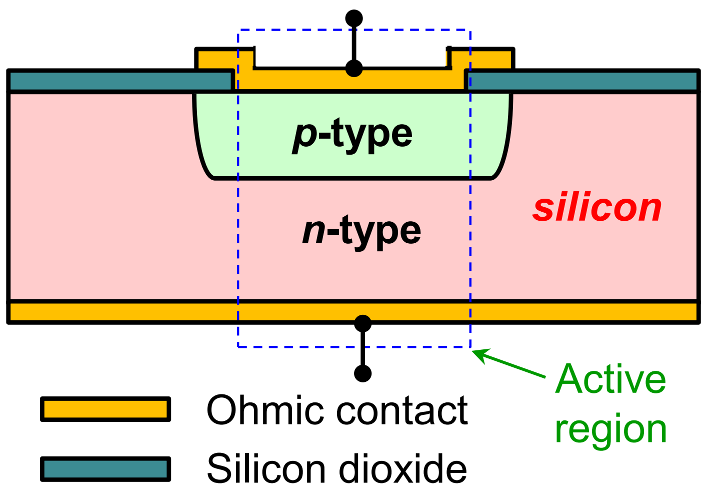
Diode (Semiconductor pn-Junction)

1. Introduction
2. Operation Regions: Forward-Bias, Reverse-Bias, and Breakdown
3. Current-Voltage Characteristic
4. Modeling the Diode: Large-Signal Model and Small-Signal Model
5. The Diode Circuit(s): Rectifier and Voltage Regulator
6. Charge Stored and Capacitive Effect

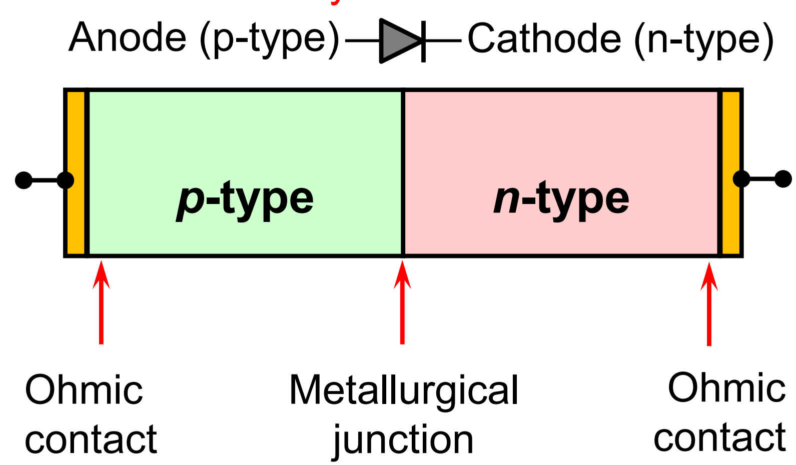
Reference

❑ A.D. Sedra & K.C. Smith, "Microelectronic Circuits – Theory and Application", 5th Edition (International Version), Oxford University Press, Chapter 2.

Diode – Introduction (Structure)



Realistic cross-section of fabricated silicon *pn*-junction diode



Simplified structure (active region) & circuit symbol of a semiconductor *pn*-junction.

The diode to be discussed is a semiconductor *pn*-junction.

- Made using a single crystal semiconductor (typically silicon), with impurities added to one side to contain many negative charge carriers (electrons), called an *n*-type semiconductor; and to the other side to contain many positive charge carriers (holes), called a *p*-type semiconductor.
- In a semiconductor, there are two types of charge carriers: electrons (with charge of -1.602×10^{-19} C) and holes (with charge of $+1.602\times10^{-19}$ C). This is in contrast to metals, which have only electrons.

Diode – Introduction (Semiconductor)

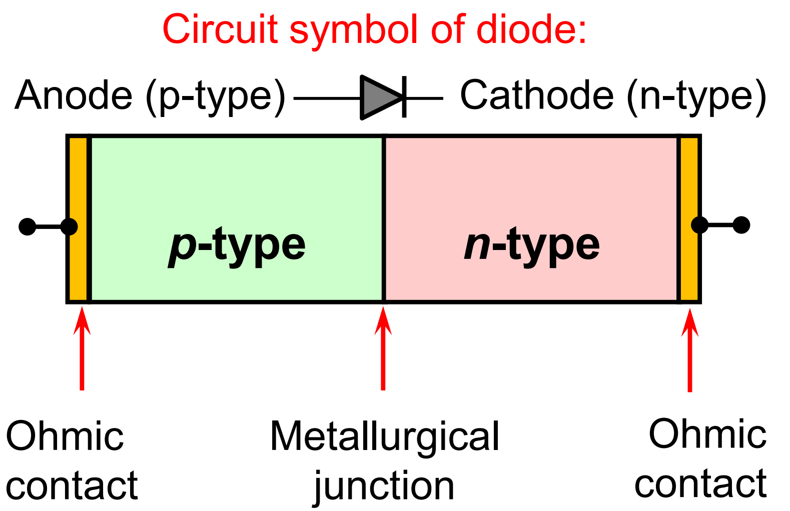
- Semiconductors have electrical conductivities (or resistivity) between that of metals (conductors) and insulators.
- Unlike metal and insulator, a unique property of semiconductor is that impurities can be added (in a controlled manner) into it –
  - to make it *n*-type or *p*-type, and
  - to change its conductivity (or resistivity) and carrier concentration.

$\boxed{R = \rho \frac{l}{A}}$

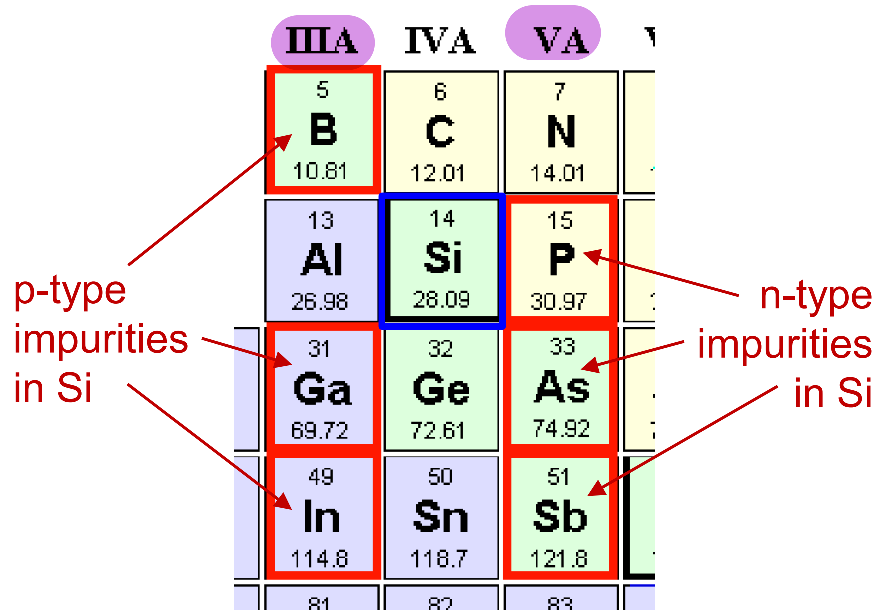
	Material	Typical Resistivity* (Ω-cm)	Typical Carrier Concentration (cm^{-3})
Metal	Copper Gold Aluminum Stainless Steel 316)	1.69×10^{-6} 2.20×10^{-6} 2.67×10^{-6} $70\text{-}78 \times 10^{-6}$	$\sim 10^{23}$ (electron)
Semiconductor	Germanium Silicon Gallium Arsenide	46 2.3×10^{5} 10^{8}	Wide range up $\sim 10^{18\text{-}19}$ (with impurity added)
Insulator	Silicon Nitride Silicon Dioxide Polyimide	10^{14} 10^{14}-10^{16} 10^{18}	Negligible

* Resistivity is reciprocal of conductivity. Temperature ~ 300 K (room temperature).

Diode – Introduction (Semiconductor)



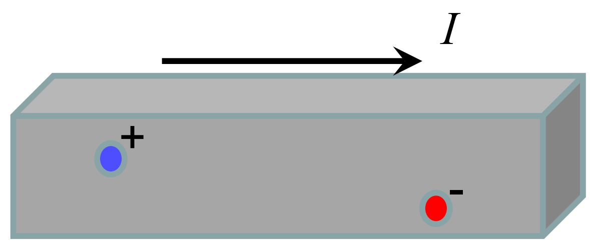
Simplified structure and circuit symbol of a semiconductor pn junction.



- The process of adding impurities to semiconductor is known as doping.
- Impurities added to semiconductor to make it *n*-type and *p*-type are different. For silicon (a group IV element) –
  - *p*-type impurity is a group III element (Boron, Aluminium and Gallium).
  - *n*-type impurity is a group V element (Phosphorus, Arsenic and Antimony).
- The process of doping can also change a *p*-type semiconductor to *n*-type semiconductor, and vice versa. For example, by adding more *n*-type impurities to an originally *p*-type semiconductor, it can be changed to *n*-type. This allows the making of *pn*-junction, and transistors (BJT and MOSFET).

Diode – Introduction (Origin of Current)

- Take note there are two types of charge carrier movement, leading to two types of current: drift and diffusion.



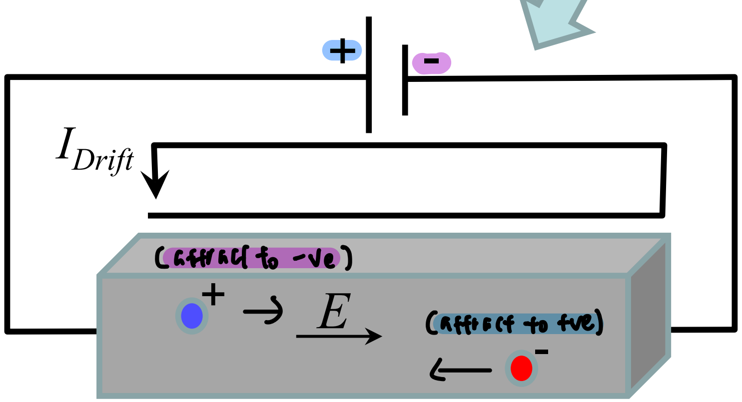
Movement of charge carriers (electrons or holes) gives rise to current

+ve

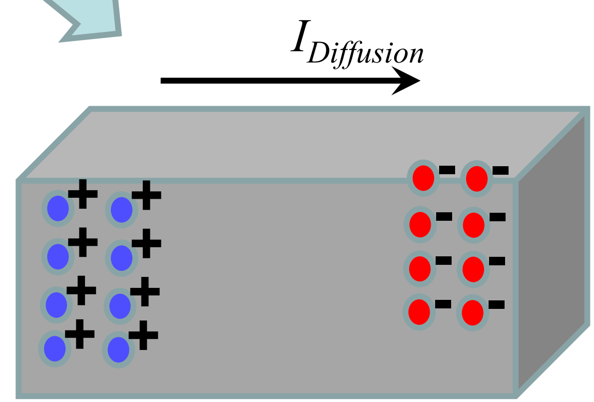
Two types of movements

Drift Current, I_{Drift}

Diffusion Current, $I_{Diffusion}$



The current in all electronic devices originates from either or sum of the two mechanisms



spread out

Charge carriers move/drift in the presence electric field. Carriers drift at a velocity proportional to the electric field.

Charge carriers diffuse owing to the difference in carrier concentration. The resulting diffusion current is proportional to the concentration gradient.

Diode – Introduction (Carriers and Carrier Movement in Devices)

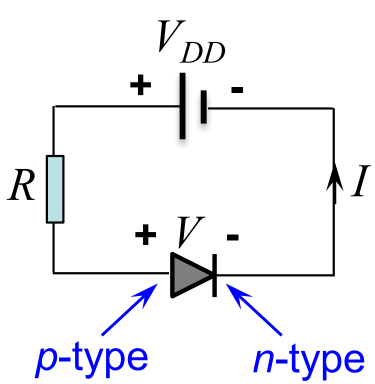
Devices	Dominant Carrier Movement Mechanism	Type of Carriers
Resistor	Drift	▪ Electrons (Metal) ▪ Electrons and holes (Semiconductor)
Diode	Diffusion	▪ Electrons and holes
BJT (Bipolar Junction Transistor)	Diffusion	▪ Electrons and holes
MOSFET (Metal Oxide Semiconductor Field Effect Transistor)	Drift	▪ Electrons (NMOS) ▪ Holes (PMOS)

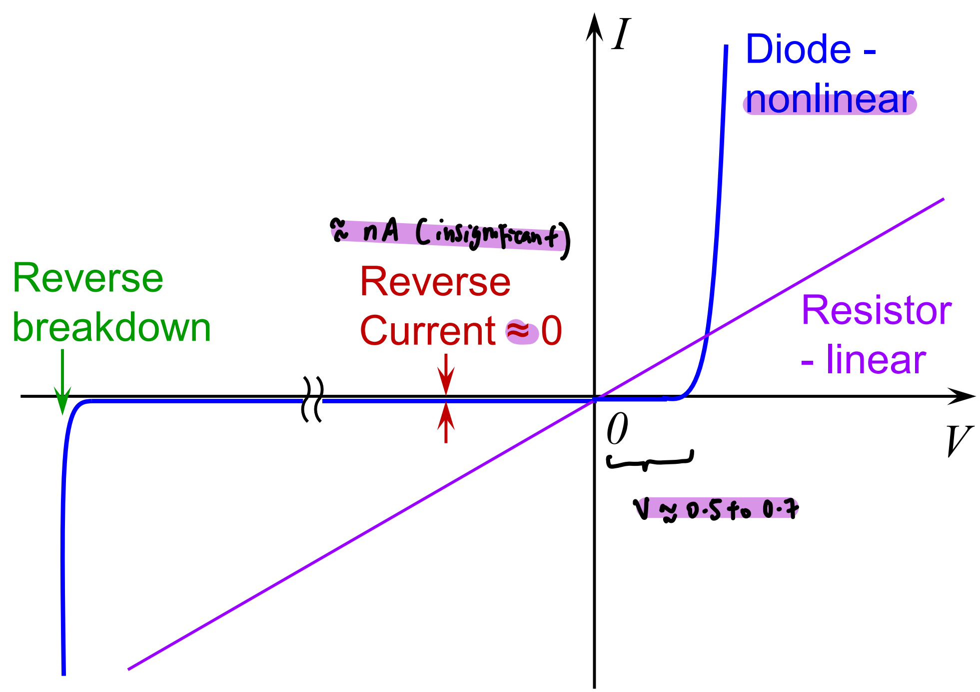
one side p-type
one side n-type
(diffuse)

Diode – Introduction (IV Characteristic)

Diode (semiconductor *pn*-junction) is the simplest (2-terminal) and most fundamental *nonlinear* circuit element.

