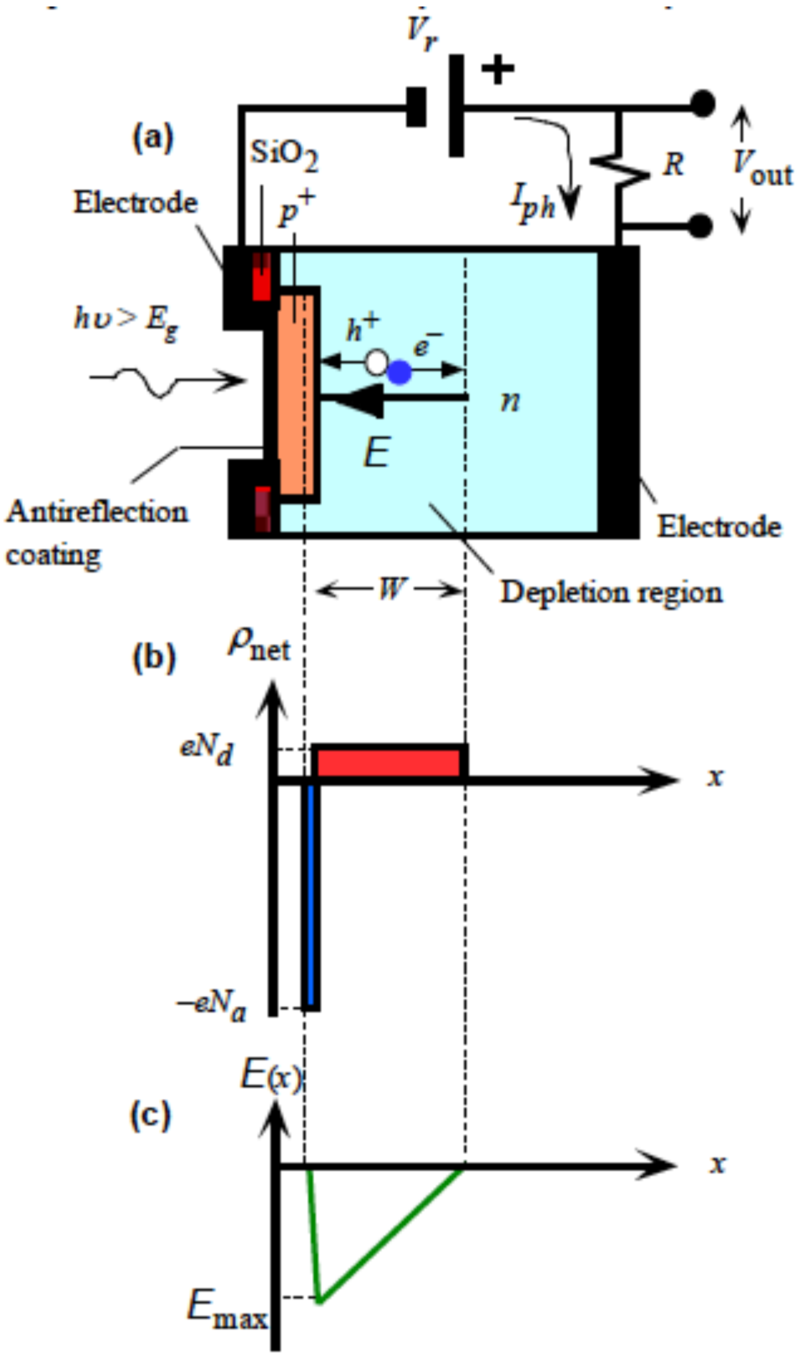
Physics of Semiconductor Devices

Lecture 13

Achintya Dhar
Department of Physics
Email-id: achintya.dhar@gmail.com



Photodiode

ɔtodiodes are compact, inexpensive, sensitive, and t; but they have limited spectral response.

- The p^+ side is on the order of less than a micron thick (formed by planar diffusion into n-type epitaxial layer).
- A ***space charge*** distribution occurs about the junction within the ***depletion layer.***
- The depletion region extends predominantly into the lightly doped n region (up to 3 microns max)

(a) A schematic diagram of a reverse biased *pn* junction photodiode. (b) Net space charge across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the *p* and *n* sides. (c). The field in the depletion region.

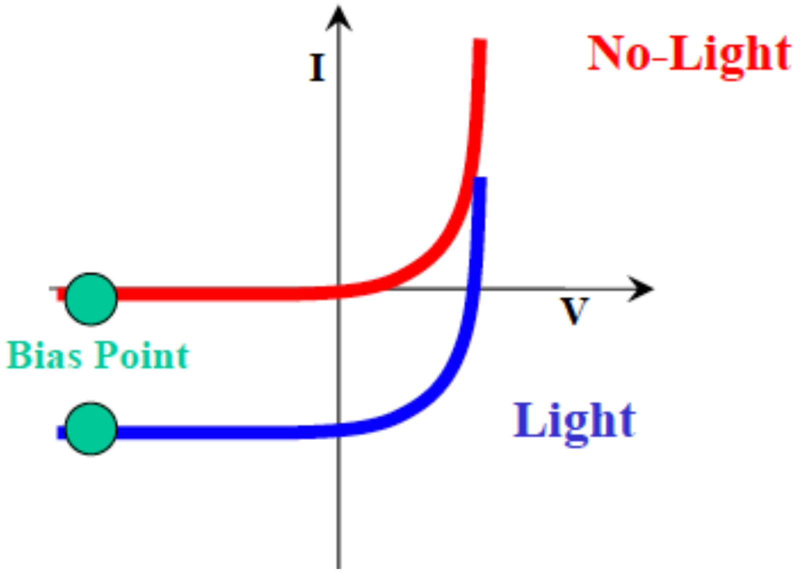
Photodiode

$$I_{total} = I_{dark} + I_{Due\ to\ Light}$$

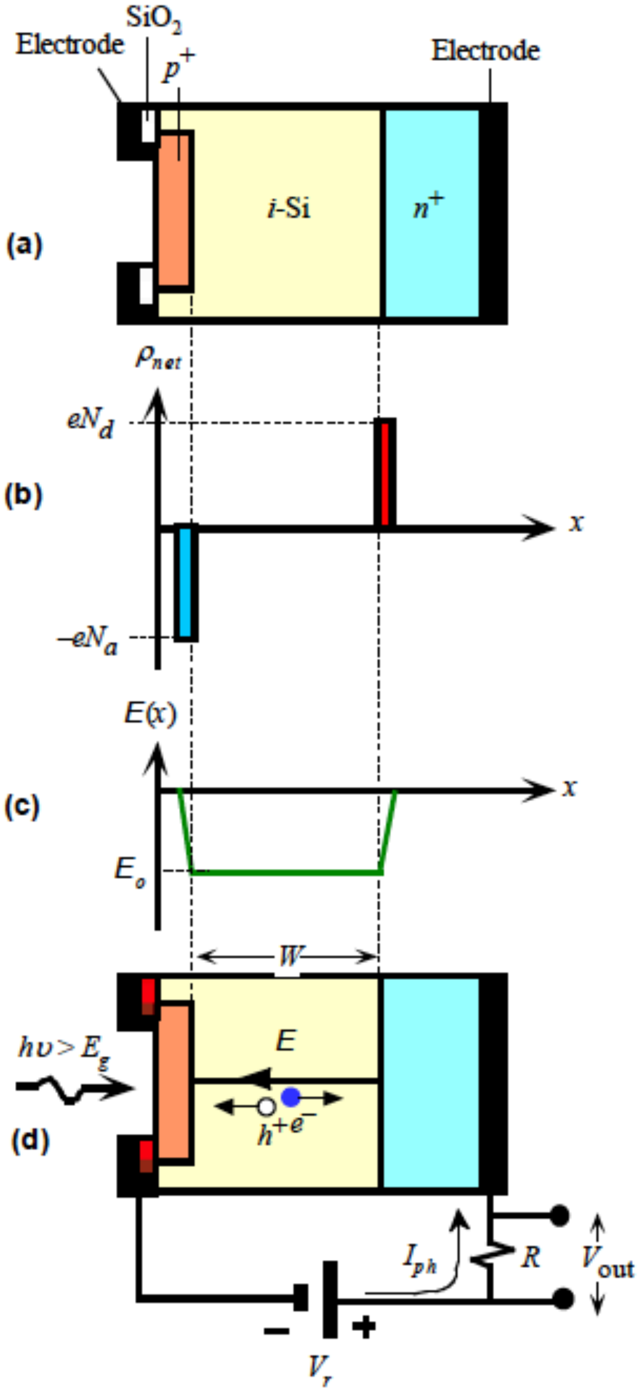
$$I_{total} = I_o\left(e^{\left(V_D/V_T\right)} - 1\right) + I_{Due\ to\ Light}$$

$$I_{total} = \underbrace{\left(I_o e^{\left(V_D/V_T\right)} - I_o\right)}_{\text{No-Light}} + \underbrace{(-qA)\overbrace{(L_N + W + L_P)}G_L}_{\text{Light}}$$

Every EHP created within the depletion region (W) and within a diffusion length away from the depletion region is collected (swept across the junction by the electric field) as photocurrent (current resulting from light). All other EHP's recombine before they can be collected.



P-i-N Photodiode



- Lower doping levels cause depletion region to become thicker which in turn reduces diode capacitance.

- PIN photodiode implements this concept by insertion of a thick, high Z low doped n-type layer (middle layer) between the p and n layers of the original model.

- The middle layer is called the ***intrinsic layer*** or I-layer.

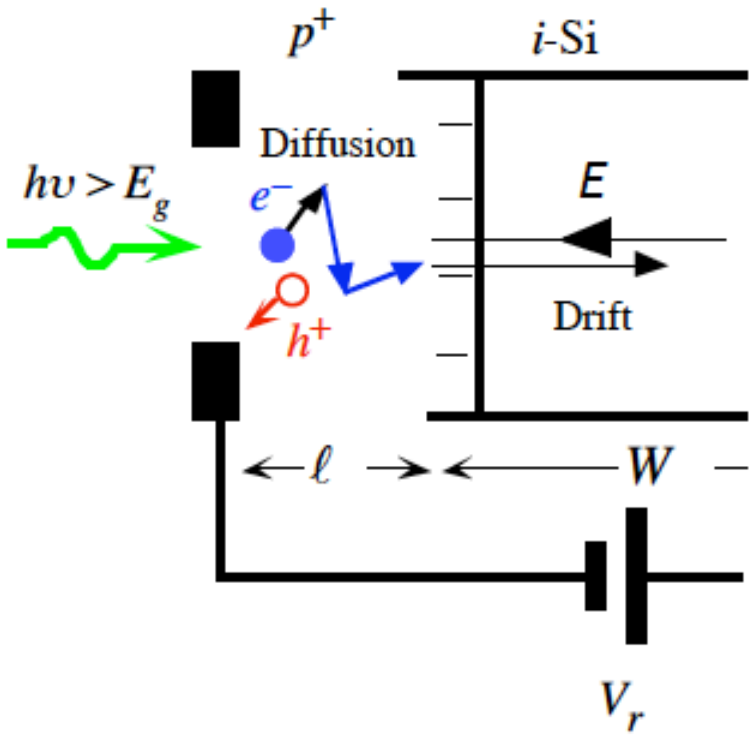
- A moderate quantity of reverse bias can extend the depletion layer to the bottom of the I-layer.

Result: 1. Faster response time.

2. Improved (wider) spectral response.

The schematic structure of an idealized *pin* photodiode (b) The net space charge density across the photodiode. (c) The built-in field across the diode. (d) The *pin* photodiode in photodetection is reverse biased.

