EEE337 Semiconductor Electronics
EEE348 Electronics and Devices
(Microwave devices)

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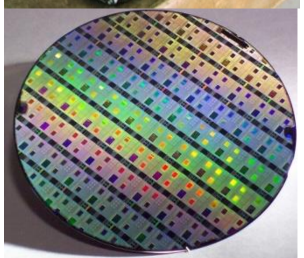
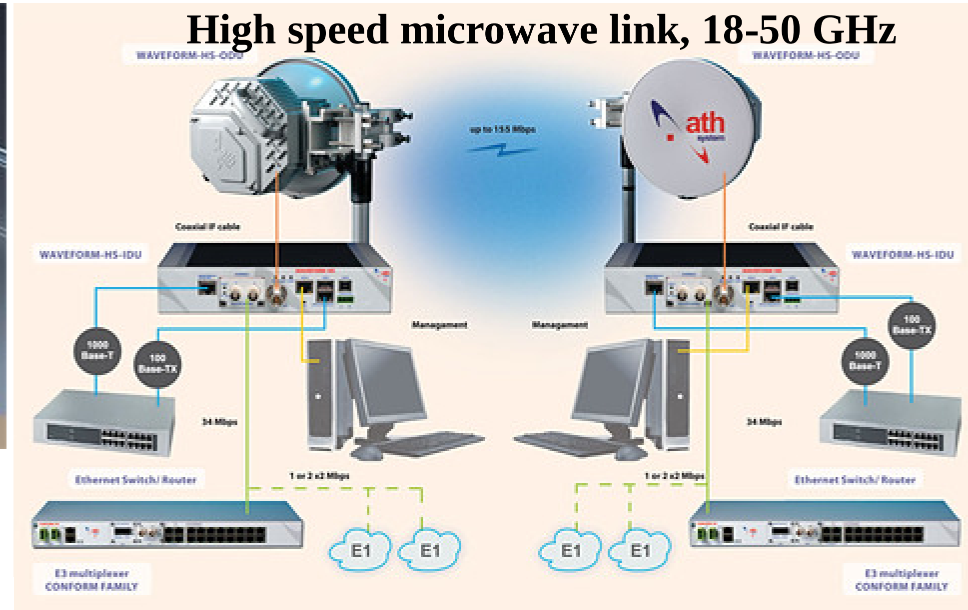
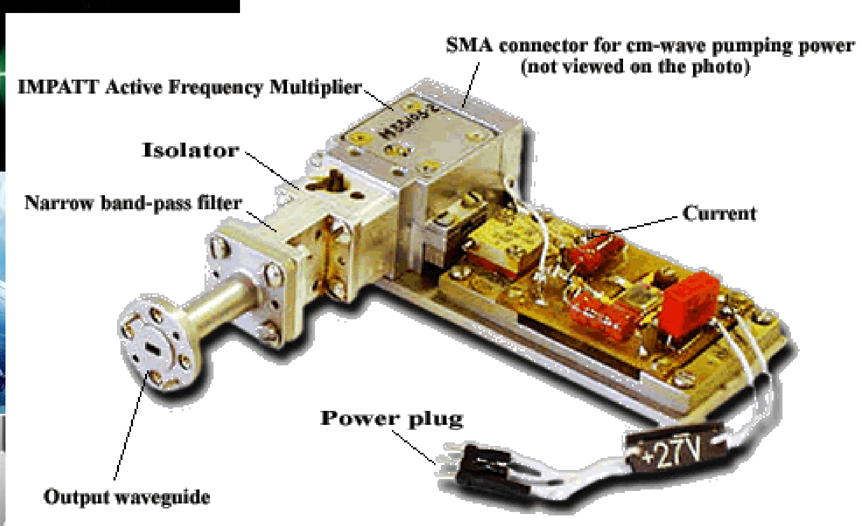
Microwave applications

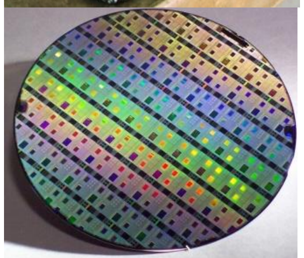


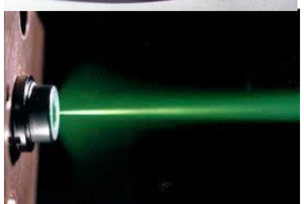




Microwave frequency multiplier

Microwave bands





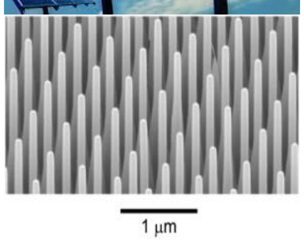
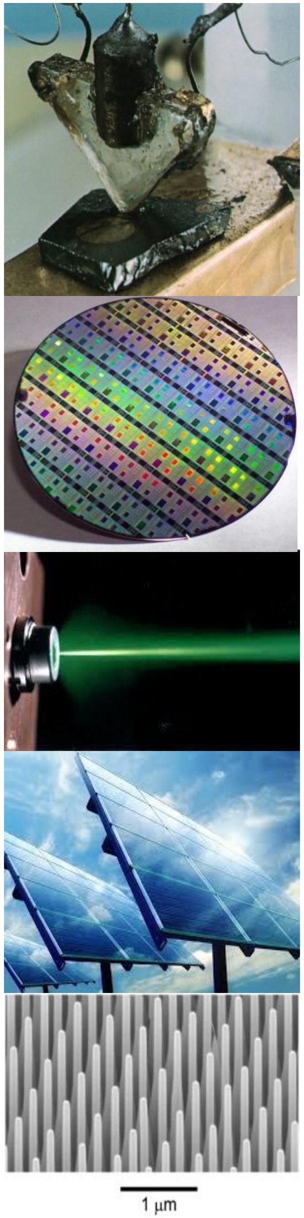
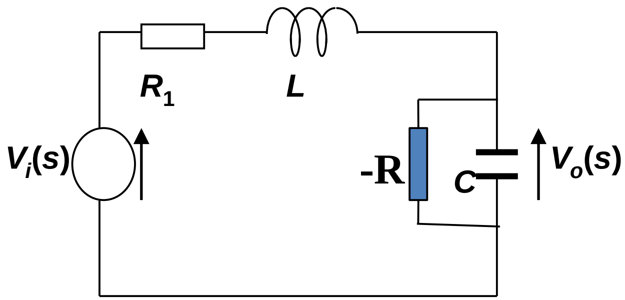
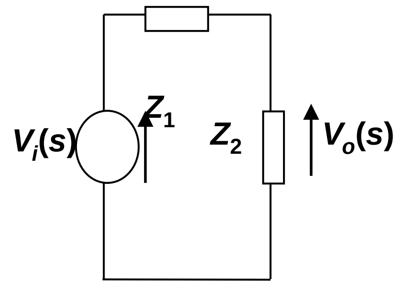


