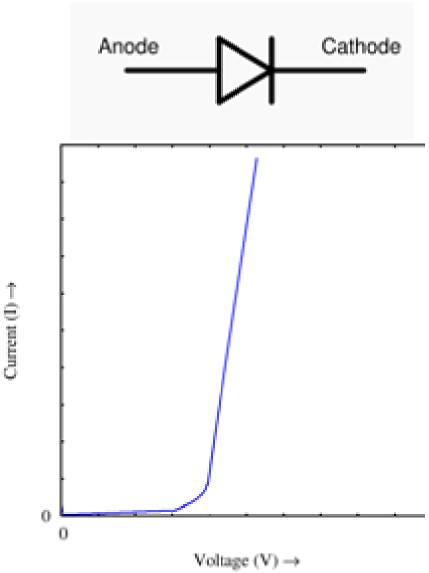
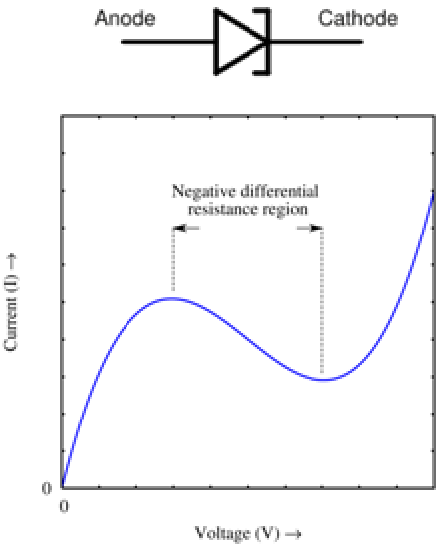
Tunnel Diodes (Esaki Diode)

Tunnel diode is the p-n junction device that exhibits negative resistance. That means when the voltage is increased the current through it decreases.

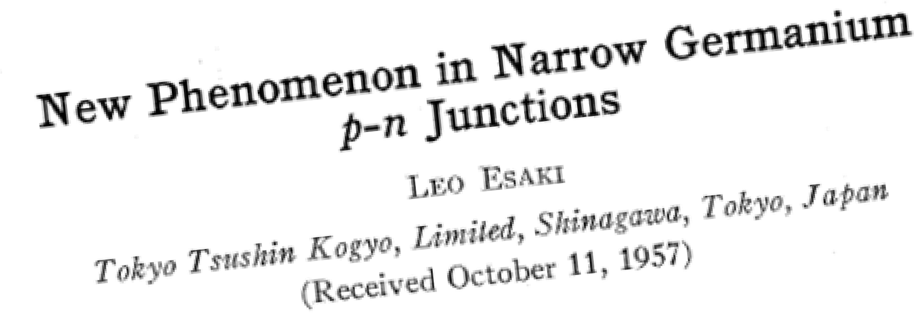


Regular p-n Diode



Tunnel Diode

Esaki diodes was named after Leo Esaki, who in 1973 received the Nobel Prize in Physics for discovering the electron tunneling effect used in these diodes. Esaki reported the first paper on tunnel diodes in Physical Review in 1958



New Phenomenon in Narrow Germanium *p-n* Junctions

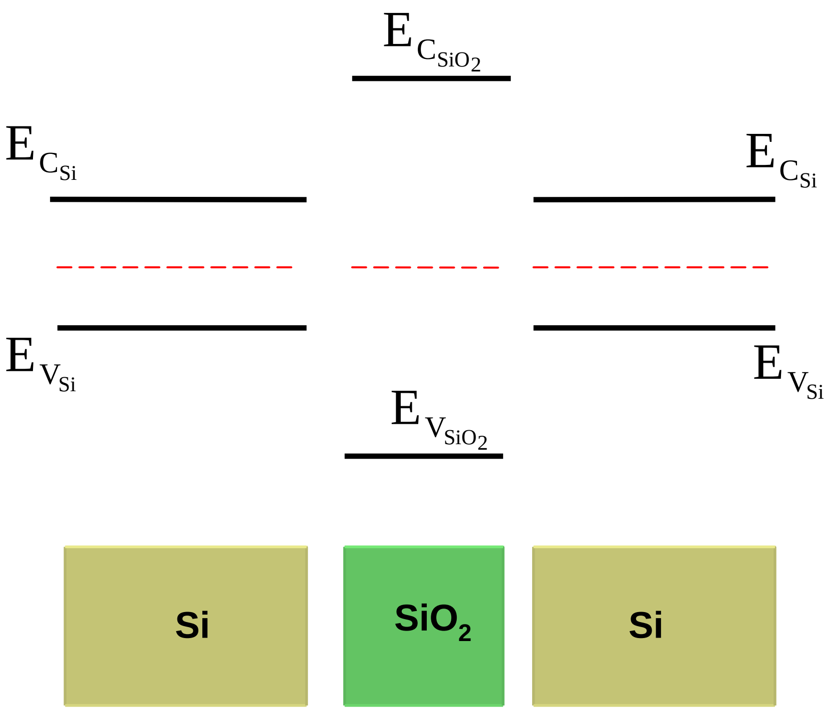
Leo Esaki

Tokyo Tsushin Kogyo, Limited, Shinagawa, Tokyo, Japan

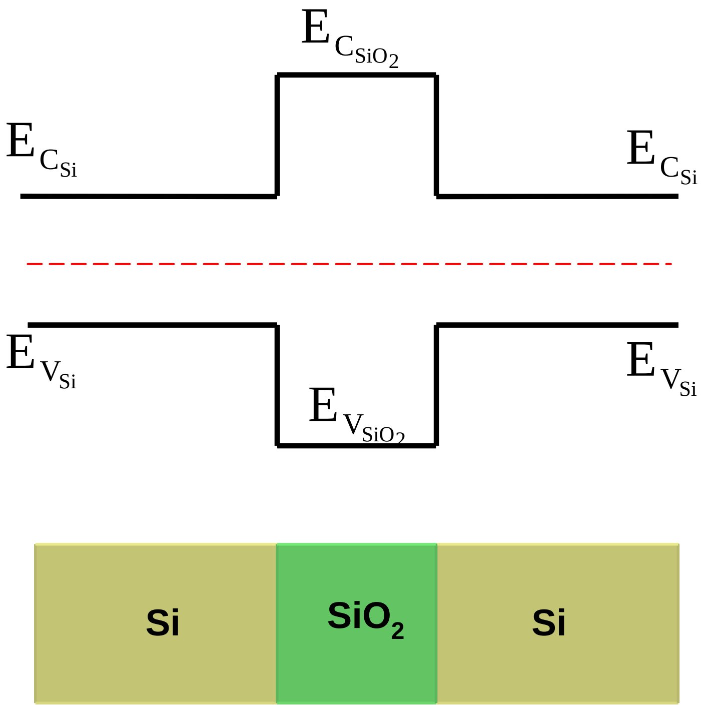
(Received October 11, 1957)

Part I Tunnel Diode principles
Concept of Electron Tunneling

Before contact

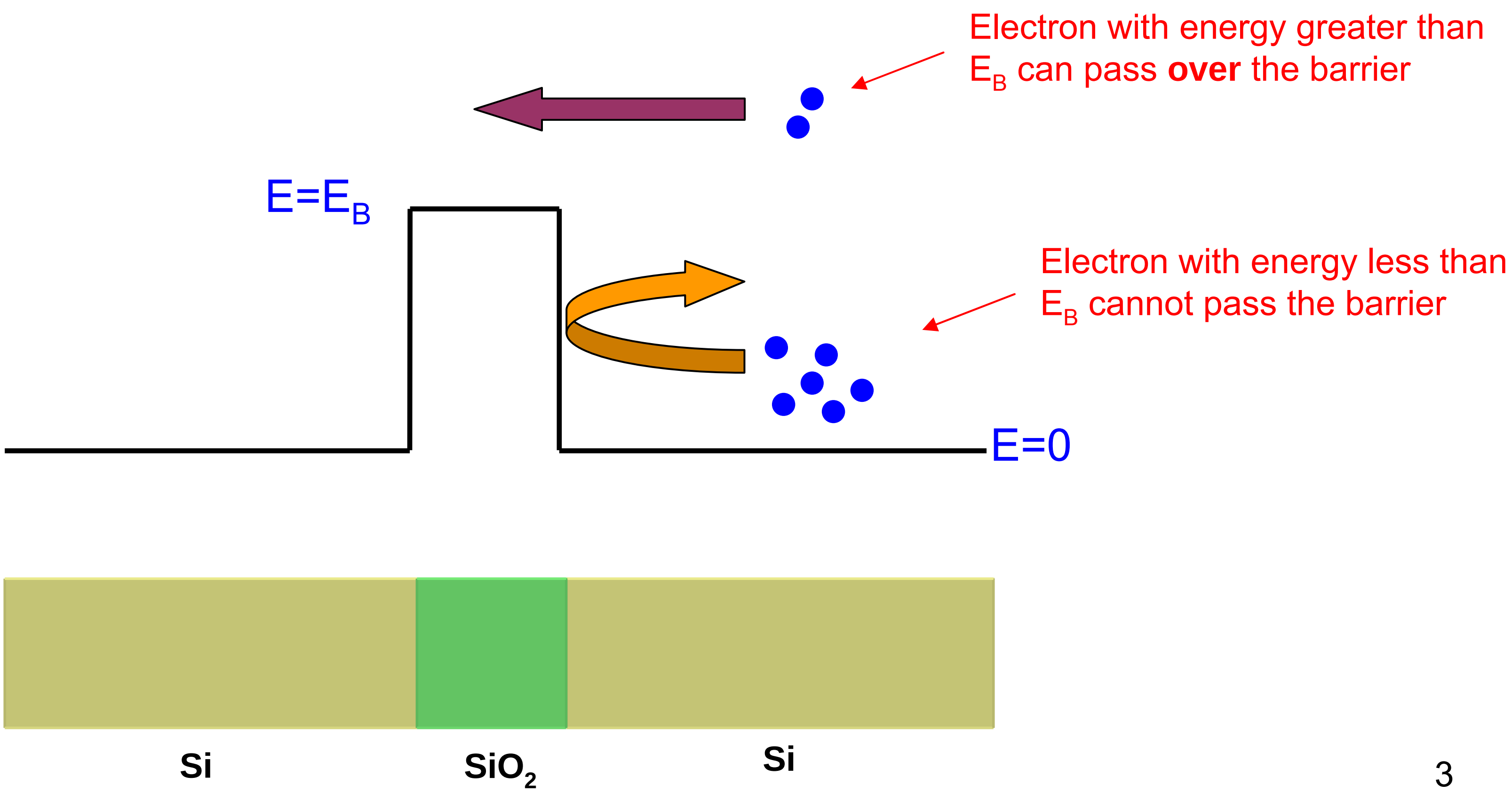


After contact



*…continued…*Concept of Electron Tunneling

- For **thick barrier**, both Newtonian and Quantum mechanics say that the electrons **cannot** cross the barrier.
- It can only pass the barrier if it has more energy than the barrier height.