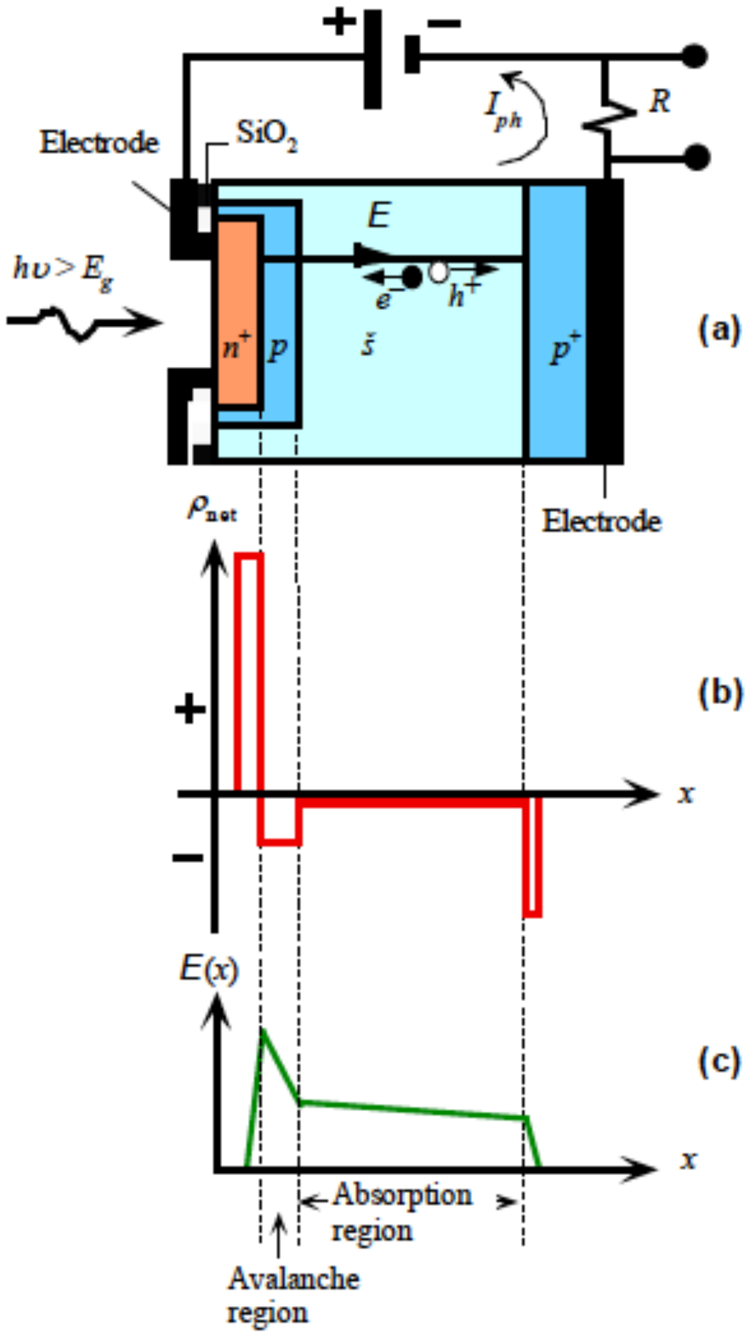
PIN Photodetectors



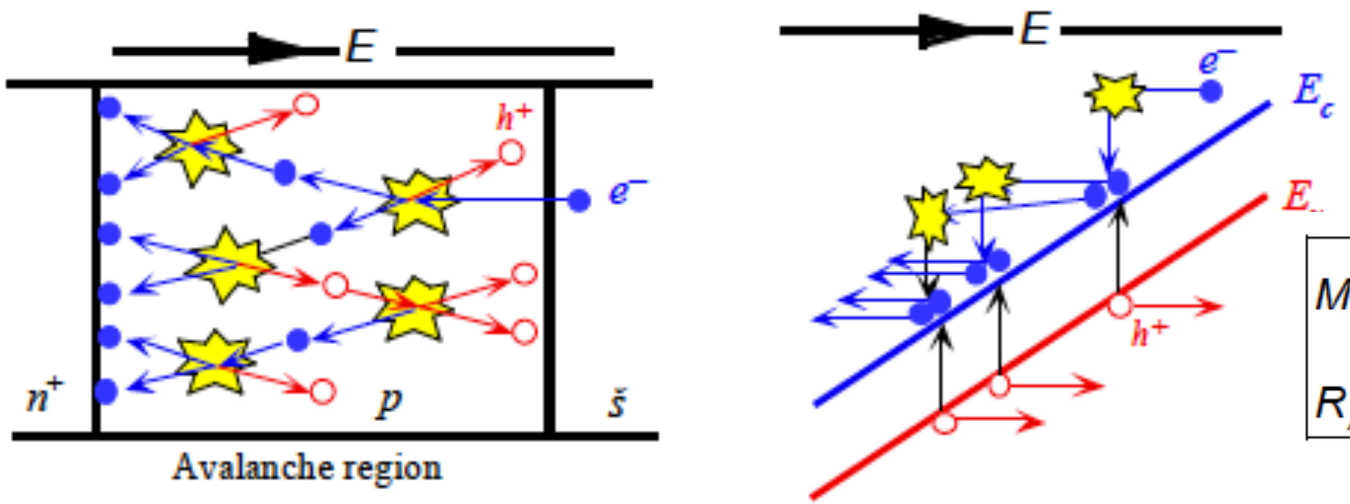
A reverse biased pin photodiode is illuminated with a short wavelength photon that is absorbed very near the surface. The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*-layer and drifted across.

Avalanche Photodiodes (APDs)

→ A photodiode with built-in gain



(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.



(a) **(b)**

$$M \equiv \frac{I_{APD}}{I_{ph}} \quad (\text{"Multiplication Factor"}, \sim 10\text{-}100)$$

$$R_{APD} = MR_0$$

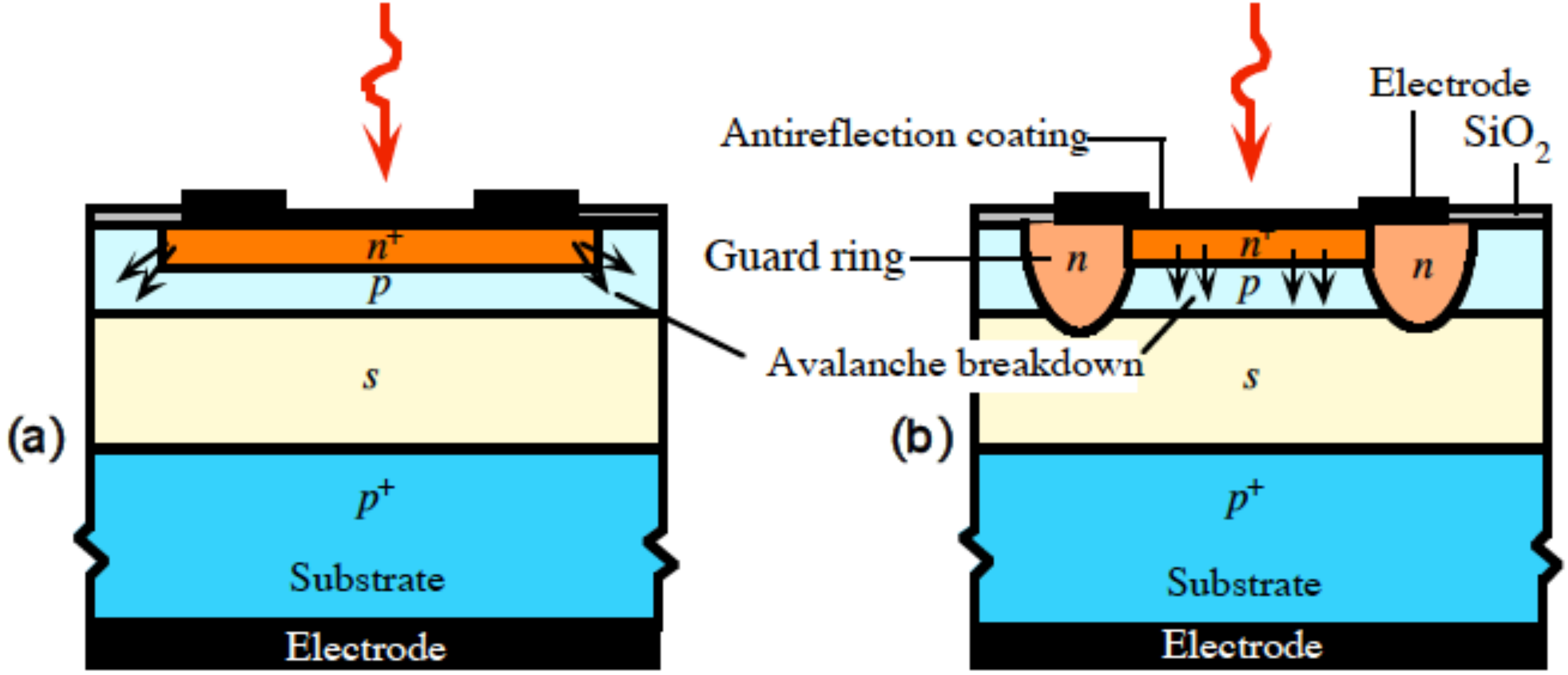
Note that the quantum efficiency for an "APD" can be greater than one.

(a) A pictorial view of impact ionization processes releasing EHPs and the resulting avalanche multiplication. (b) Impact of an energetic conduction electron with crystal vibrations transfers the electron's kinetic energy to a valence electron and thereby excites it to the conduction band.

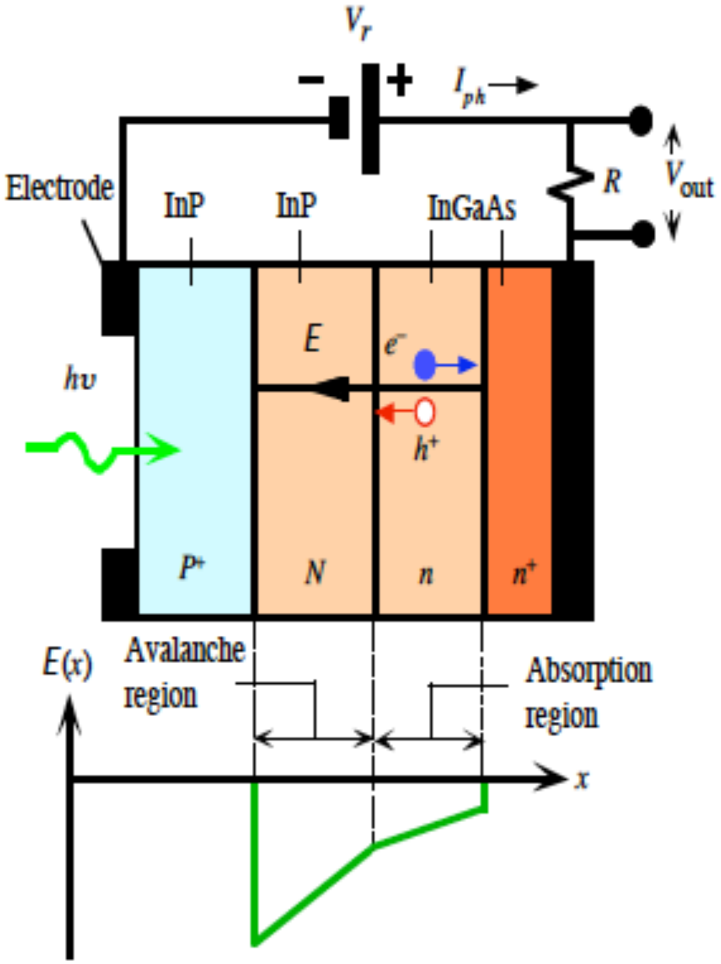
Typical Characteristics of Different PDs

TABLE 5.2 Typical characteristics of some *pn* junction, pin and APD type photodetectors based on Si, Ge and InGaAs. t_r is the rise time of the photocurrent from 10% to 90% of its final value when an optical step excitation is applied with photodetector under normal operating conditions (under reverse bias). I_{dark} is typical dark current at normal operating conditions for photosensitive area less than 1 mm^2.