- It allows a current flow through it easily in one direction (known as the forward direction, $V > 0$), but not in the opposite direction (known as the reverse direction, $V < 0$), except for the reverse breakdown region.
- Unlike a resistor, which is a *linear* element that has a linear current-voltage relation.
- Diode can be used as a switch and in a rectifier circuit to convert ac into dc.





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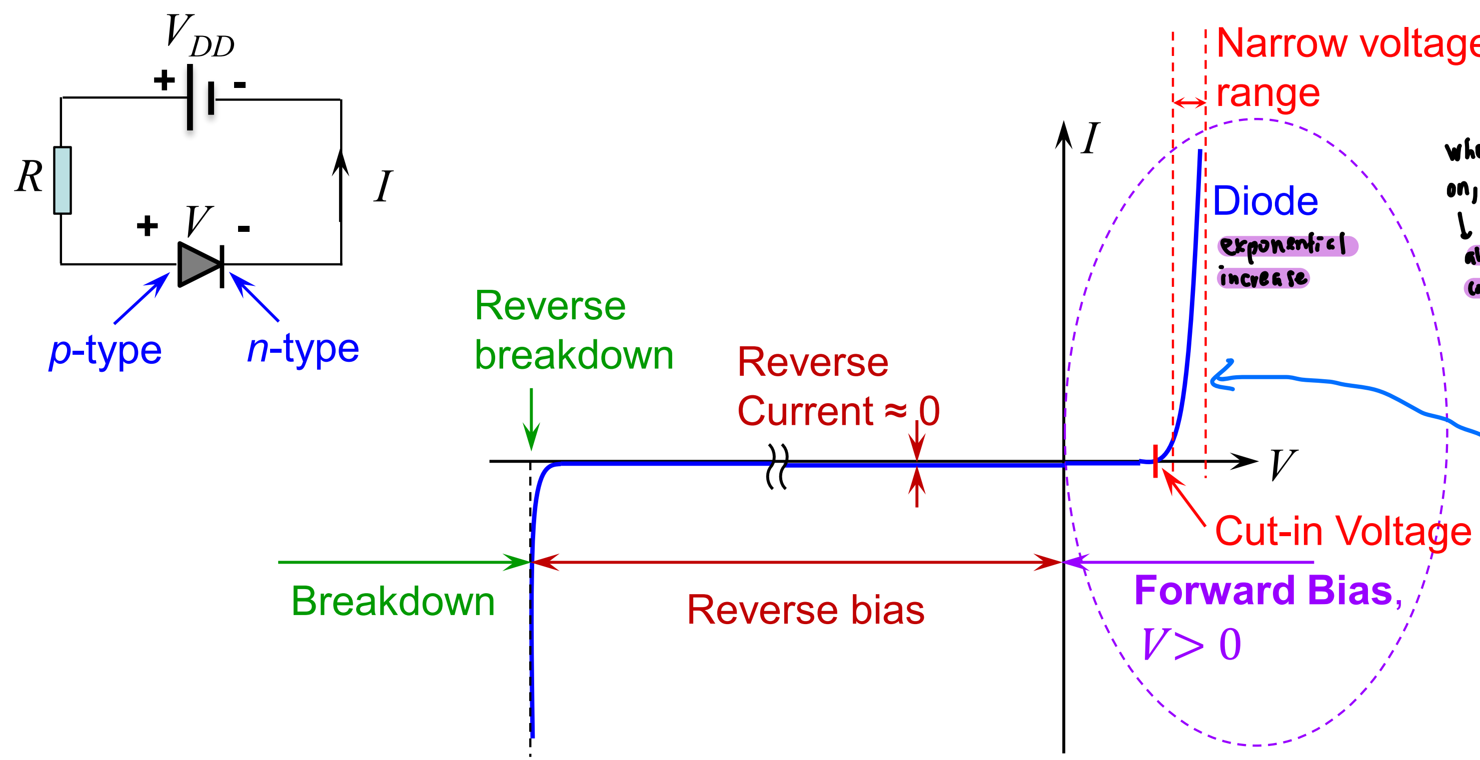
Diode – Forward Bias Operation

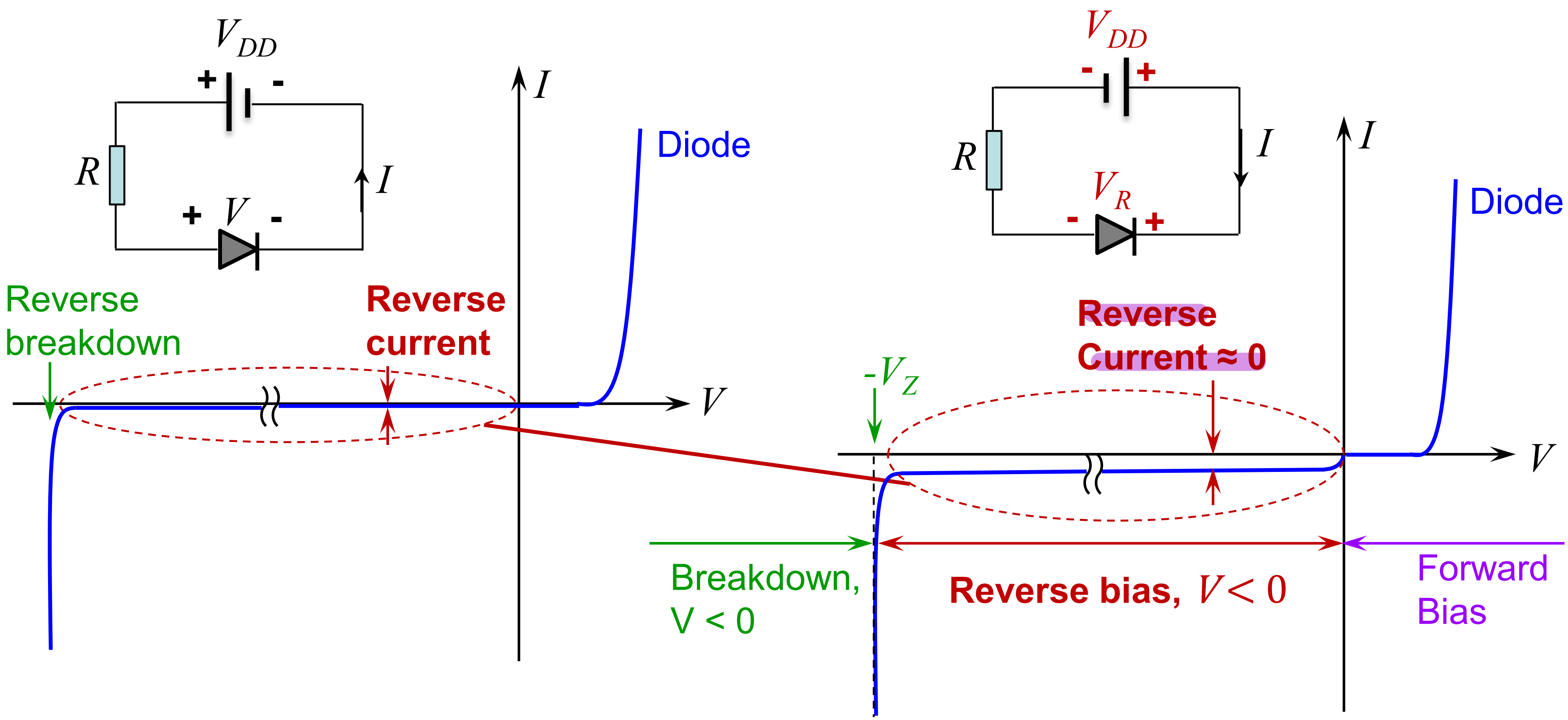


when silicon diode turn on, voltage drop is 0.7V.

already conducting

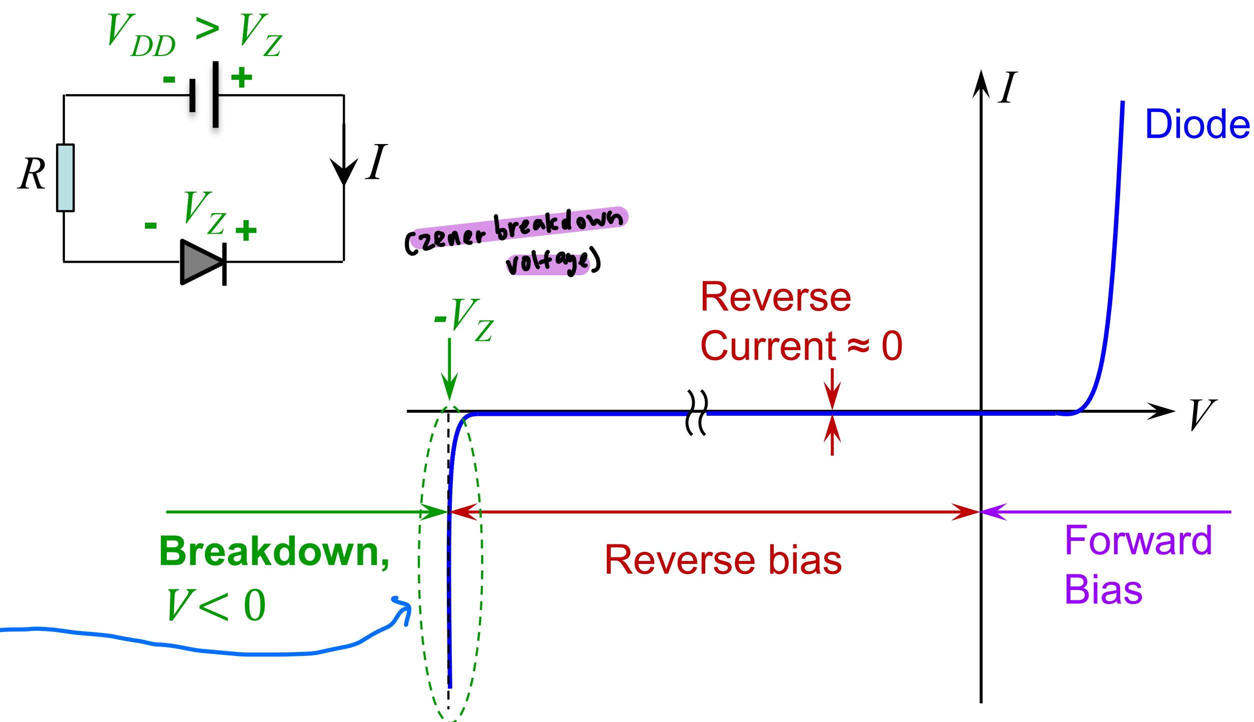
- Under forward-bias ($V > 0$), an external voltage is applied such that the p-type terminal is at a higher (positive) voltage with respect to the n-type terminal.
  - Forward current flows through the diode from the p-type to n-type side.
- The forward current remains small (≈ 0 practically) until the cut-in voltage, and increases quickly with a small increase in V thereafter.
- With a substantial forward current, the voltage drop across the diode lies in a narrow range.

Diode – Reverse Bias Operation (Non-Breakdown Region)



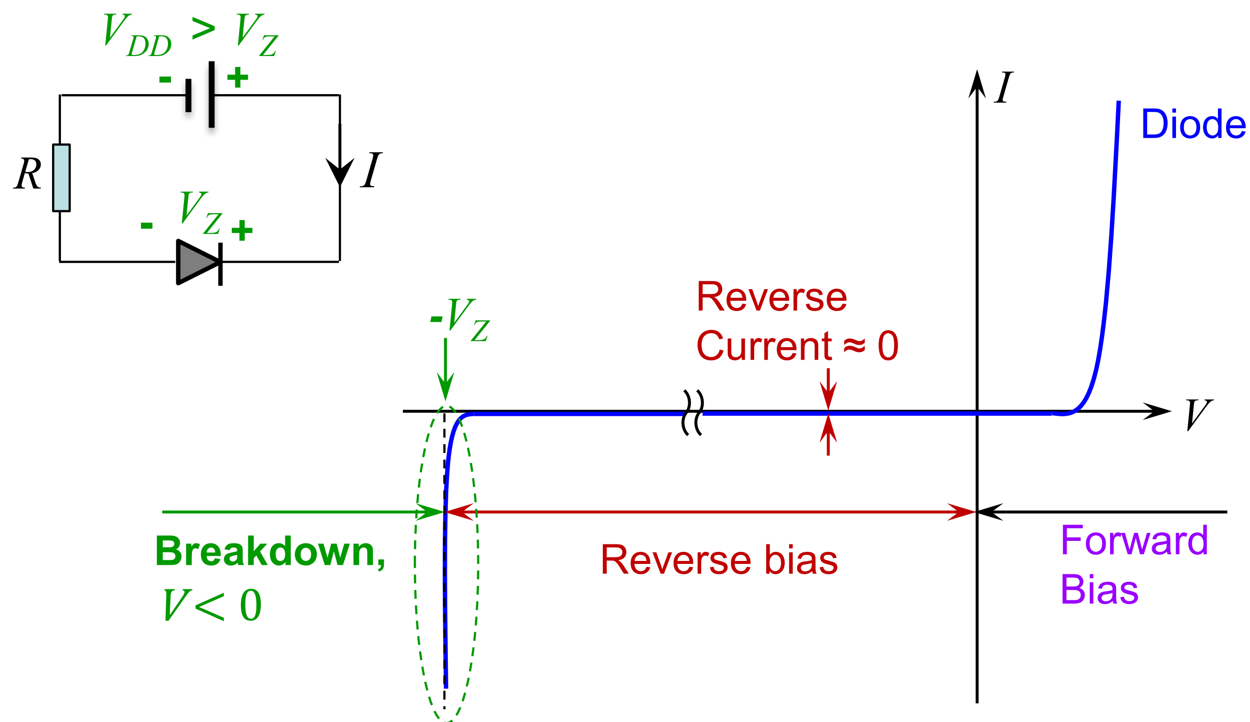
- Under reverse-bias (V < 0), an external voltage is applied such that the *p*-type terminal is at a lower (or negative) voltage with respect to the *n*-type terminal.
  - Reverse current flows through the diode from the *n*-type to *p*-type side.
- For reverse bias voltage magnitude, $|V| = V_R < V_Z$, the breakdown voltage, reverse current is very small and can be treated practically as zero, meaning the diode is equivalent to an open circuit.

