EECE251

Circuit Analysis I

Set 6: Diodes

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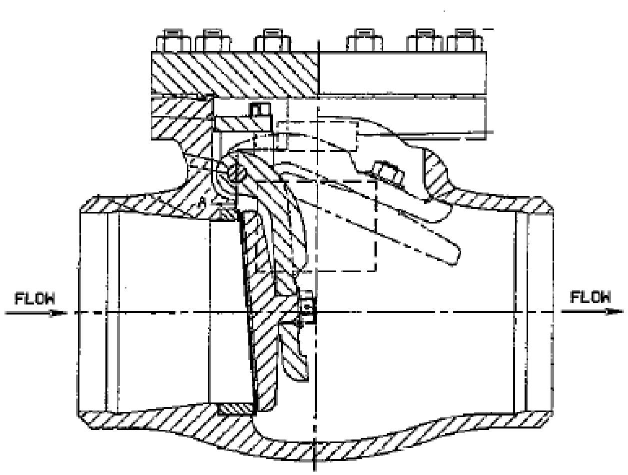
Thanks to Dr. Linares and Dr. Yan for sharing their notes on diodes (the basis for these slides).

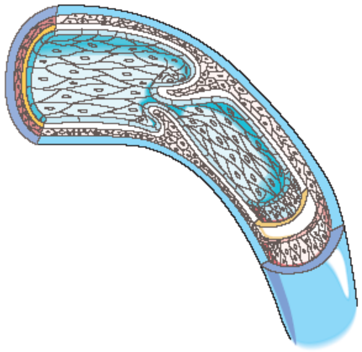
Valves

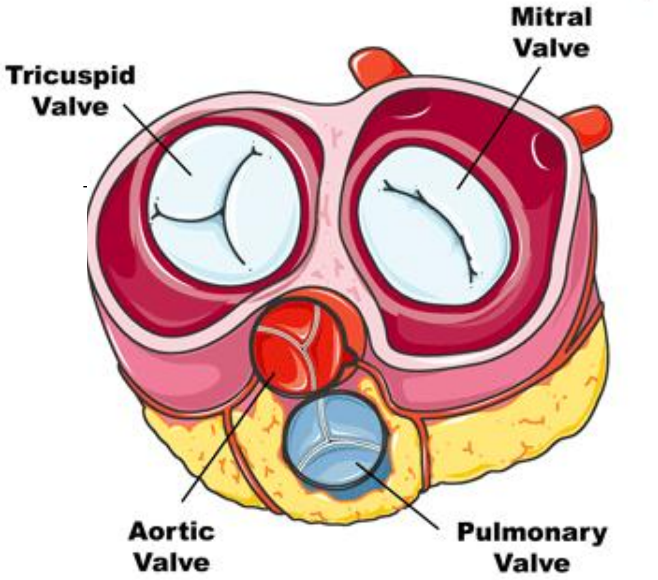
- Valves are typically used to control the flow of something!

- Valves are everywhere!
  - mechanical systems
  - biological systems
  - …

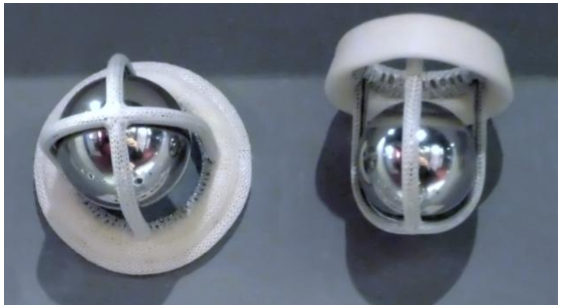


Check Valve





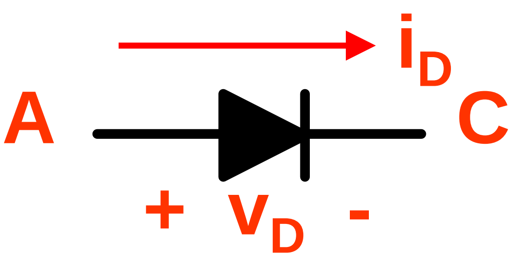
Starr-Edwards Valve

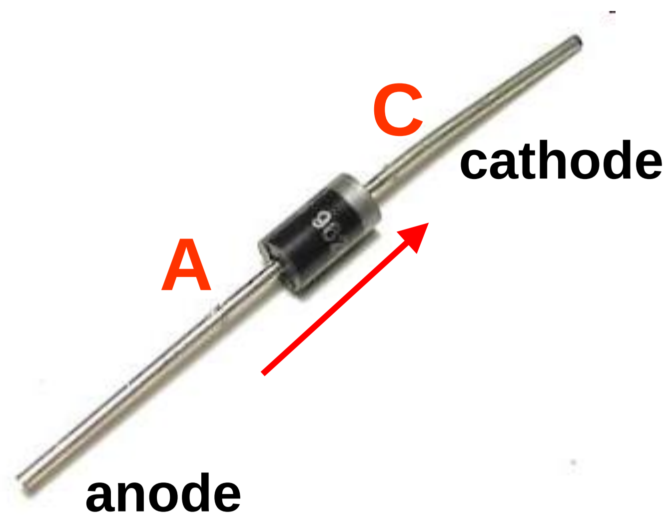


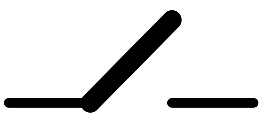
An Electric Valve! (AKA: Diode)

- Diodes can be considered as electric valves where permit current flow in only one direction

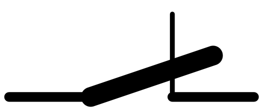
- Ideal diode:







$$\text{If } v_D < 0 \text{ then } i_D = 0$$



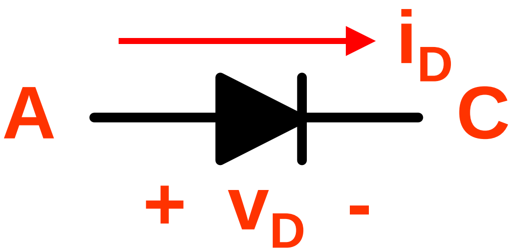
$$\text{If } i_D > 0 \text{ then } v_D = 0$$