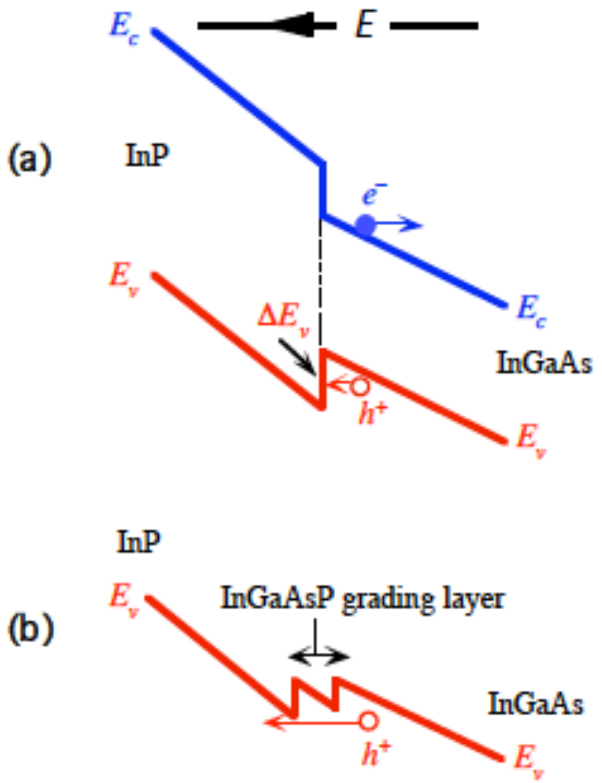
Photodiode	λ_{range} nm	λ_{peak} nm	R at λ_{peak} A/W	Gain	t_r (ns)	I_{dark}
Si *pn* junction	200–1100	600–900	0.5–0.6	<1	0.5	0.01–0.1 nA
Si *pin*	300–1100	800–900	0.5–0.6	<1	0.03–0.05	0.01–0.1 nA
Si APD	400–1100	830–900	40–130	10–100	0.1	1–10 nA
Ge *pn* junction	700–1800	1500–1600	0.4–0.7	<1	0.05	0.1–1 μA
Ge APD	700–1700	1500–1600	4–14	10–20	0.1	1–10 μA
InGaAs-InP *pin*	800–1700	1500–1600	0.7–0.9	<1	0.03–0.1	0.1–10 nA
InGaAs-InP APD	800–1700	1500–1600	7–18	10–20	0.07–0.1	10–100 nA



(a) A Si APD structure without a guard ring. (b) A schematic illustration of the structure of a more practical Si APD

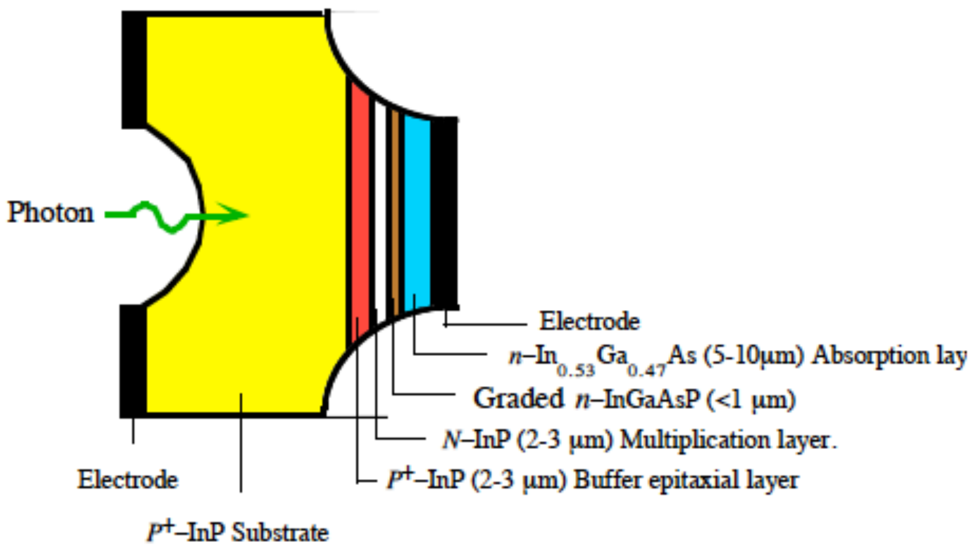


Simplified schematic diagram of a separate absorption and multiplication (SAM) APD using a heterostructure based on InGaAs-InP. P and N refer to p and n -type wider-bandgap semiconductor.

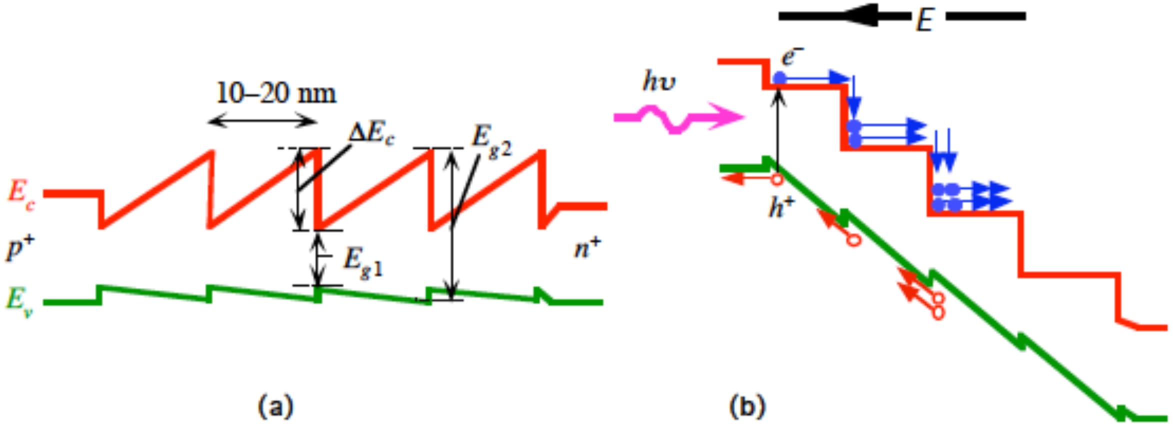


(a) Energy band diagram for a SAM heterojunction APD where there is a valence band step ΔE_v from InGaAs to InP that slows hole entry into the InP layer.

(b) An interposing grading layer (InGaAsP) with an intermediate bandgap breaks ΔE_v and makes it easier for the hole to pass to the InP layer



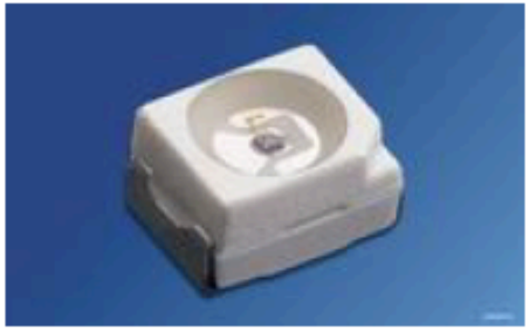
Simplified schematic diagram of a more practical mesa-etched SAGM layered APD.



Energy band diagram of a staircase superlattice APD (a) No bias. (b) With an applied bias.

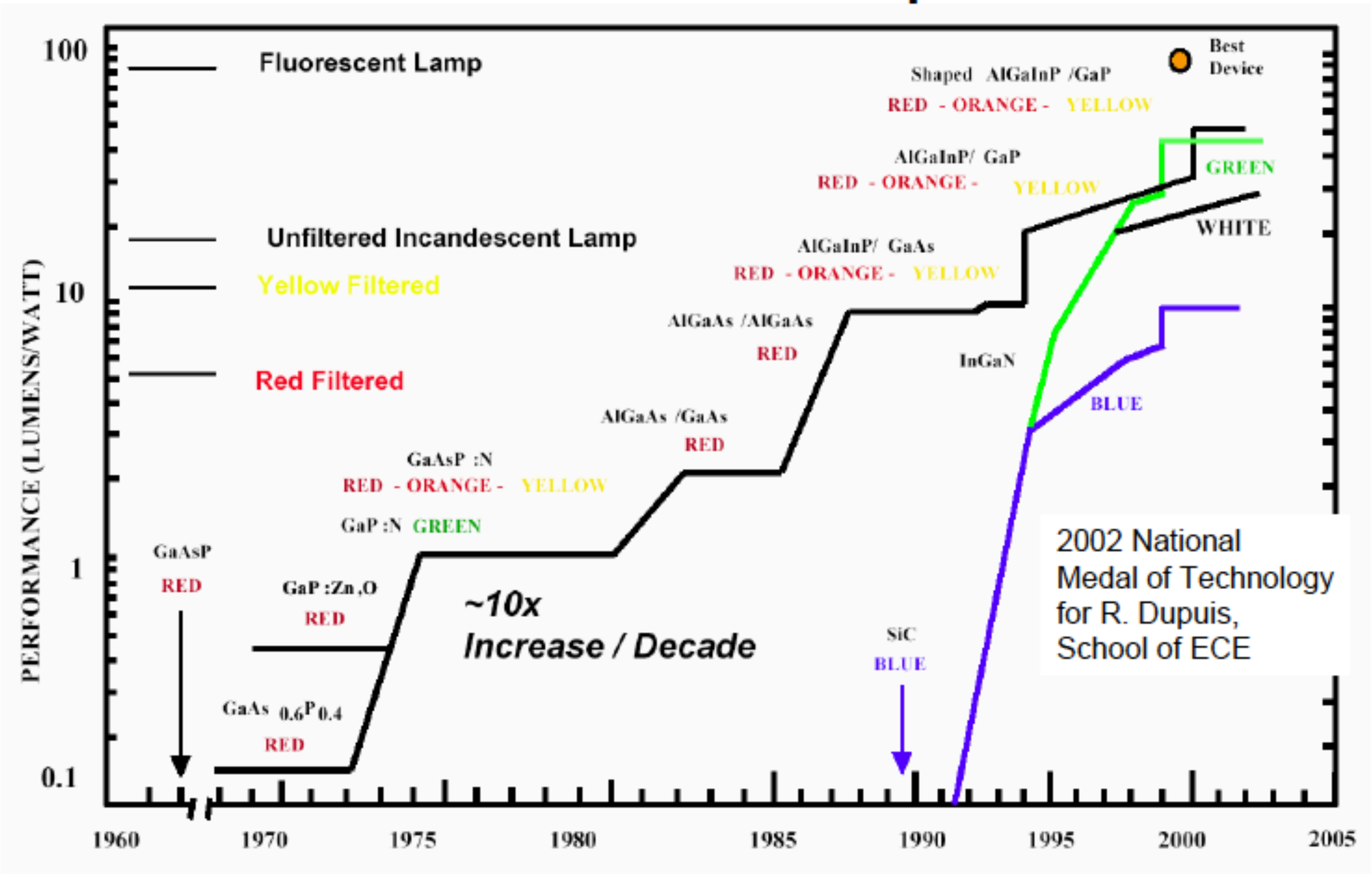
Light Emitting Devices – Basics

- Emission of photons by recombination of electrons and holes in direct bandgap materials
- **Photoluminescense**: excess electrons and holes required for the radiative recombination are generated by photon absorption
- **Electroluminescense**: excess electrons and holes required for the radiative recombination are result of an electrical current