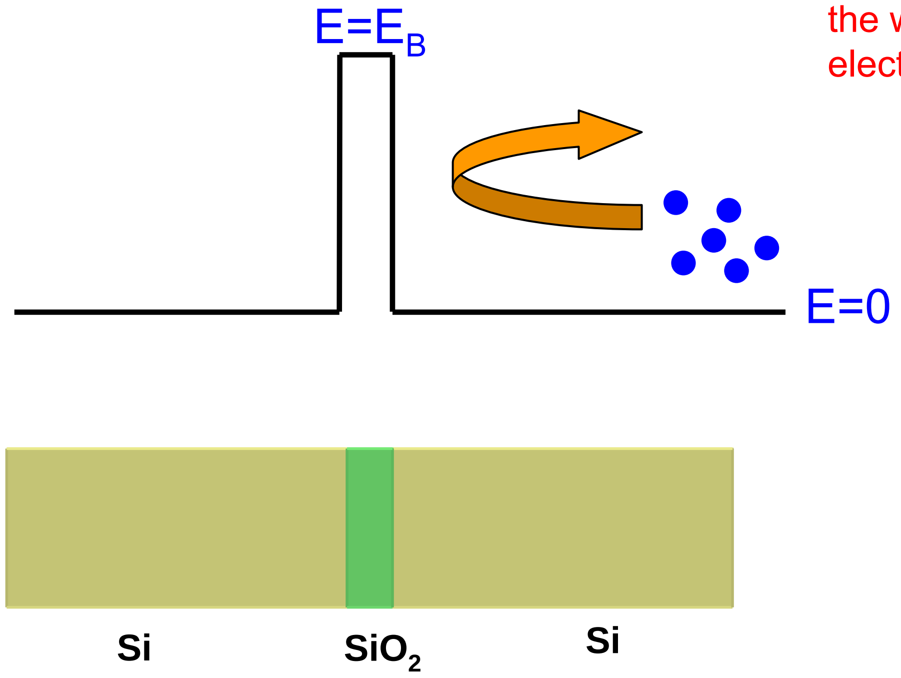


Electron with energy greater than E_B can pass **over** the barrier

Electron with energy less than E_B cannot pass the barrier

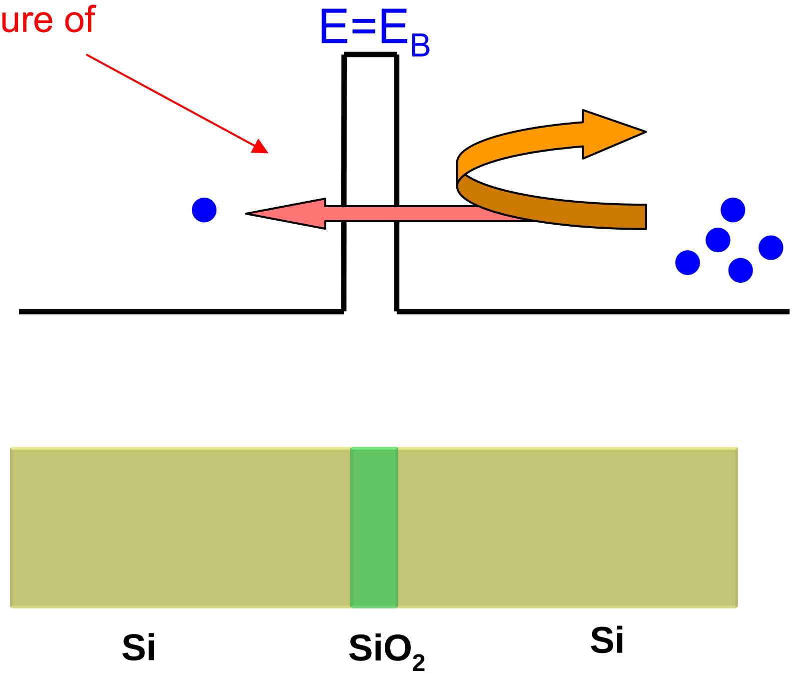
…*continued…*Concept of Electron Tunneling

- For **thin barrier**, Newtonian mechanics still says that the electrons **cannot** cross the barrier.
- However, Quantum mechanics says that the electron wave nature will allow it to **tunnel** through the barrier.



Newtonian Mechanics

Tunneling is caused by the wave nature of electron

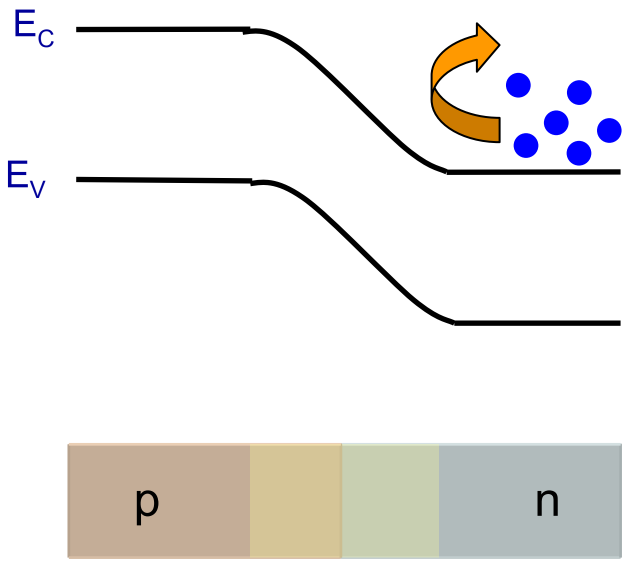


Quantum Mechanics

Electron Tunneling in p-n junction

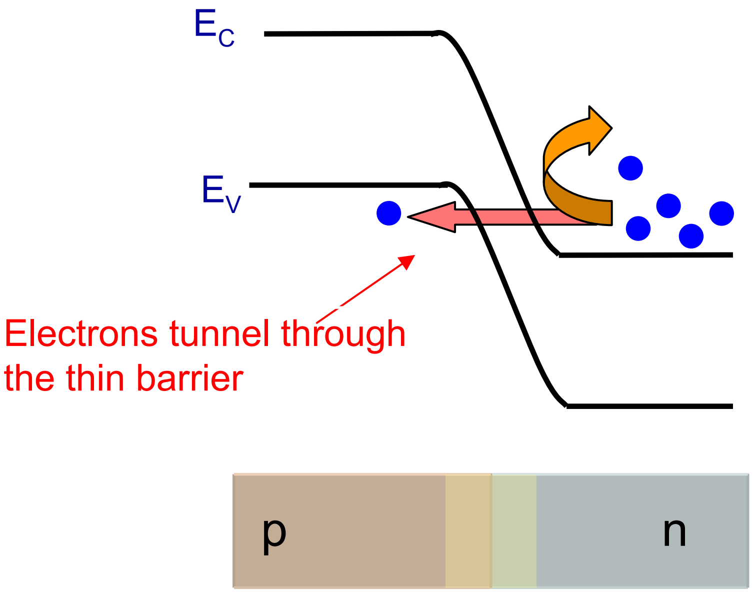
- When the p and n region are highly doped, the depletion region becomes very thin (~10nm).
- In such case, there is a finite probability that electrons can tunnel from the conduction band of n-region to the valence band of p-region
- During the tunneling the particle ENERGY DOES NOT CHANGE

Thick depletion layer



High doping

Thin depletion layer



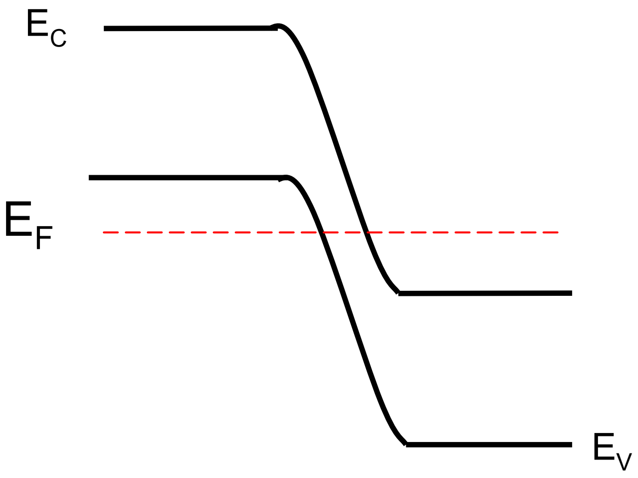
Electrons tunnel through the thin barrier

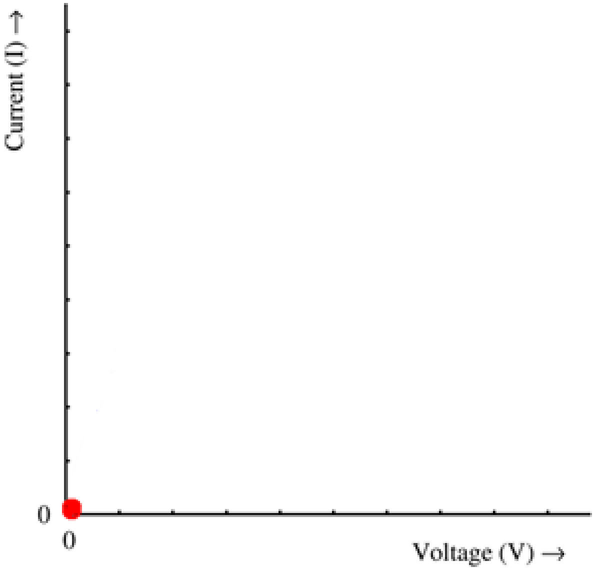
Tunnel Diode Operation

- When the semiconductor is very highly doped (the doping is greater than N_o) the Fermi level goes above the conduction band for n-type and below valence band for p-type material. These are called degenerate materials.

Under Forward Bias

Step 1: At zero bias there is no current flow

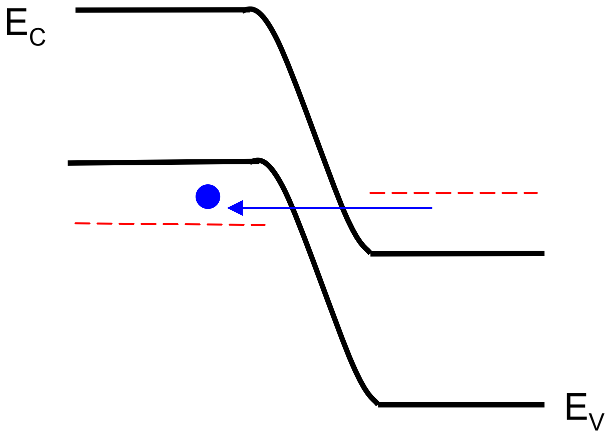


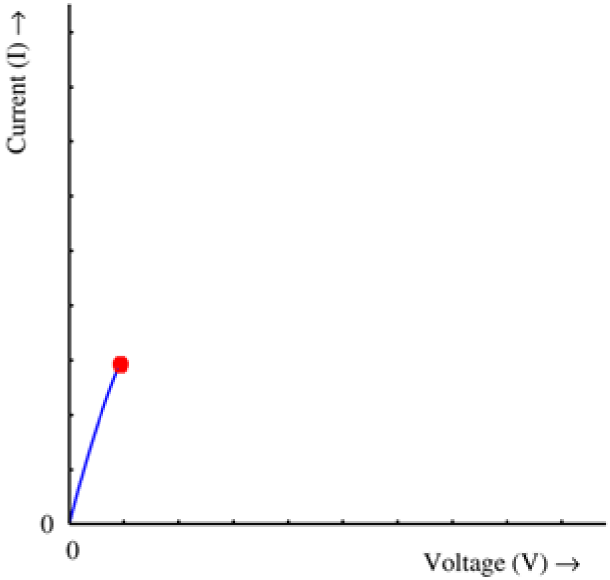


*…continued…*Operation of a Tunnel Diode

Step 2: **A small forward bias is applied. Potential barrier is still very high – no noticeable injection and forward current through the junction.**

However, electrons in the conduction band of the n region will tunnel to the empty states of the valence band in p region. This will create a forward bias tunnel current