TABLE 1: MICROWAVE LETTER BAND DESIGNATIONS		
Band	Frequency range	Applications
L	1 to 2 GHz	Satellite, navigation (GPS, etc.), cellular phones
S	2 to 4 GHz	Satellite, SiriusXM radio, unlicensed (Wi-Fi, Bluetooth, etc.), cellular phones
C	4 to 8 GHz	Satellite, microwave relay
X	8 to 12 GHz	Radar
K_u	12 to 18 GHz	Satellite TV, police radar
K	18 to 26.5 GHz	Microwave backhaul
K_a	26.5 to 40 GHz	Microwave backhaul
Q	30 to 50 GHz	Microwave backhaul
U	40 to 60 GHz	Experimental, radar
V	50 to 75 GHz	New WLAN, 802.11ad/WiGig
E	60 to 90 GHz	Microwave backhaul
W	75 to 110 GHz	Automotive radar
F	90 to 140 GHz	Experimental, radar
D	110 to 170 GHz	Experimental, radar

RLC circuit







$$\frac{V_o(s)}{V_i(s)} = \frac{1/LC}{s^2 + (R/L)s + 1/LC} \qquad H(s) = \frac{N(s)}{s^2 + 2\zeta\omega_n s + \omega_n{}^2}$$

Consider an RLC circuit. From the transfer function, it can be shown that the damping factor and the Q-factor are given by

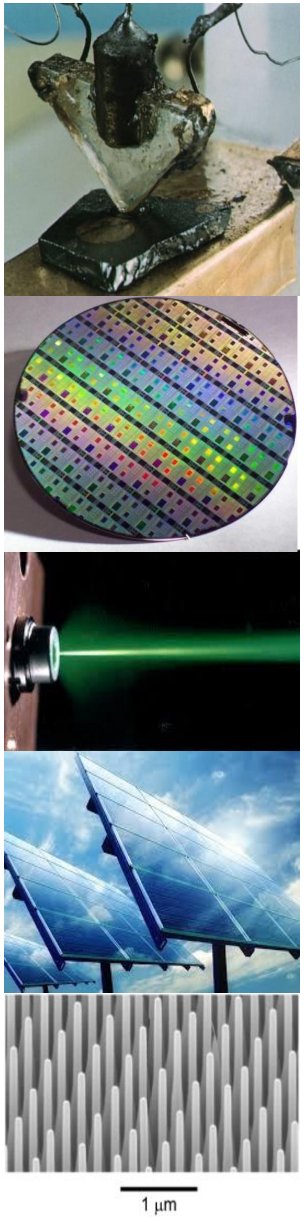
$$\zeta = \frac{R}{2\omega_n L} \quad \text{and} \quad Q = \frac{1}{2\zeta}$$

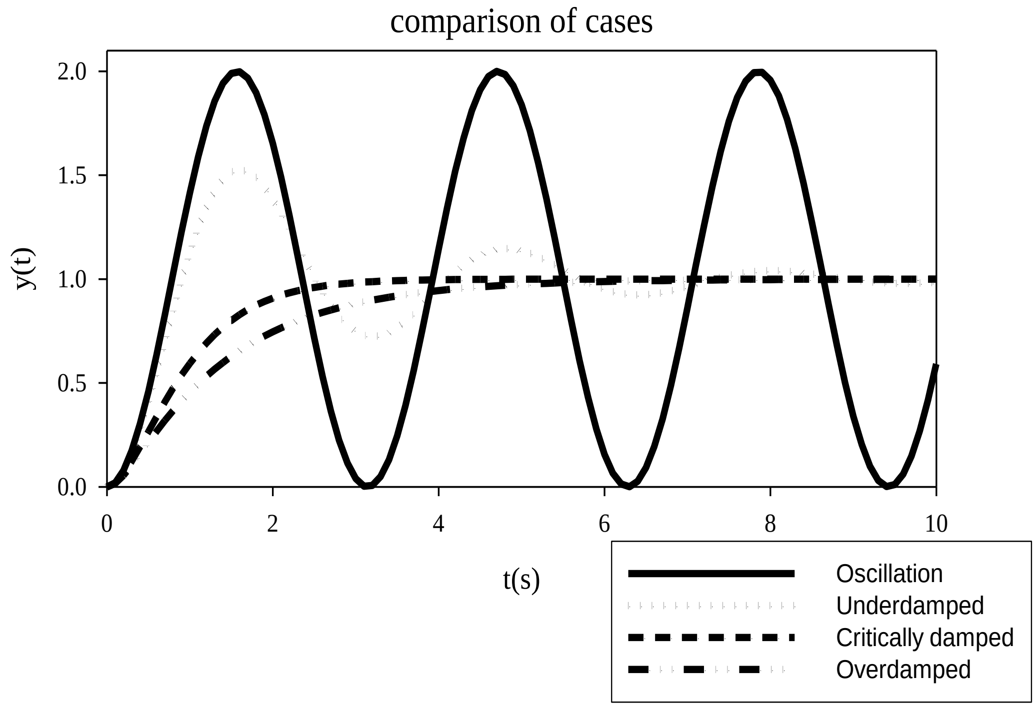
In most circuits R is finite and the damping factor is non-zero (Q-factor is not infinite). Therefore when a step signal is applied at the input, a damped oscillation is produced because $0<\zeta<1$.

