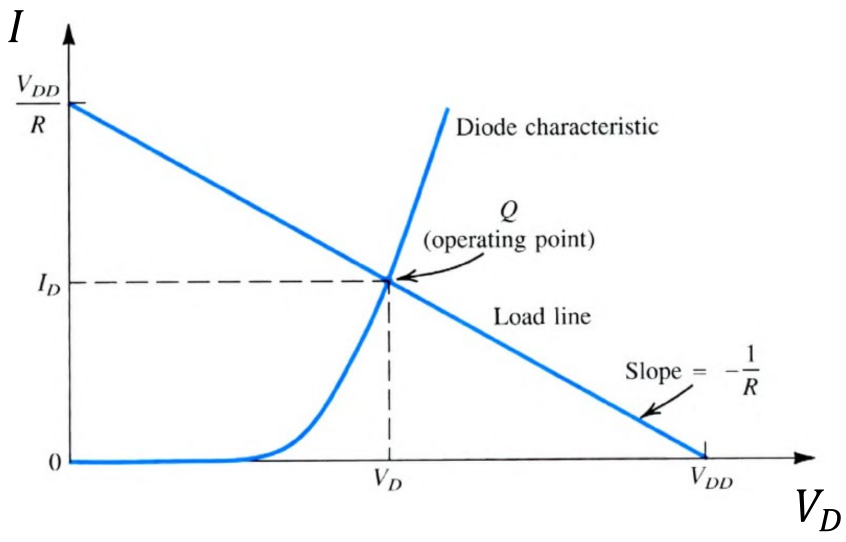
LTspice simulation

- **Extract** of Spice parameters for diode
  - Some parameters are disabled by default
  - Default temperature 27℃= 300 K

Spice symbol	**S & S symbol**	**Unit**	**Default value**	**1N4148** Motorola	**Description**
ICE	In_S	A	1e-14	2.52 n	Saturation current
N	n	-	1	1,752	Emission coefficient
RS	$R._S$	Ω	0	0.568	Ohmic resistance
VJ	V_0	V	1		Built-in potential
CJ0	C_{j0}	F	0	4 p.m	Zero-bias depletion cap.
M	m	-	0.5	0.4	Grading coefficient
TT	τ_T	p	0	20 n	Transit time
BV	V_{ZK}	V	inf.		Breakdown voltage
IBV	In_{ZK}	A	reach		Reverse current @ V_{ZK}

PN diode

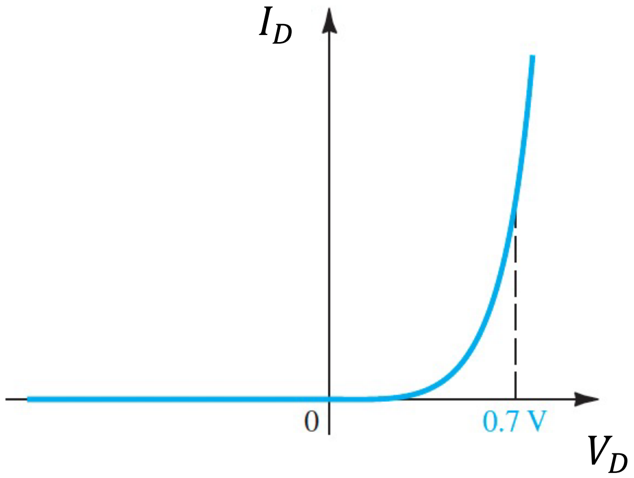




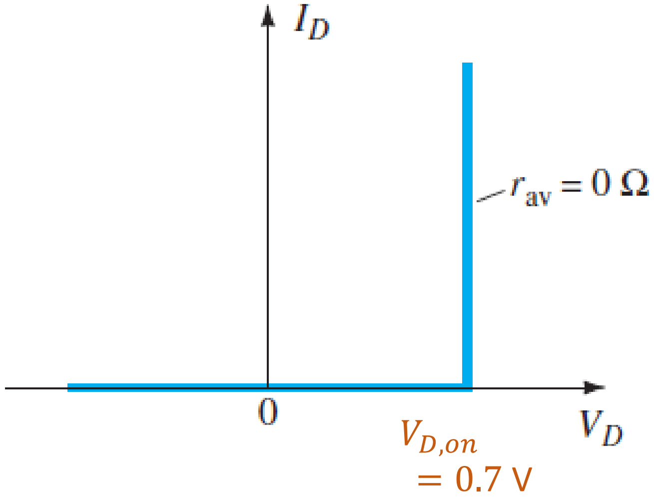
Can we solve the circuit by hand?