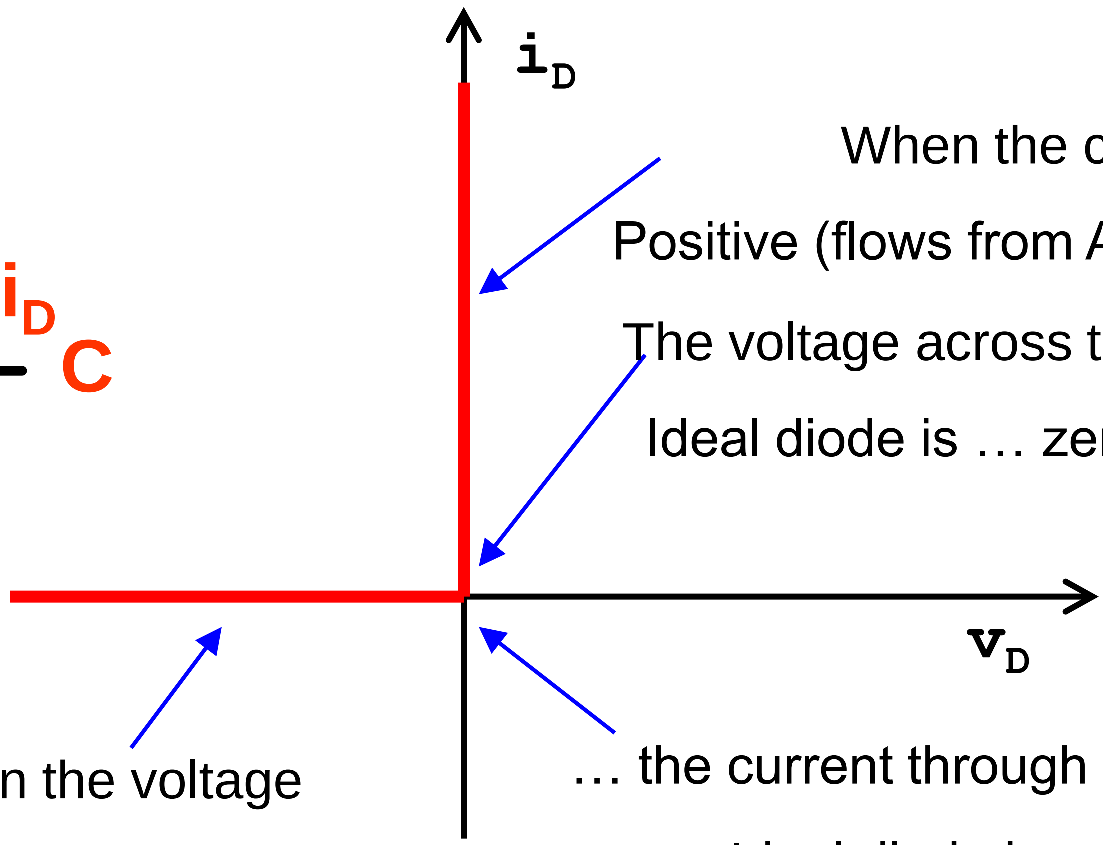
Ideal Diode

- If the diode is conducting,
  - we say it is "closed" or "on" (as if it were a closed switch)
  - It behaves like a "wire" or "short circuit"

- If the diode is NOT conducting,
  - We say it is "open" or "off" (as an open switch)
  - It behaves as an open circuit

Ideal Diode Characteristic





When the current is Positive (flows from A to C)…

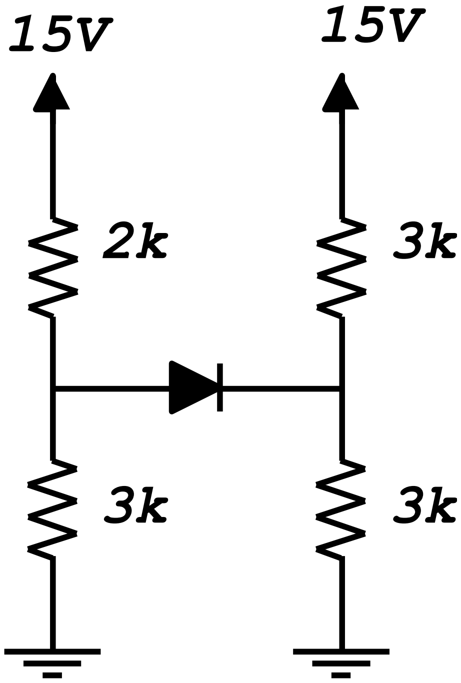
The voltage across the Ideal diode is … zero!

When the voltage across the diode is negative …

… the current through the Ideal diode is zero!

Example

- In the following circuit, assume the diode is ideal. Is it on or off and what is the current through it?



Solving Circuits Containing Ideal Diodes

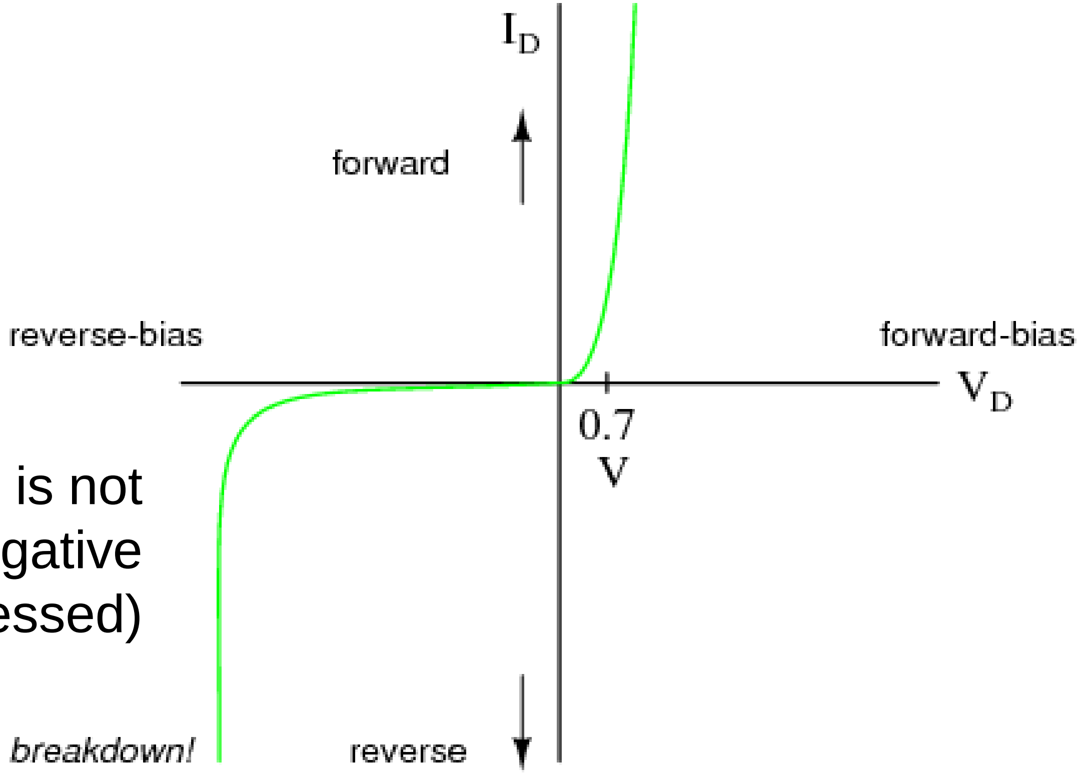
- If there is only one diode there are two possibilities to consider and only one of them is valid (the diode is either on or off).
  - Basically we can check the voltage across the diode (assuming that it is open) and if the voltage is negative then the diode is indeed open otherwise the diode is closed and we can analyze the circuit by replacing the diode with a short circuit.

- What if there are two diodes?

- What is there are “n” diodes?

Characteristic of a Real Diode

- Here is a I-V curve for a typical silicon diode. Depending on the application and the required accuracy, a revised version of the diode model may be used.



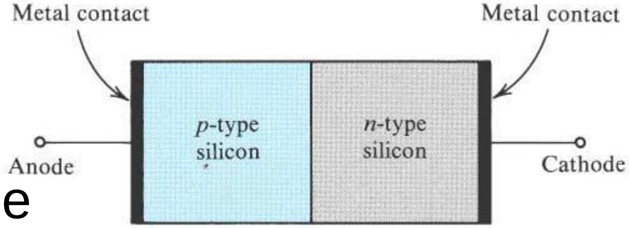
The BD voltage is not to scale (the negative V axis is compressed)

Some Basics

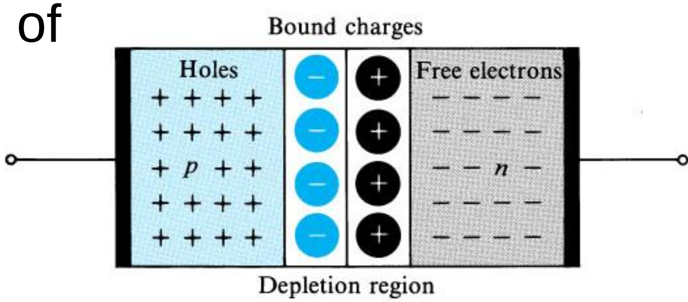
- Diodes are made of semiconductor material!
- Semiconductors are materials whose electrical properties are somewhat in between those of conductors and insulators!
- Examples: Silicon, Germanium, Gallium Arsenide (GaAs), …
- In semiconductors, a charge carrier can be either a (free) electron or a hole (absence of an electron).
- "Doped" semiconductor has impurities intentionally diffused into the material to manipulate the majority of charge carriers to be either electrons (n-type for "negative doping", e.g., using Phosphorous in Silicon) or holes (p-type for "positive doping", e.g., using Boron in Silicon).