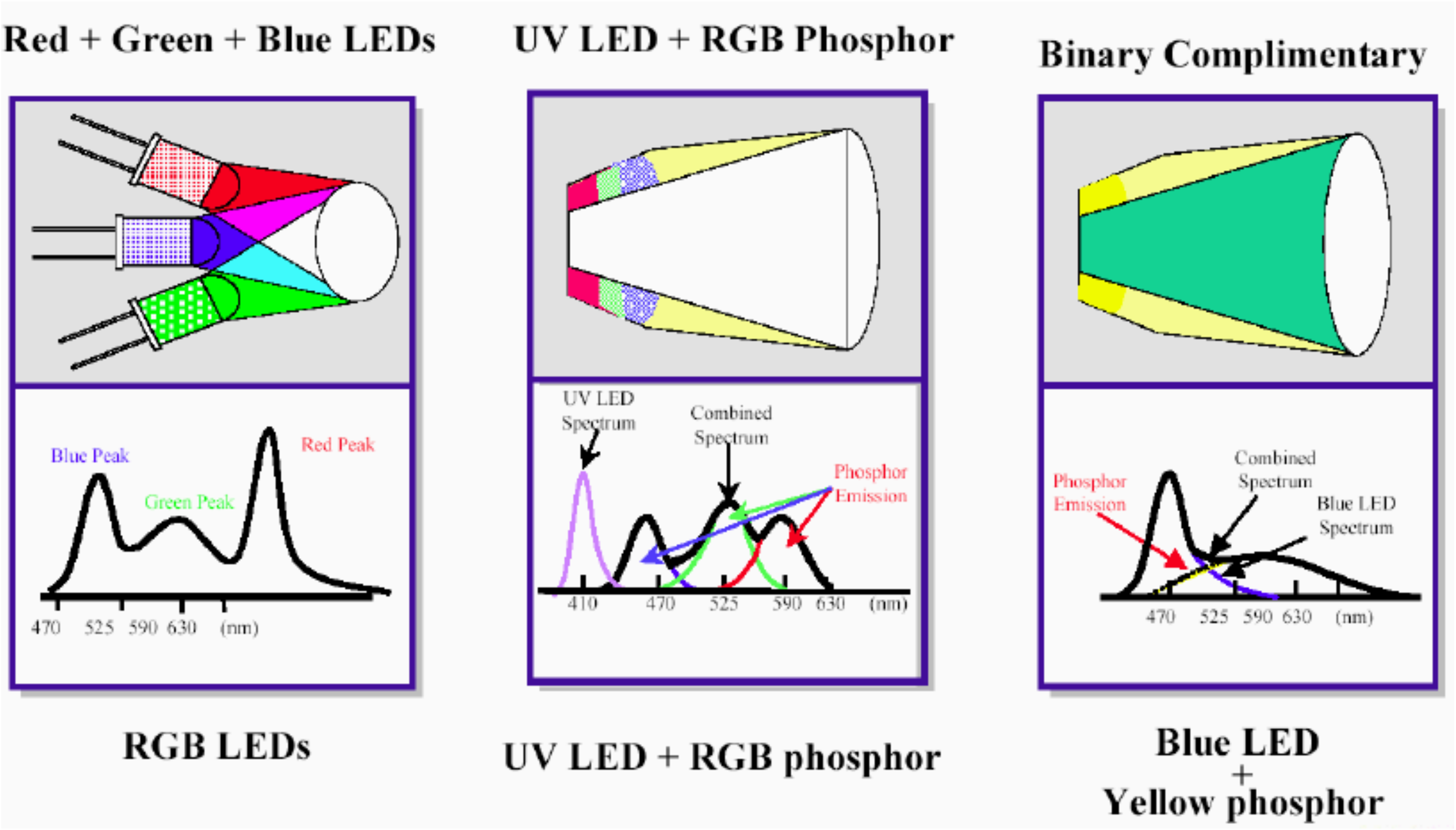


www.osram.com

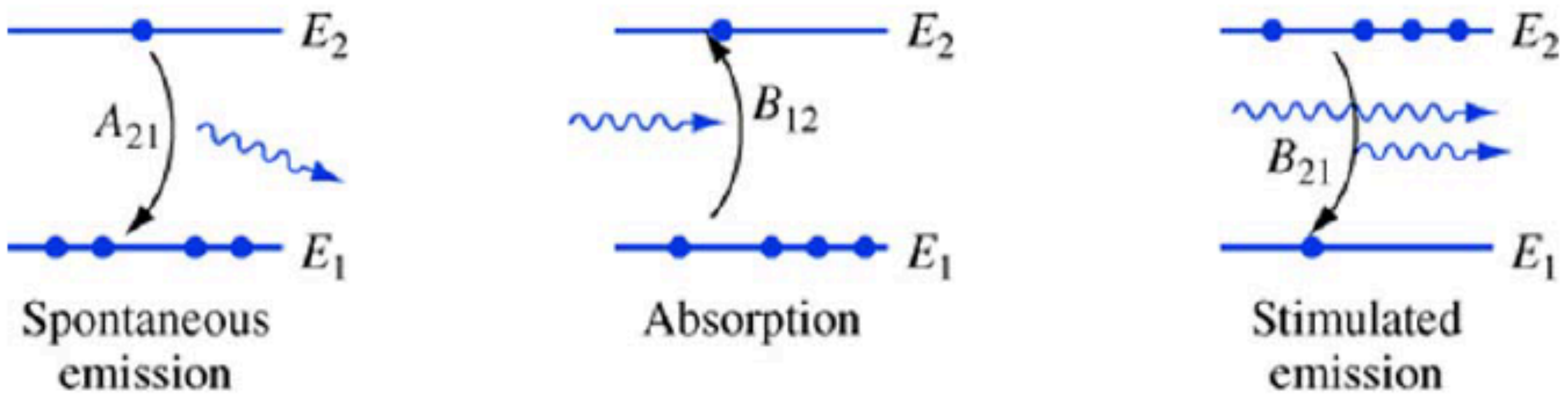
The LED Development



How to Make White LEDs?

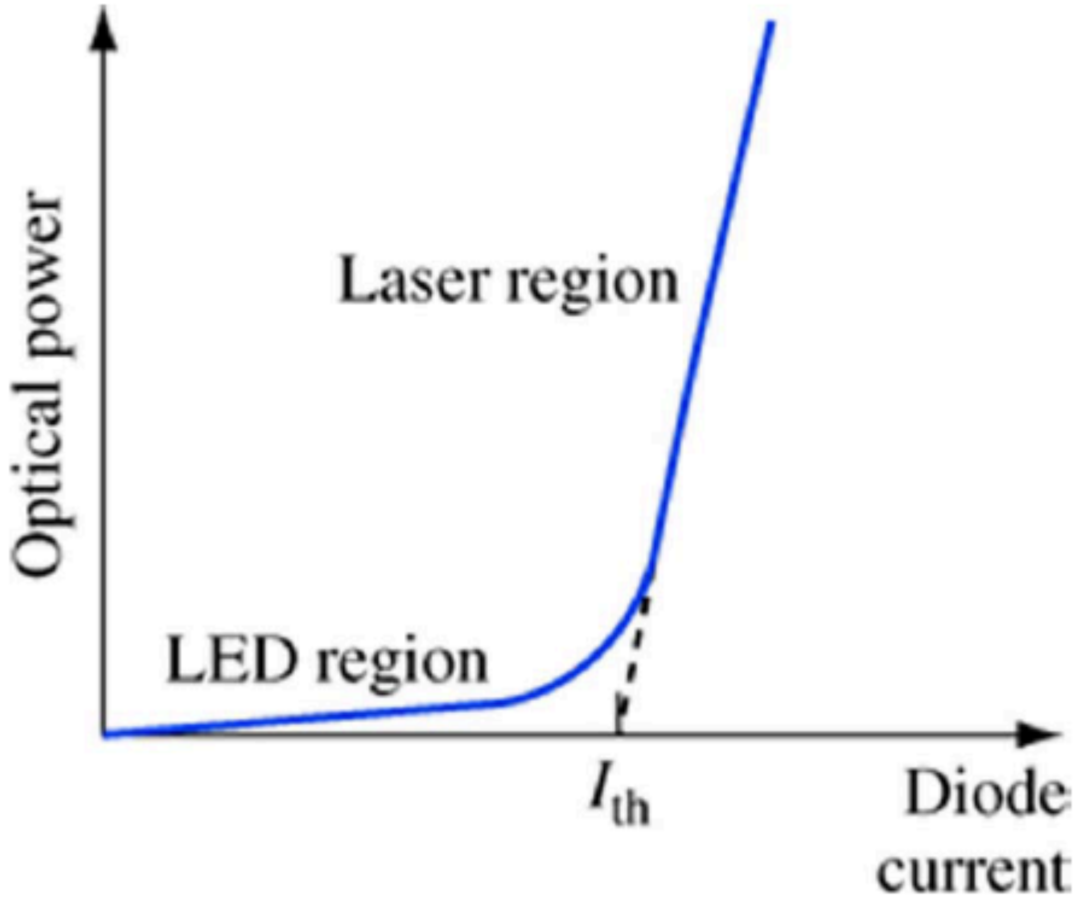


Spontaneous Light Emission



- **We can add to our understanding of absorption and spontaneous radiation due to random recombination another form of radiation – Stimulated emission.**
- **Stimulated emission can occur when we have a "population inversion", i.e. when we have injected so many minority carriers that in some regions there are more "excited carriers" (electrons) than "ground state" carriers (holes).**
- **Given an incident photon of the bandgap energy, a second photon will be "stimulated" by the first photon resulting in two photons with the same energy (wavelength) <u>and phase</u>.**
- **This phase coherence results in minimal divergence of the optical beam resulting in a directed light source.**

Spontaneous vs Stimulated Light Emission

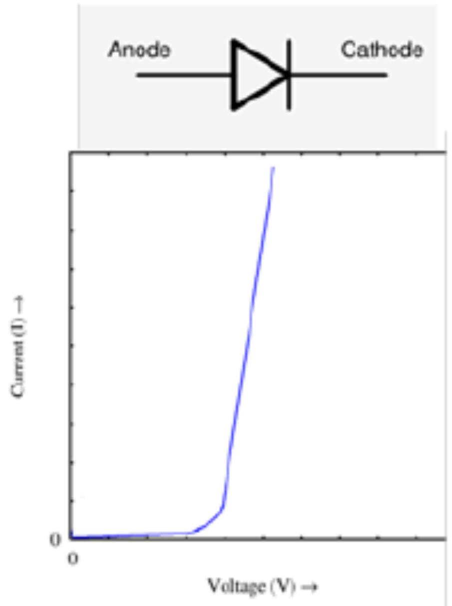


The power-current curve of a laser diode. Below threshold, the diode is an LED. Above threshold, the population is inverted and the light output increases rapidly.