PN diode models

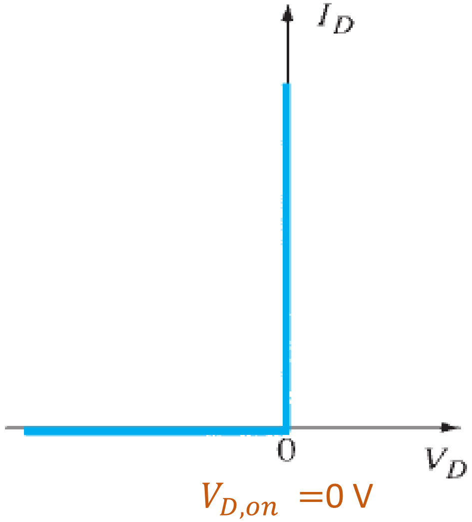
Exponential model
(usage rate =10-20%)



Constant voltage drop model
(usage rate = 70-80%)

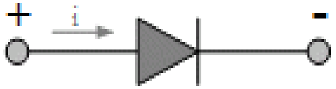


Ideal model
(usage rate =10-20%)

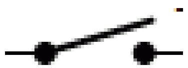


$$I_D \approx I_s\, e^{\frac{V_D}{V_T}}$$

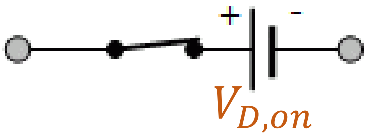
The diode has two states:



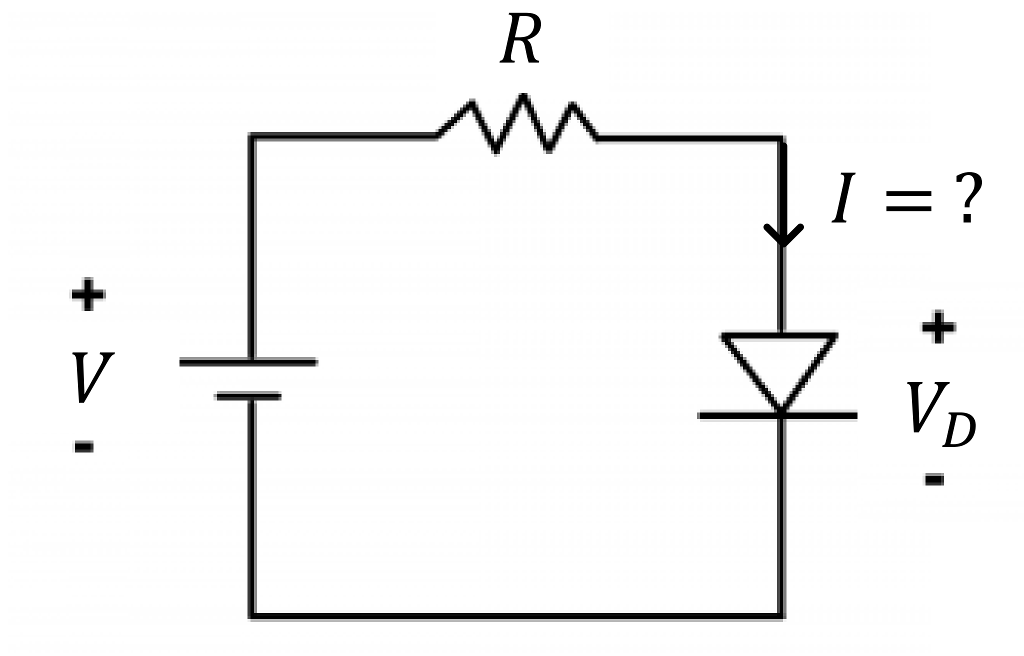
- $V_D < V_{D,on}$ → diode is off → open circuit