The "pn" Junction

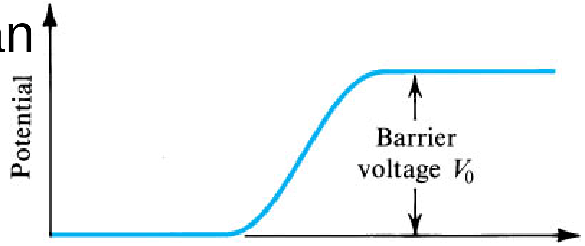
- A diode is formed by a "*pn junction*".



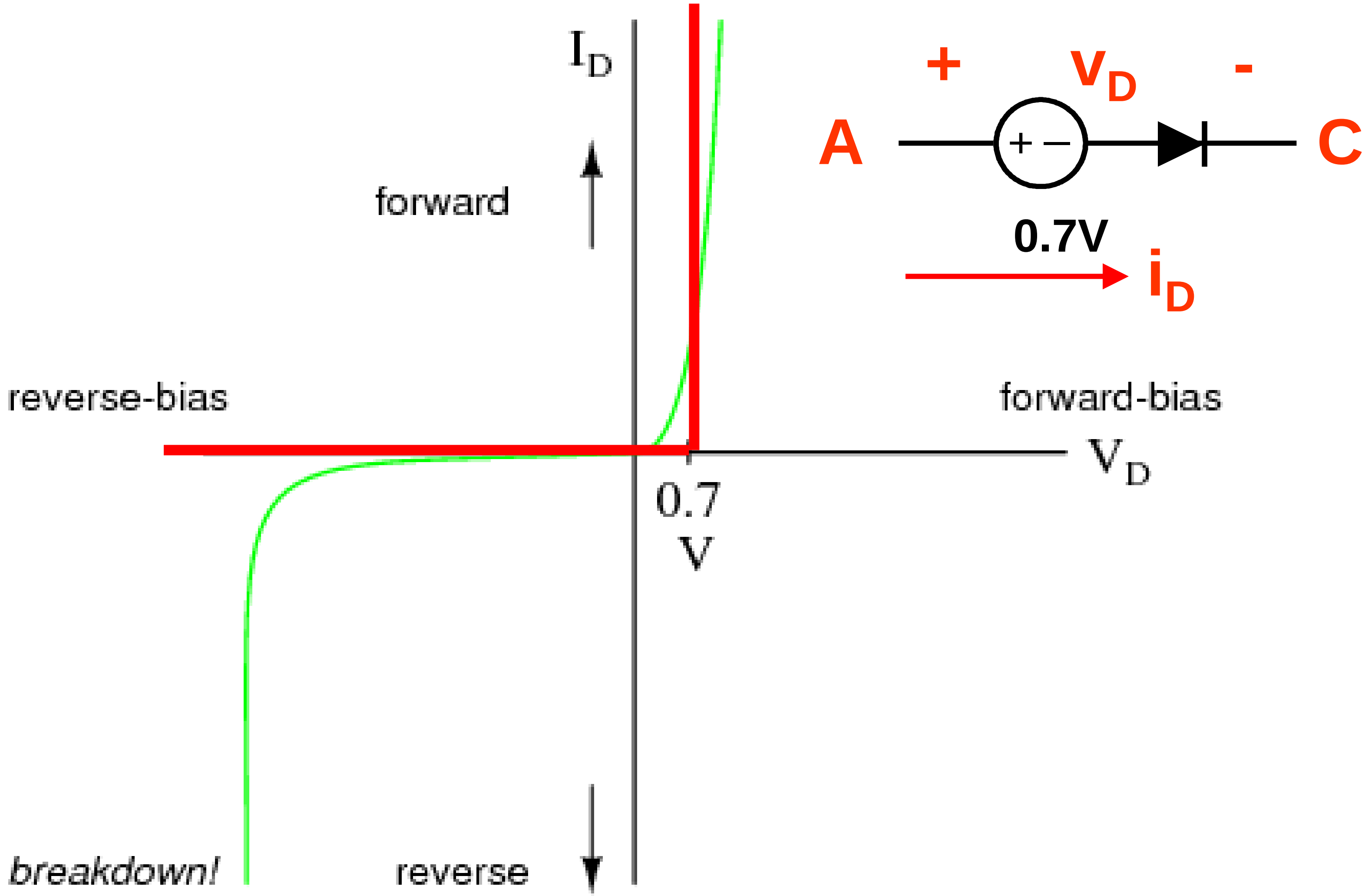
- At the junction, excess electrons on the n side combine with excess holes on the p side, causing a depletion region that is depleted of charge carriers.



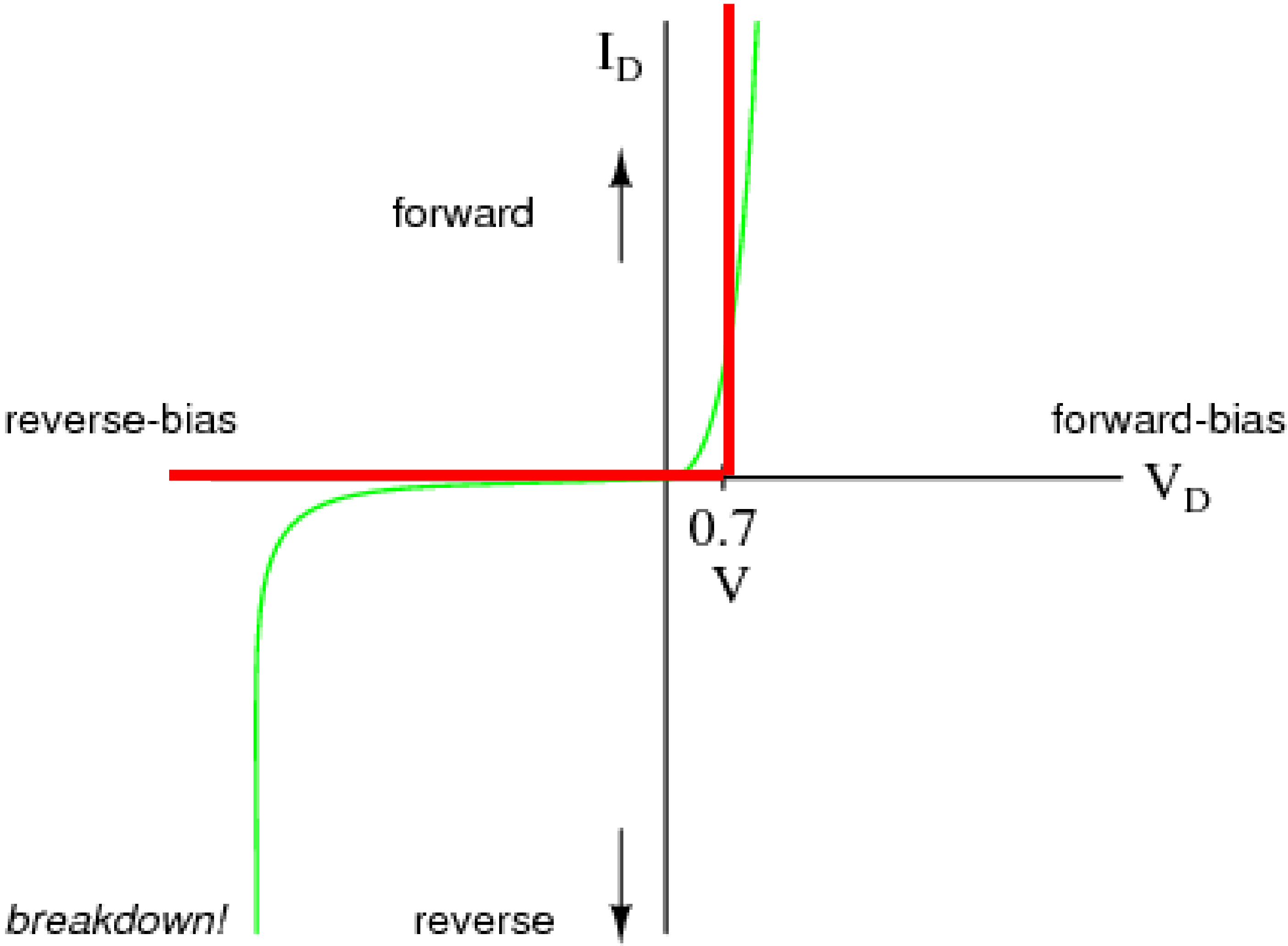
- This depletion region results in a "barrier" voltage (~0.7V for Si, and ~0.3V for Ge); if the voltage of the anode (p side) is raised to overcome this barrier, the charge carriers can move again, giving rise to current.