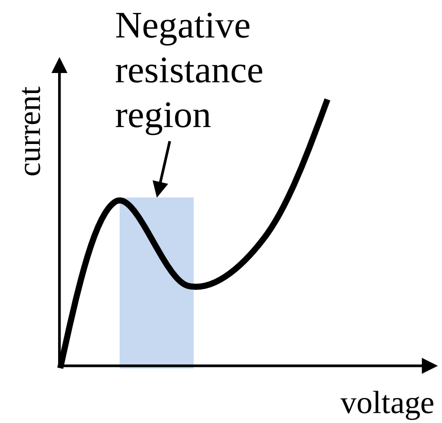
However if we can achieve $\zeta = 0$, an oscillation, with a frequency ω_n is produced. This can be achieved if we can cancel the circuit resistance with a device having a negative resistance.

$$\omega_n = \sqrt{\frac{1}{LC}}$$

2^{nd} order system unit step response

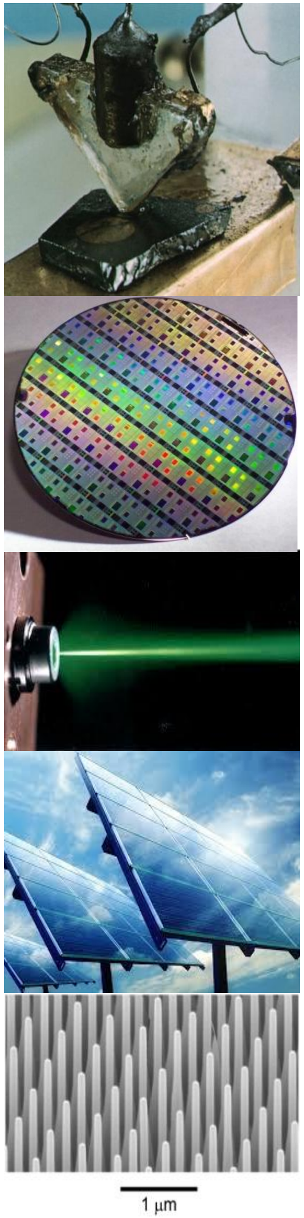






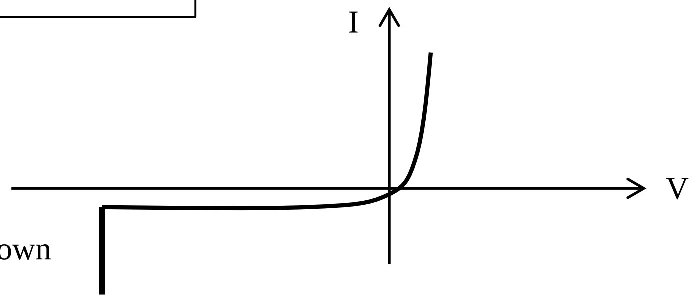
A sustained oscillation can therefore be achieved by combining a negative resistance device with a resonant circuit.

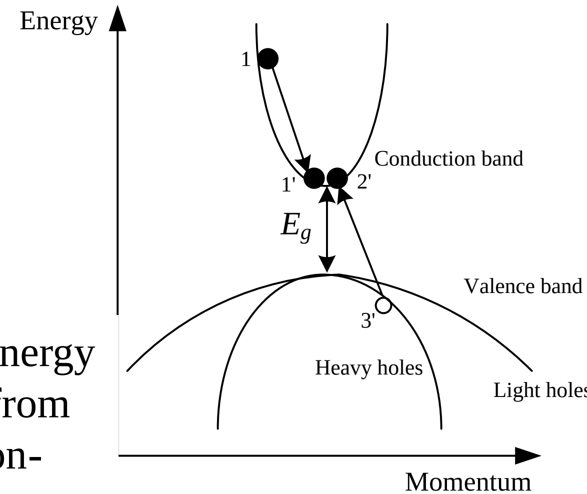
Important electronic devices with negative resistance include **tunnel diode, Gunn diode and IMPATT diode.** They are important devices for microwave oscillators at high frequencies (>10GHz).



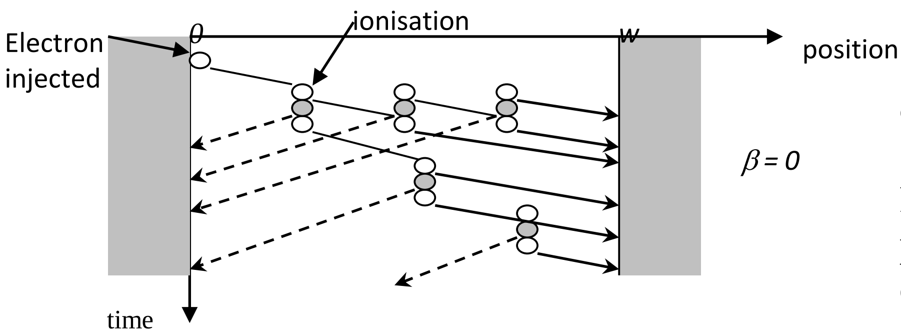
IMPATT diode

Avalanche photodiodes



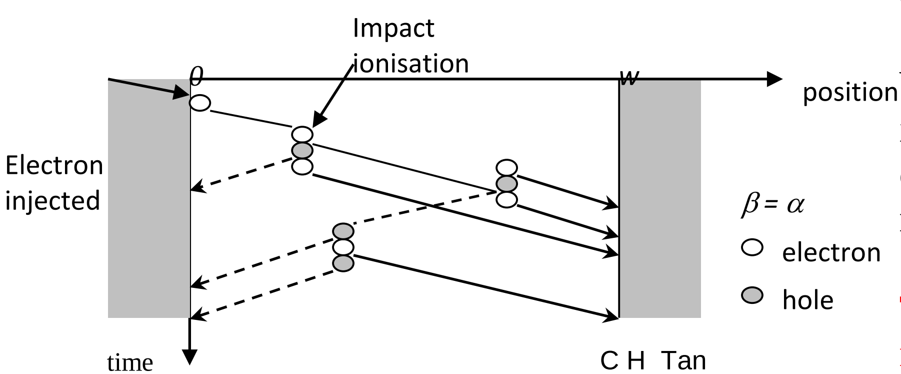


When operated close to the reverse breakdown voltage a high energy electron can collide with a lattice atom to promote an electron from VB to CB. Since a hole is also produced, we have a new electron-hole pair.



β and α are the hole and electron ionisation coefficients, respectively.