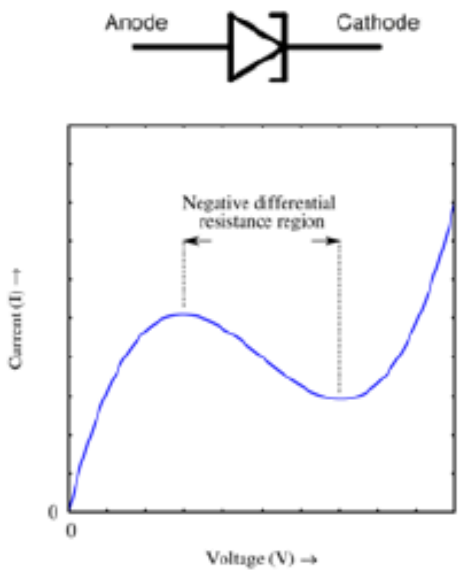
Tunnel Diodes (Esaki Diode)

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

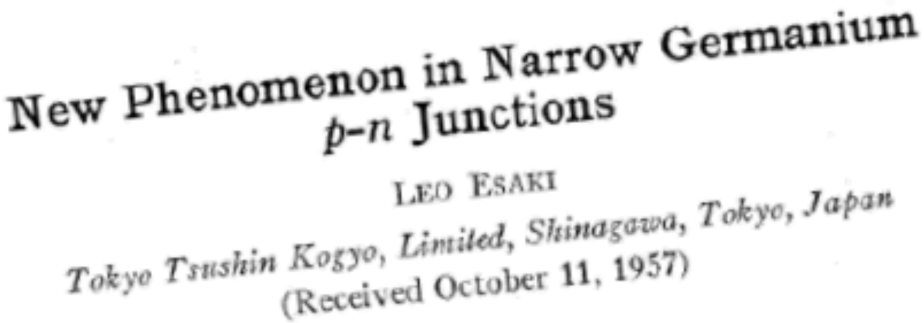
Esaki diodes was named after Leo Esaki, who in 1973 received the Nobel Prize in Physics for discovering the electron tunneling effect used in these diodes. Esaki reported the first paper on tunnel diodes in Physical Review in 1958



Regular p-n Diode



Tunnel Diode



New Phenomenon in Narrow Germanium *p-n* Junctions

LEO ESAKI

Tokyo Tsushin Kogyo, Limited, Shinagawa, Tokyo, Japan

(Received October 11, 1957)