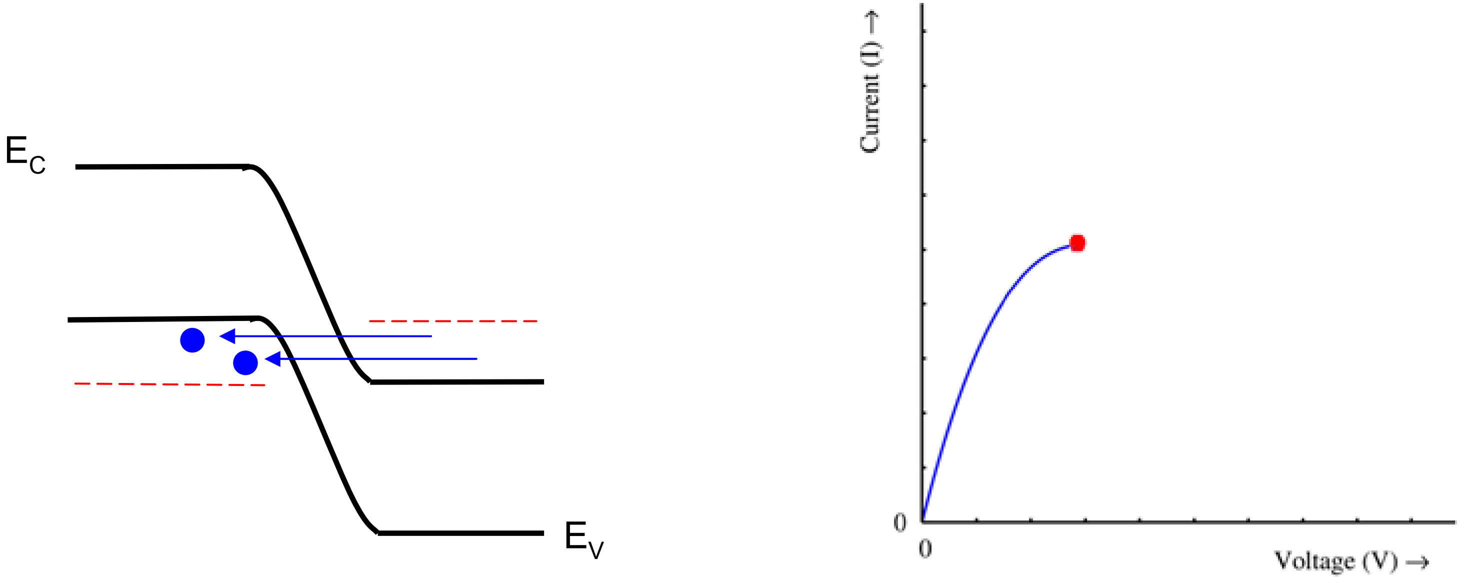




Direct tunneling current starts growing

*…continued…*Tunnel Diode Operation

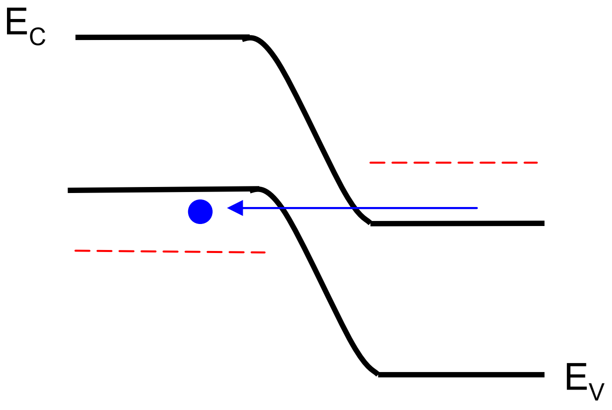
Step 3: **With a larger voltage the energy of the majority of electrons in the n-region is equal to that of the empty states (holes) in the valence band of p-region; this will produce maximum tunneling current**

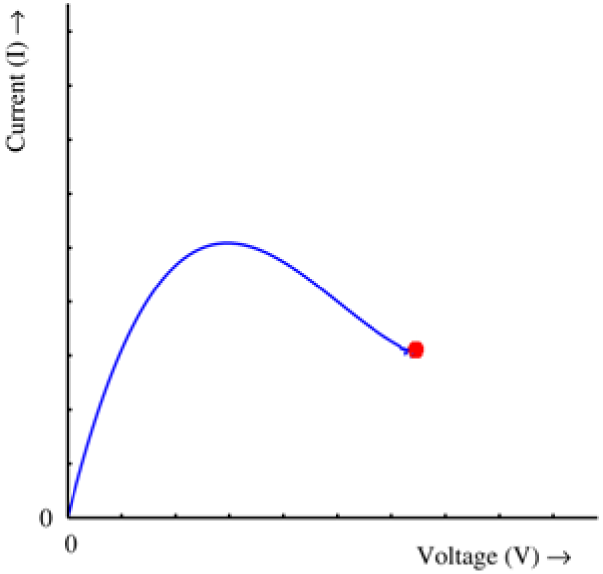


Maximum Direct tunneling current

*…continued…*Tunnel Diode Operation

Step 4: **As the forward bias continues to increase, the number of electrons in the n side that are directly opposite to the empty states in the valence band (in terms of their energy) decrease. Therefore decrease in the tunneling current will start.**

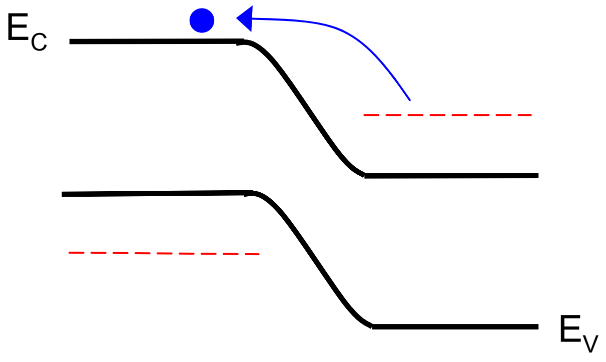


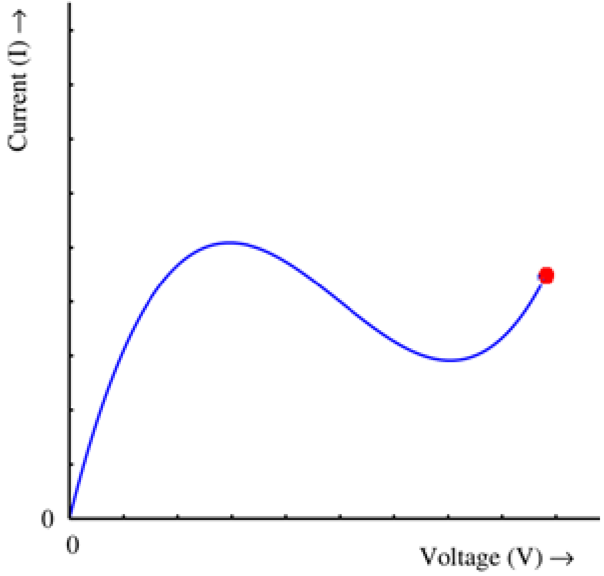


Direct tunneling current decreases

*…continued…*Tunnel Diode Operation

Step 5: **As more forward voltage is applied, the tunneling current drops to zero. But the regular diode forward current due to electron – hole injection increases due to lower potential barrier.**

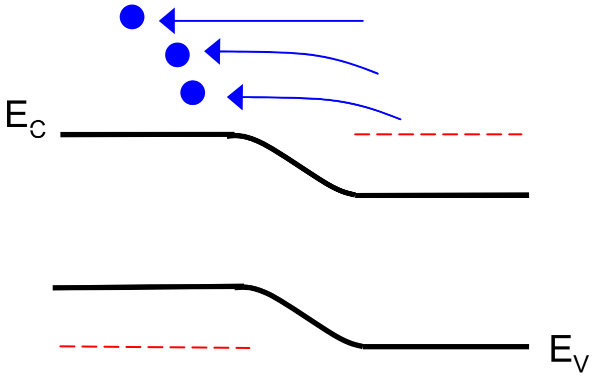


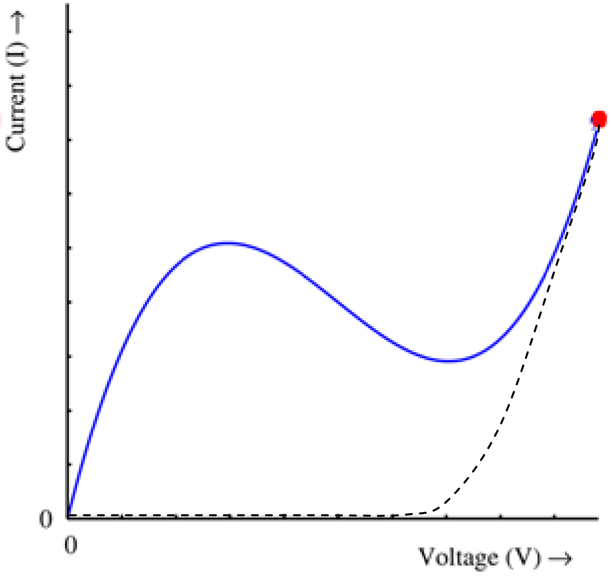


No tunneling current; diffusion current starts growing

*…continued…*Operation of a Tunnel Diode

Step 6: **With further voltage increase, the tunnel diode I-V characteristic is similar to that of a regular p-n diode.**



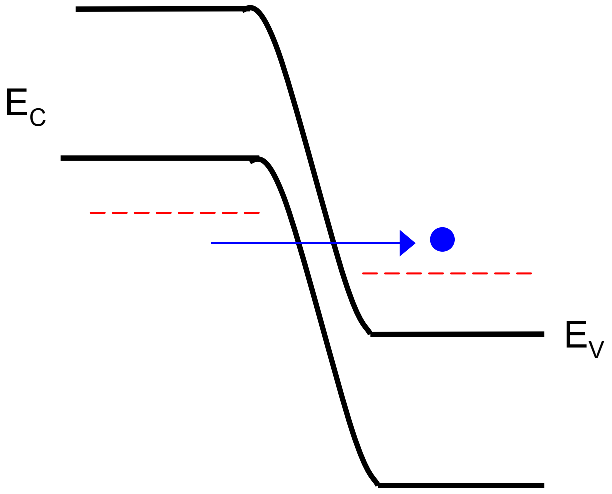


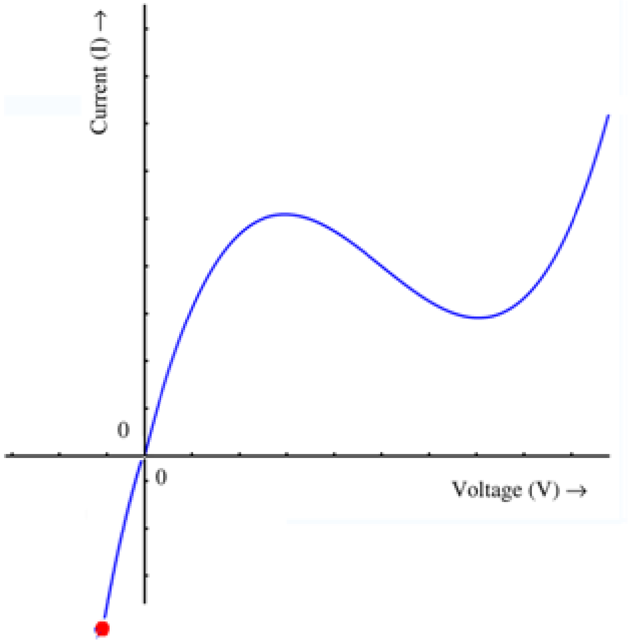
*…continued…*Operation of a Tunnel Diode

Under Reverse Bias

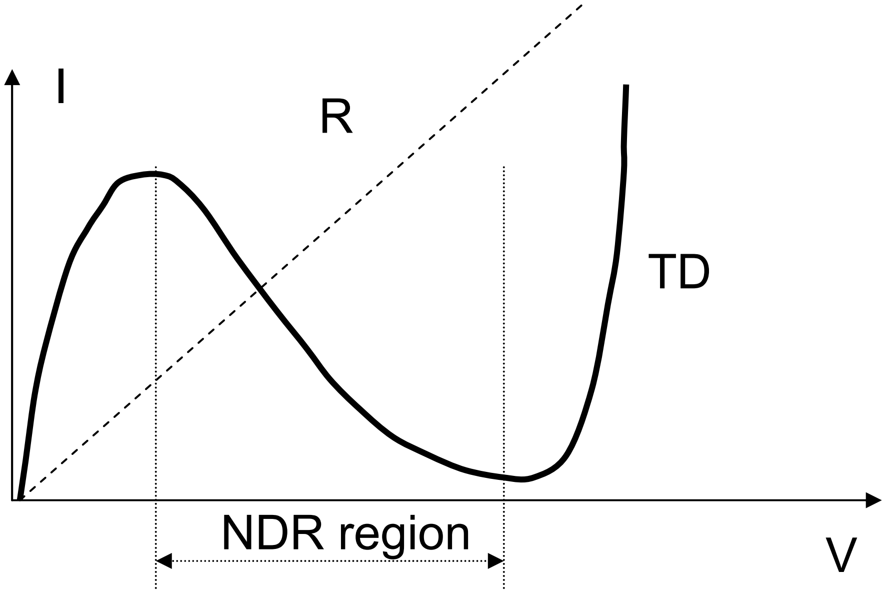
In this case the, electrons in the valence band of the p side tunnel directly towards the empty states present in the conduction band of the n side creating large tunneling current which increases with the application of reverse voltage.