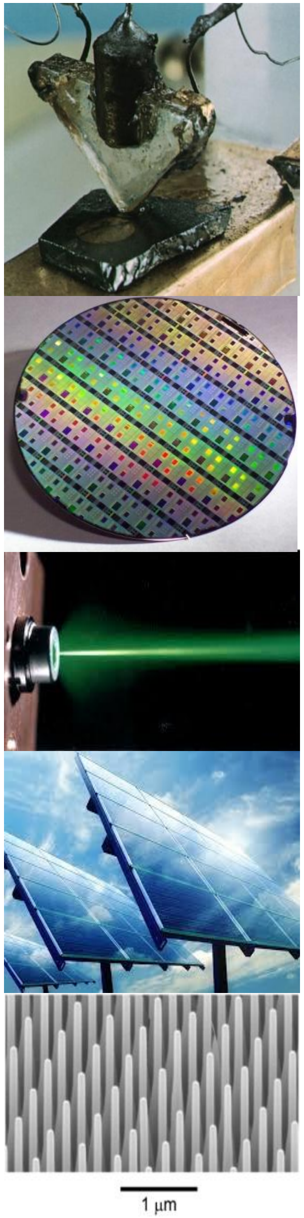
For k = 0 there is large number of electrons present at a given time. If one of the electrons does not impact ionise, the effect on gain is small.



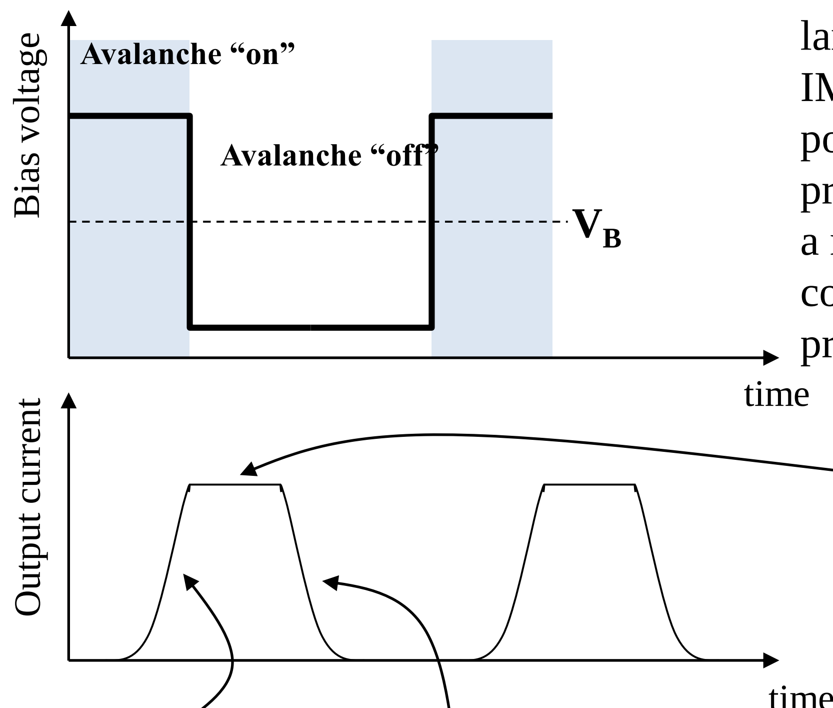
When k =1, there are much fewer electrons in the high field region. Hence if one of them does not ionise, the gain is significantly reduced.

The randomness in impact ionisation is minimum when k = 0.

IMPATT diode



Impact ionisation **a**valanche **t**ransit- **t**ime (IMPATT) diode employs impact ionisation and transit time properties, to produce a negative differential resistance at high frequencies.



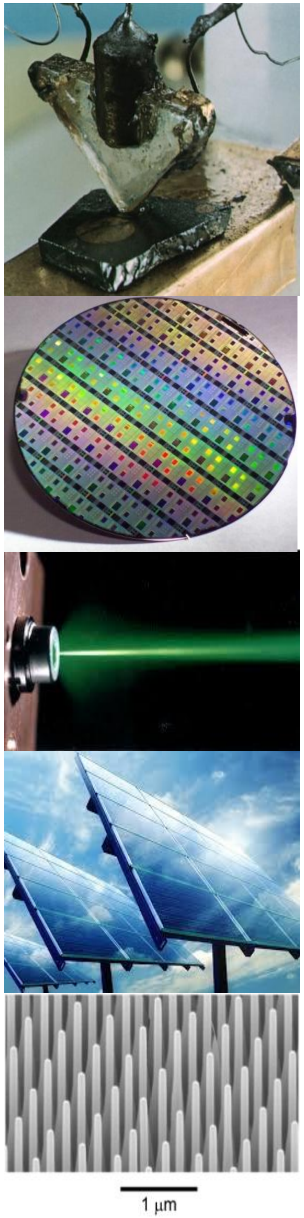
A small ac input voltage produces a large ac output current. This allows IMPATT diode to produce high output power. The small ac voltage can be produced by applying a voltage step to a resonant circuit (such as by connecting an inductor to the diode) to produce oscillation.

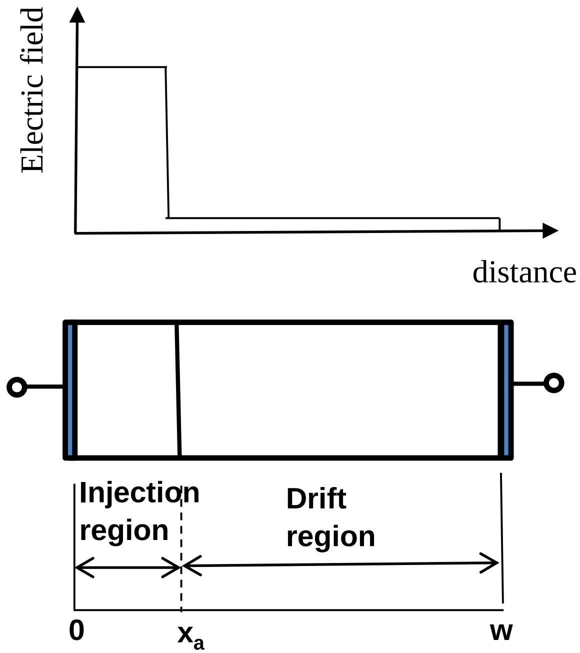
When the bias voltage is below V_B, avalanche multiplication is switch “off” and the output current remains constant for a fixed duration (as carriers drift across a low field drift region).

When the bias voltage is above V_B, avalanche multiplication is switch “on” and produces an increasing output current.

As the carriers exit the device, output current decays.