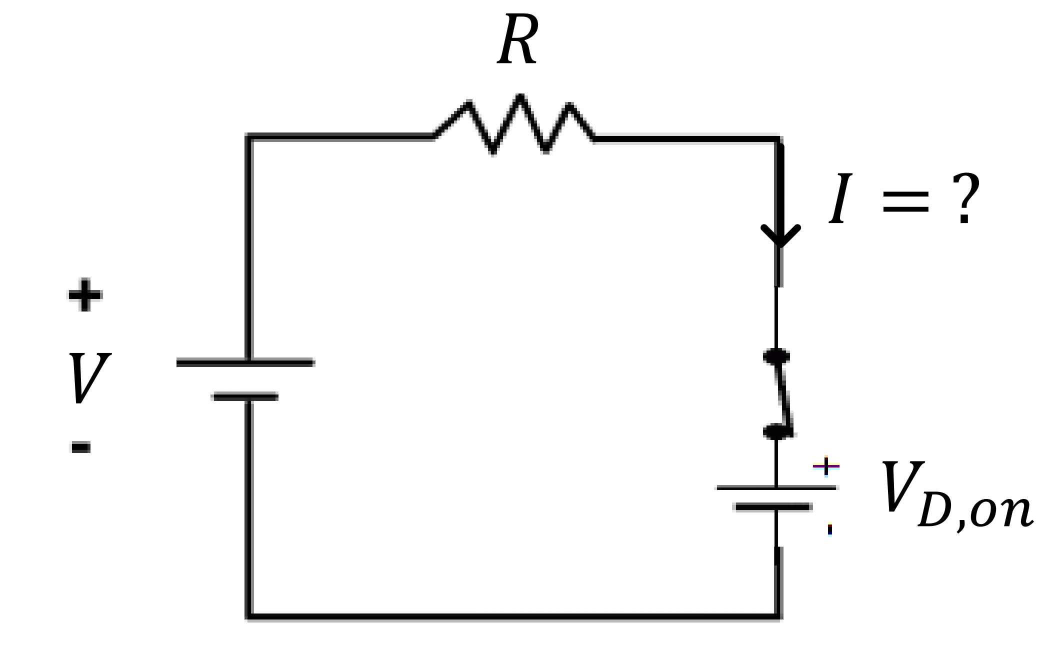


- $V_D \geq V_{D,on}$ → diode is on → a voltage drop



PN diode circuit



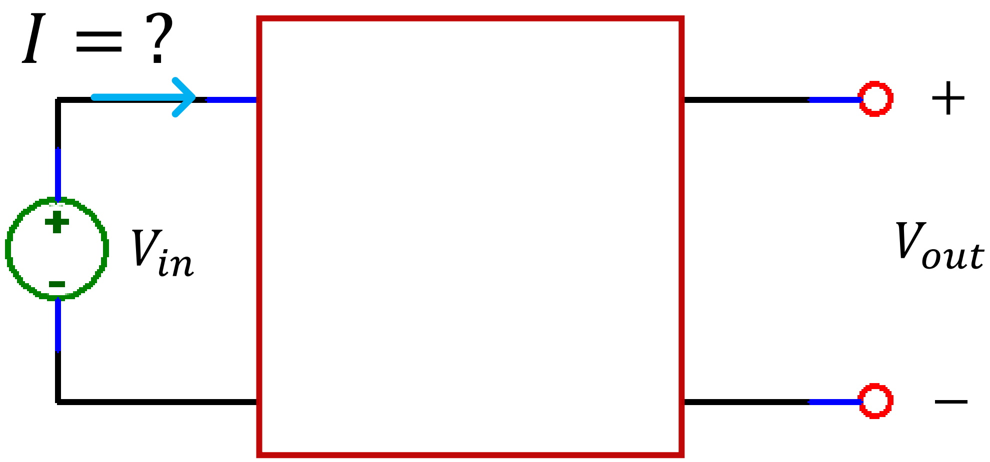


Assuming the constant voltage drop model, can we solve the circuit by hand?