The TD reverse I-V is similar to the Zener diode with nearly zero breakdown voltage.





Part II
Circuits with the Tunnel Diodes



Typical Tunnel Diode (TD) I-V characteristic has two distinct features:

(1) it is STRONGLY non-linear (compare to the resistor I-V).

Current - Voltage relationships for TDs cannot be described using the Ohm’s law

(2) it has a ***negative differential resistance*** (NDR) region

Tunnel Diode I-V

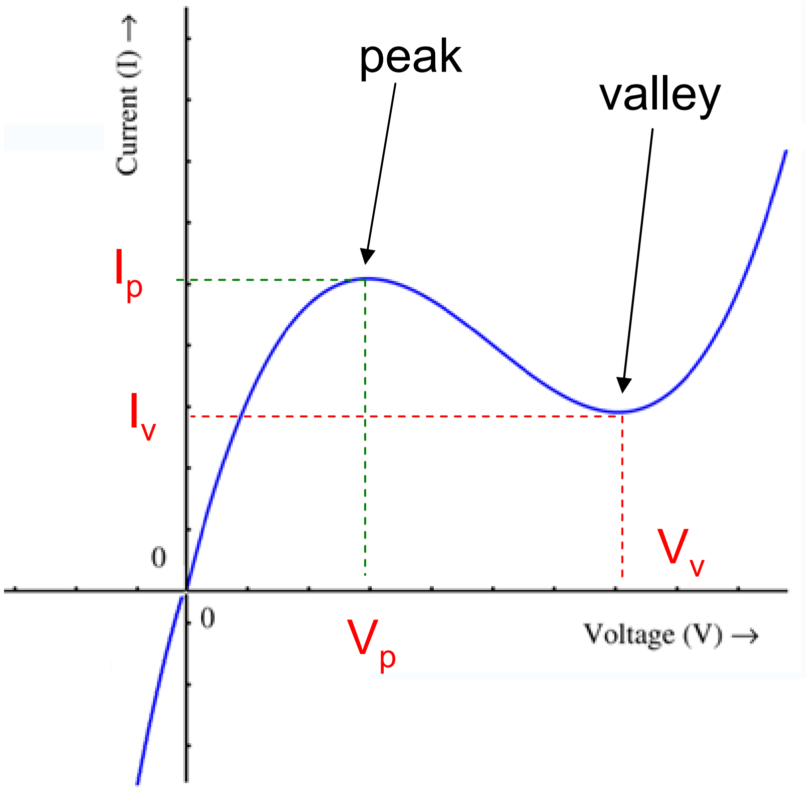
- The total current I in a tunnel diode is given by

$$I = I_{tun} + I_{diode} + I_{excess}$$

- The p-n junction current,

$$I_{diode} \approx I_s \exp\left[\left(\frac{V}{\eta V_{th}}\right) - 1\right]$$

I_s saturation current, η is the ideality factor and $V_{th} = kT/q$



Tunnel Diode I-V

- The tunnel current,

$$I_{tun} = \frac{V}{R_0} \exp\left[-\left(\frac{V}{V_0} \right)^m \right]$$

Typically, m = 1….3; V_0 = 0.1….0.5 V

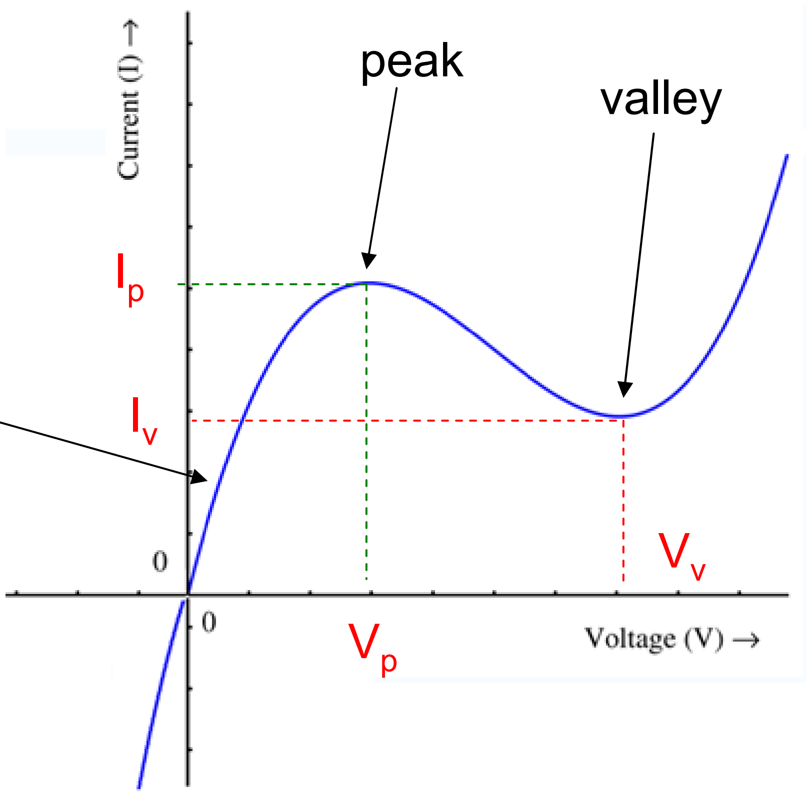
R_0 is the TD resistance in the ohmic region

The maximum |NDR| can be found as

$$|R_{d\,\max}| = R_0 \frac{\exp\left(\frac{1+m}{m} \right)}{m}$$

The peak voltage V_p:

$$V_p = \left(\frac{1}{m} \right)^{1/m} V_0$$



Tunnel Diode I-V

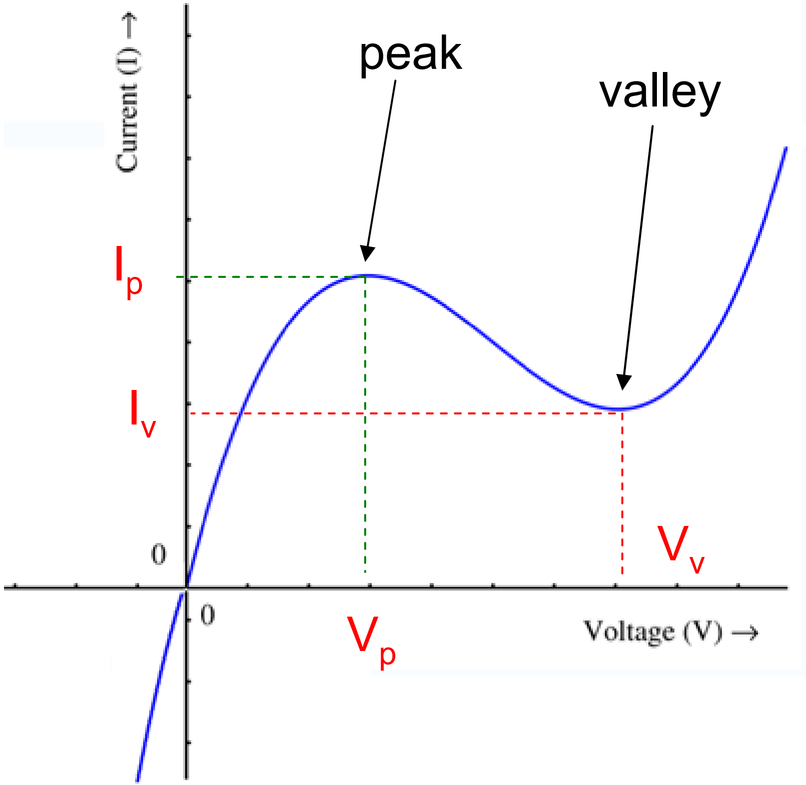
- The excess current,

$$I_{excess} = \frac{V}{R_v} \exp\left[\left(\frac{V - V_v}{V_{ex}}\right)\right]$$

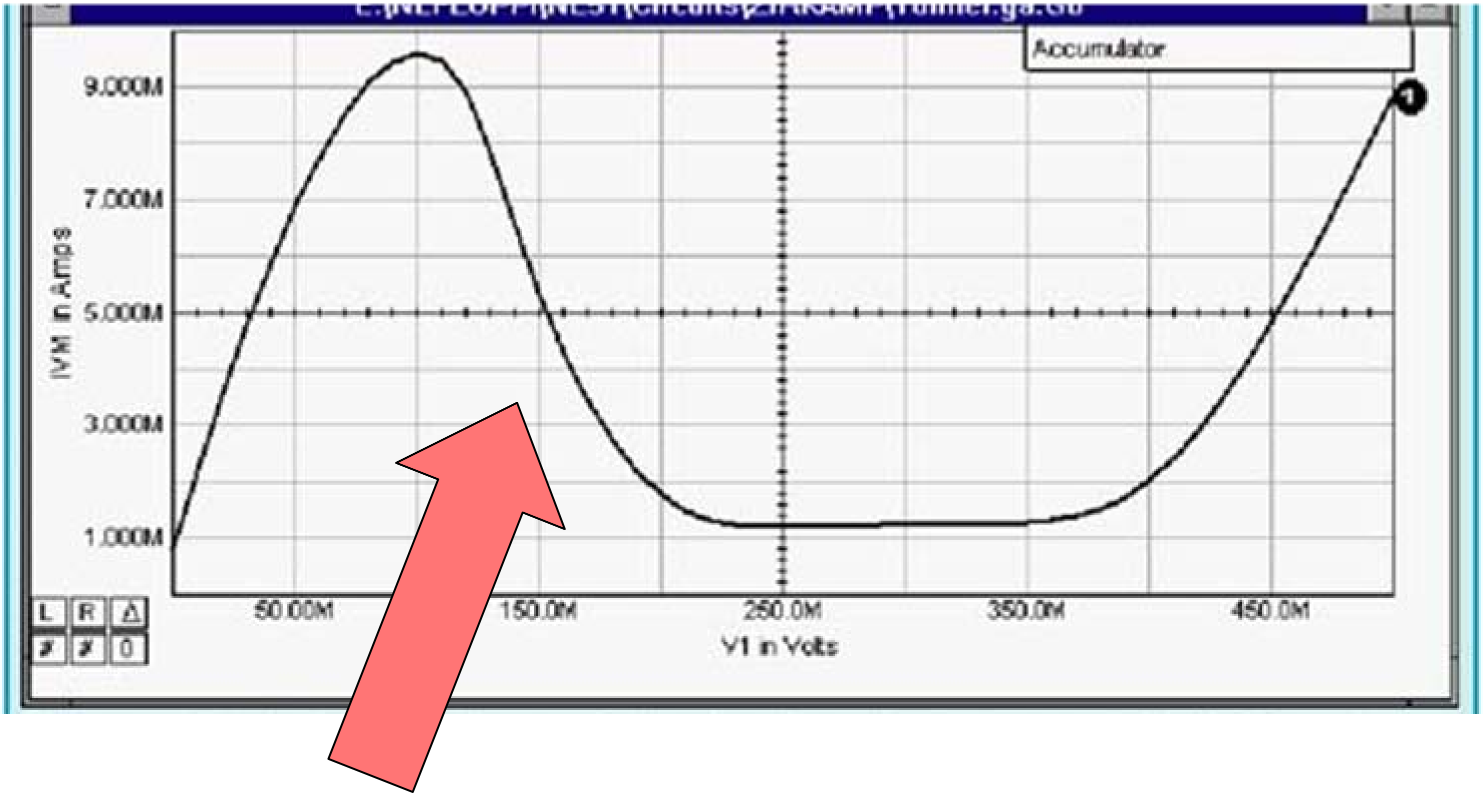
I_{excess} is an additional tunneling current related to parasitic tunneling via impurities.