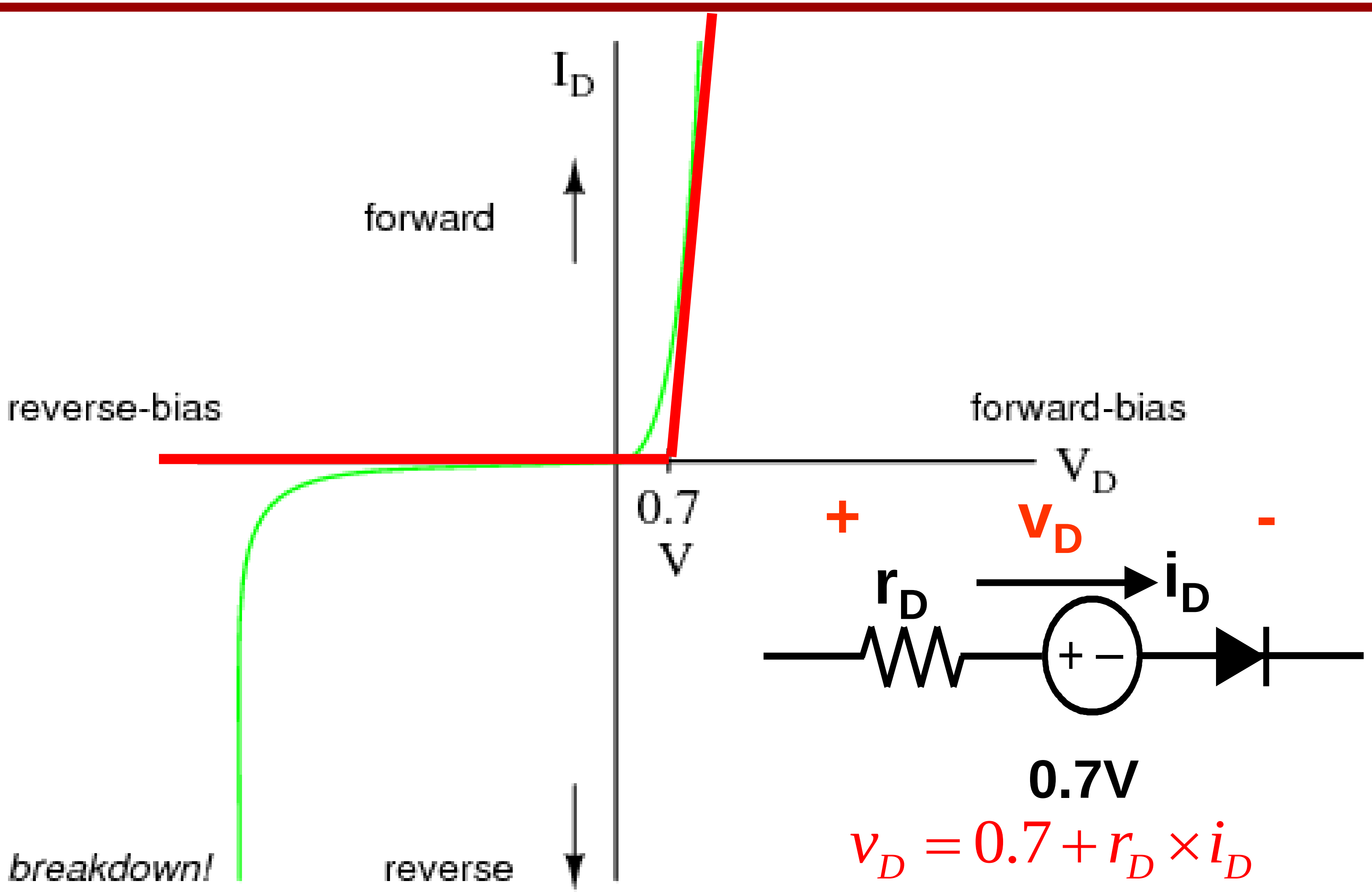
First Approximation (Constant Voltage Model)