Basic IMPATT structure

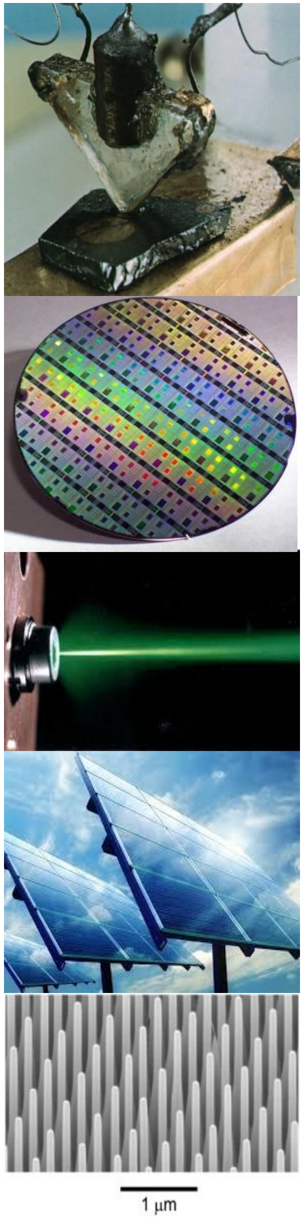


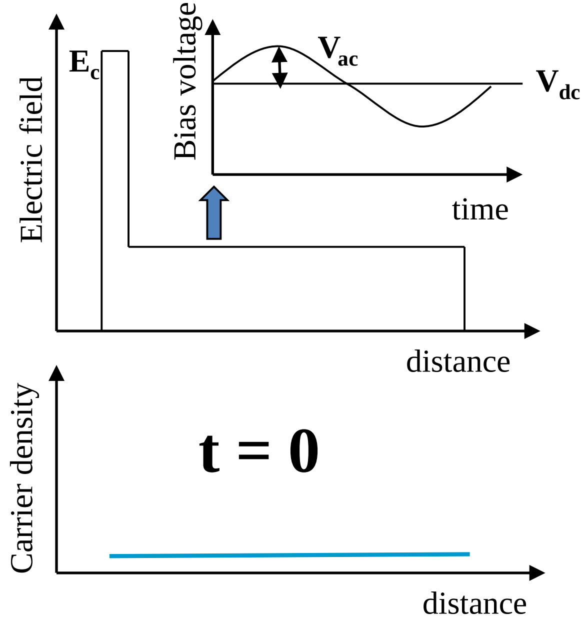


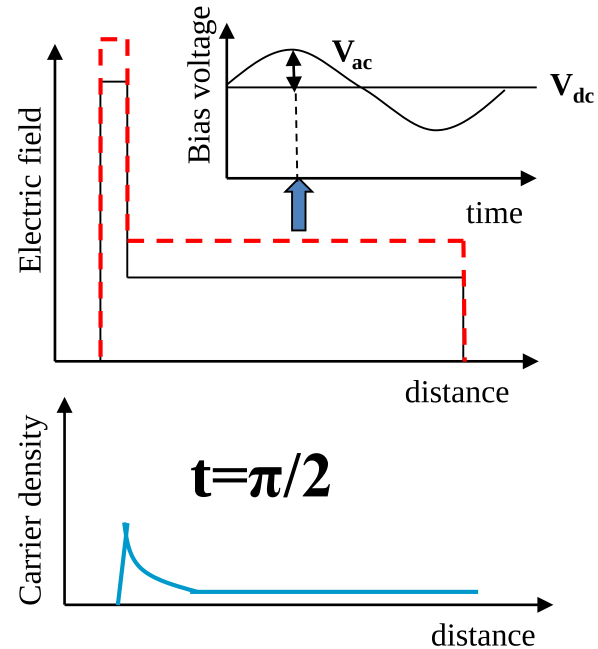
The electric field profile and the schematic of an idealised IMPATT diode is shown on the left. Charge carriers are generated by impact ionisation in the injection region. The IMPATT diode is biased such that the field in the injection region (or avalanche region) is above the breakdown field. These charges are then injected into the drift region which has low electric field to ensure that the charges do not experience impact ionisation while they drift.

The time delay between output current and input voltage is controlled by the avalanche duration and the transit time. The avalanche duration which consists of the time it takes to built up the avalanche process and for the avalanche process to terminate. It is largely controlled by the thickness of the avalanche region and the ionisation coefficients. Naturally the avalanche duration is proportional to the avalanche region thickness while the transit time is determined by carrier drift velocity and the thickness of the drift region. The primary design aim is to ensure that the avalanche duration is small compare to the transit time.

How IMPATT works



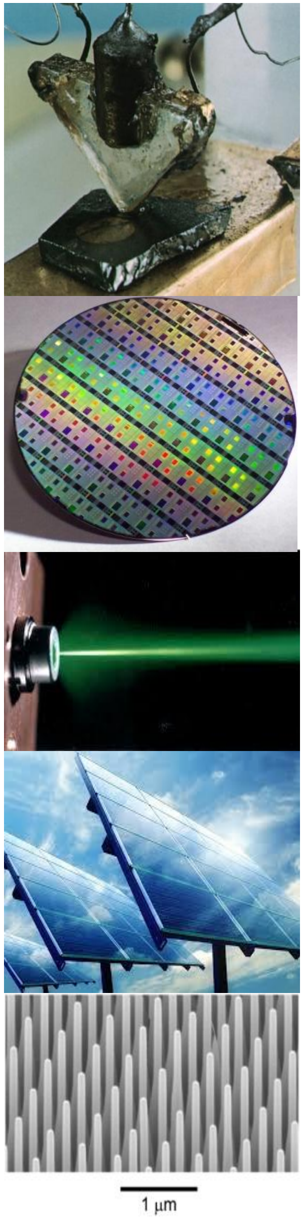


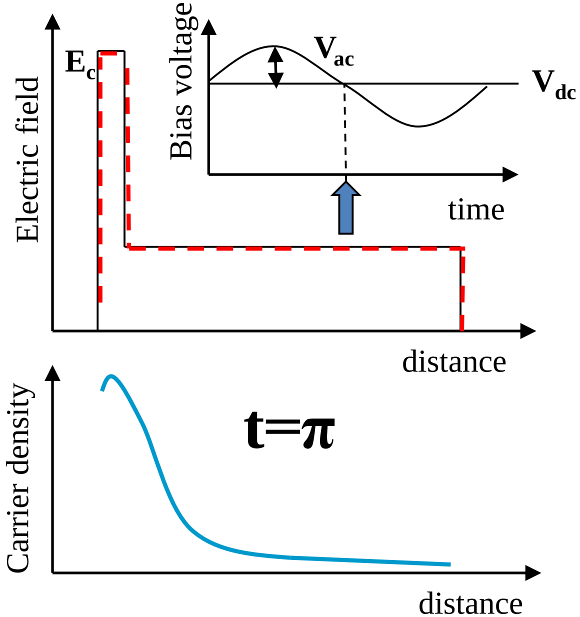


At t = 0, a small number of carriers are present in the diode. V_{dc} ~ breakdown voltage V_B. As the voltage increases above V_B, these carriers begin to multiply through impact ionisation. As the carriers multiply, some of them are also being swept out by the electric field.