Diode – Reverse Bias Operation (Breakdown Region)



- With an external voltage supply that reverse biases the diode, $V_{DD} > V_Z$ (breakdown voltage), the diode reverse current is no longer ≈ 0, but can be very large, while its voltage is practically not changed and stays at $-V_Z$. This condition is known as breakdown.
- Under breakdown operating condition, the voltage across the pn junction diode is 'clamped' at $-V_Z$. Minus sign highlights that breakdown is a reverse biased condition.

Diode – Reverse Bias Operation (Breakdown Region)



- Operation in the breakdown region does not destroy the diode, provided the current through it is kept below a certain level, such that the power dissipation ($V \times I$) is below what the diode can handle.

$\boxed{P = VI \;/\; P = I^2R \;/\; P = \frac{V^2}{R}}$

- While operating in the breakdown region, current can be limited by connecting a resistor, R, of suitable value in series with the *pn* junction diode -

$$I = \frac{V_{DD} - V_Z}{R}$$

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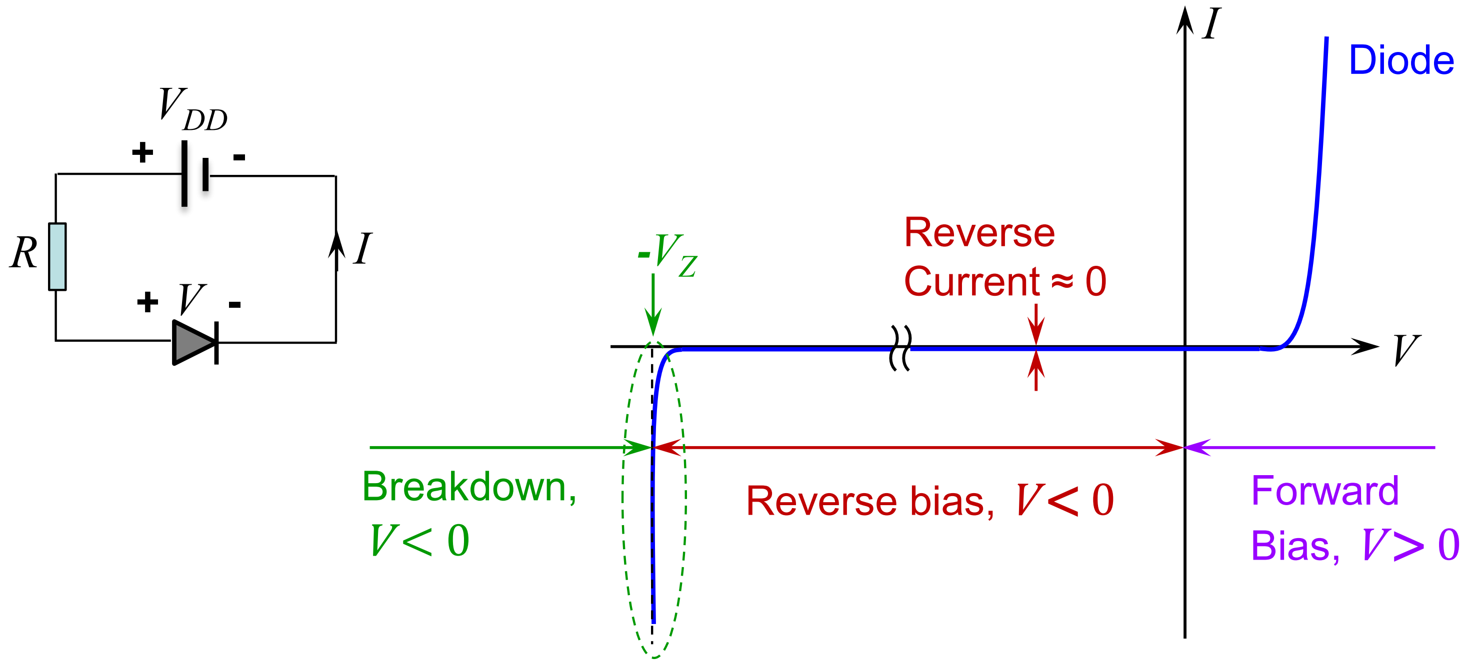
Diode – Current-Voltage Characteristic



Current-voltage (IV) relationship of a "real" *pn*-junction diode -

$$\boxed{I = I_S\left(e^{\frac{V}{nV_T}} - 1\right)} \tag{2.1}$$

between 1 ~2

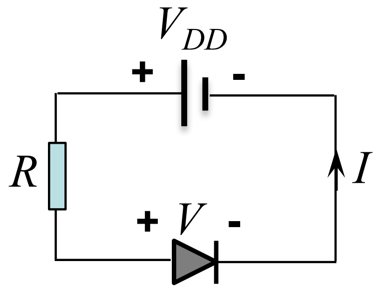
- ❑ V is the voltage across the diode: $V > 0$ for forward bias and $V < 0$ for reverse bias.
- ❑ I is the current flowing through the diode: $I > 0$ for forward bias and $I < 0$ for reverse bias.

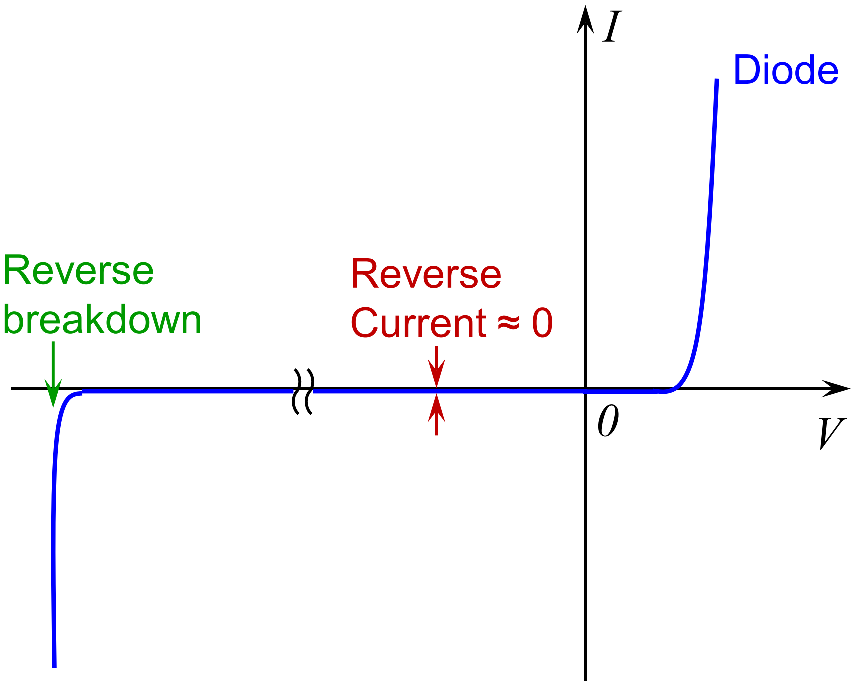
(take more convenient value when doing calculation)

- ❑ V_T is the thermal voltage, $V_T = kT/q$ = 0.0259 V ≈ 0.025 V at T = 300 K.

(27°C)

Diode – Current-Voltage Characteristic





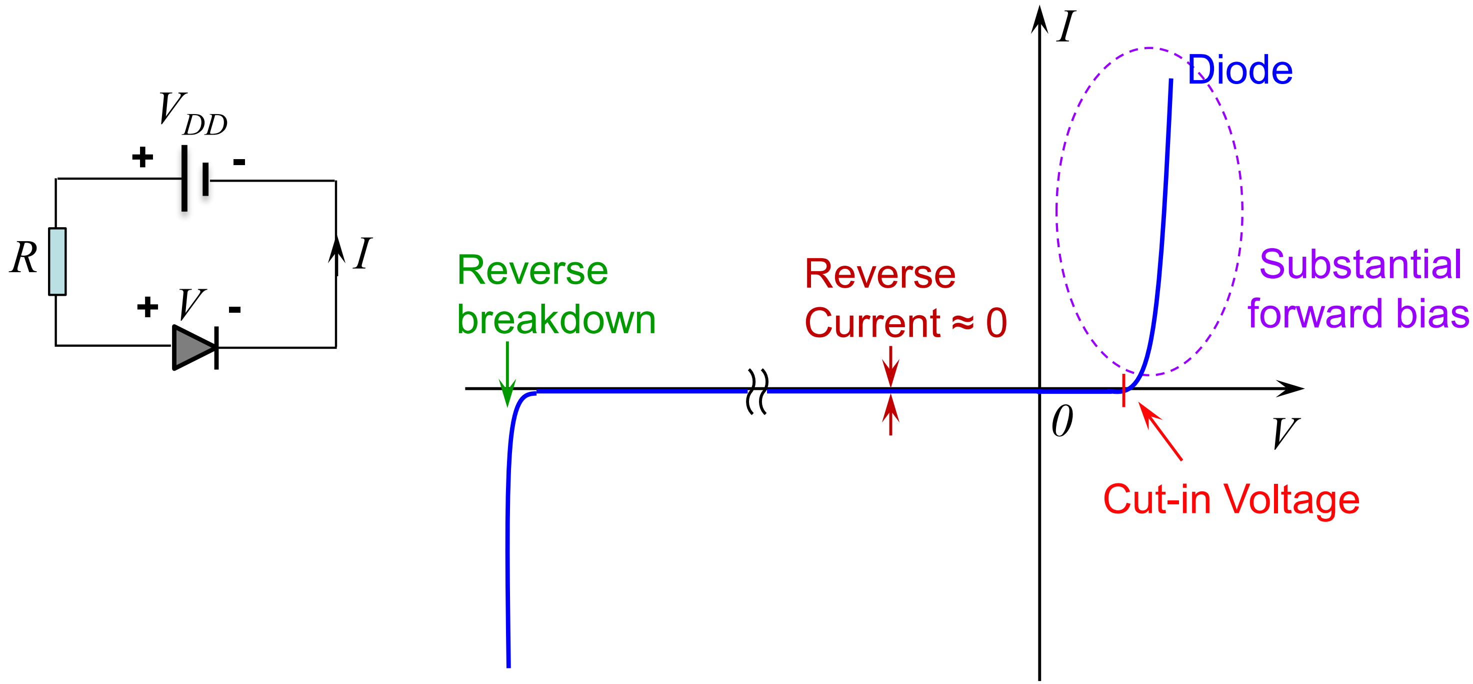
Current-voltage (IV) relationship of a "real" *pn*-junction diode -

$$I = I_S\left(e^{\frac{V}{nV_T}} - 1\right) \tag{2.1}$$

- ❑ n is the exponential factor, and has a value between 1 and 2, depending on the material and physical structure of the semiconductor *pn*-junction.
  - For an ideal *pn*-junction diode, $n = 1$.
- ❑ I_S is the reverse saturation current, a parameter of the diode and it is a strong function of temperature. It increases with increasing temperature.

($\uparrow T$, $\uparrow I_s$)

Diode – Current-Voltage Characteristic (Forward Bias)



Current-voltage (IV) relationship of a "real" *pn*-junction diode -

$$I = I_S\left(e^{\frac{V}{nV_T}} - 1\right) \qquad (2.1)$$

❑ For substantial forward bias (V > cut-in voltage > 0), $e^{\frac{V}{nV_T}} \gg 1$ and

much greater than

$$I = I_S\left(e^{\frac{V}{nV_T}} - 1\right) \approx I_S\, e^{\frac{V}{nV_T}} \qquad (2.2a)$$

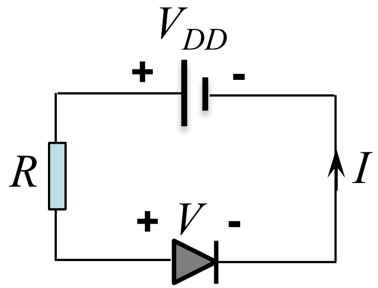
→ 1 becomes negligible

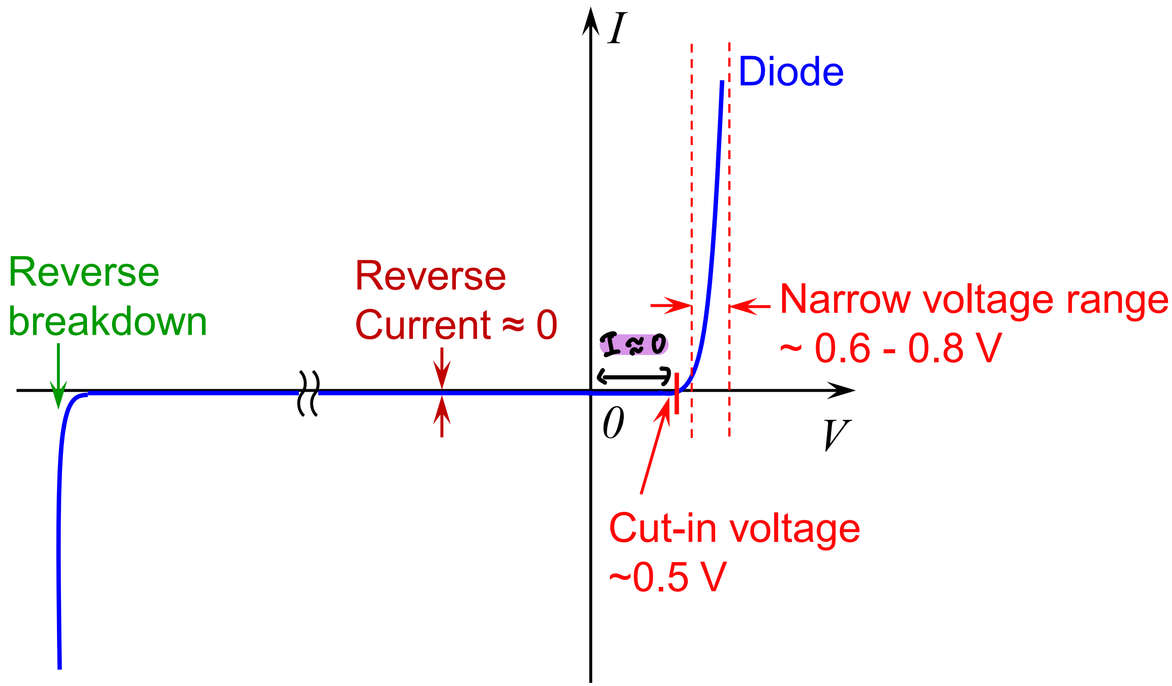
or $$V \approx nV_T \ln(I/I_S)^* \qquad (2.2b)$$

→ taking $\log_e$ both sides

*A linear relation between V and $\ln(I)$.