$$I = \frac{V - V_{D,on}}{R}$$

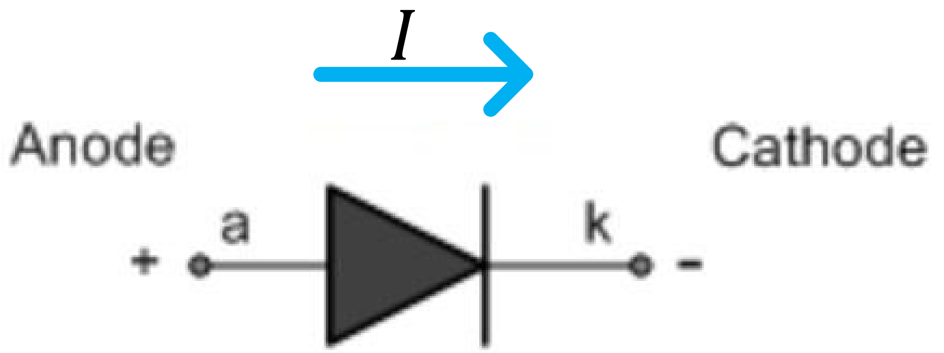
Types of characteristics for circuits

- I-V characteristics
- Input-output characteristics
- Time response

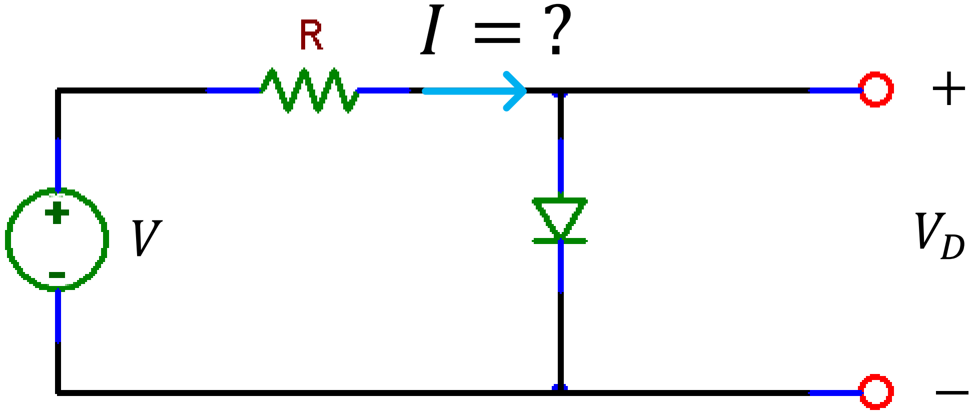


Principle of diode circuit analysis

- Begin by assuming a certain state of diodes, i.e., on or off, check the final results against these assumptions.
- If a diode is about to turn on or off, it must sustain a voltage of $V_{D,on}$, but the current flowing through it is small, i.e., approximating 0 A
- If a diode is on and carries a current, the current must flow from the anode to the cathode, i.e., along the direction of the arrow.