This current usually determines the minimum (valley) current, I_v

R_v and V_{ex} are the empirical parameters; in high-quality diodes, R_v >> R_0. V_{ex} = 1…..5 V

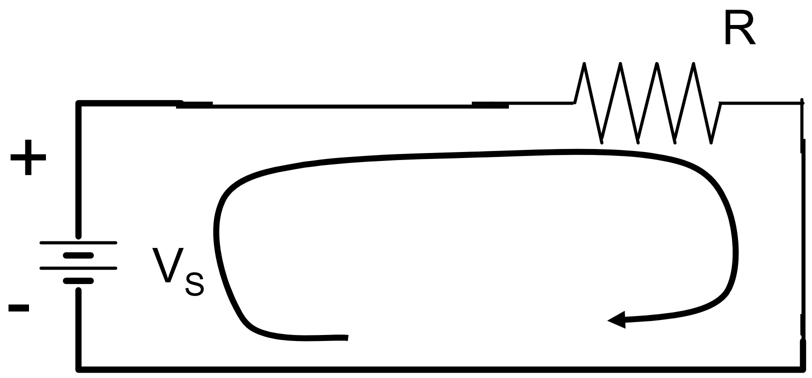


NDR of the Tunnel Diode



Tunnel Diode *differential resistance* is NEGATIVE in the voltage range 100 mV – 200 mV

Energy dissipation in resistors and Energy generation in Negative Resistors



Power = Voltage x Current = $I^2 R$

If current direction is from “-” toward “+”, then R =V/I is negative;

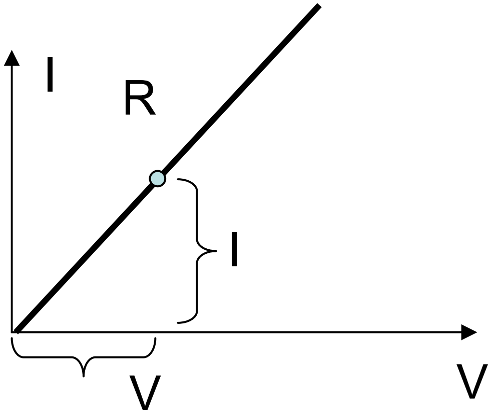
For R<0, P <0,

Positive power means energy dissipation (e.g. conversion into the Joule heat);

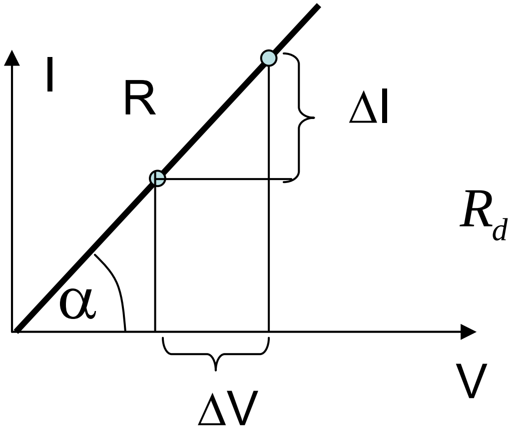
Negative power corresponds to the power GENERATION (Energy supply);

Differential resistance and negative differential resistance

Static resistance:
R = V/I



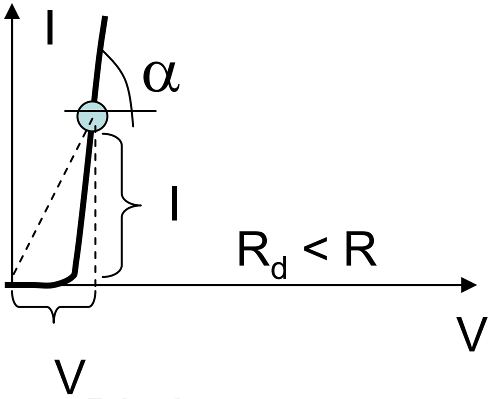
Differential resistance: $R_d = \dfrac{\partial V}{\partial I} \approx \dfrac{\Delta V}{\Delta I}$



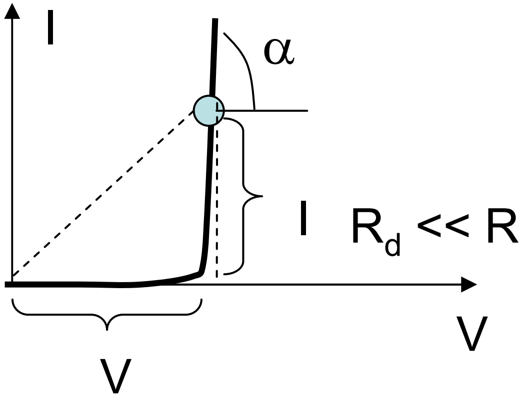
$$R_d = \cot(\alpha)$$

For linear (“Ohmic”) components, R = R_d.

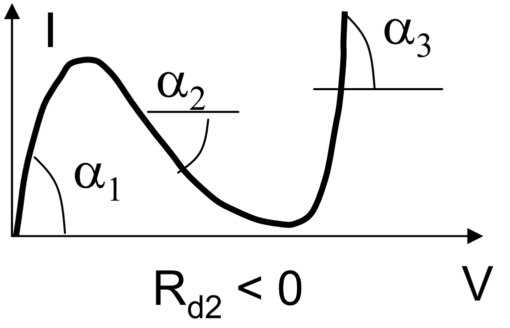
For many semiconductor devices, R ≠ R_d:



Diode
(forward bias)

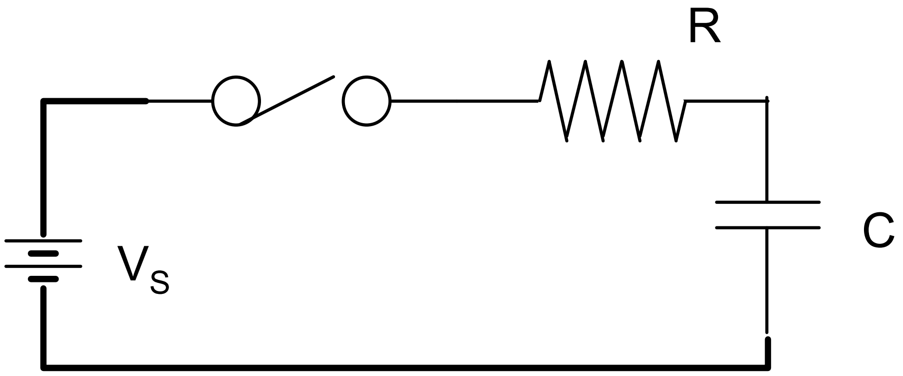


Zener Diode
(reverse bias)



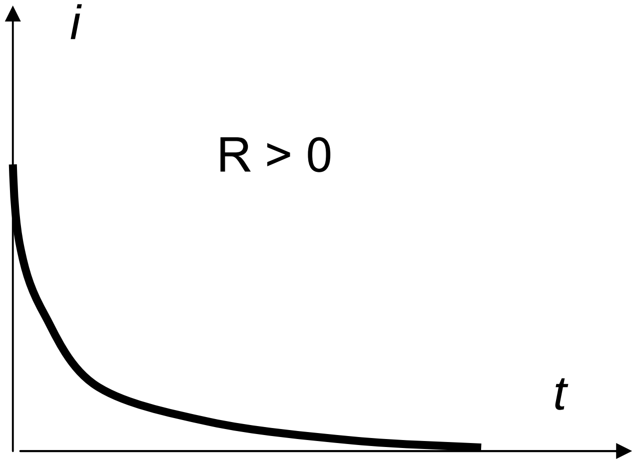
TD

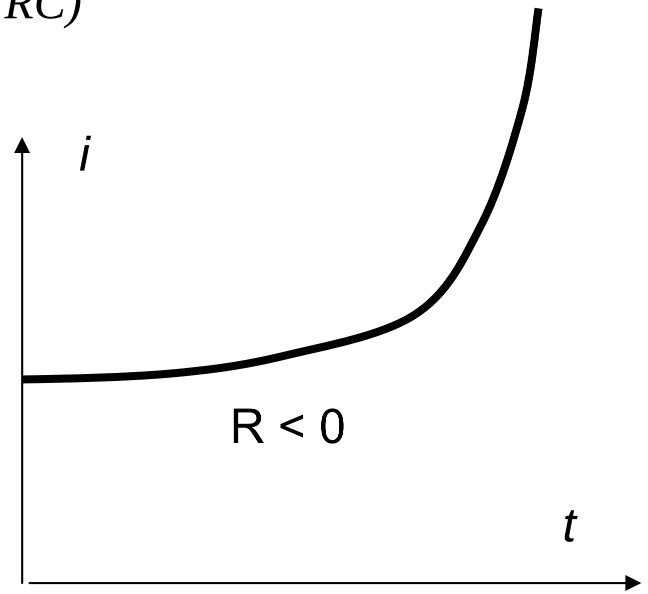
Transients in Negative Differential Resistance Circuits



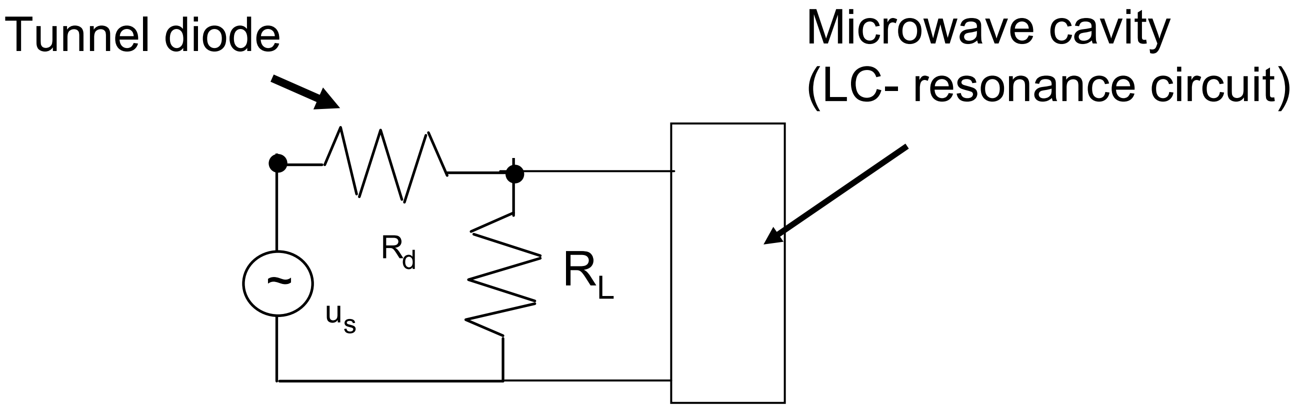
After turning the switch ON:

$$i(t) = \frac{V_S}{R} \times e^{-t/(RC)}$$





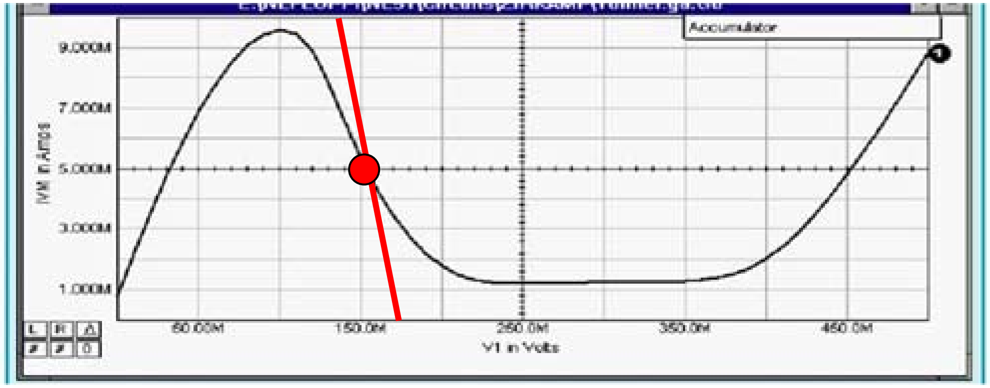
Tunnel Diode as a microwave oscillator



Tunnel diode

Microwave cavity
(LC- resonance circuit)