Diode – Current-Voltage Characteristic (Forward Bias)



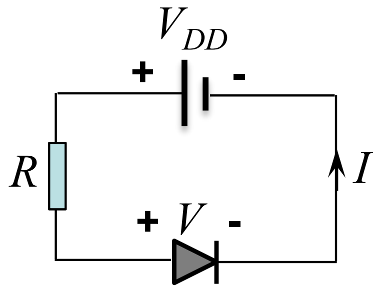


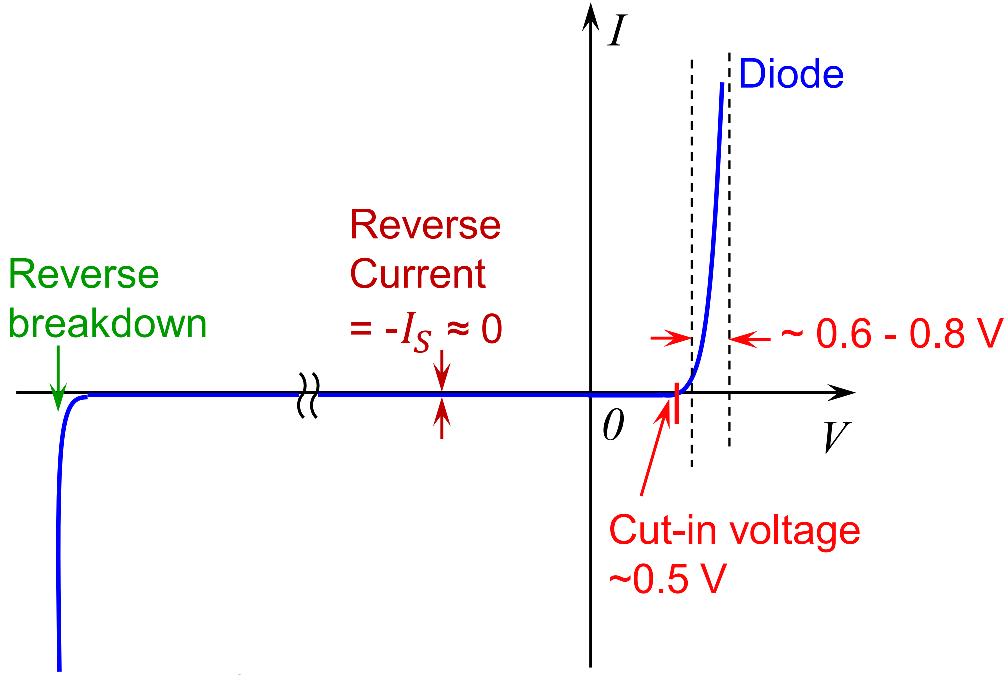
Current-voltage (IV) relationship of a "real" *pn*-junction diode -

$$I = I_S\left(e^{\frac{V}{nV_T}} - 1\right) \qquad (2.1)$$

- Owing to the exponential IV relationship –
  - $I \approx 0$ for $V <$ ~0.5 V (known as the cut-in voltage)
  - For a fully conducting *pn*-junction diode ($V >$ ~0.5 V and with substantial current flowing through), the voltage drop across it lies in a narrow range, ~0.6 to 0.8 V. => take avg: 0.7 V

Diode – Current-Voltage Characteristic (Reverse Bias)





Current-voltage (IV) relationship of a "real" *pn*-junction diode -

$$I = I_S\left(e^{\frac{V}{nV_T}} - 1\right) \qquad (2.1)$$

- In reverse bias, $V < 0$, for $|V| >$ a few times nV_T, $e^{\frac{V}{nV_T}} \ll 1$ and
  much less than
  $$I = I_S\left(e^{\frac{V}{nV_T}} - 1\right) \approx -I_S \text{ (for Non- breakdown region)}$$
- Reverse current is a constant independent on V, having a magnitude of I_S, the **reverse saturation current**, a very small number (practically zero).

N.B. Equation (2.1) does not predict the breakdown characteristic.

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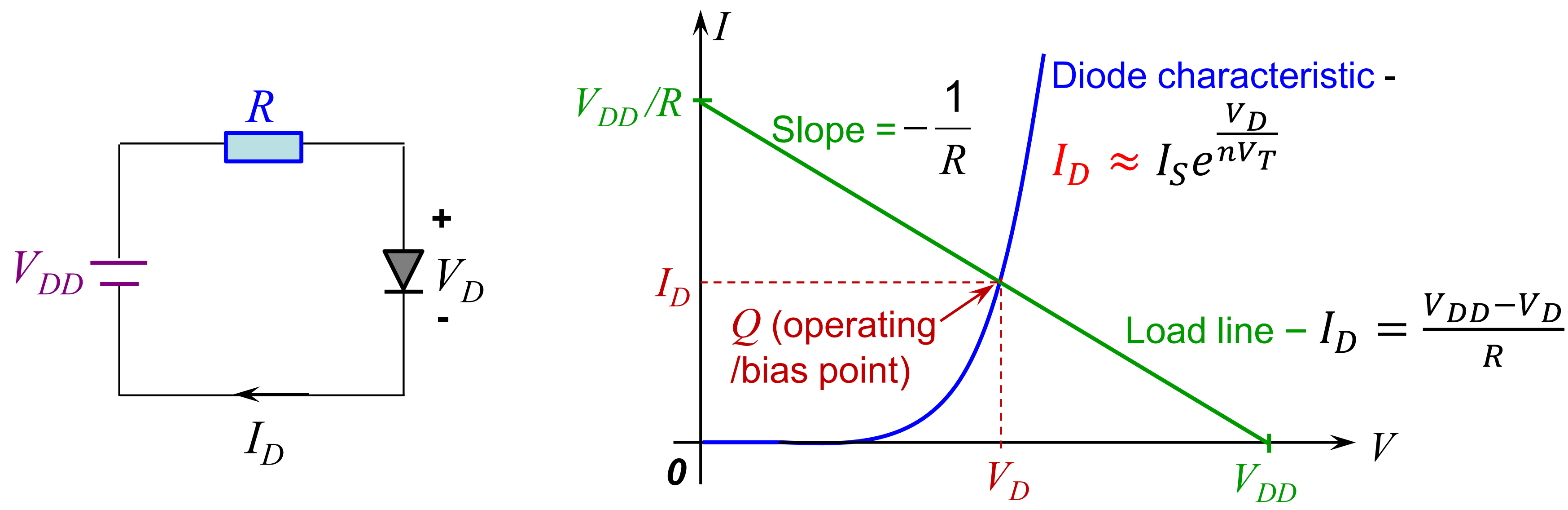
Diode – Modeling the Diode – Large-Signal Model



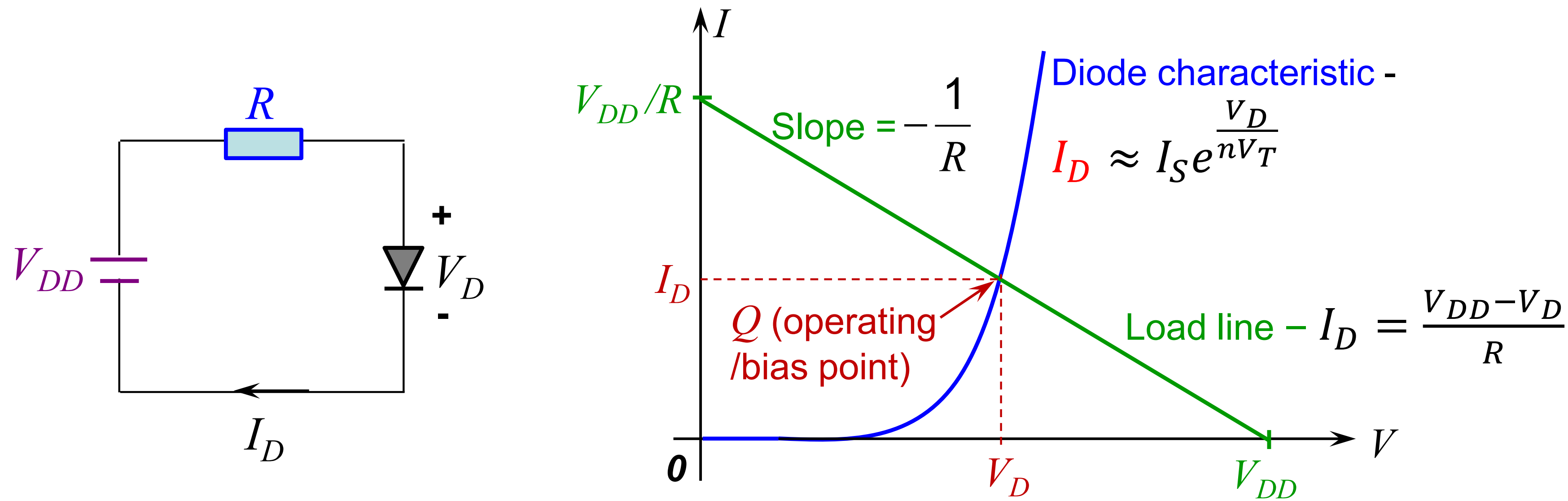
Why the need to model diode?

- Consider the analysis of the above simple circuit shown, which uses a diode in forward bias. Assuming V_{DD} > 0.5 V, the IV characteristic of the diode is based on pg 16

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right) \approx I_S e^{\frac{V_D}{nV_T}} \qquad (2.3)$$

- I_D and V_D are the current through the diode and voltage across the diode, respectively.

Diode – Modeling the Diode – Large-Signal Model



- I_D and V_D are also governed by the Kirchhoff Voltage Law (KVL) –

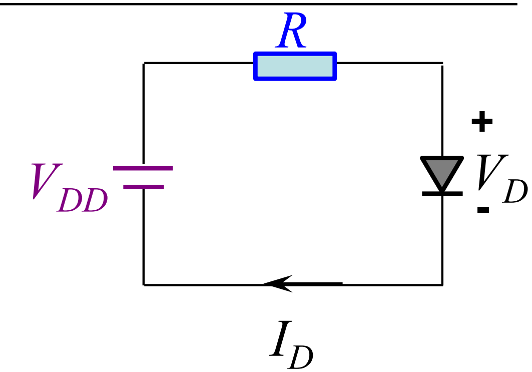
Load line: $$\boxed{I_D = \frac{V_{DD}-V_D}{R}} \qquad (2.4)$$

- Equation (2.4) is known as the load line of the circuit.
- I_D and V_D cannot be determined easily by solving equations (2.3) and (2.4) simultaneously, owing to the exponential IV characteristic of the *pn*-junction diode.
- They can be determined by the intersection of equations (2.3) and (2.4) graphically (as shown above).
- They can also be solved using a simple iterative procedure (see work example).

Diode – Modeling the Diode – Large-Signal Model

Work Example - Iterative Method

Determine the current I_D and voltage V_D of the circuit shown below by means of iteration for V_{DD} = 5 V and R = 1 kΩ. It is given that the diode has a current of 1 mA at a voltage of 0.6 V and that its voltage drop changes by 0.1 V for every decade change in current.



- ❑ I_D and V_D are governed by equations (2.3) and (2.4).
- ❑ We need to find nV_T first in order to use the diode equation (2.3) in the iteration process.

take loge both sides

$$I_D \approx I_S e^{\frac{V_D}{nV_T}}$$ (V_{DD} = 5 V ⇒ diode operates in substantial forward bias)

$$\Rightarrow V_D \approx nV_T \ln(I_D/I_S)$$

- ❑ Given that at $V_D = 0.6\text{ V}$, $I_D = 1\text{ mA} \Rightarrow 0.6\text{ V} = nV_T \ln(1\text{ mA}/I_S)$

→ to find original

- ❑ Subtracting the above two equations yields

$\ln\left(\frac{x}{y}\right) = \ln x - \ln y$

$$V_D - 0.6\text{ V} = nV_T \ln(I_D/I_S) - nV_T \ln(1\text{ mA}/I_S)$$

$$nV_T(\ln I_D - \ln I_S) - nV_T(\ln 1\text{mA} - \ln I_S)$$

$$= nV_T(\ln I_D - \ln I_S - \ln 1\text{mA} + \ln I_S)$$

$$= nV_T(\ln I_D - \ln 1\text{mA})$$

$$\Rightarrow V_D - 0.6\text{ V} = nV_T \ln(I_D/1\text{ mA})$$

Diode – Modeling the Diode – Large-Signal Model

- Given that V_D changes by 0.1 V for every decade change in I_D, i.e., for (V_D – 0.6 V) = 0.1 V, $I_D/\,1\text{ mA}$ = 10, leading to

$$V_D - 0.6\text{ V} = nV_T \ln(I_D/1\text{ mA}) \Rightarrow 0.1 = nV_T \ln(10)$$

$$\Rightarrow nV_T = 0.043$$

The iteration process proceeds as follows -

1) We ① first assume $V_D = V_{D0}$ = 0.7 V, the mid voltage value of the range shown on slide pn-17 (~0.6 – 0.8 V), which is based on the diode characteristic, i.e., equation (2.3).