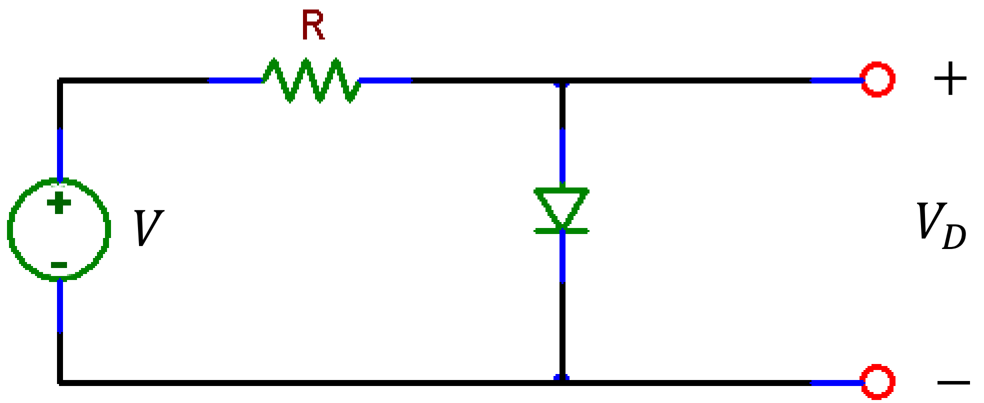


PN diode circuit—I-V



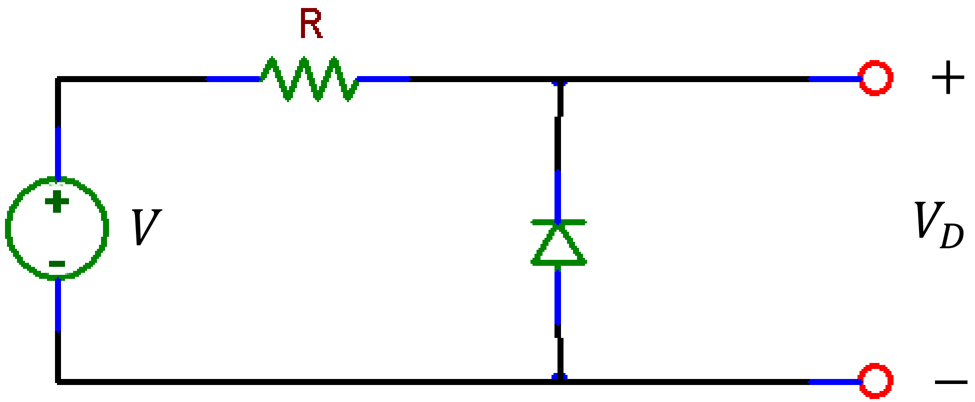
Assuming the constant voltage drop model, plot the I-V curve for the diode in reverse and forward bias regions.

PN diode circuit – input-output



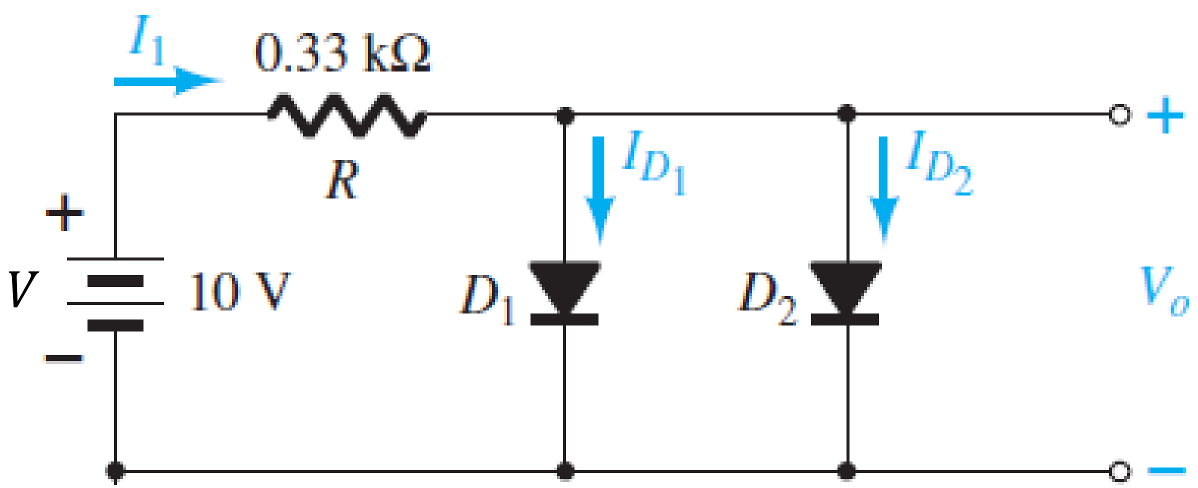
Assuming the constant voltage drop model, plot the $V_D - V$ curve for the diode in reverse and forward bias regions.

Quiz: PN diode circuit – input - output



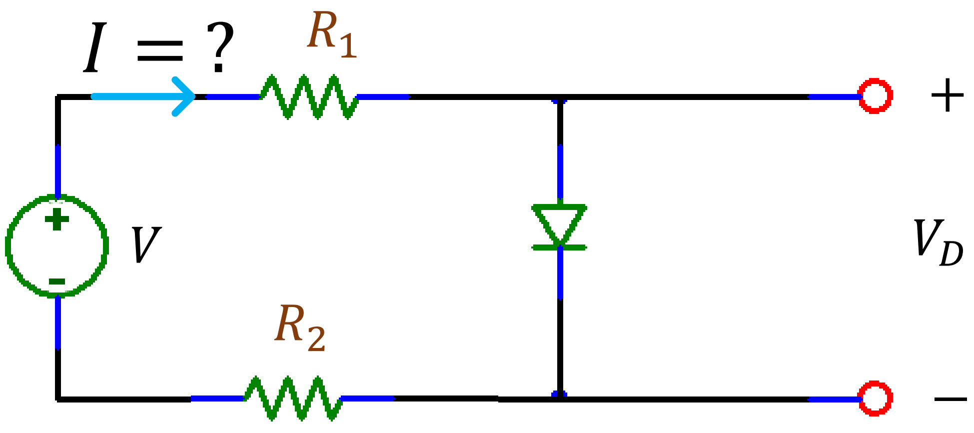
Assuming the constant voltage drop model and flip the diode upside down, plot the $V_D - V$ curve for the diode in reverse and forward bias regions.