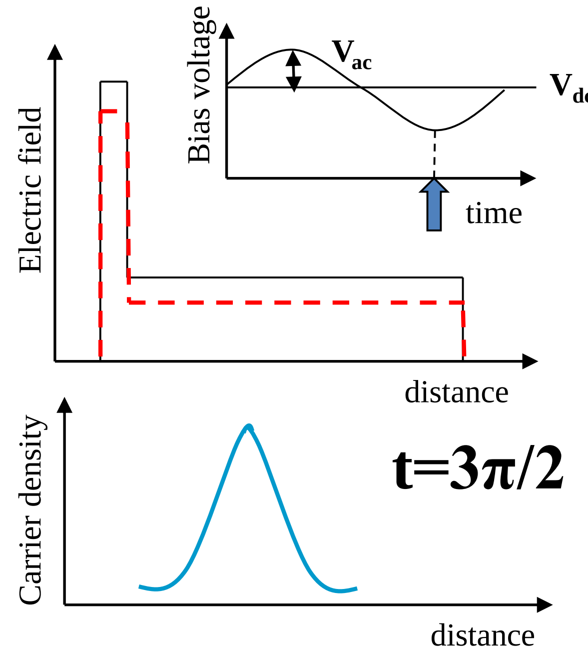
At t = $\pi/2$, the carrier density has increased exponentially relative to t = 0. The electric field is now at its highest to maximise the impact ionisation. So the carrier density in the avalanche region will continue to increase exponentially.

How IMPATT works



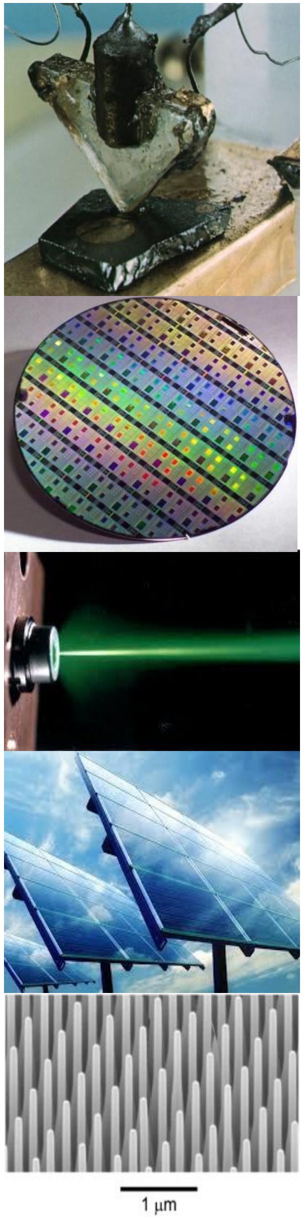


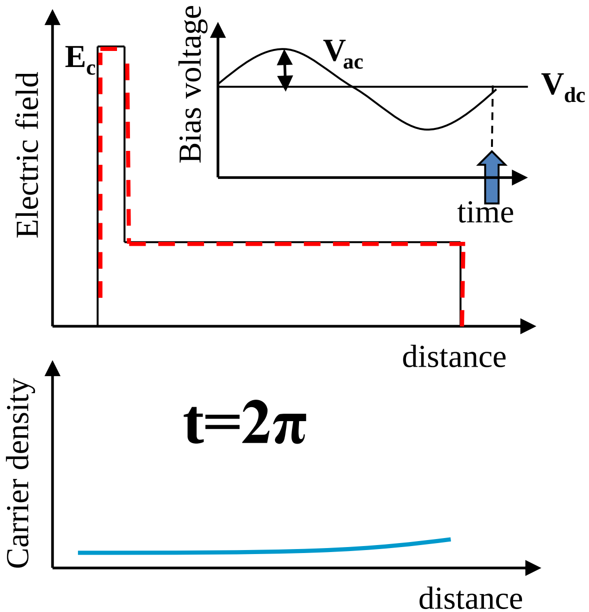
At t = π, the carrier density in the avalanche region is at its maximum. We now have a high concentration of carriers being injected into the drift region. At π< t <2π, the bias is below V_B, so the avalanche process stops.

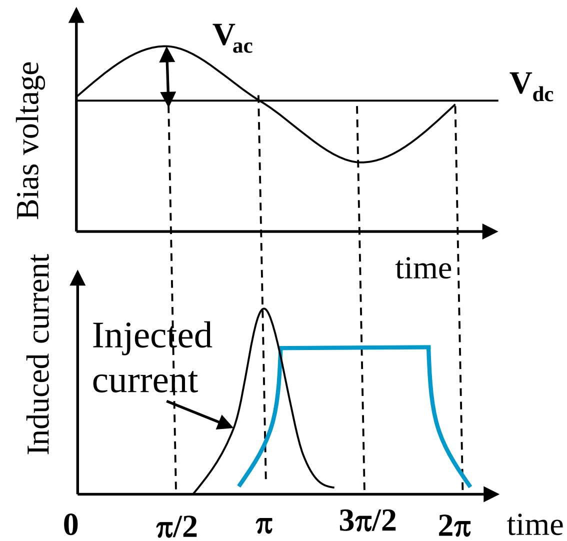


At t = 3π/2, the voltage is at the minimum and the field drops to its minimum too. The avalanche process in the avalanche region stops. The large concentration of carriers now drift through the drift region without experiencing impact ionisation during π< t <2π.