2) Next, substitute $V_D = V_{D0}$ = 0.7 V into equation (2.4), the KVL equation, we make an initially estimate for I_D (= I_{D0}) –

guess 0

$$I_{D0} = \frac{V_{DD} - V_{D0}}{R} = \frac{5 - 0.7}{1000} = 4.3\text{ mA}$$

3) Using the estimated I_{D0} = 4.3 mA, a better estimate for V_D (= V_{D1}) is obtained using the diode equation -

$$V_D - 0.6\text{ V} = nV_T \ln(I_D/1\text{ mA}) \Rightarrow V_{D1} - 0.6\text{ V} = 0.043 \ln(4.3\text{ mA}/1\text{ mA})$$

$$\Rightarrow V_{D1} = 0.6627\text{ V}$$

Diode – Modeling the Diode – Large-Signal Model

4) Substitute V_{D1} = 0.6627 V into equation (2.4), a better estimate for I_D ($= I_{D1}$) is obtained

$$I_{D1} = \frac{V_{DD}-V_{D1}}{R} = \frac{5-0.6627}{1000} = 4.3373 \text{ mA}$$

5) Thus, after the 1st iteration I_{D1} = 4.3373 mA and V_{D1} = 0.6627 V. The 2nd iteration proceeds in a similar manner, by repeating steps 3 and 4:

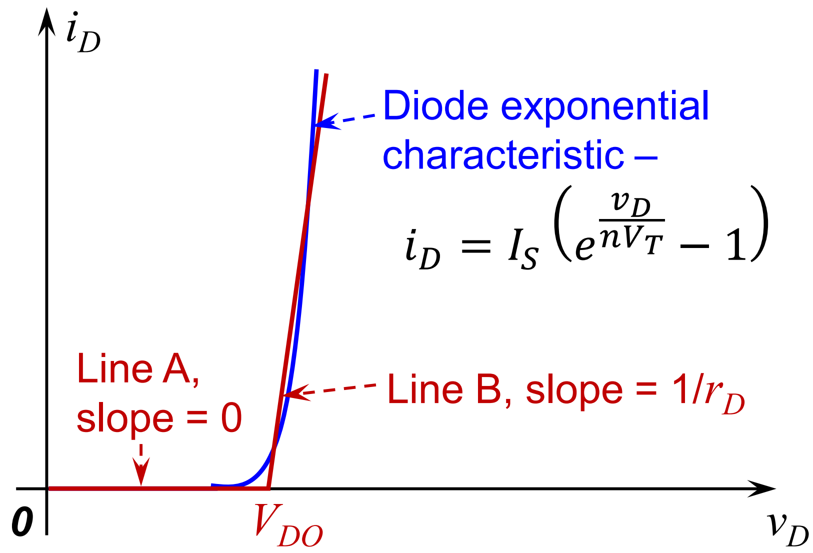
$$V_{D2} - 0.6 \text{ V} = 0.043 \ln(4.3373 \text{ mA}/1 \text{ mA}) \Rightarrow V_{D2} = 0.6631 \text{ V}$$

$$I_{D2} = \frac{V_{DD}-V_{D2}}{R} = \frac{5-0.6631}{1000} = 4.3369 \text{ mA}$$

6) 2nd iteration yields I_{D2} = 4.3369 mA and V_{D2} = 0.6631 V, which are close to values obtained after the 1st iteration (less than 0.06% difference), hence further iterations are not necessary, as the values of V_D and I_D have converged.

- $\boxed{\text{Take note that equations (2.3) and (2.4) are used alternately.}}$

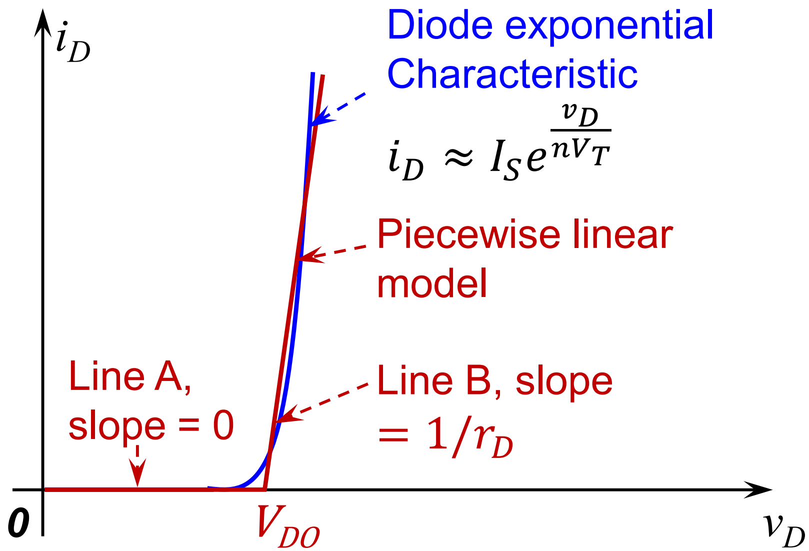
Diode – Modeling the Diode – Large-Signal Model

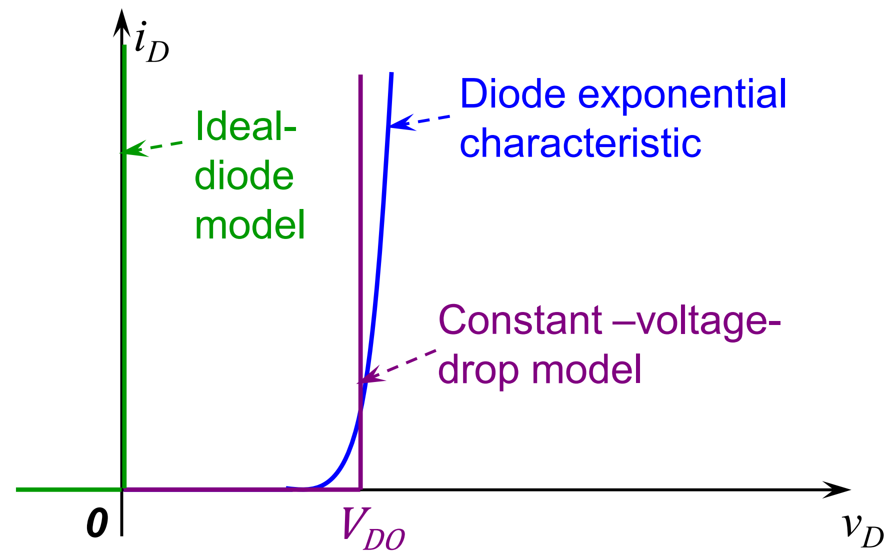


Why the need to model diode?

- For more complex circuits, the analysis by means of the graphical method may not be possible and the iterative method may be too tedious owing to the exponential IV characteristic of diode.
- To speed up circuit analysis, simpler model for the diode is used. This is at the expense of precise results.
- The forward bias diode exponential characteristic can be approximated by two straight lines: Line A with zero slope, and Line B with a slope $1/r_D$. This approximation is known as the piecewise-linear model.

Diode – Modeling the Diode - Large-Signal Model

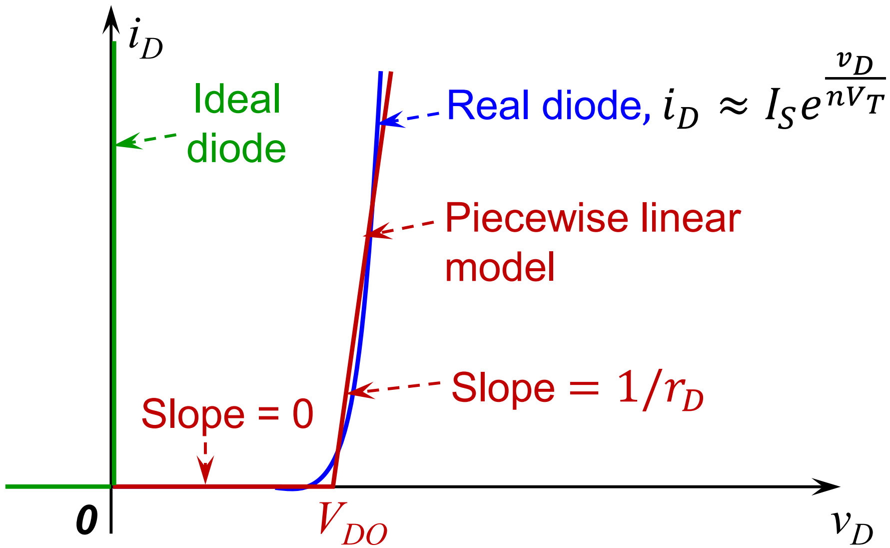


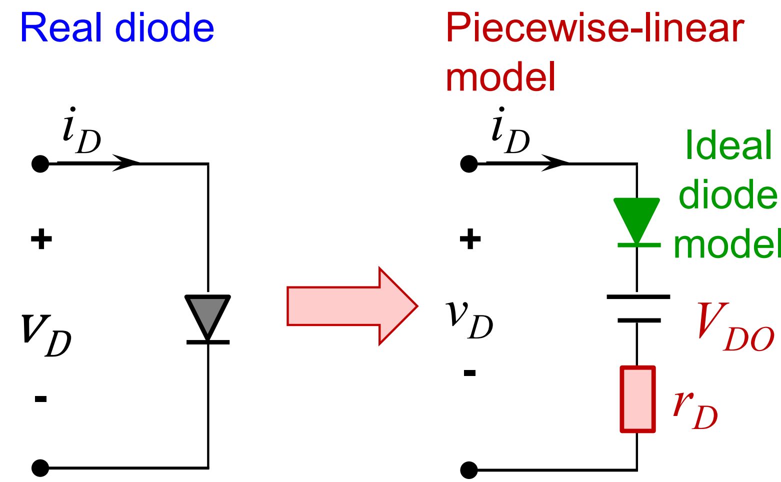


Large-signal model

- The piecewise-linear model:
  - $i_D = 0, \quad v_D \le V_{DO}$ (Line A) (2.5)
  - $i_D = (v_D - V_{DO})/r_D, \quad v_D \ge V_{DO}$ (Line B) (2.6)
  - V_{DO} and r_D are model parameters. Choice of lines A and B (or V_{DO} and r_D) is not unique.
  - Closer approximation obtained by restricting the operation range.
- The ideal-diode model: $V_{DO} = 0$ and $r_D = 0$.
- The constant-voltage-drop model: $r_D = 0$ and V_{DO} is usually taken as 0.7 V.

Diode – Modeling the Diode - Large Signal Model





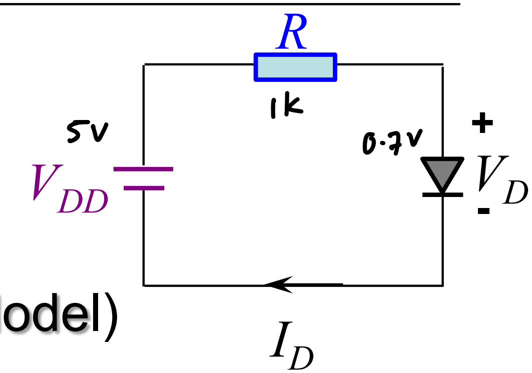
<u>The large-signal model</u>

- ❑ In the **equivalent circuit** of the piecewise-linear model of diode, an ideal diode model is included to restrict i_D flow in the **forward bias direction** only.
- ❑ The large signal model can be used to replace the diode in the dc (large signal) circuit analysis (see work example to follow).
- ❑ Symbols for diode current and voltage have been replaced by i_D and v_D. They represent the 'total' current and voltage of a diode and will be elaborated in subsequent slides.

Diode – Modeling the Diode - Large-Signal Model

Work Example - Using Constant-Voltage-Drop Model (For DC Analysis)

Determine the current I_D and voltage V_D of the circuit shown below for V_{DD} = 5 V and R = 1 kΩ. It is given that the diode has a current of 1 mA at a voltage of 0.6 V and that its voltage drop changes by 0.1 V for every decade change in current.



- Since V_{DD} = 5 V, diode operates in substantial forward bias (> 0.5V)

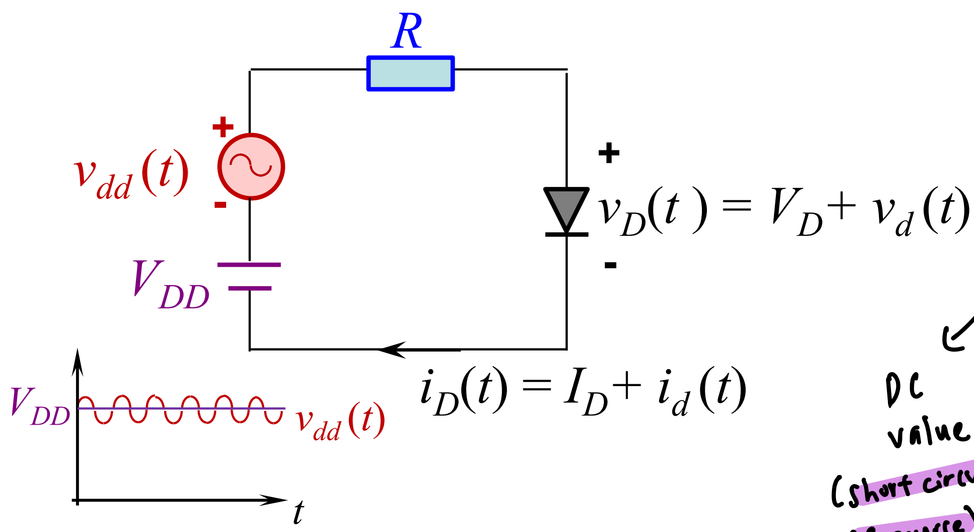
  $\Rightarrow V_D = V_{D0} \approx$ 0.7 V (using the Constant-Voltage-Drop Model)

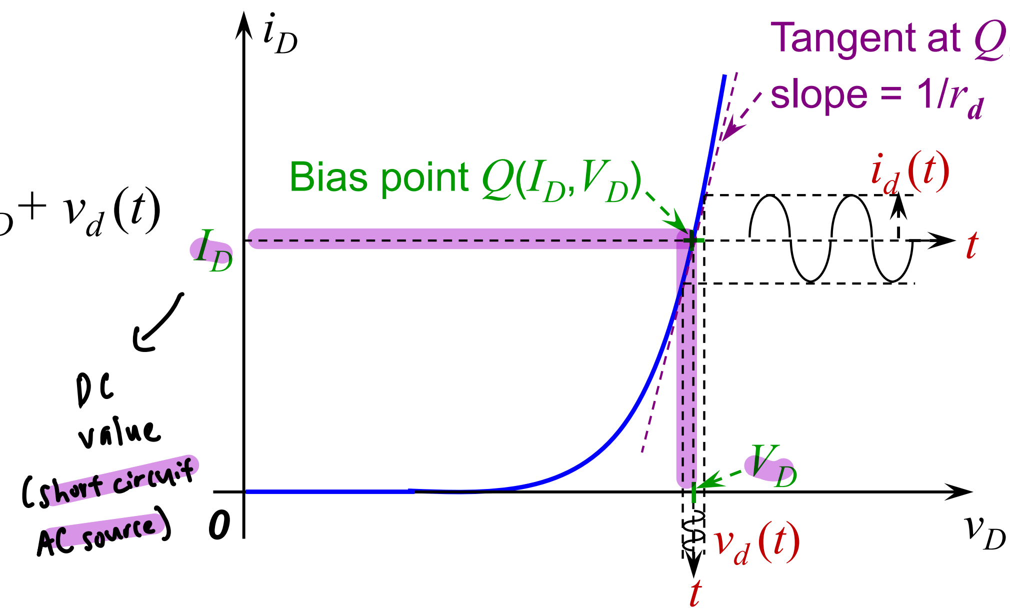
  $$I_D = \frac{V_{DD} - V_D}{R} \approx \frac{5 - 0.7}{1\text{k}} = 4.3 \text{ mA (by means of KVL equation)}$$

- Errors incurred in comparison to results obtained using iterative method:
  - I_D: 4.3 mA versus 4.3369 mA $\Rightarrow$ -0.85% error
  - V_D: 0.7 V versus 0.6631 V $\Rightarrow$ +5.56% error

- Analysis is much easier using the constant-voltage-drop model for diode! At the expense of small error.