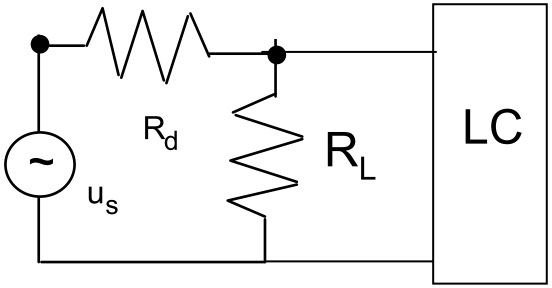
Load resistance is chosen so that $R_L < |R_d|$ in the NDR region

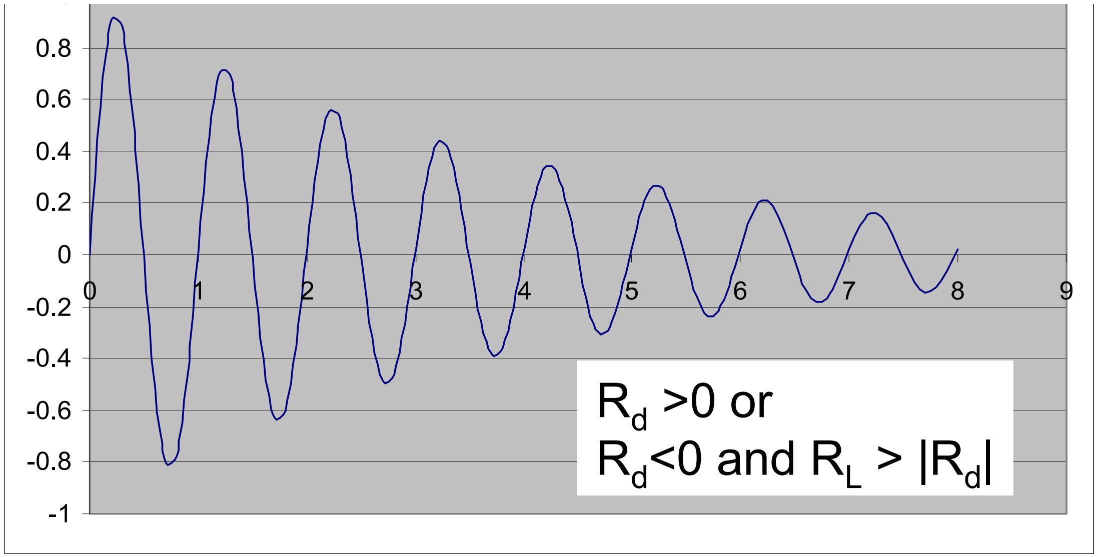


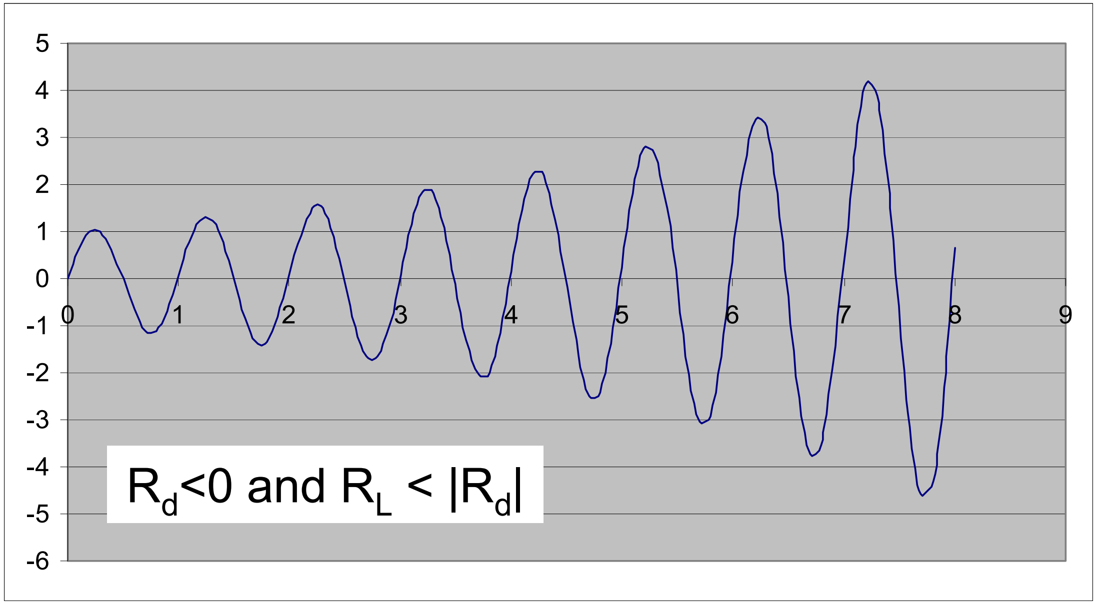
At the TD ***operating point,*** the total circuit differential resistance is ***negative***

Tunnel Diode as a microwave oscillator

Transient in resonant cavity after turning the bias voltage ON







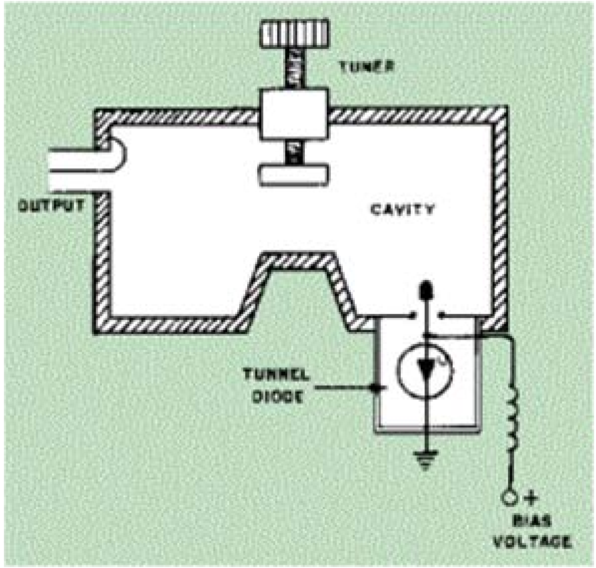
The resonant circuit with NDR can oscillate. Maximum frequency of the TD-oscillator is limited by the characteristic tunneling time:

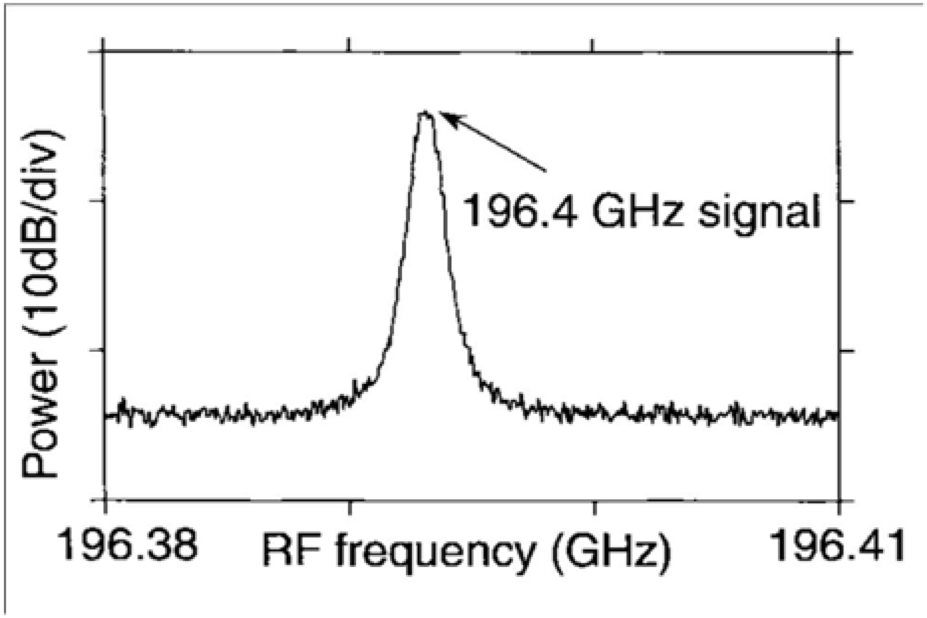
$f_{MAX} \leq (1/2\pi)(1/\tau_{tun})$

Tunneling time in TDs is extremely small: << 1 ps

F_{MAX} > 100 GHz

Tunnel Diode microwave oscillators





After: M. Reddy et.al,

IEEE ELECTRON DEVICE LETTERS, VOL. 18, NO. 5, MAY 1997

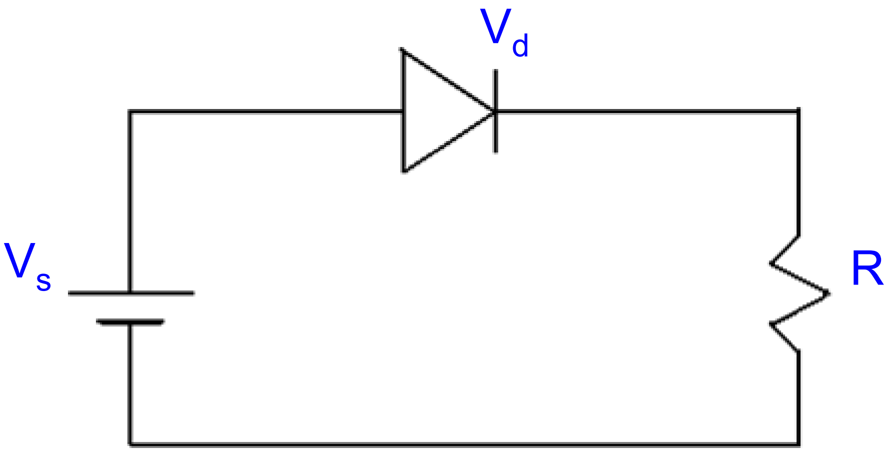
~ 600 GHz oscillation frequencies has been achieved.