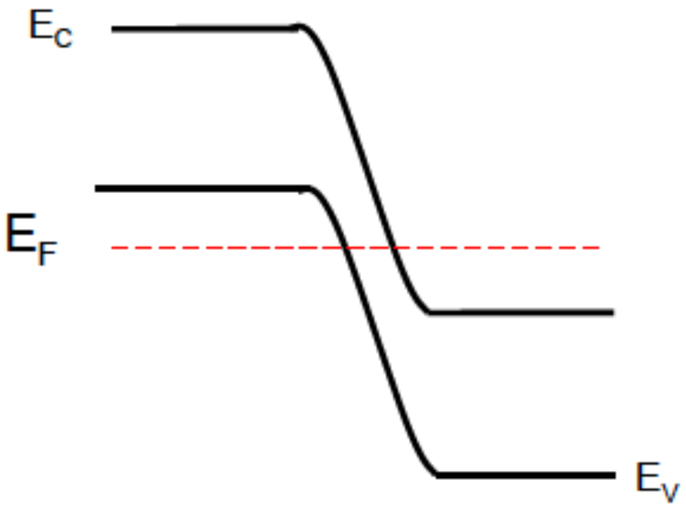
1

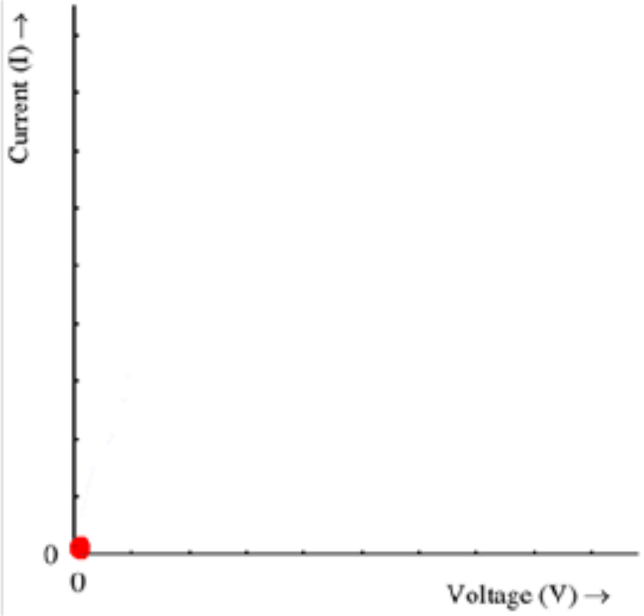
Tunnel Diode Operation

- 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

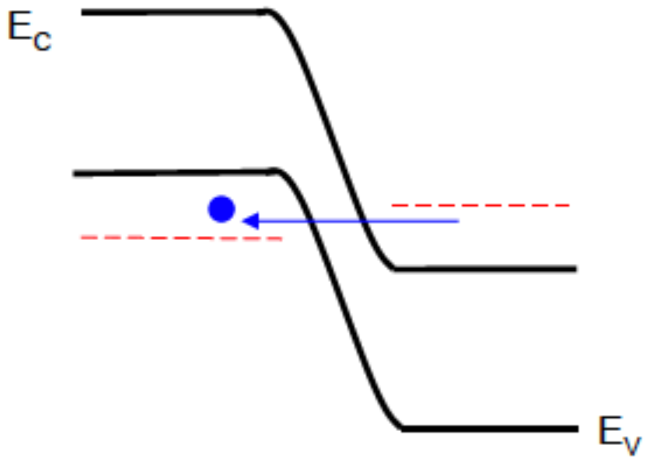


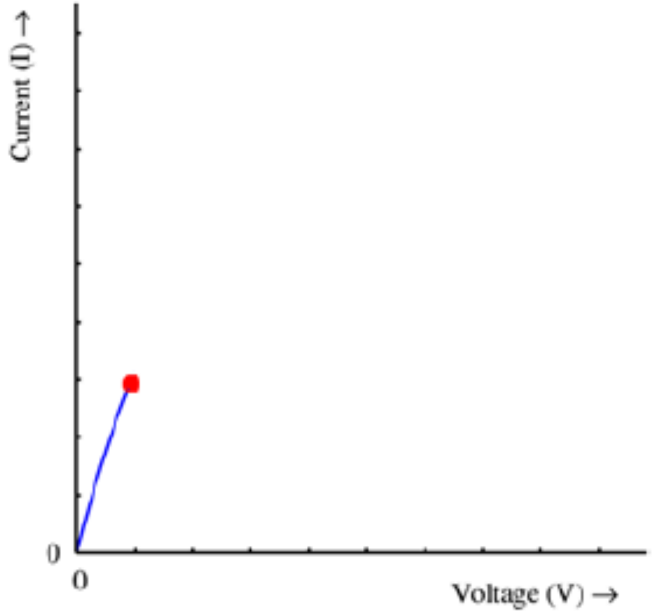


…continued…Tunnel Diode Operation

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

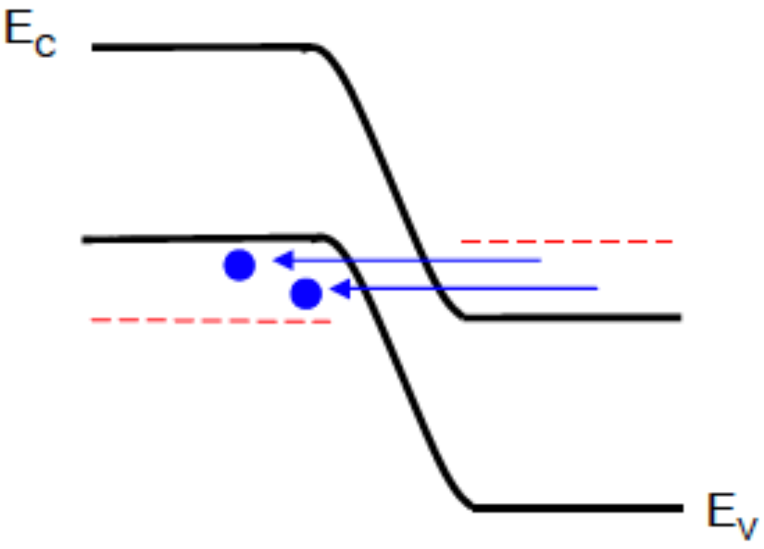


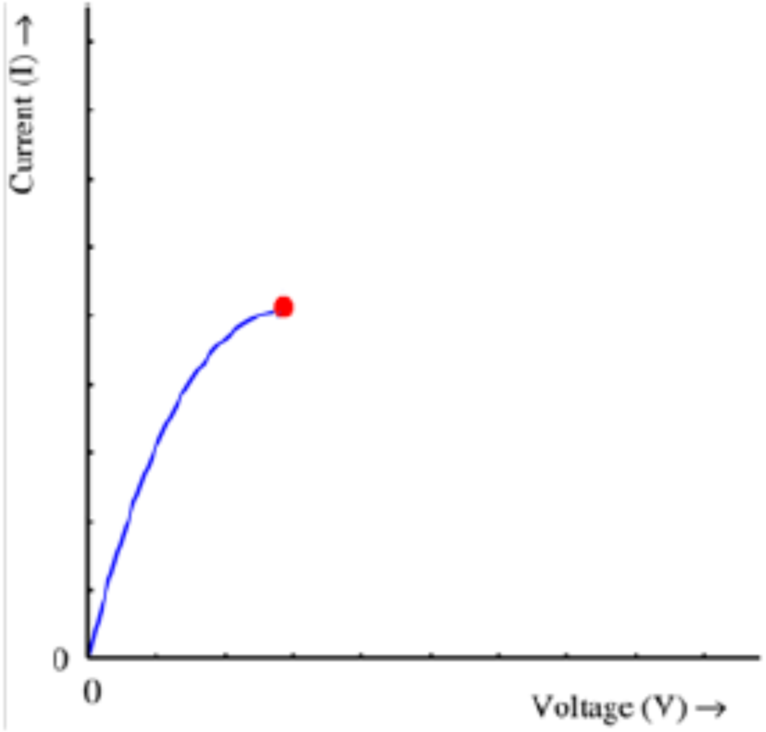


Direct tunneling current starts growing

*…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**

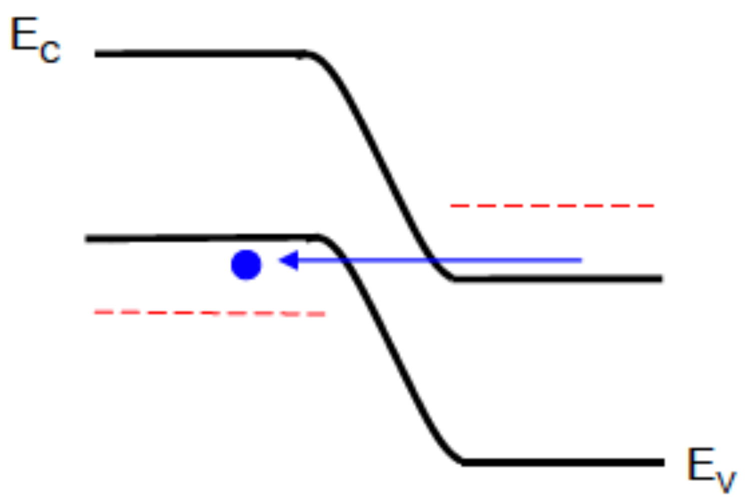


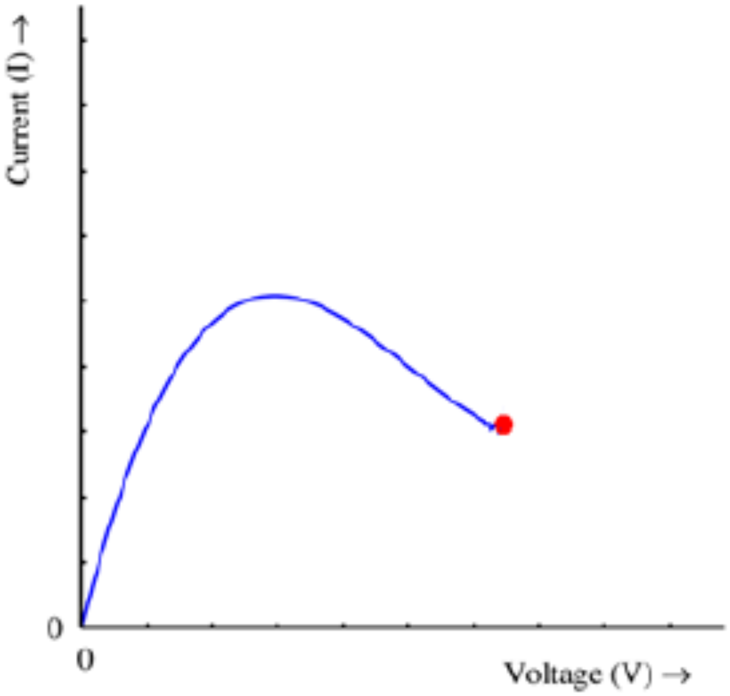


Maximum Direct tunneling current

...*continued*...Tunnel Diode Operation

<u>Step 4:</u> **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.**

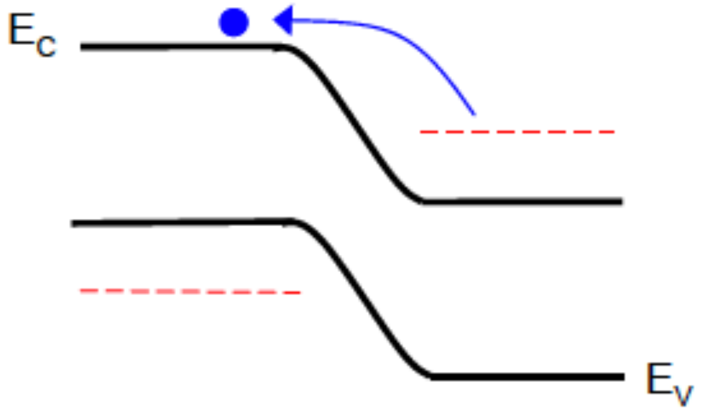


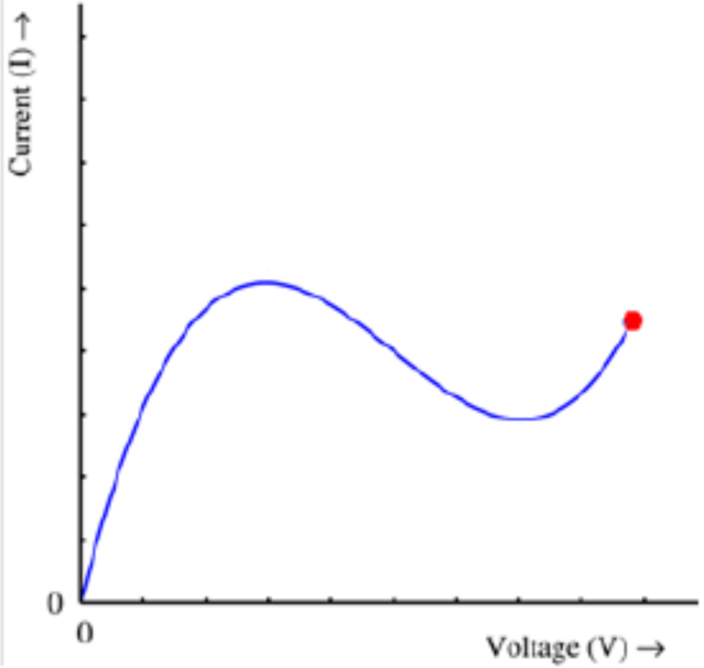


Direct tunneling current decreases

…*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.



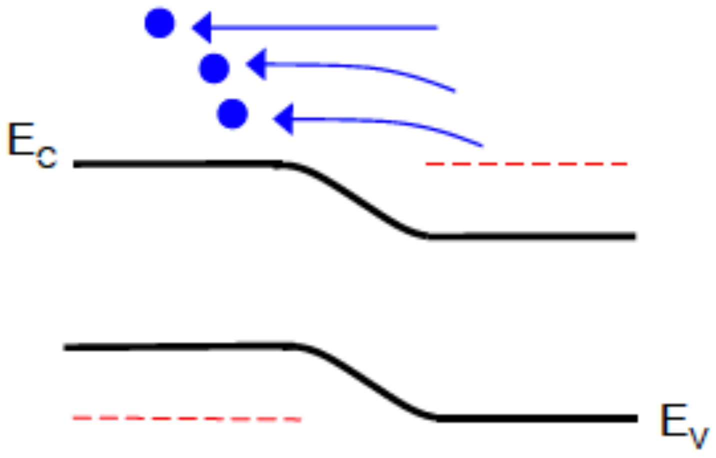


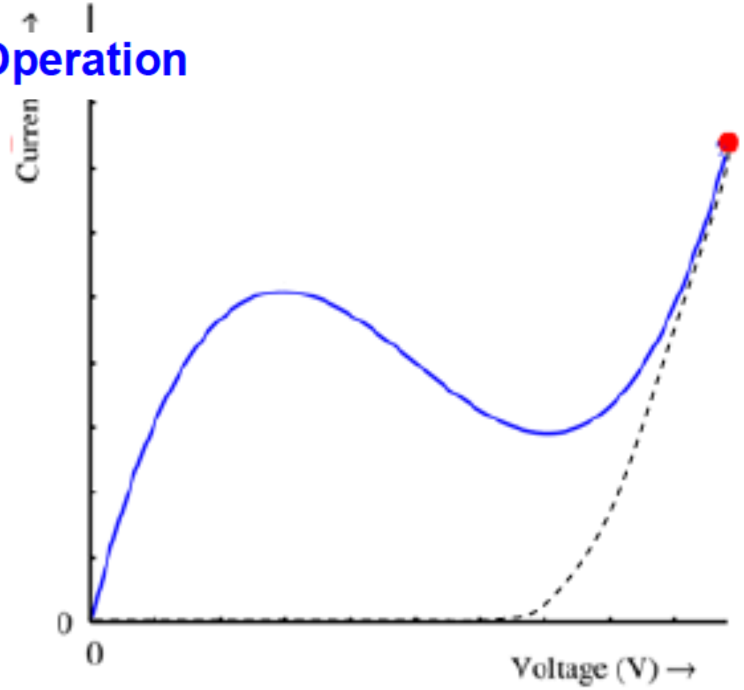
No tunneling current; diffusion current starts growing

*…continued…*Operation of a Tunnel Diode

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

*…continued…*Tunnel Diode Operation

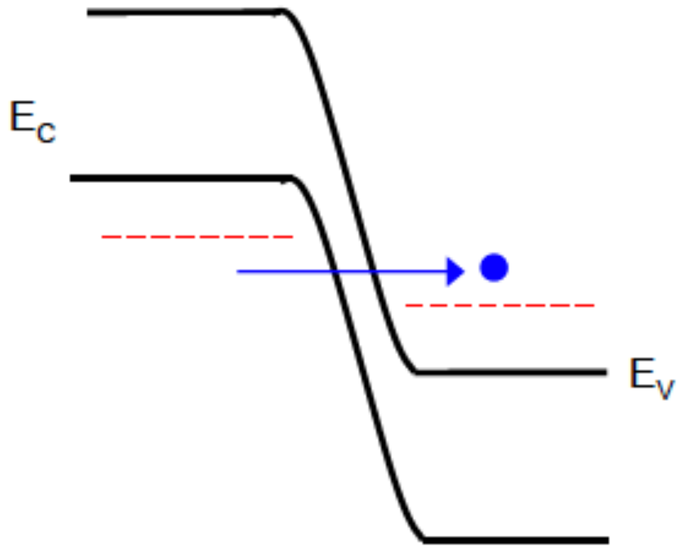


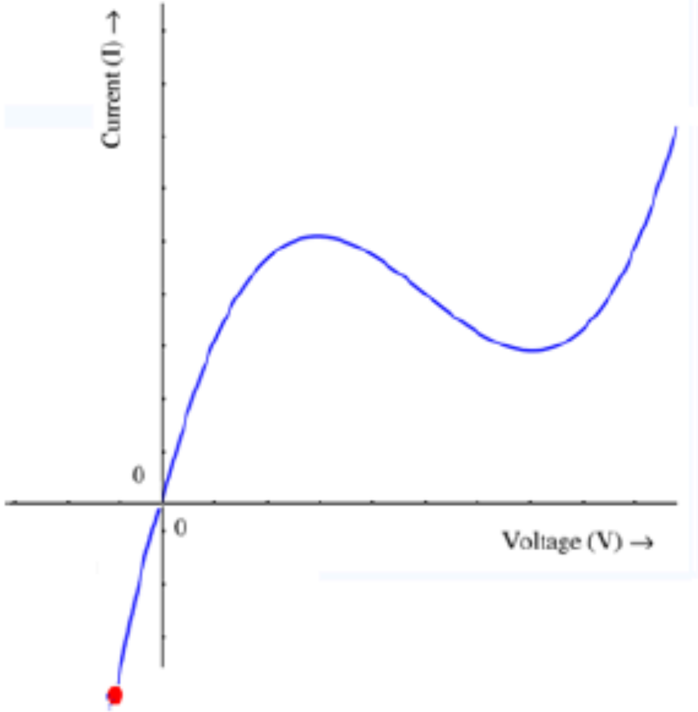


…*continued*…Operation of a Tunnel Diode

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.





Tunnel Diode I-V

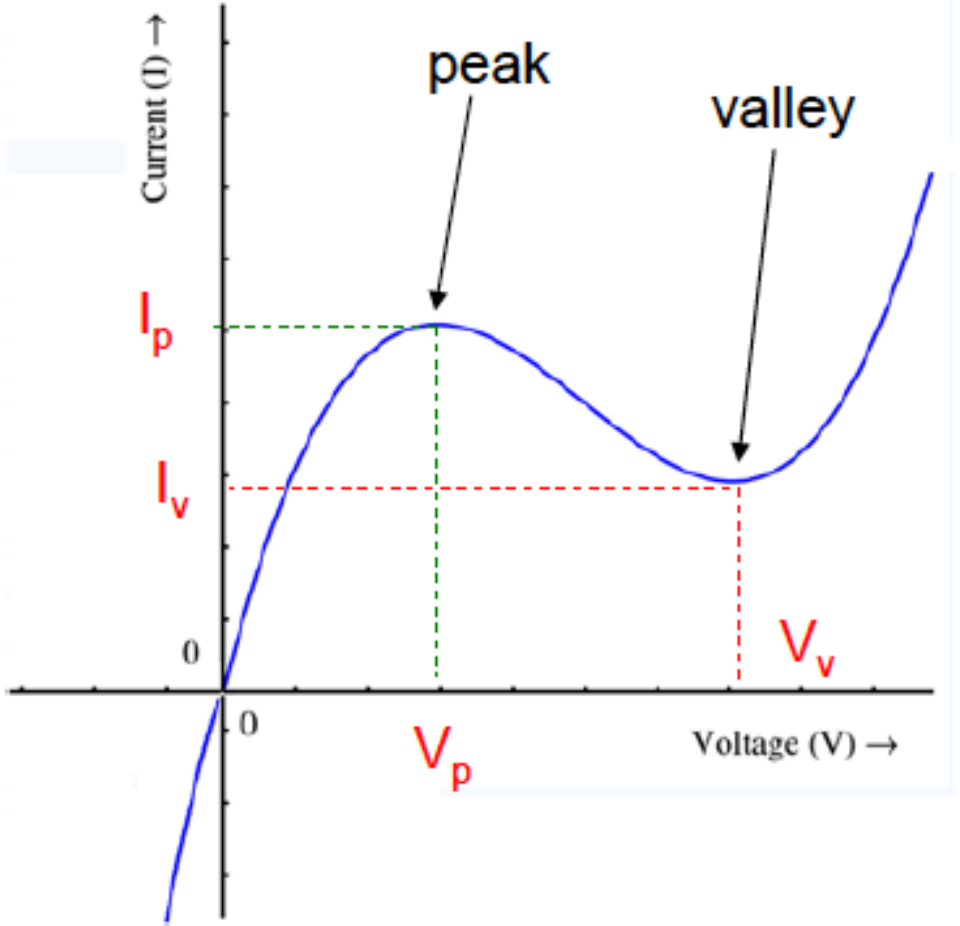
- The total current I in a tunnel diode is given by