How IMPATT works





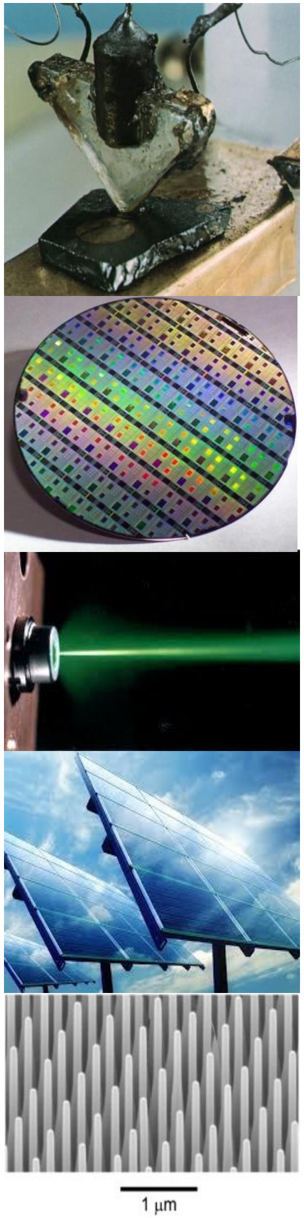


At t = 2π, most of the carriers have reached the terminal. The carrier concentration is now very low in the device.

Due to delay introduced by impact ionisation process and the transit time, the output current has a phase delay of π. This produces the negative differential resistance in IMPATT.

How do we achieve the required electric field profile?

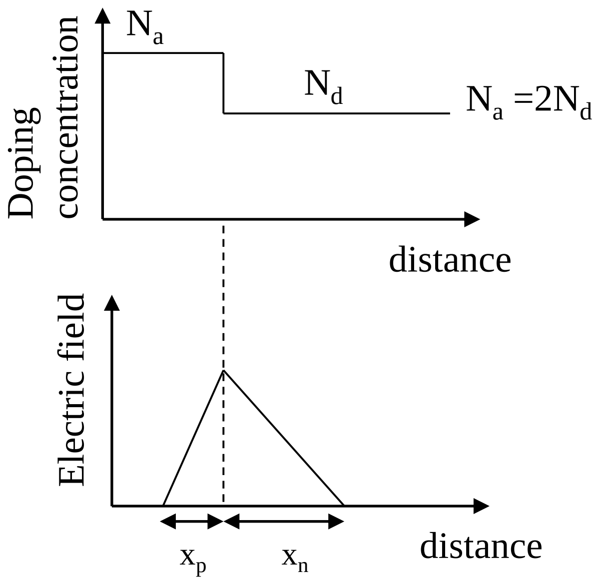
Electric field profile

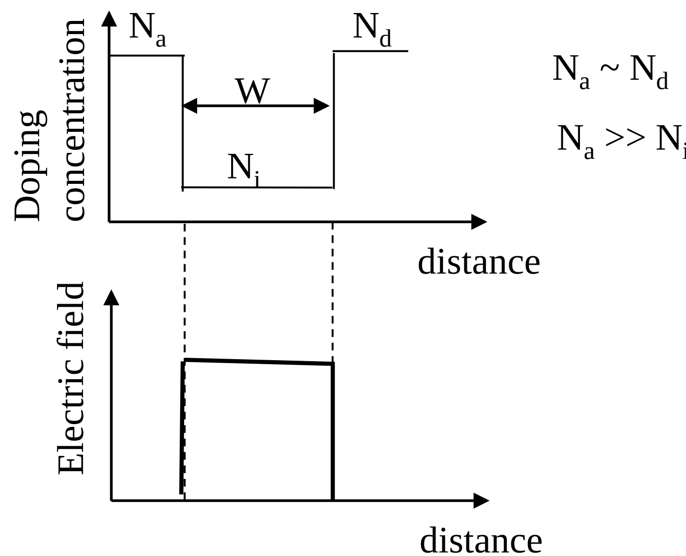


The electric field profile can be obtained by solving the Poisson equation

$$\frac{\partial E}{\partial x} = \frac{q}{\varepsilon}\left(N_d - N_a + p - n\right)$$

N_a =acceptor concentration
N_d= donor concentration
p and n are the minority hole and electron concentrations





The electric field is related to the voltage across the diode by

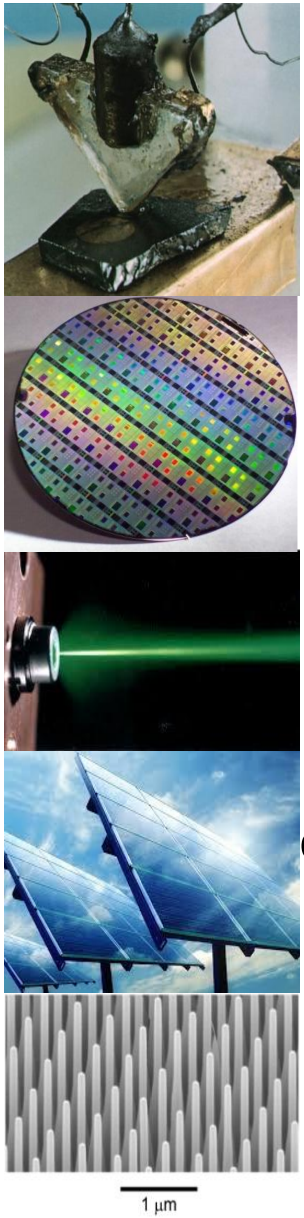
$$V = \int_0^W E(x)dx$$

The area under the electric field plot equals the total bias voltage.