Example



Assuming the constant voltage drop model and the diode in reverse and forward bias regions, I_1 , I_{D1}, I_{D2} and V_o = ?

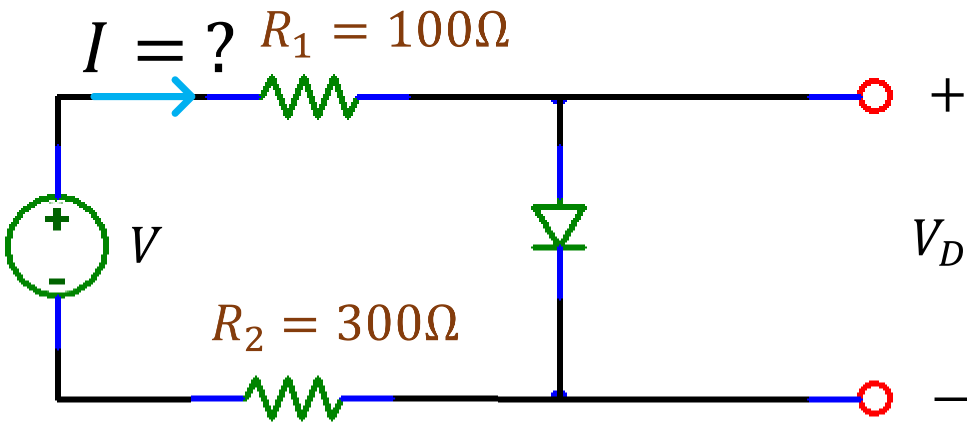
PN diode circuit



Assuming the constant voltage drop model and the diode in reverse and forward bias regions,

- plot the I-V curve
- Plot the V_{R1}-V curve
- Plot the V_D-V curve
- Plot the V_{R2}-V curve

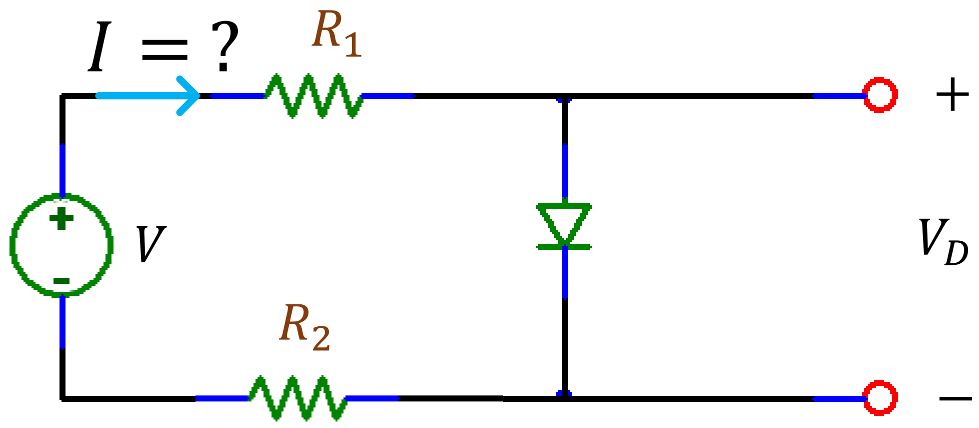
Quiz: PN diode circuit



Assuming the constant voltage drop model and the diode in reverse and forward bias regions, the diode is on or off? I=? V_{R1}=? V_D=? V_{R2}=?

- When V = 0.5 V
- When V = 0.7 V
- When V = 2 V

PN diode circuit--LTspice



Assuming the constant voltage drop model and the diode in reverse and forward bias regions,

- plot the I-V curve
- Plot the V_{R1}-V curve
- Plot the V_D-V curve
- Plot the V_{R2}-V curve