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

- 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 $V_{th} = kT/q$



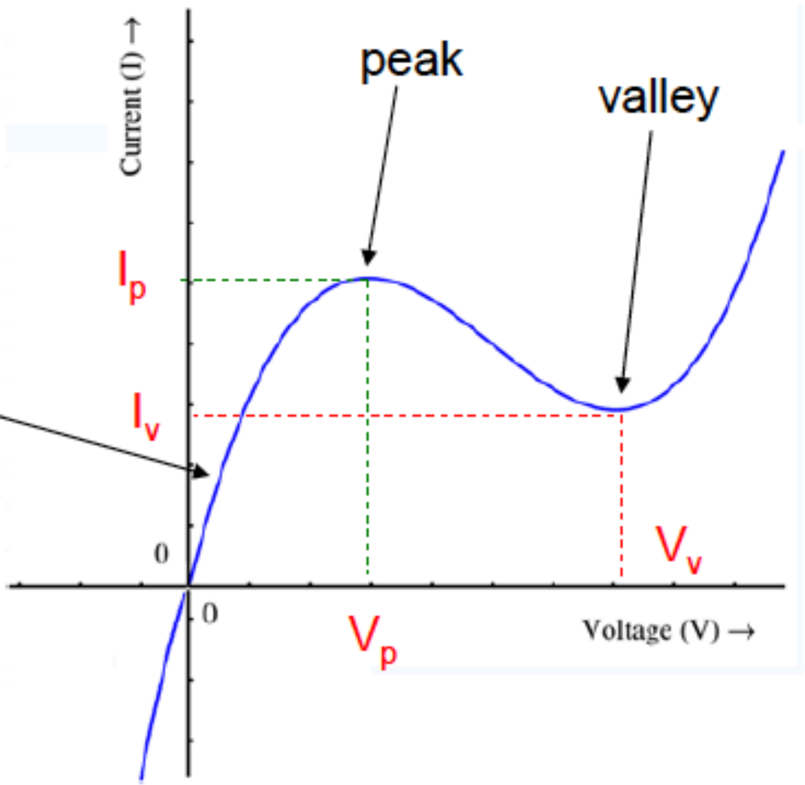
Tunnel Diode I-V

- 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

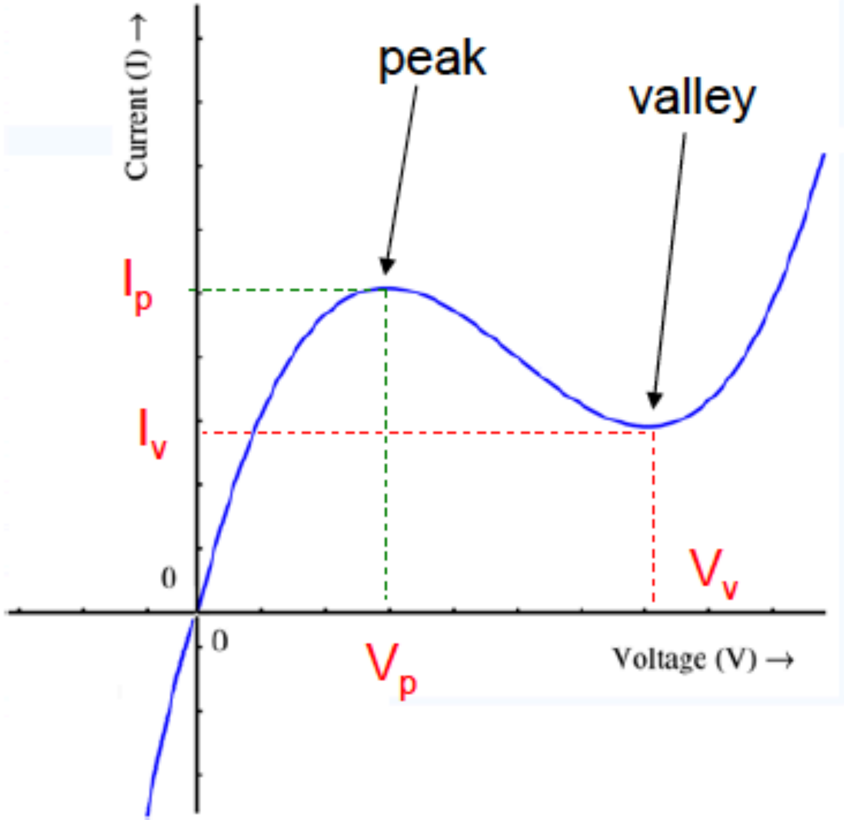
- The excess current,

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

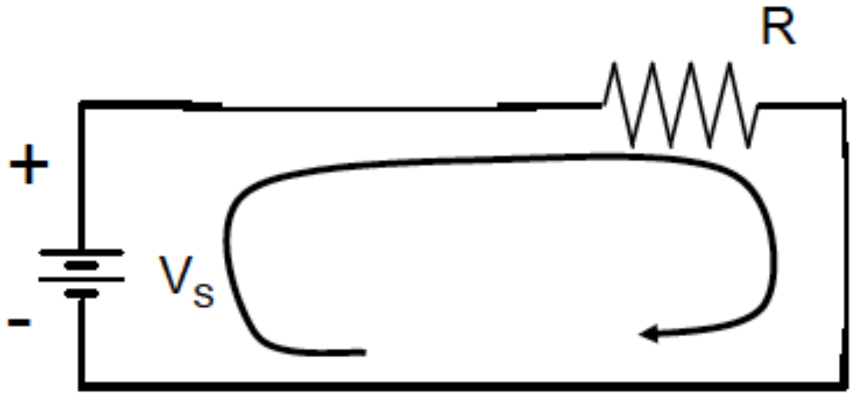
I_{excess} is an additional tunneling current related to parasitic tunneling via impurities.

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



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,

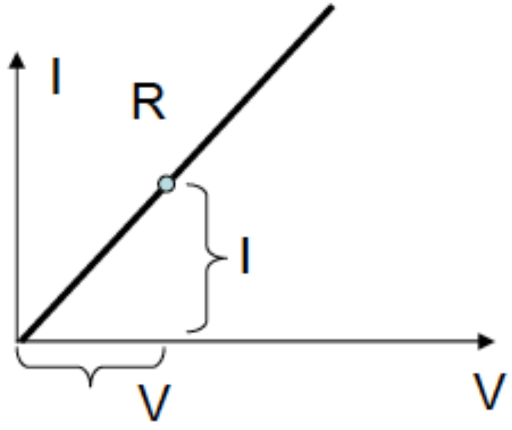
Positive power means energy dissipation (e.g. conversion into the Joule heat);

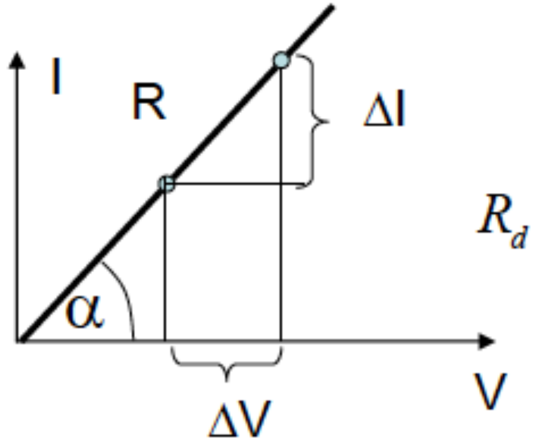
Negative power corresponds to the power GENERATION (Energy supply);

Differential resistance and negative differential resistance

Static resistance:
R = V/I

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

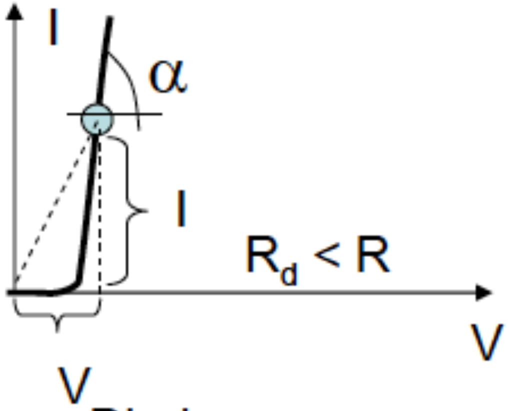




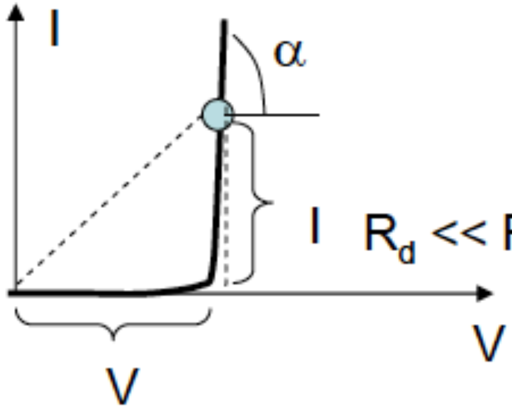
$R_d = \cot(\alpha)$

For linear ("Ohmic") components, $R = R_d$.

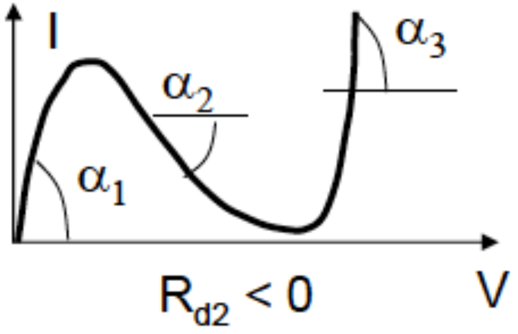
For many semiconductor devices, $R \neq R_d$:



Diode
(forward bias)

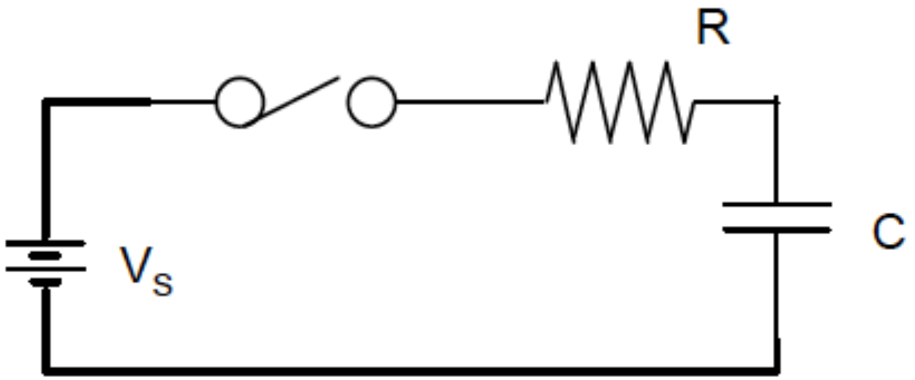


Zener Diode
(reverse bias)