Second Approximation

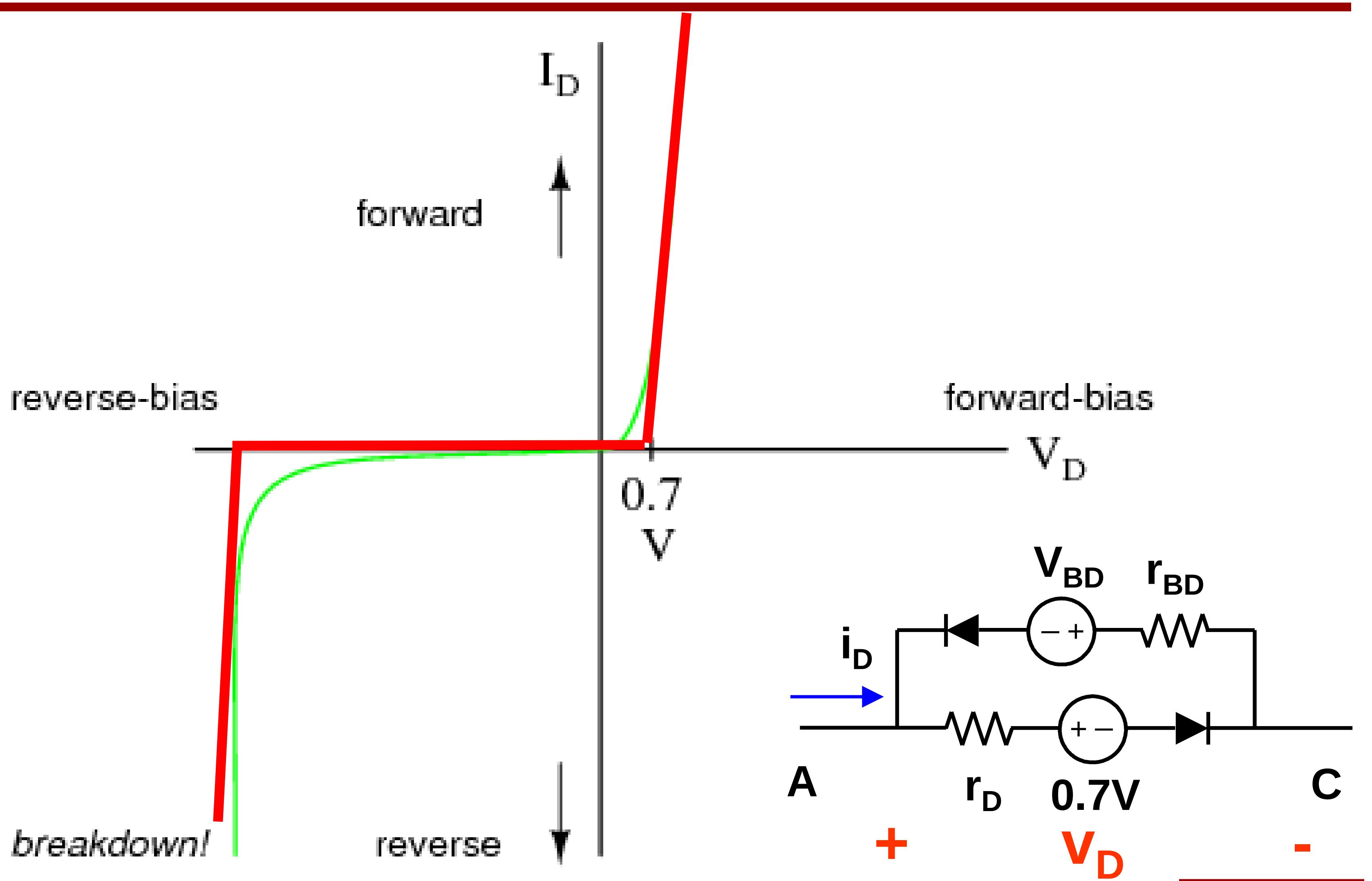


Second Approximation (Piecewise Linear)



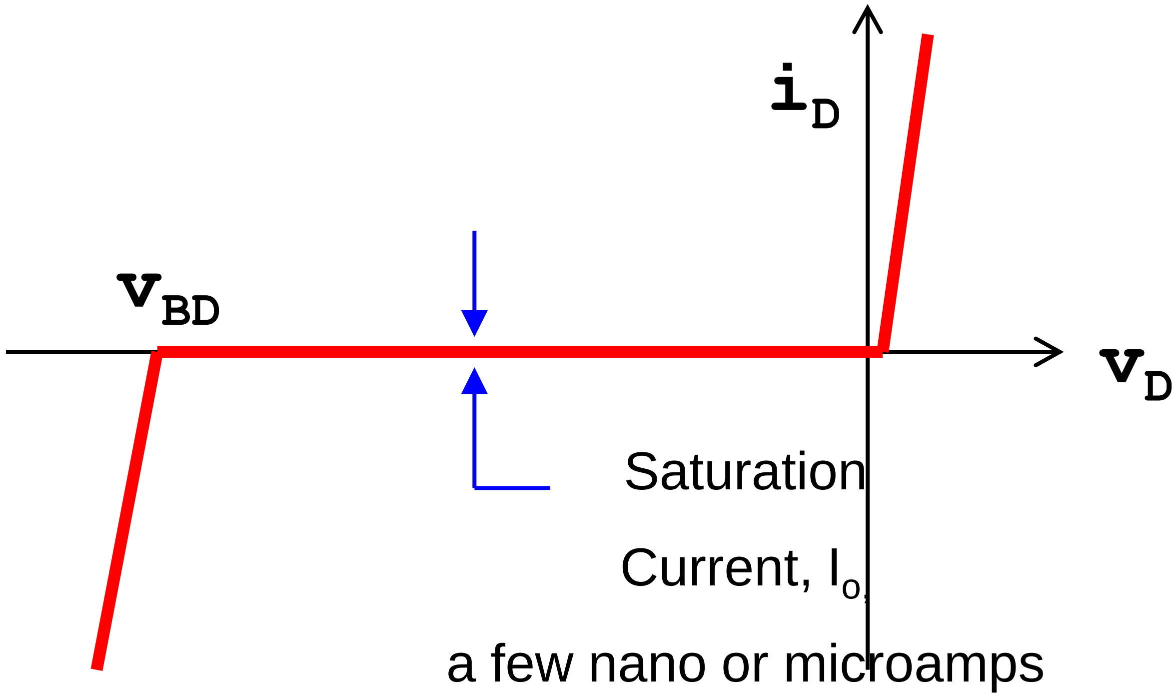
$$v_D = 0.7 + r_D \times i_D$$

Third Approximation (Piecewise Linear)

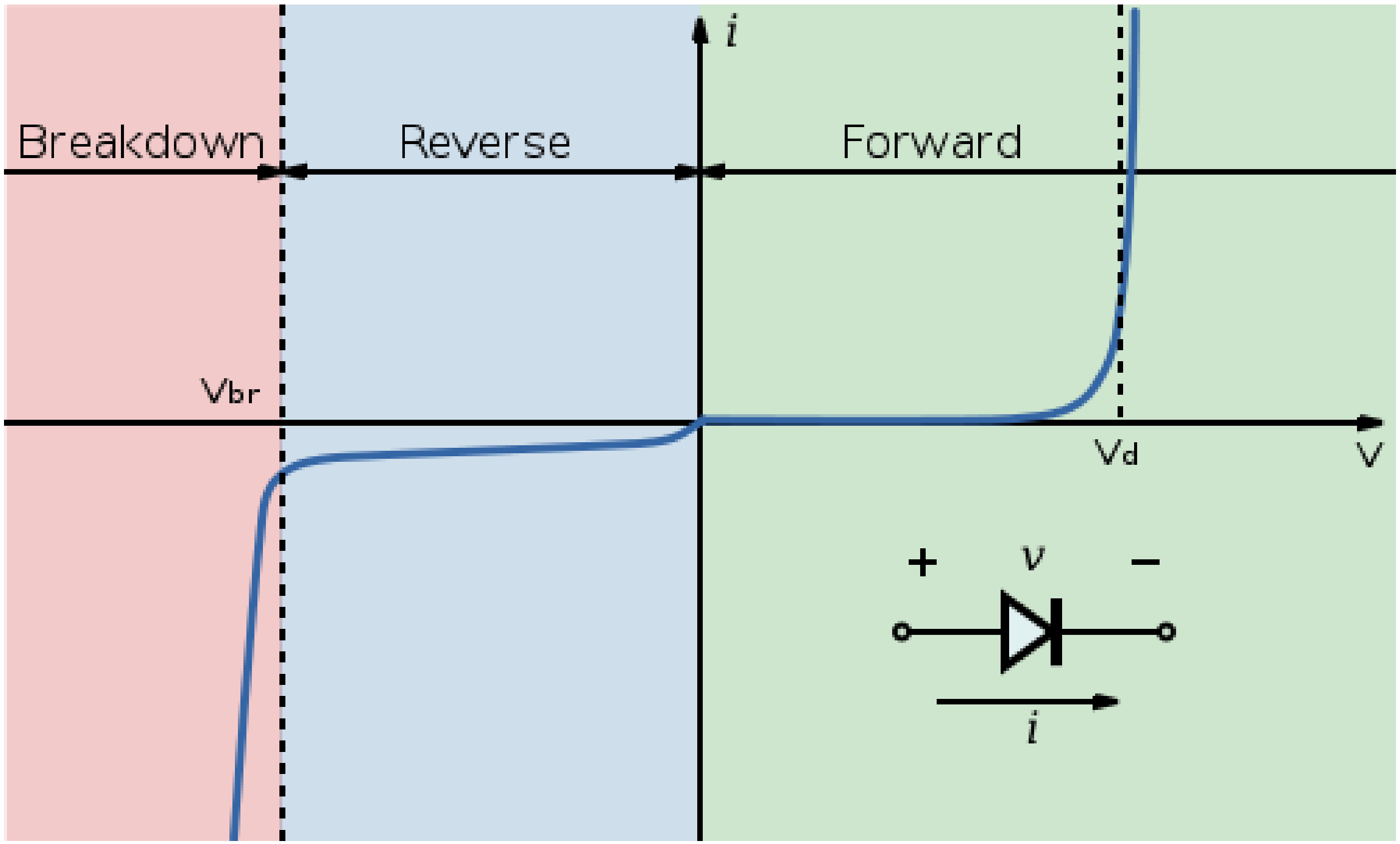


Reverse Current

- When the diode is off, its current (referred to as reverse current) is NOT quite zero …