Nonlinear Circuit Analysis: Load Line technique

$$V_s = V_d + IR$$

$$\Rightarrow I = -\frac{V_d}{R} + \frac{V_s}{R}$$

$$\boxed{I = \left(-\frac{1}{R}\right)V_d + \left(\frac{V_s}{R}\right)}$$

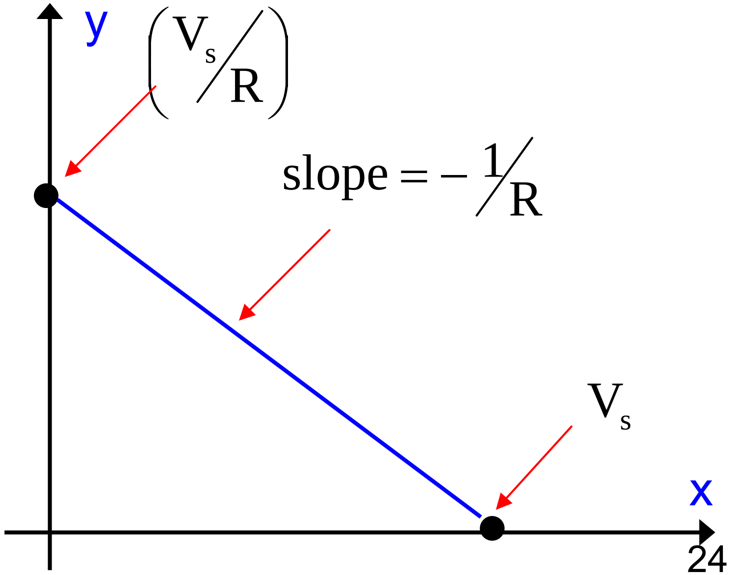


$$y = mx + c$$

$X-axis$ intercept, V_s

$Y-axis$ intercept, $c = {}^{V_s}\!/_{R}$

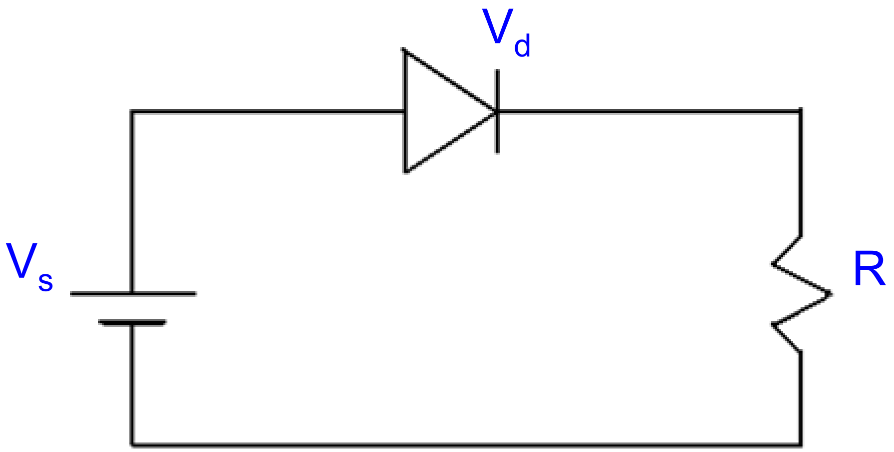
Slope, $m = -{}^{1}\!/_{R}$



Nonlinear Circuit Analysis: Load Line technique

$$V_s = V_d + I \times R$$

$$I = \left(-\frac{1}{R}\right)V_d + \left(\frac{V_s}{R}\right)$$

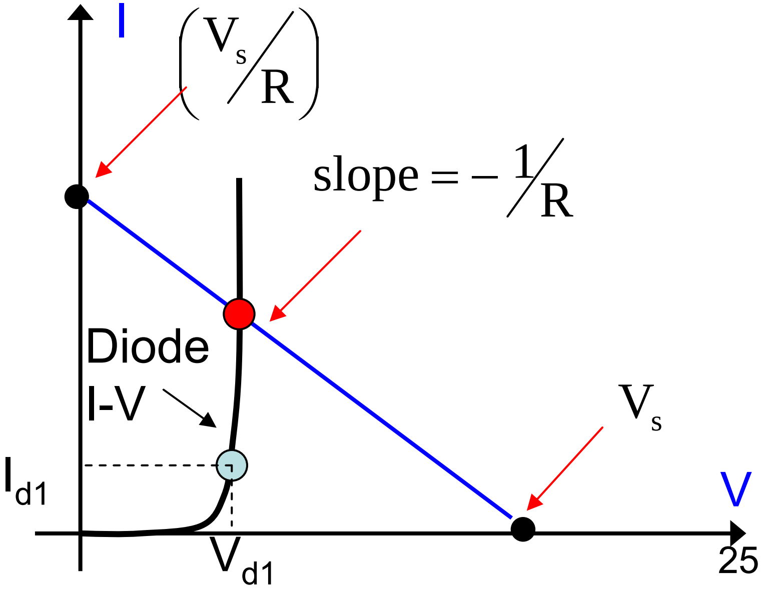


In the load line equation,
I is the resistor current when the voltage across the diode is V_d

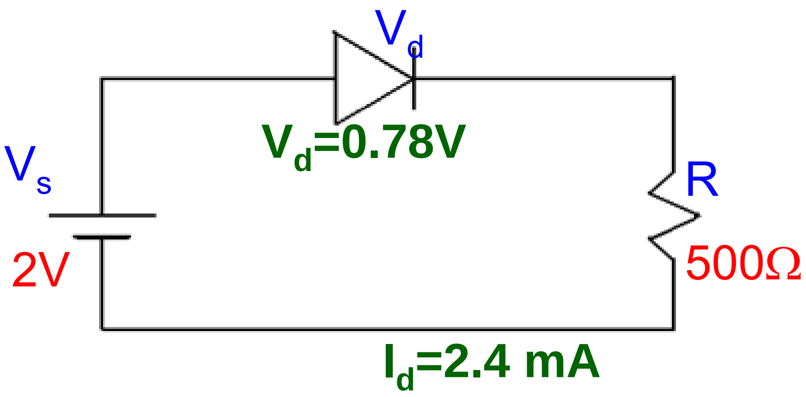
On the other hand, when the voltage across the diode is V_d, the diode current is given by the diode I-V curve

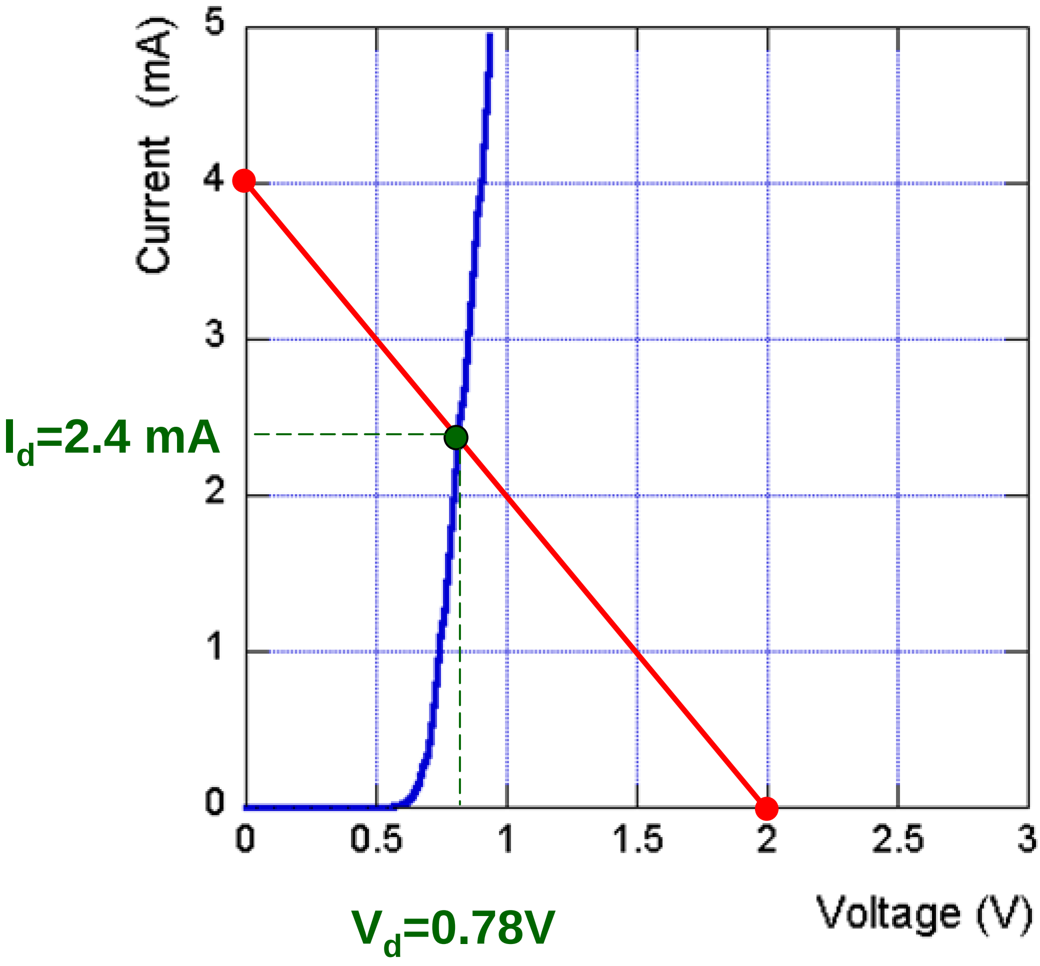
For example, when the diode voltage is V_{d1} the diode current is I_{d1}

However, in this circuit, I_d must be equal I_R.
Hence the actual operating point is given by the load line – I-V intercept.