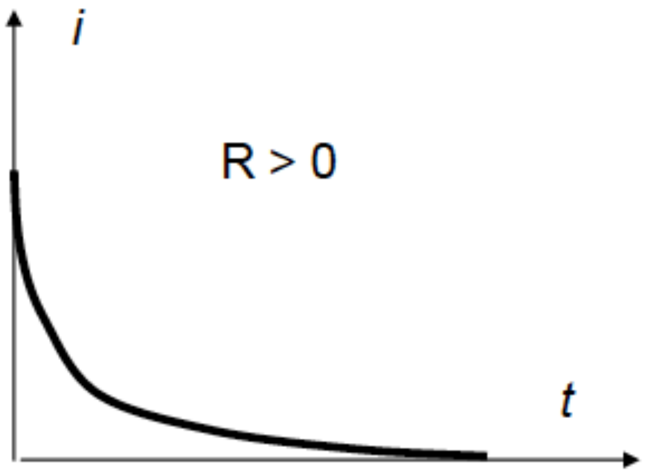
TD

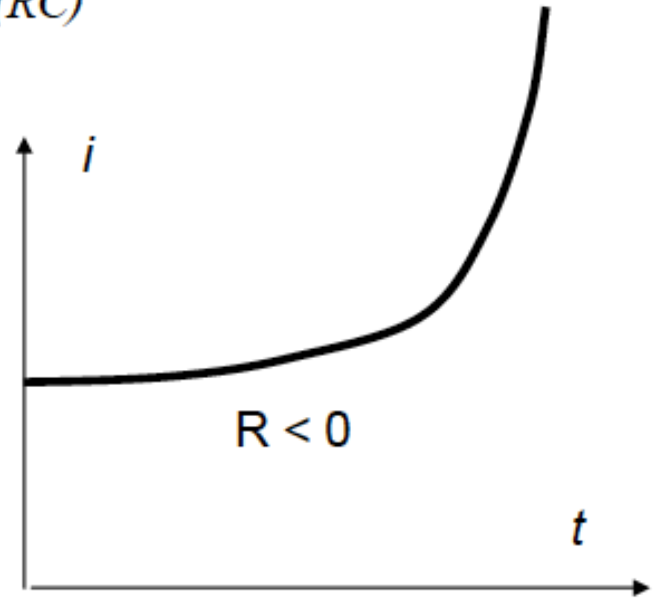
Transients in Negative Differential Resistance Circuits



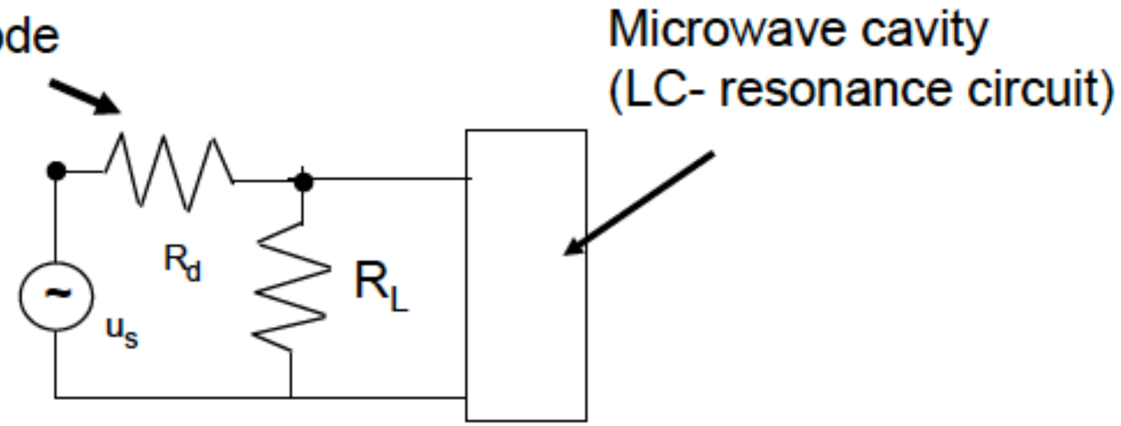
After turning the switch ON:

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





Tunnel Diode as a microwave oscillator

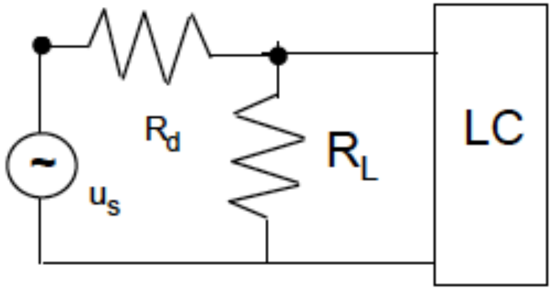


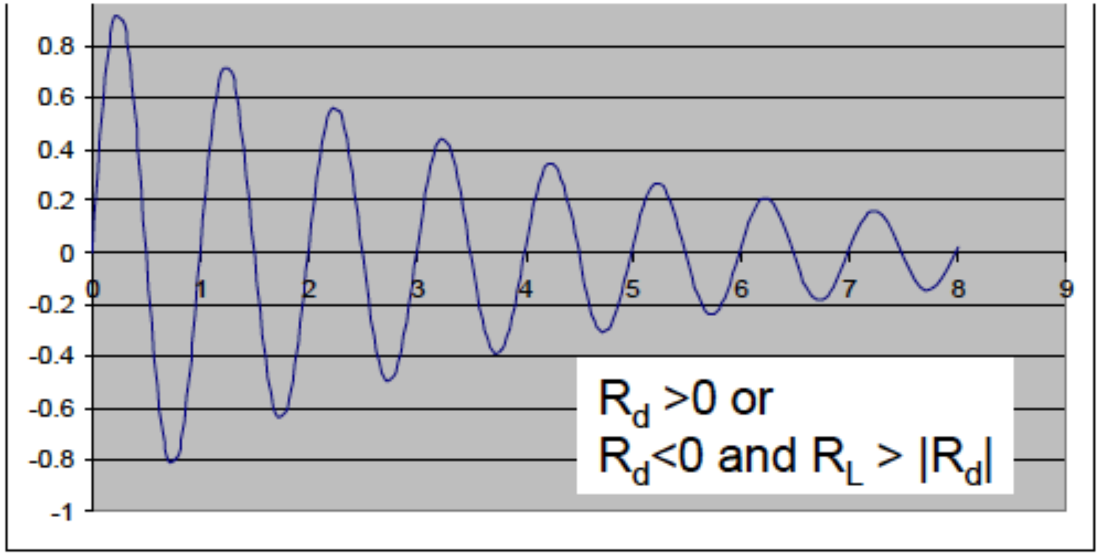
Load resistance is chosen so that $R_L < |R_d|$ in the NDR region

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



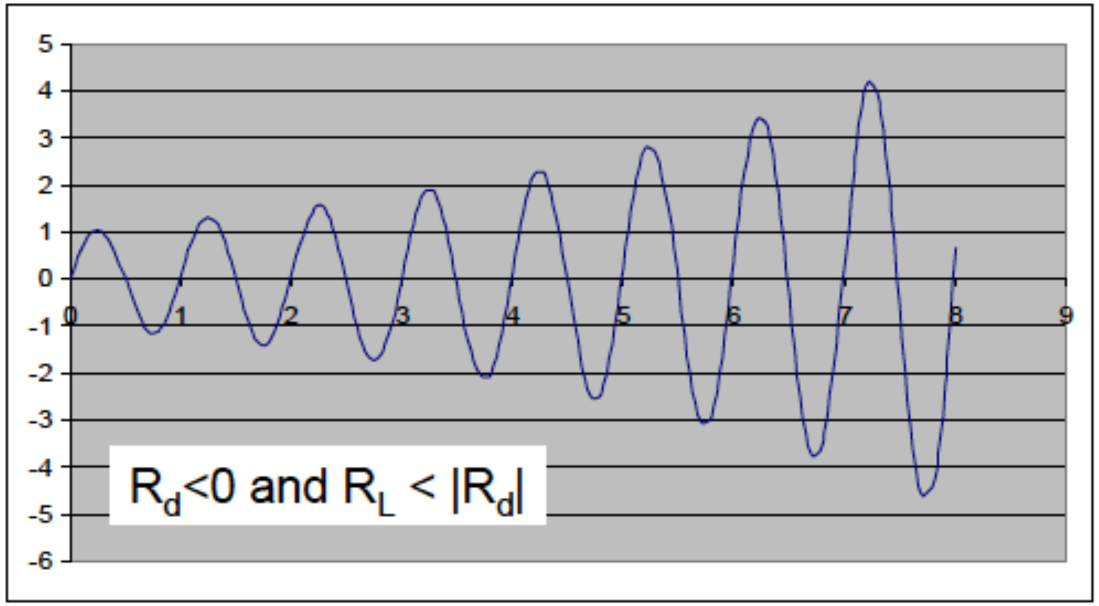


The resonant circuit with NDR can oscillate. Maximum frequency of the TD-oscillator is limited by the characteristic tunneling time:

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

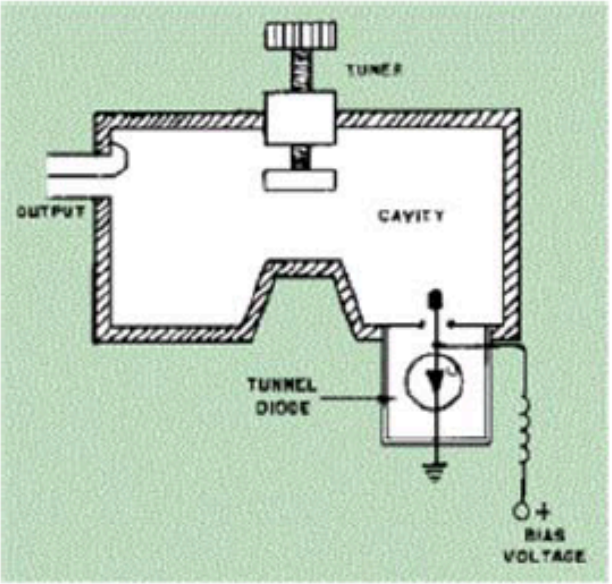
Tunneling time in TDs is extremely small: << 1 ps

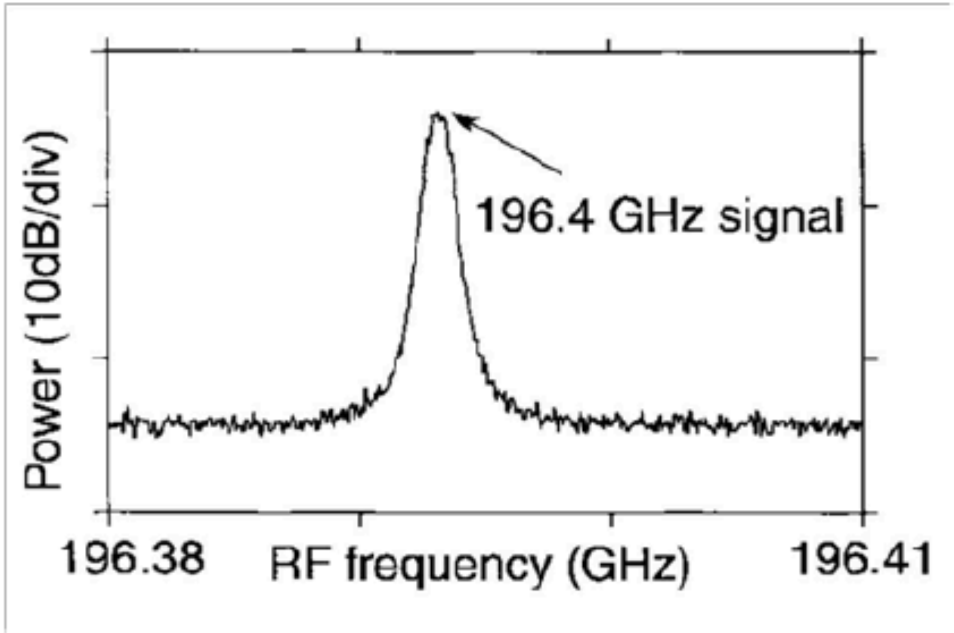
F_{MAX} > 100 GHz



22

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.