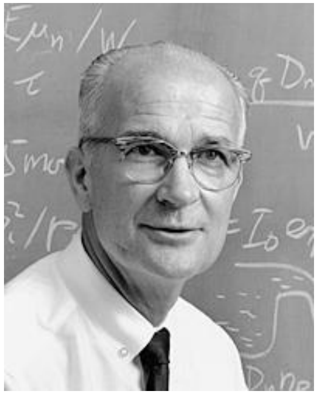


Zones of Operation

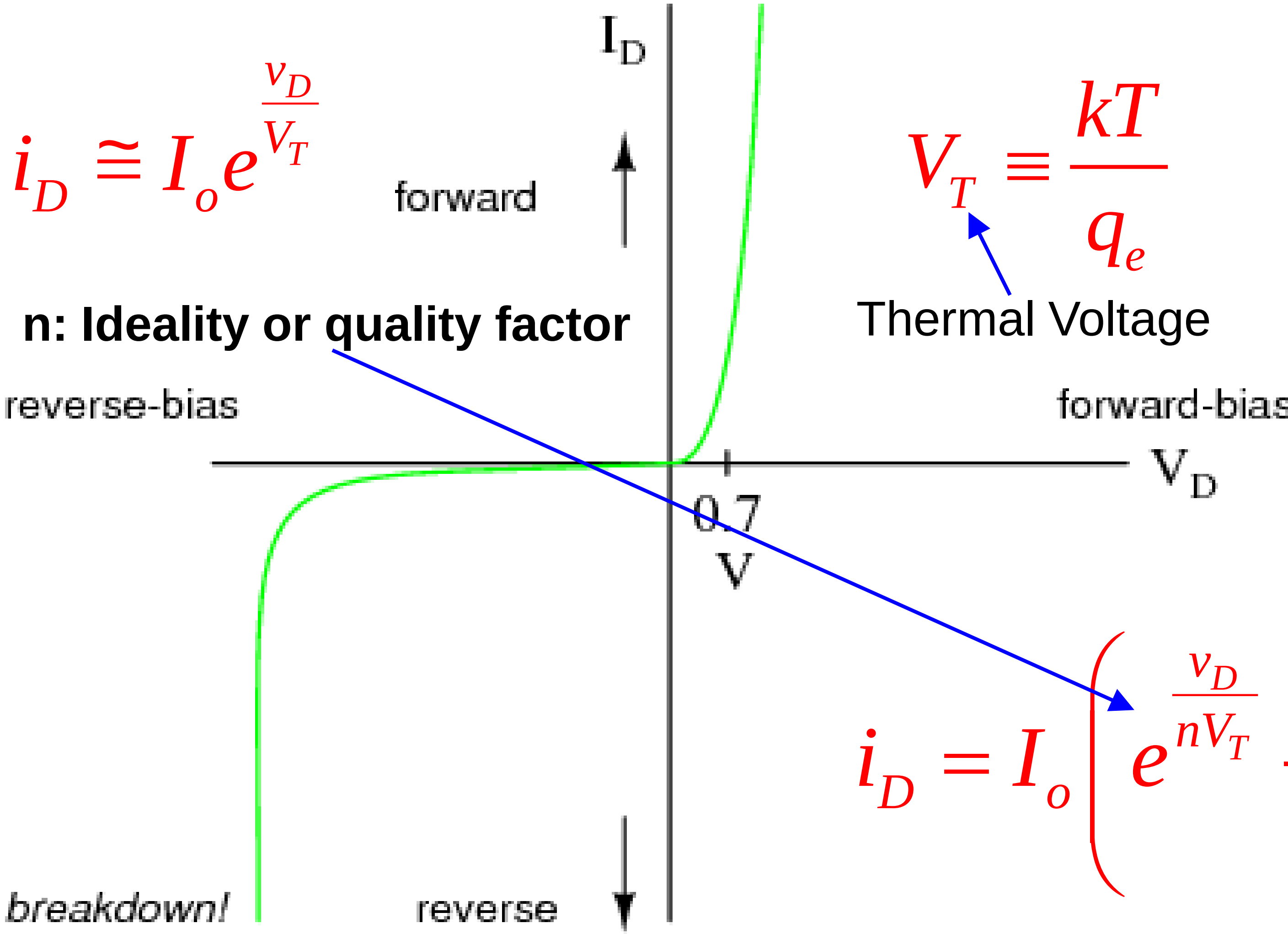


Who was Shockley?

- William Bradford Shockley Jr. (February 13, 1910 – August 12, 1989) an American physicist and inventor. Along with **John Bardeen** and **Walter Houser Brattain**, **Shockley** co-invented the transistor, for which all three were awarded the 1956 **Nobel Prize** in Physics.
- Shockley's attempts to commercialize a new transistor design in the 1950s and 1960s led to California's **"Silicon Valley"** becoming a hotbed of electronics innovation. In his later life, Shockley was a professor at Stanford. (from Wikipedia)



The actual VI curve …



$$i_D \cong I_o e^{\frac{v_D}{V_T}}$$

$$V_T \equiv \frac{kT}{q_e}$$

Thermal Voltage

n: Ideality or quality factor

$$i_D = I_o\left(e^{\frac{v_D}{nV_T}} - 1\right)$$

The actual VI curve …

$$i_D = I_o e^{\frac{v_D}{V_T}}$$

$$V_T \equiv \frac{kT}{q_e}$$

Thermal Voltage

k = Boltzman constant

T = temperature, ^oK

q_e = electron charge, C

Example

- For n=1 and v_D>>V_T we have: $i_D = I_o e^{\frac{v_D}{V_T}}$ where $V_T \equiv \frac{kT}{q_e}$

- Given these equations, compute the thermal voltage at room temperature, i.e., 2^{o}C. If I_o=3 nA, find the voltage and power of the diode when the current is 2 A.

Practical Limitations

- Consider the 1N4148

  (datasheet: http://www.vishay.com/docs/81857/1n4148.pdf)

  Sample table from data sheet

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_{FAV}	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

Practical Limitations

- Sample graph from the datasheet (Does this graph make sense?! Is the behaviour similar to what is expected based on Shockley's model?)