Load Line : example

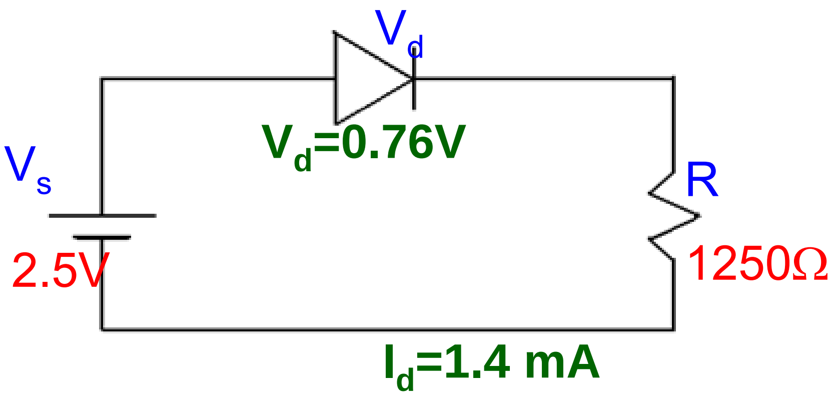




V axis intercept, V_s = 2 V

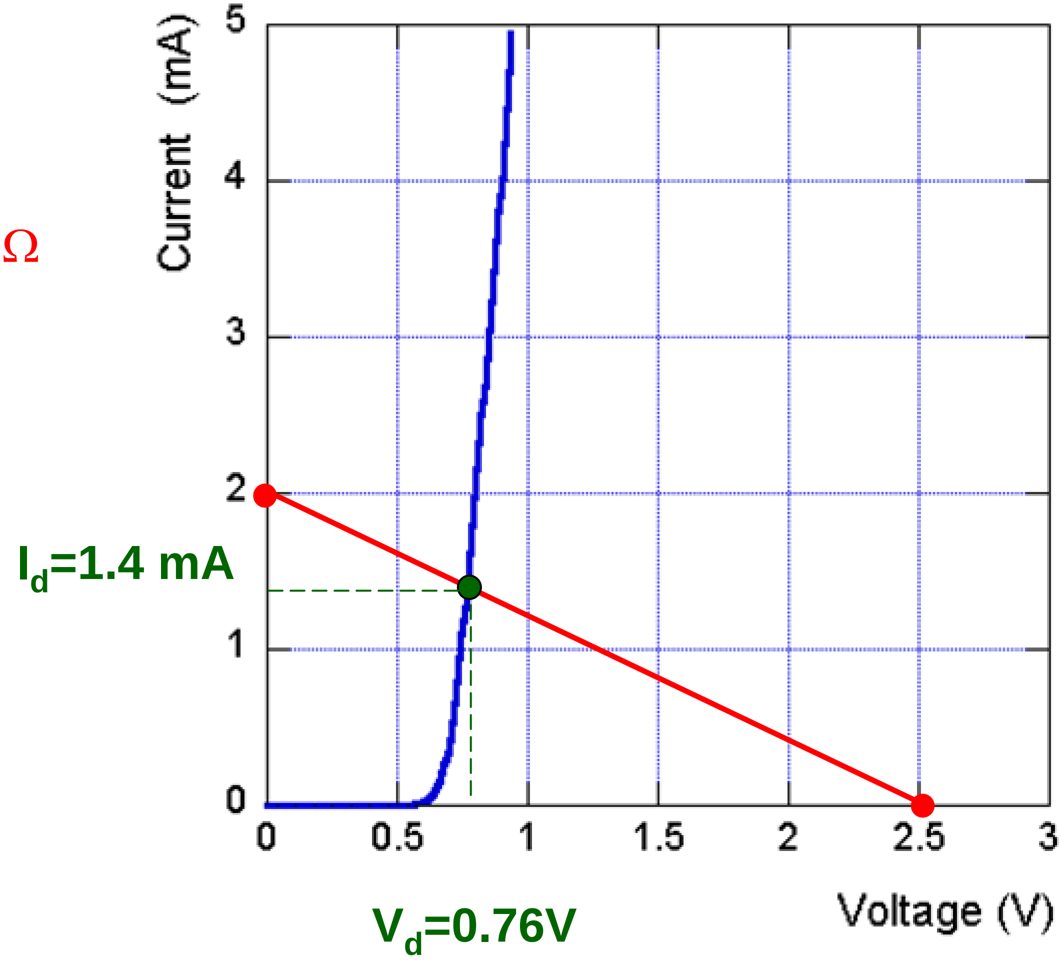
I axis intercept, (V_s/R) = 4 mA

Load Line : another example

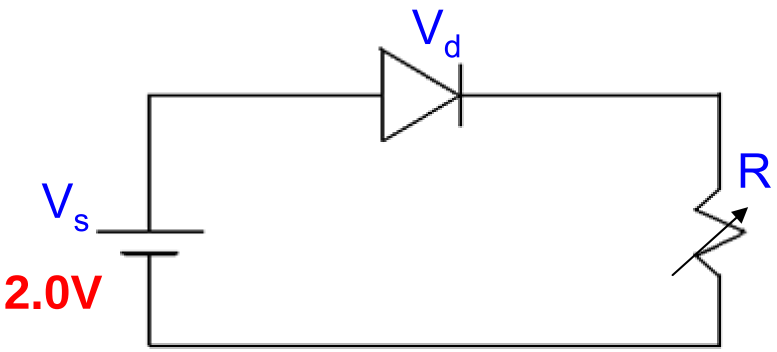


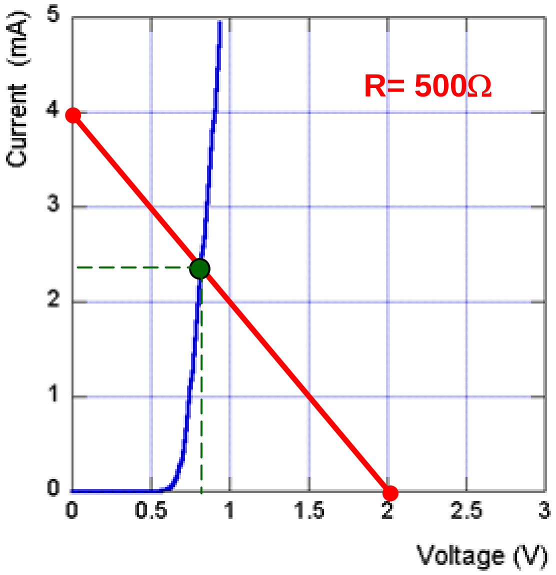
V axis intercept, V_s = 2.5 V

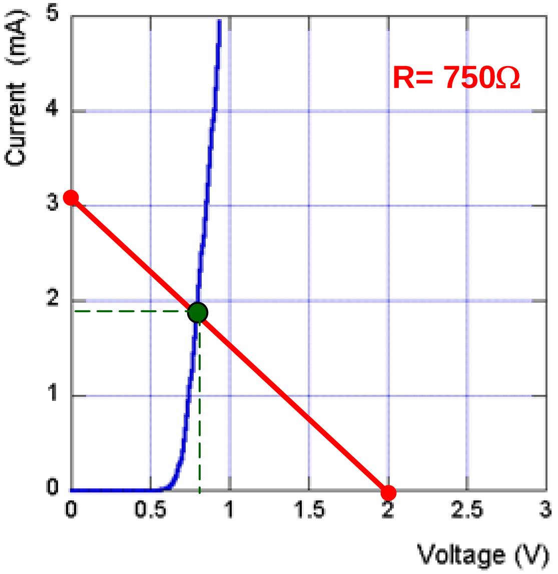
I axis intercept, (V_s/R) = 2 mA

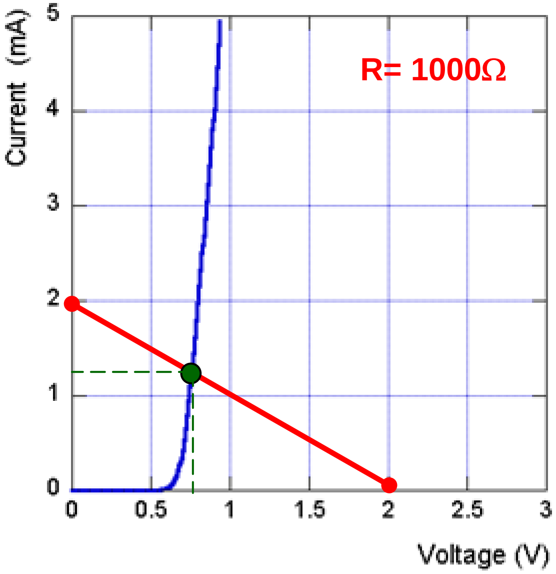


…*continued…* Load Line (Variation of R)

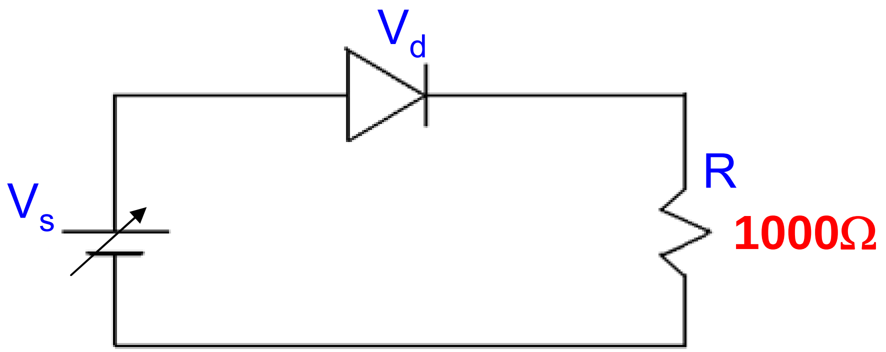


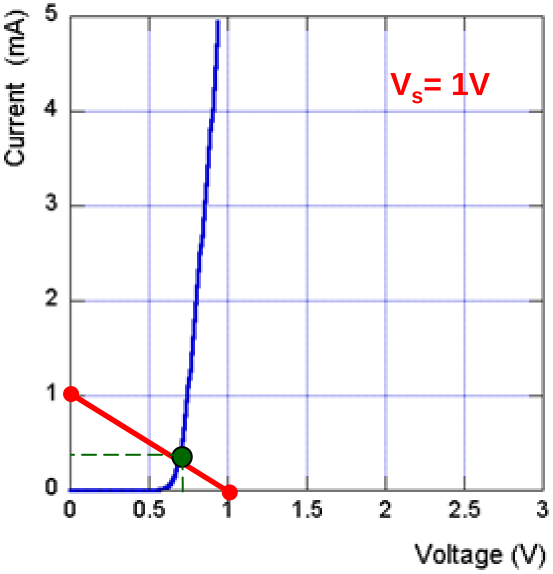


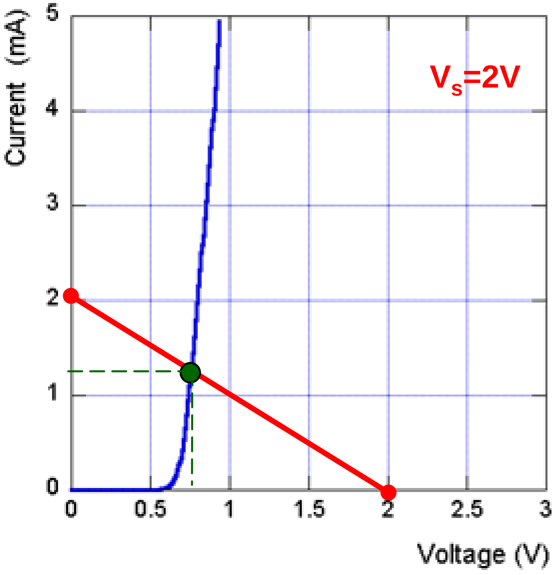


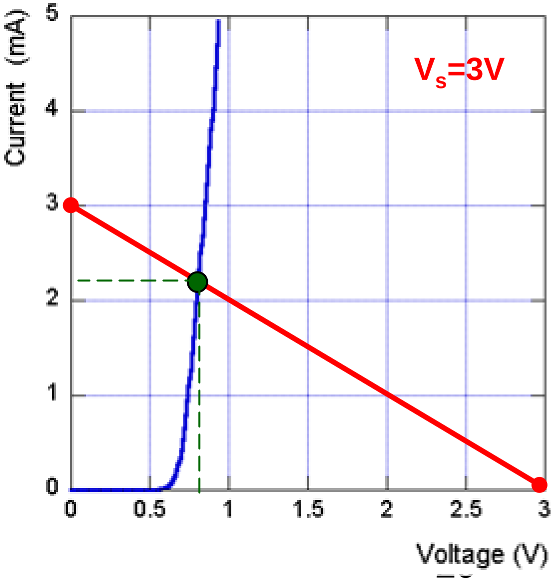


…*continued…* Load Line (Variation of V_s)

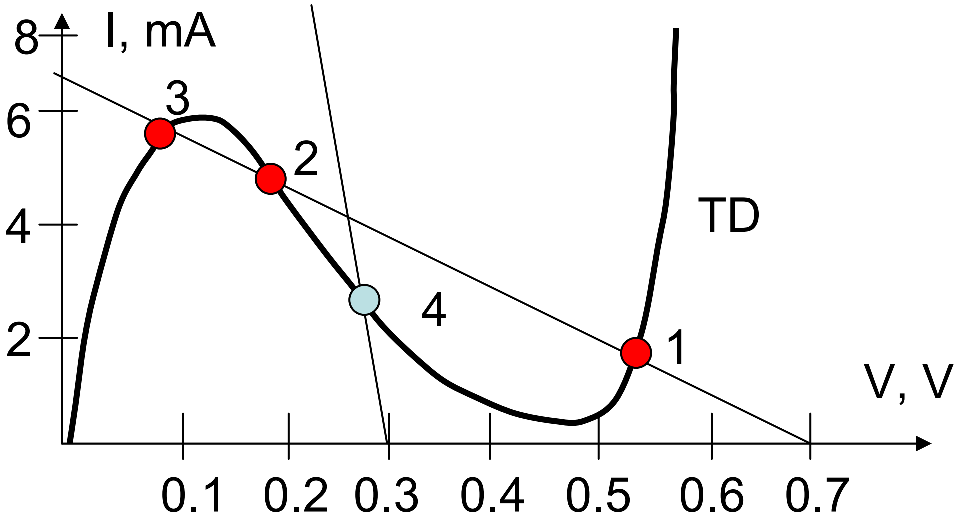


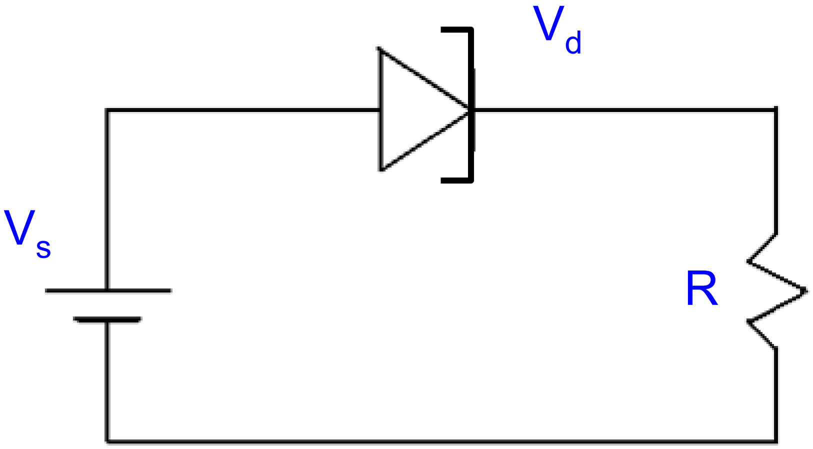






Circuit with the Tunnel Diode and Resistor





Example 1: V_s = 0.7 V; R = 100 Ω; $\Rightarrow I_{max} = 0.7\text{V}/100\ \Omega = 7\ \text{mA}$

The circuit has three possible operating points. Point 2 is typically unstable (depending on parasitic L and C components.

The circuit will operate at the point 1 or point 3 depending on the history.

Example 2: V_s = 0.3 V; R ≈ 10 Ω; $\Rightarrow I_{max} \approx 30\ \text{mA}$

The circuit has only one operating point - point 4.

The total differential resistance is NEGATIVE (because R < $|R_d|$).

Depending on the L and C components, the circuit can be stable (amplifier) or unstable (oscillator)