Diode – Modeling the Diode - Small-Signal Model





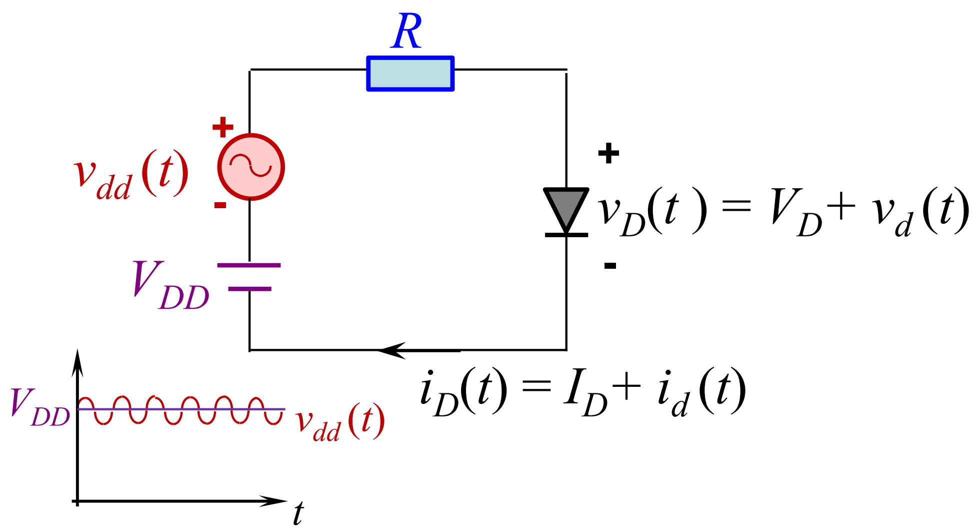
Small-signal operation

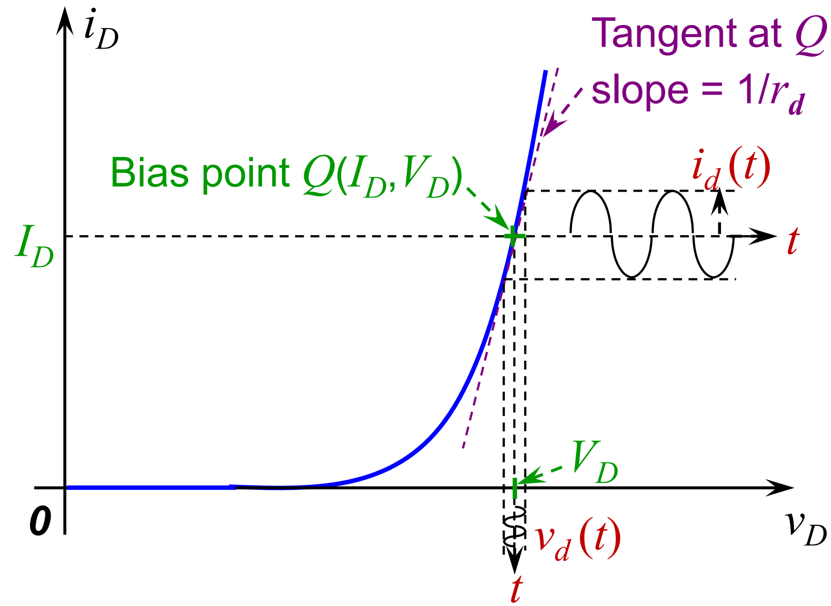
- There are circuits with time varying signal in addition to the dc supply (V_{DD}), as shown in the circuit above, where $v_{dd}(t)$ is an ac signal with a small amplitude. The circuit analysis is complicated owing to the non-linear nature of the diode.

- Concept of small-signal operation: a small amplitude time varying signal, such as a small ac signal, $v_{dd}(t)$, can be considered as a small add-on to the dc supply, V_{DD}. Analysis of circuit can then be divided into two parts:
  - dc analysis – consider only the effect of dc supply, V_{DD}.
  - ac (small signal) analysis – consider only the effect of small ac signal, $v_{dd}(t)$.

The solutions are added together using superposition to give the total effect.

Diode – Modeling the Diode (dc and ac symbols)

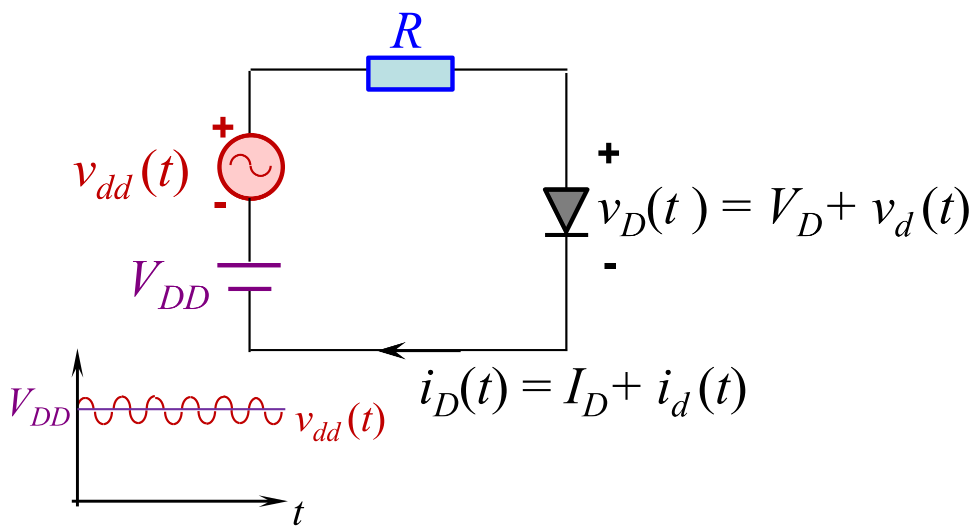


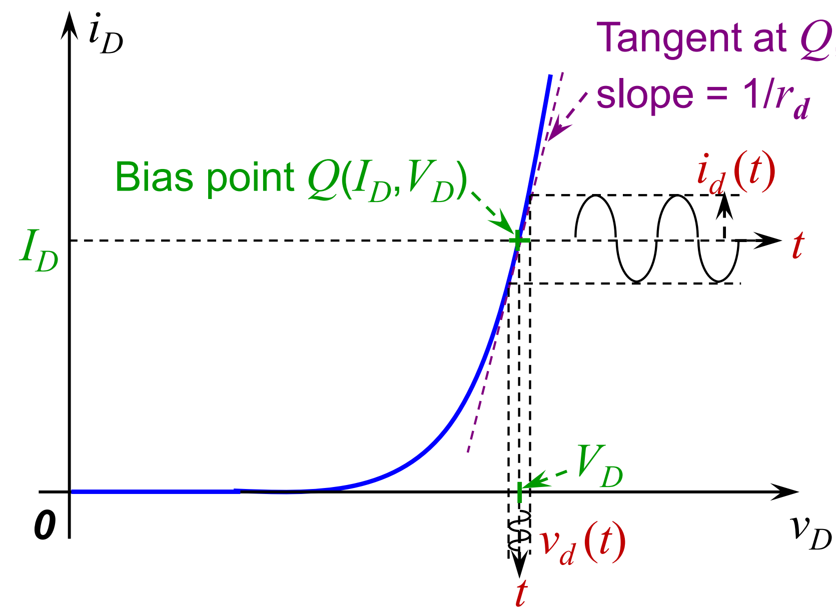


<u>Notations for dc and ac values (examples)</u>

- dc current: I_D
  - Capital Symbol
  - Capital subscript
- ac current: i_d
  - Lower case symbol
  - Lower case subscript
- Total current: $i_D = I_D + i_d$
  - Lower case symbol
  - Capital subscript

Diode – Modeling the Diode - Small-Signal Model



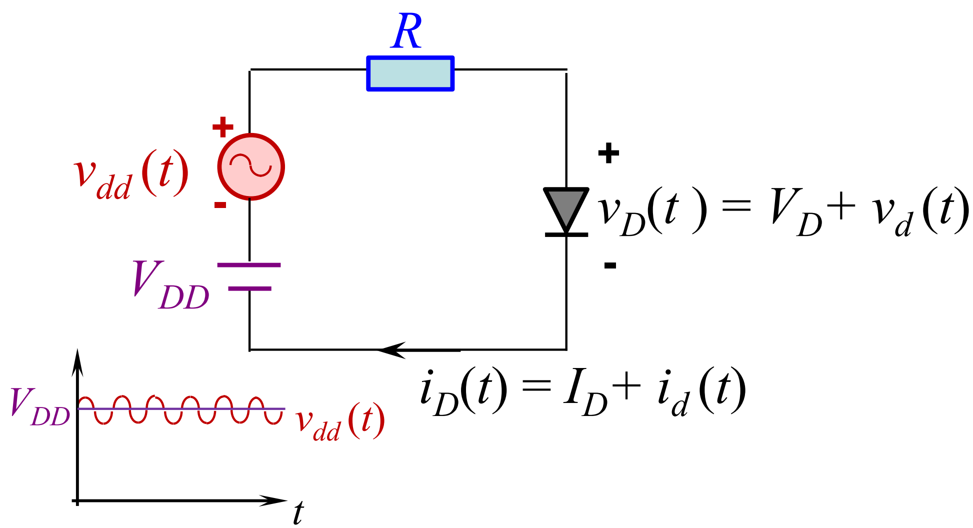


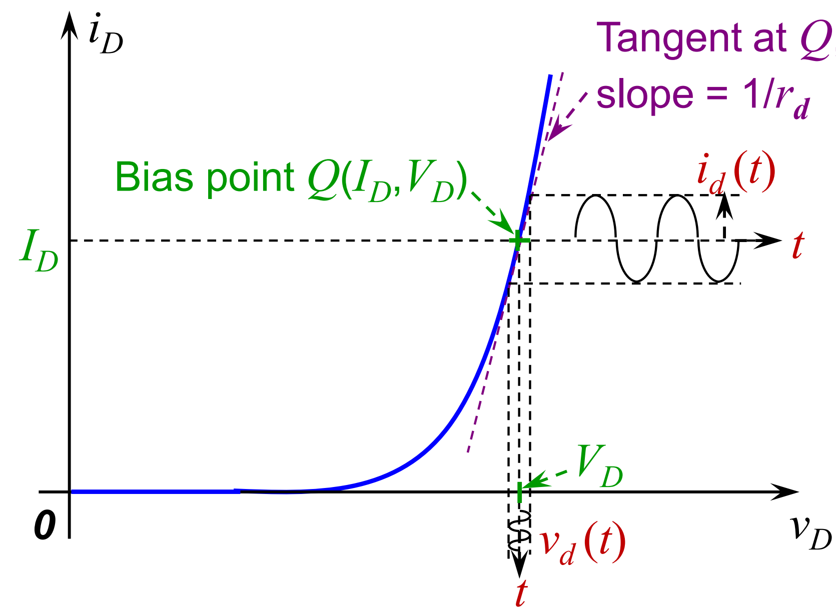
Small-signal operation

AC signal

- **dc analysis**: The dc source, V_{DD}, is used to bias the diode to operate at a point on its forward IV characteristic, $Q(I_D,V_D)$, known as the bias point, around which the diode small ac signals, $v_d(t)$ and $i_d(t)$, operate.
  - The dc bias point $Q(I_D,V_D)$ can first be determined using the large-signal model, and in the absence of the small-signal ac source, $v_{dd}(t)$.
- **ac (small-signal) analysis**: How do we analyze the diode small-signal operation around the bias point, $Q(I_D,V_D)$?