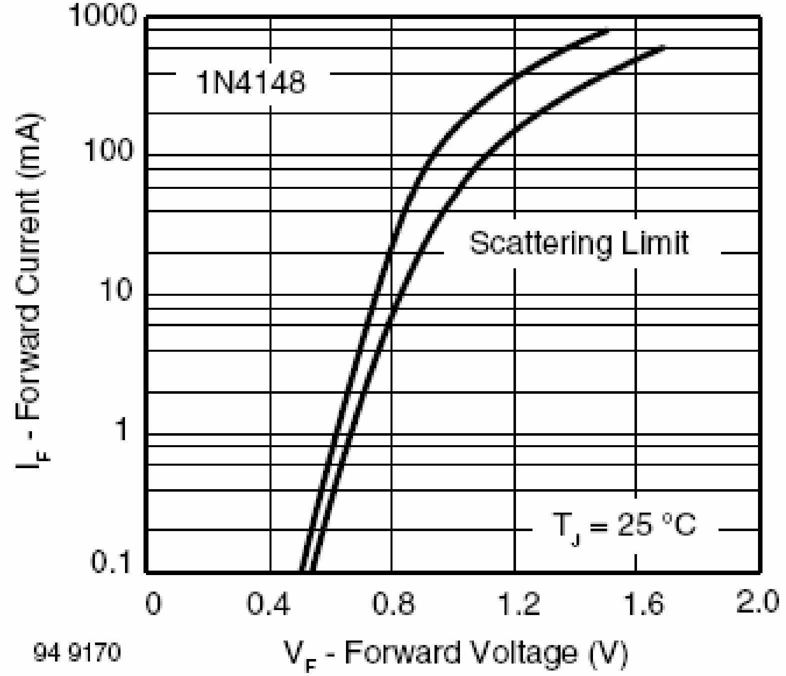
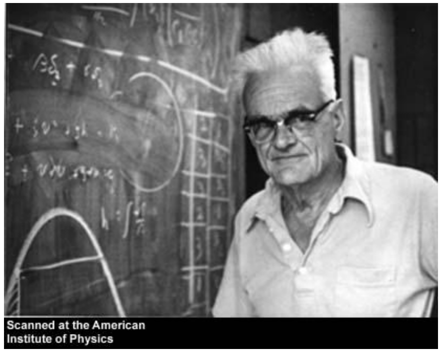


Figure 2. Forward Current vs. Forward Voltage

Zener Diodes

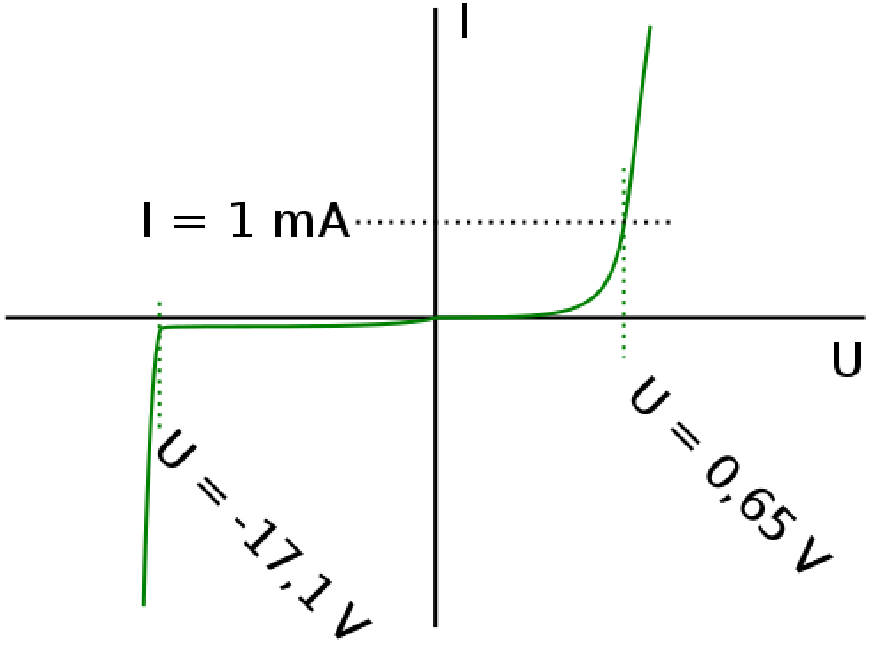
- Clarence Melvin Zener (1905-1993) was the American physicist who first described the property concerning the breakdown of electrical insulators. His findings were later exploited by Bell Labs in the development of the Zener diode, which was duly named after him (source: Wikipedia)



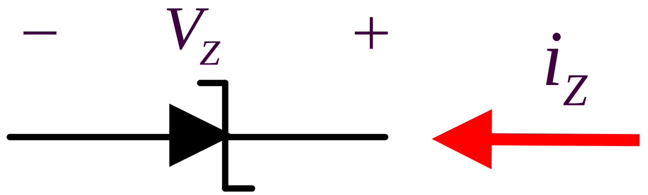
- Zener diodes are designed to operate "backwards"!

Zener Diodes

Diodes I-V plot.

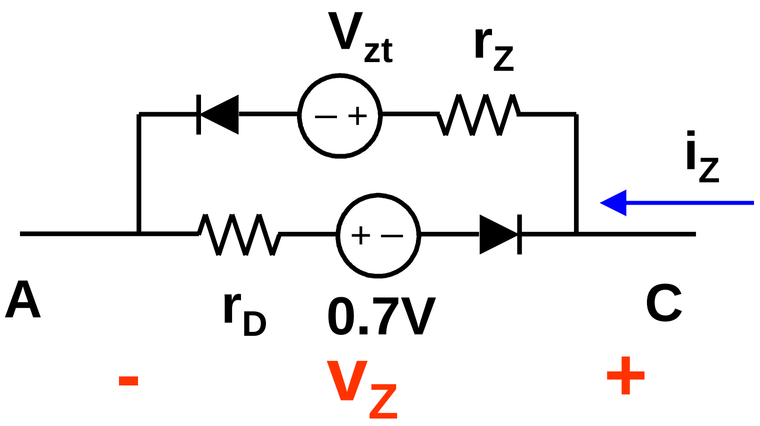


- Rename the breakdown voltage of the diode as "Zener Voltage", V_z and use the following polarity and current direction (what would the graph look like?



Zener Diode Model

In the useful Zener region the Zener diode behaves, almost, like an ideal voltage source! It keeps its voltage V_Z regardless of the current (up to a maximum power)

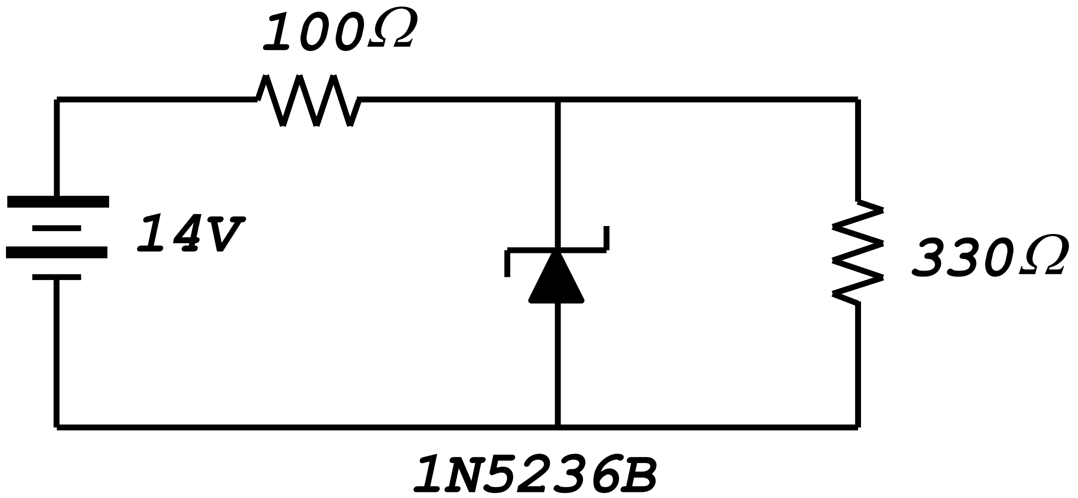


Zener Specifications

- Useful datasheet specifications:
  - Maximum power
  - Zener voltage, V_{ZT} (2V, 5V, 7.2V, …)
  - Current at V_{ZT}, I_{ZT}
  - Minimum Zener current, I_{ZK} (“knee”)
  - Dynamic R_k
  - Dynamic R_{ZT}
  - …

Use of the Zener diode

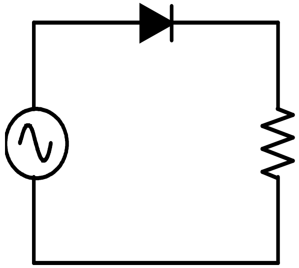
- To "clamp" a voltage output …



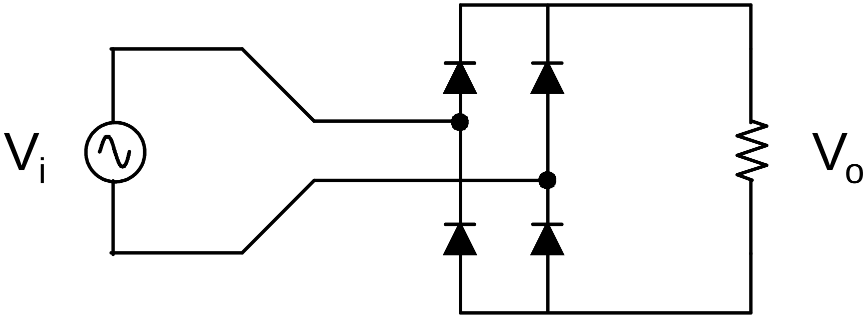
Diode Applications

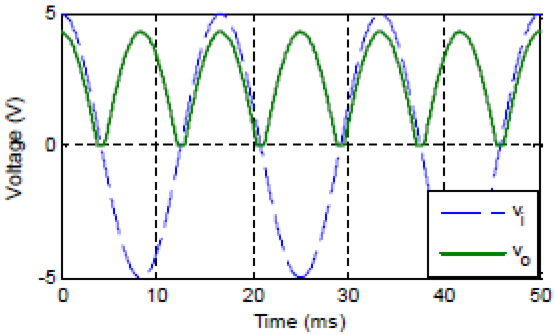
- Diodes are commonly used for rectification!
  - For example to produce DC power from an AC power

- Half-wave rectification

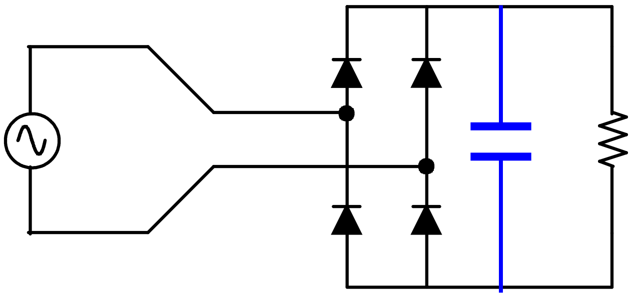


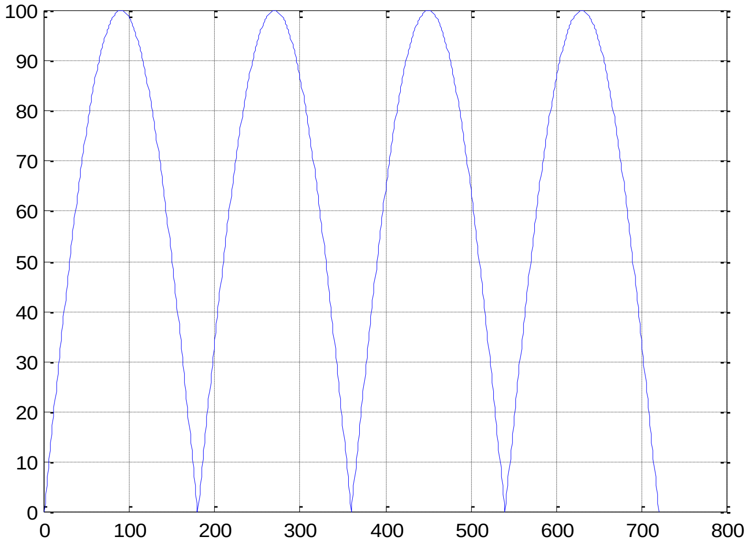
- Full-wave rectification



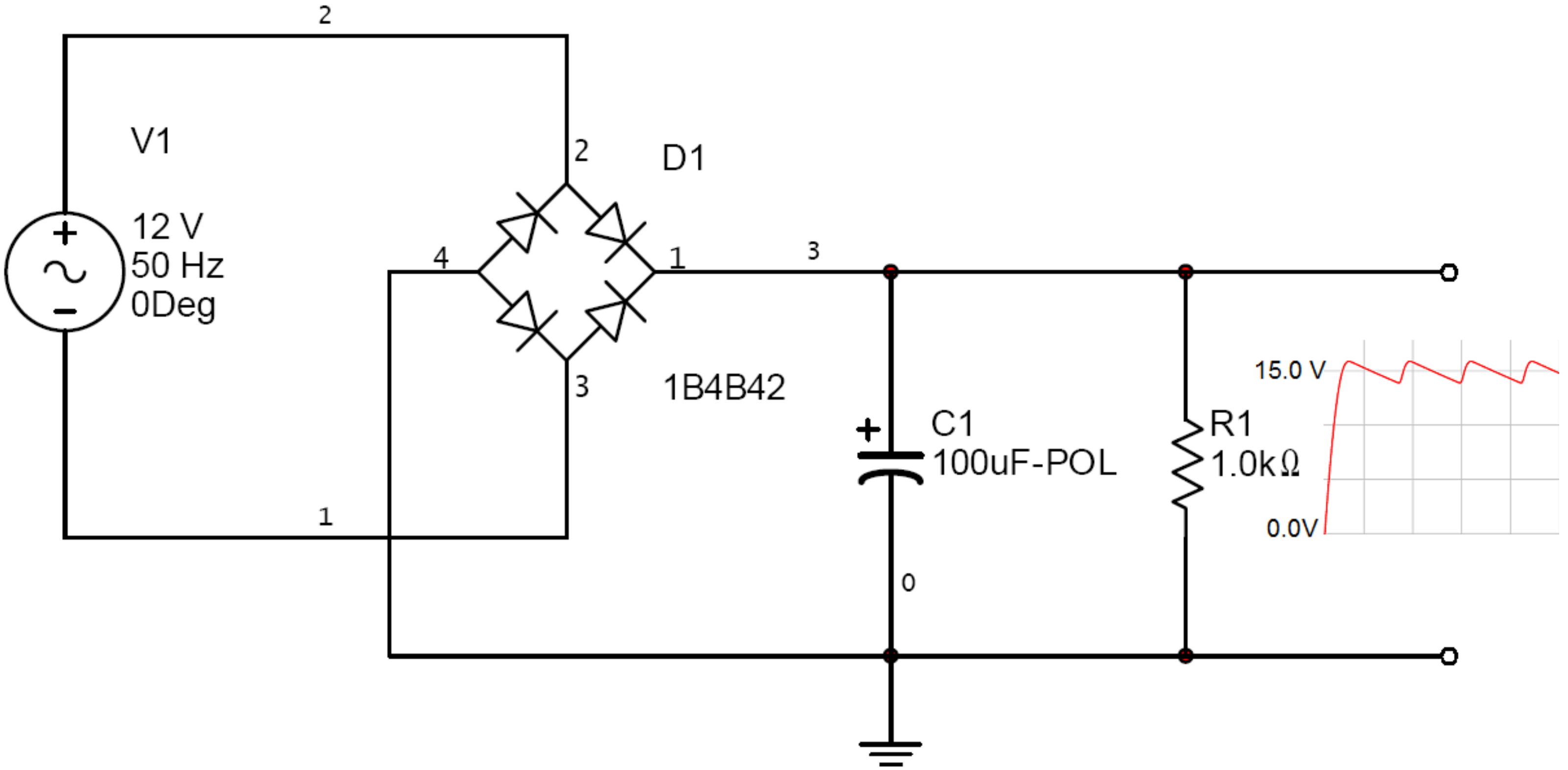


Full Wave Rectifier with Smoothing Filter





A Full-Wave Bridge



Can you think of a way to use a Zener diode in this structure?