Diode – Modeling the Diode - Small-Signal Model

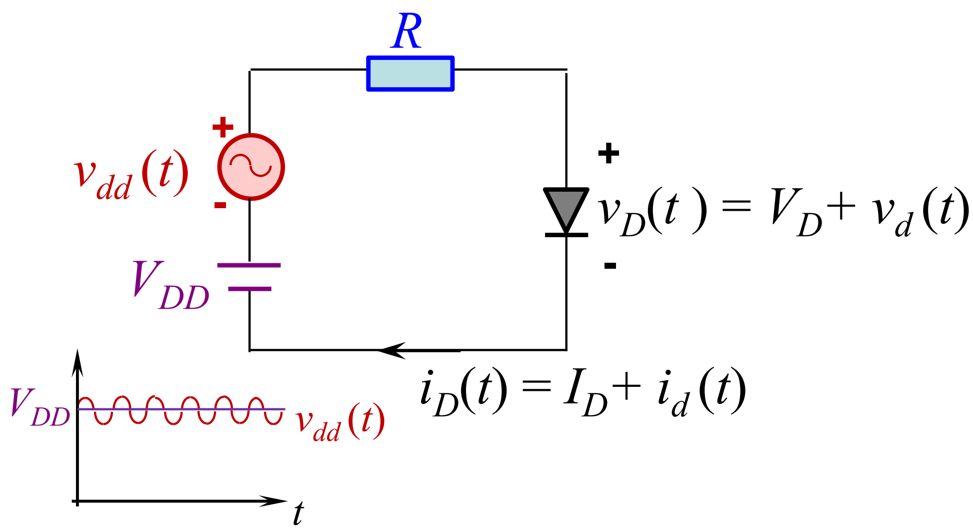


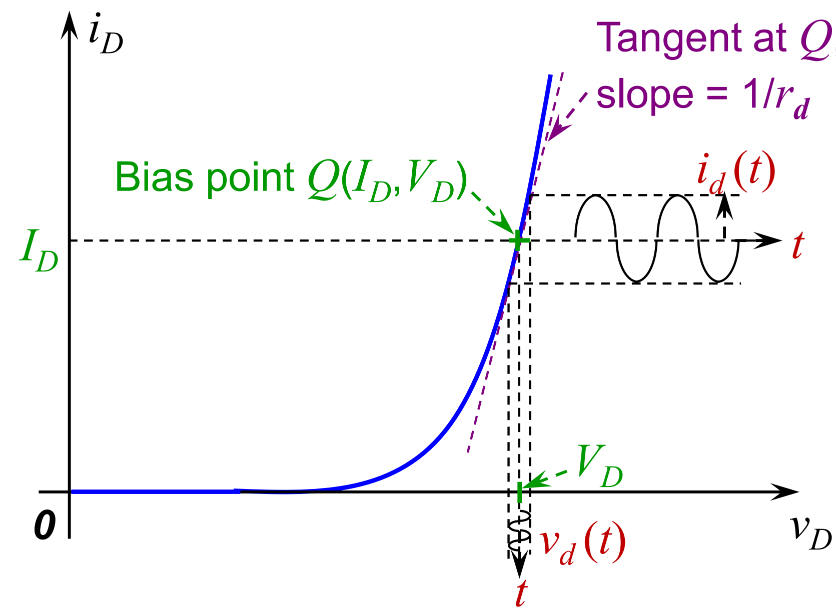


Small-signal operation

- In the presence of V_{DD} and $v_{dd}(t)$, the total instantaneous diode voltage and current, $v_D(t)$ and $i_D(t)$, are plotted above and given as follows -
  - $v_D(t) = V_D + v_d(t)$ (2.7) → DC + AC signal
  - $i_D(t) = I_D + i_d(t)$ (2.8)
- V_D and I_D are the diode dc bias voltage and current, respectively. They are the values without the small-signal ac source $v_{dd}(t)$ and are related as follows –
  - $I_D \approx I_S\, e^{\frac{V_D}{nV_T}}$ (2.9) → pg 16

Diode – Modeling the Diode - Small-Signal Model





Small-signal operation

❑ With small-signal source $v_{dd}(t)$ applied, the total instantaneous current, $i_D(t)$, is

- $$\boxed{i_D(t) = I_S e^{\frac{v_D(t)}{nV_T}}} = I_S e^{\frac{V_D + v_d(t)}{nV_T}} = \boxed{I_S e^{\frac{V_D}{nV_T}}} e^{\frac{v_d(t)}{nV_T}} = I_D e^{\frac{v_d(t)}{nV_T}} \qquad (2.10)$$

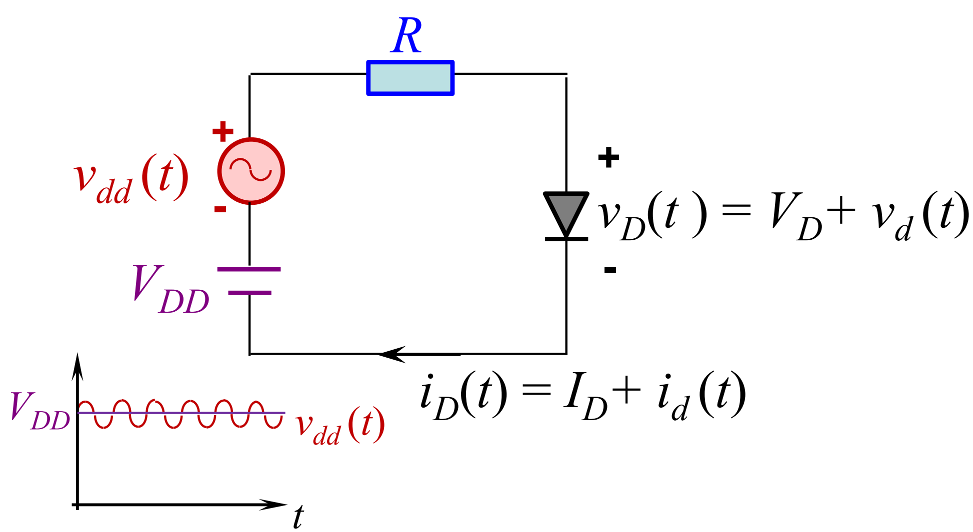
❑ Since $v_{dd}(t)$ is a small-signal source, $v_d(t)$ is expected to be small, known as the small-signal voltage of the diode; and for $v_d(t) << nV_T$, much smaller

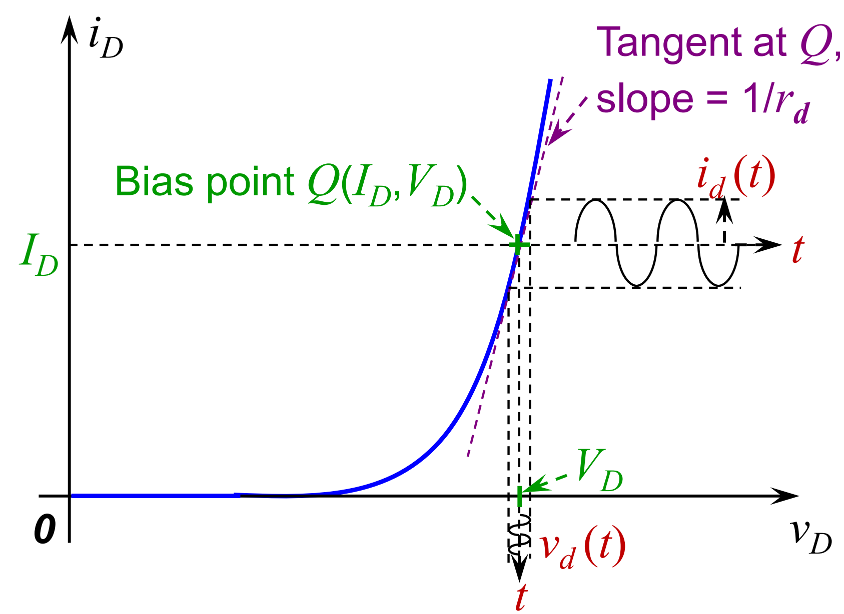
- $$i_D(t) = I_D e^{\frac{v_d(t)}{nV_T}} \approx I_D \left[1 + \frac{v_d(t)}{nV_T}\right] = I_D + \boxed{\frac{I_D}{nV_T} v_d(t)} \qquad (2.11)$$

id(t)

- Note: $e^x \approx 1 + x$, for $x \ll 1$.

Diode – Modeling the Diode - Small-Signal Model





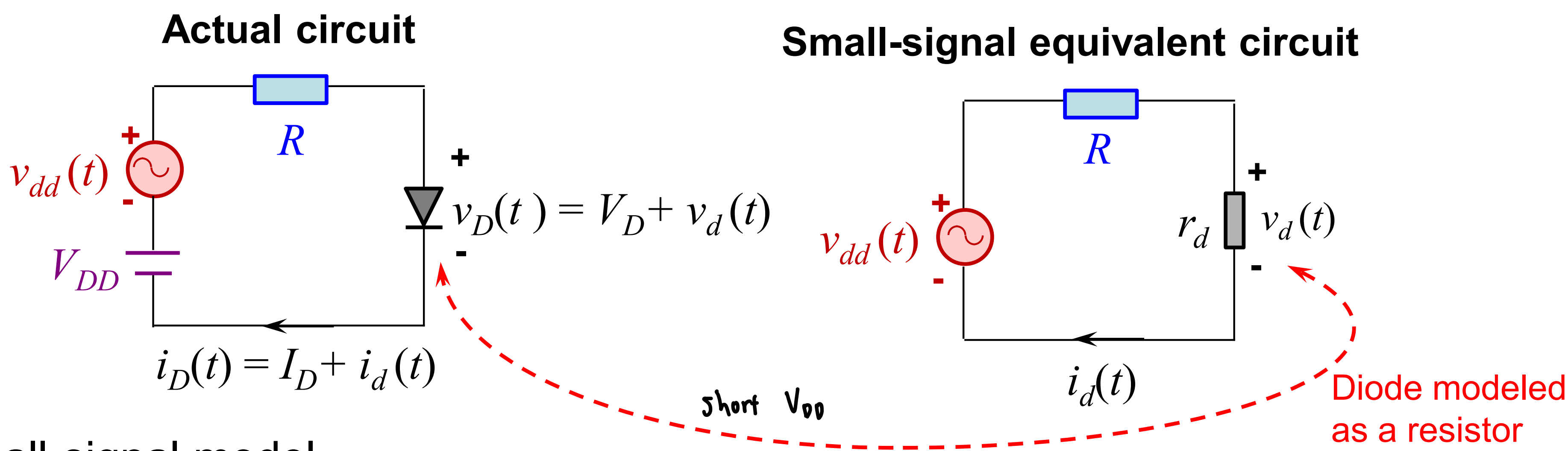
Small-signal operation

- From equation (2.11) - for small $v_{dd}(t)$, the total instantaneous current, $i_D(t)$, is the sum (superposition) of two components: a dc I_D, and an ac $\frac{I_D}{nV_T} v_d(t)$.
- The total instantaneous diode current $i_D(t)$ is also given by equation (2.8), hence the small-signal current of the diode, $i_d(t)$, is given by
  - $$i_d(t) = \boxed{\frac{I_D}{nV_T}} v_d(t) = \frac{1}{r_d} v_d(t) \qquad (2.12)$$

    ★★★ constant
  - $$\boxed{r_d = \frac{nV_T}{I_D}} \qquad (2.13)$$

    → DC (constant voltage drop model)
- r_d has the dimension of resistance and is called the diode small-signal resistance. (N.B. r_d is different from r_D in slide pn-26, a large-signal model parameter)

Diode – Modeling the Diode - Small Signal Model



<u>Small-signal model</u>

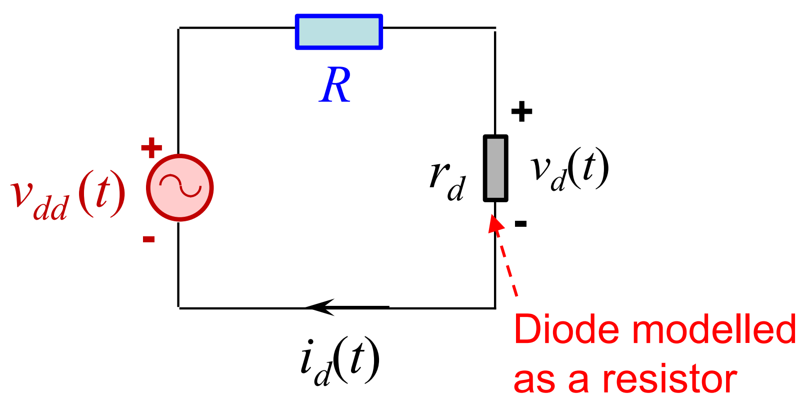
- From equation (2.12) - diode small-signal current, $i_d(t)$, is directly and linearly related to its small-signal voltage, $v_d(t)$, via r_d (similar to a resistor) -
  - $\boxed{i_d(t)} = \dfrac{I_D}{nV_T} v_d(t) = \boxed{\dfrac{1}{r_d} v_d(t)}$ (2.12)
- For small-signal operation (around a dc bias point), the diode can be replaced (or modeled) by a resistor, r_d , as shown in the circuit on the right above. There is no need for detailed calculation with time and the dc source, V_{DD}, is replaced by a short circuit (known as ac short).
  - Diode small-signal current can be determined using KVL: $\boxed{i_d(t) = \dfrac{v_{dd}(t)}{R + r_d}}$

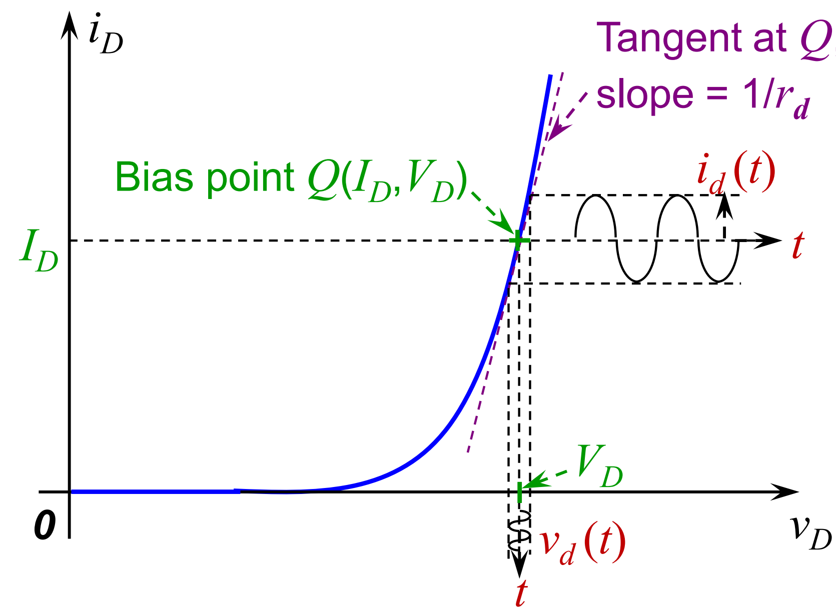
**** need to find DC current

- The bias point I_D is needed to find r_d, as seen in equation (2.13): $r_d = \dfrac{nV_T}{I_D}$.

Diode – Modeling the Diode - Small Signal Model

Small-signal equivalent circuit





Small signal model

- It has been seen that small-signal analysis can be performed separately from dc analysis with the diode modelled as a linear component resistor, r_d, and the dc source, V_{DD}, replaced by a short circuit.
- From above IV characteristic - the slope at the dc bias point $Q(I_D,V_D)$ gives approximately the inverse of diode small-signal resistance, r_d -

$$\frac{di_D}{dv_D}\Big|_{v_D=V_D} = \frac{1}{r_d} = \frac{i_d}{v_d} = \frac{I_D}{nV_T} \tag{2.14}$$

- r_d is also known as the diode incremental resistance.
- In developing the small-signal model of diode (non-linear), we have a linear relationship between its small-signal voltage, v_d ,and small-signal current, i_d.

Diode (Semiconductor pn-Junction)

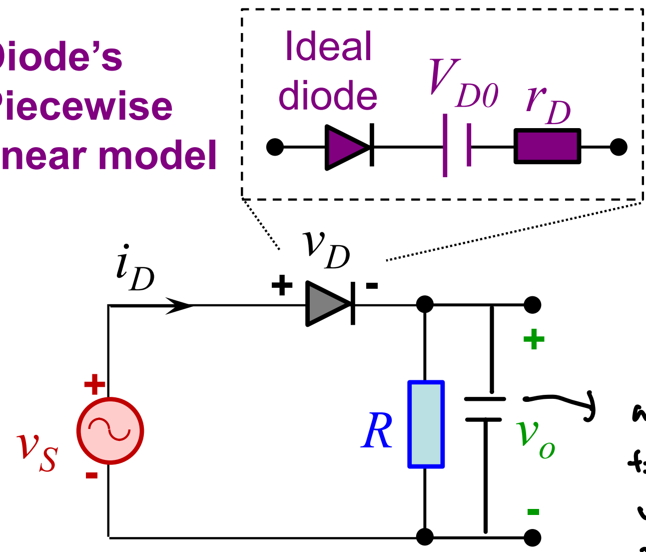
1. Introduction
2. Operation Regions: Forward-Bias, Reverse-Bias, and Breakdown
3. Current-Voltage Characteristic
4. Modeling the Diode
5. The Diode Circuit(s): Rectifier and Voltage Regulator
6. Charge Stored and Capacitive Effect

Reference

❑ A.D. Sedra & K.C. Smith, "Microelectronic Circuits – Theory and Application", 5th Edition (International Version), Oxford University Press, Chapter 2.

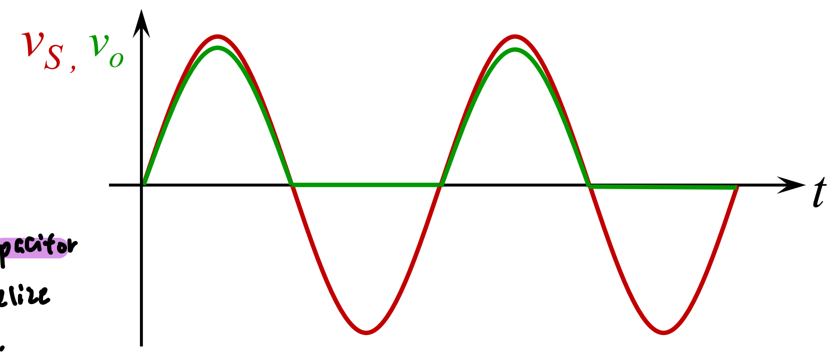
Diode – Diode Circuit(s): Half-Wave Rectifier

Diode's Piecewise linear model



add capacitor to stablelize voltage.
Bigger value capacitor, voltage ripple will be lesser

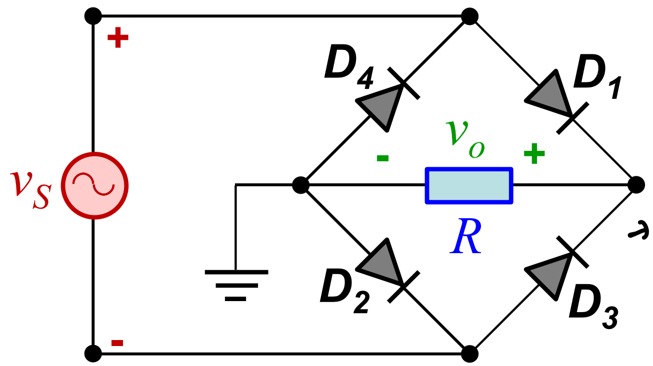
v_S is an ac signal with large amplitude



Rectifying application of diode

- During the positive half-cycles of v_S, current flows through the diode in the forward direction, hence $v_o \cong v_S - V_{D0}$ ($>> i_D r_D$) where AC source amplitude is v_S.
- During the negative half-cycles of v_S, the diode does not conduct, thus $v_o = 0$.
- Although v_S alternates in polarity and has a zero average value, v_o is unipolar /unidirectional and has a finite average value or a dc component.
- Above circuit is known as a half-wave rectifier as it utilizes alternate half-cycles of input sinusoidal AC source v_S.

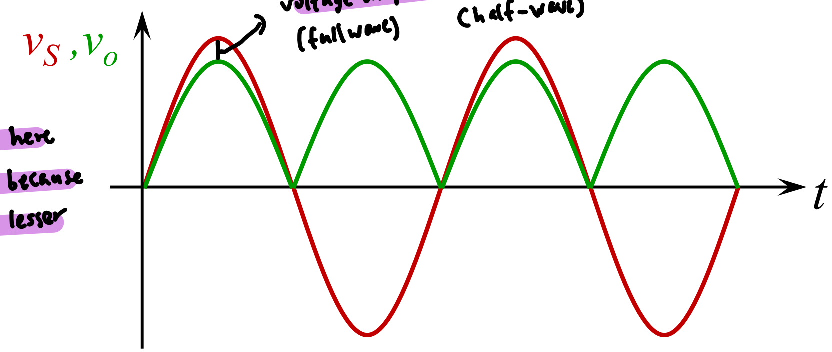
Diode – Diode Circuit(s): Full-Wave Rectifier



capacitor used here can be smaller because voltage ripple is lesser

v_S is an ac signal with large amplitude

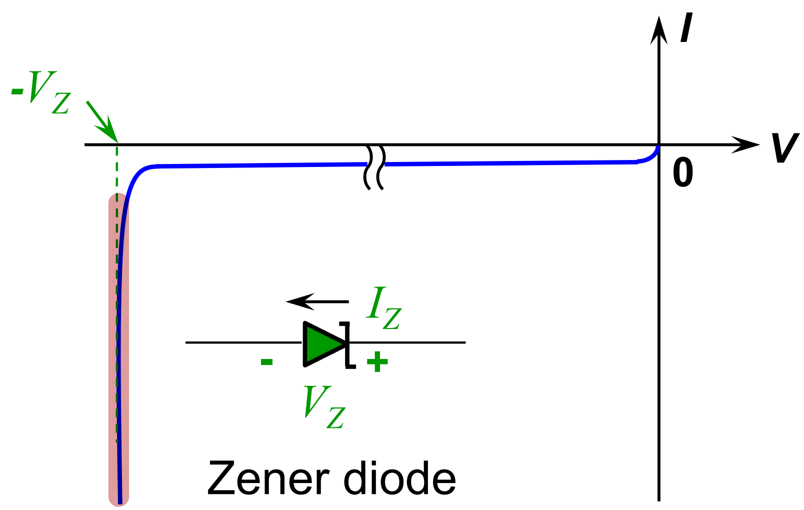
voltage drop (full wave) > voltage drop (half-wave)

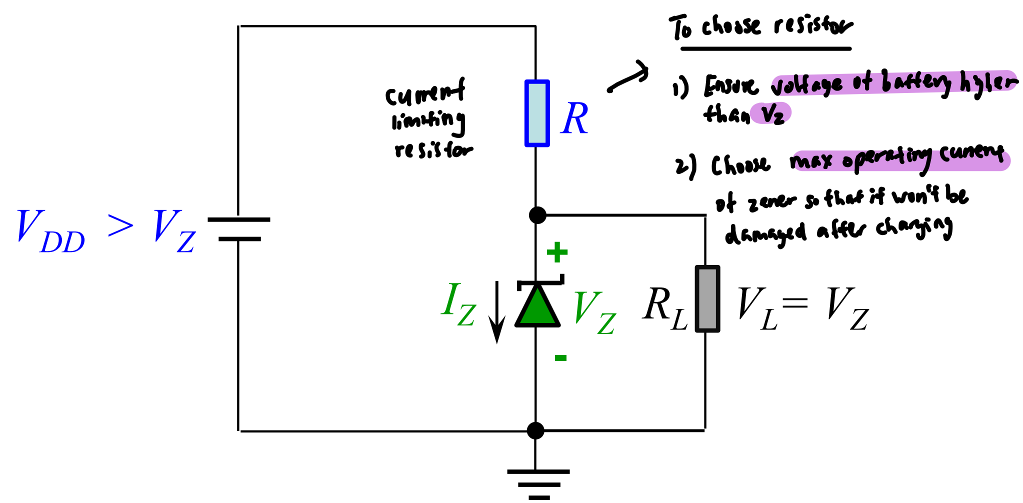


Full-wave bridge rectifier

- Full-wave rectifier utilizes both positive and negative half-cycles of input signal.
- Four diodes connected in Wheatstone bridge configuration is used.
- During the positive half-cycles of v_S, current conducts through diode D_1, load resistor R and diode D_2. In the meantime, D_3 and D_4 are reverse biased.
- During the negative half-cycles of v_S, current conducts through diode D_3, load resistor R and diode D_4, while diode D_1 and D_2 are reverse biased.
- Note that - $\boxed{v_o \cong v_S - 2\times V_{D0}.}$ ***

Diode – Diode Circuit(s): Voltage Regulator





Zener diode as a voltage reference

- Zener diodes are special diodes designed to operate in the breakdown region and they can be used in the design of voltage regulator (a circuit that provides a V_z constant dc voltage between its terminals). Zener diodes are specified with V_Z, the breakdown voltage.

- In the above circuit, as long as $V_{DD} > V_Z$ (meaning Zener diode operates in the breakdown region), the voltage across the load R_L is kept constant (or regulated) at $V_L = V_Z$ by the Zener diode. Note that $I_Z \neq 0$.

- Virtually replaced by specially designed ICs that perform voltage regulation much more effectively and greater flexibility.

Diode (Semiconductor pn-Junction)

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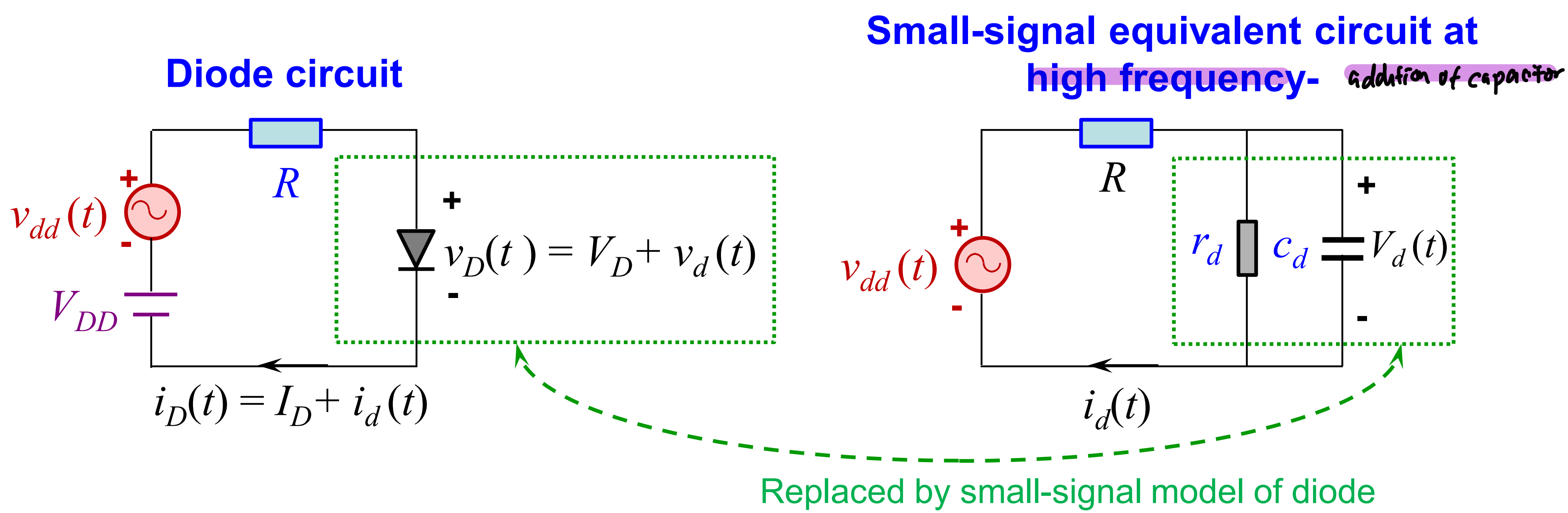
Reference

- A.D. Sedra & K.C. Smith, "Microelectronic Circuits – Theory and Application", 5th Edition (International Version), Oxford University Press, Chapter 2.

Diode – Charge Stored and Capacitive Effect

- *pn*-junction exhibits capacitive effect, as there are charges stored within it and which is a function of the voltage applied across the *pn*-junction, v_D.
- As the charges stored do not vary linearly with v_D, unlike a parallel plate capacitor. Only small-signal capacitance (= dQ/dv_D) can be defined for a *pn*-junction diode.
- At high-frequencies, capacitive effect must be included in the small-signal model of a *pn*-junction, as shown below -

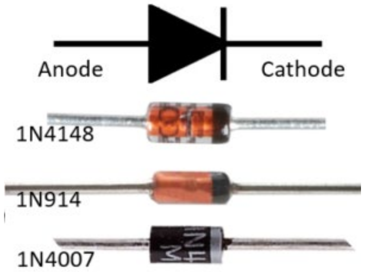


Diode – Topics Discussed

- ❑ Basics: Structure, semiconductor versus metal/insulator, n- versus p-semiconductor, doping, drift versus diffusion current
- ❑ Operation regions: forward bias (below cut-in and substantial forward bias), reverse bias (non-breakdown & breakdown)
- ❑ IV characteristic: $I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$
- ❑ Large signal model (r_D, V_{D0}) & dc large-signal analysis
- ❑ Small signal model ($r_d = \frac{nV_T}{I_D}$) & ac small-signal analysis
- ❑ Rectifiers: half-wave versus full-wave rectifier
- ❑ Zener diode & voltage regulator
- ❑ Capacitive effect – to be included at high-frequency.

Semiconductor pn-Junction Diodes Vs Vacuum Tube Diodes

Semiconductor pn-Junction Diodes -



Vacuum Diodes -