The electric field is constant (such as in a p-i-n diode) we have

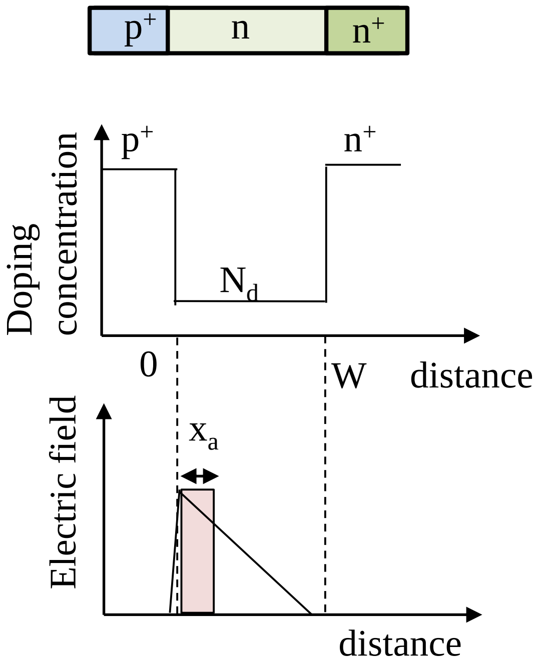
$$V = \int_0^W Edx = EW$$

Electric field profile

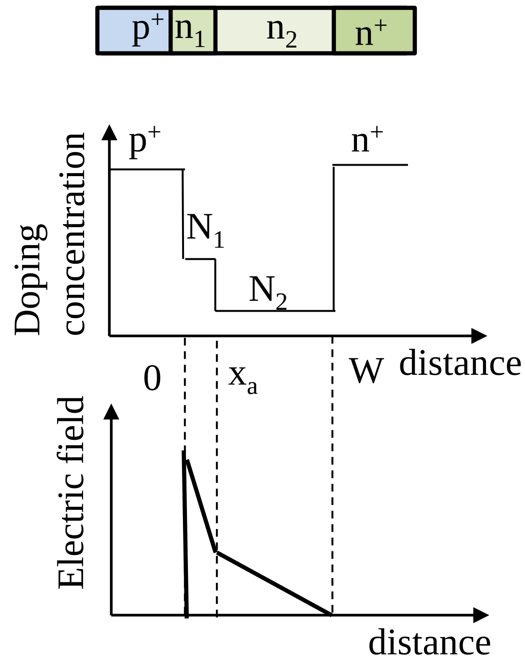


Some simple examples of electric field profile are shown below (Sze and Lee p. 264).

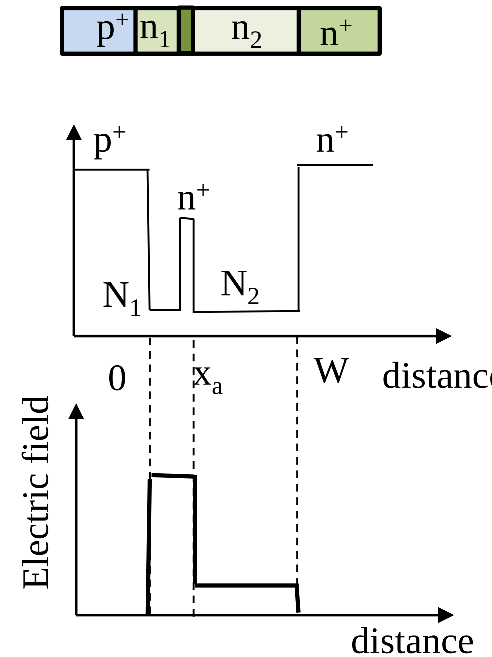
p^+n structure



hi-lo structure



lo-hi-lo structure



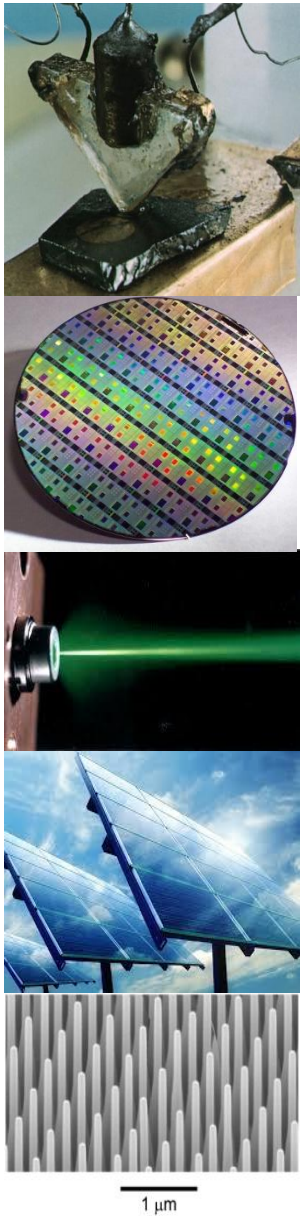
One-sided abrupt junction

$$V_B(p^+n) = \frac{E_m W}{2} = \frac{\varepsilon E_m^{\ 2}}{2qN_d}$$

$$V_B(hi-lo) = \left(E_m - \frac{qN_1 x_a}{2\varepsilon}\right)x_a + \frac{1}{2}\left(E_m - \frac{qN_1 x_a}{2\varepsilon}\right)(W - x_a)$$

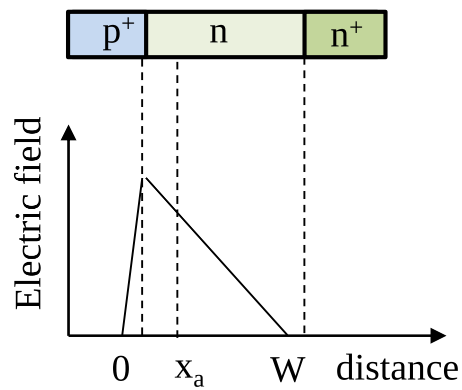
$$V_B(lo-hi-lo) = E_m x_a + \left(E_m - \frac{qQ_c}{\varepsilon_s}\right)(w - x_a)$$

Electric field profile

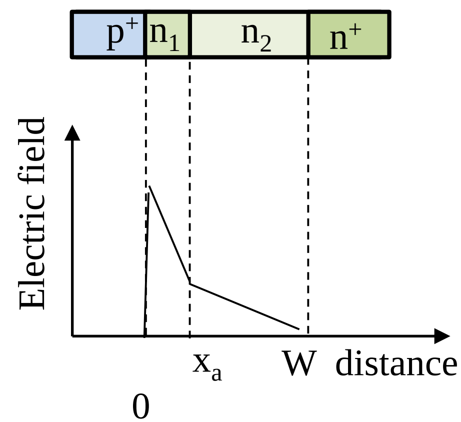


The drift process involves only one carrier, usually the electron, in these single drift IMPATT diodes.

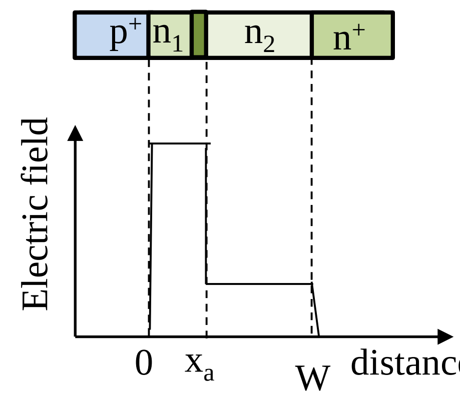
p^+n structure



hi-lo structure



lo-hi-lo structure

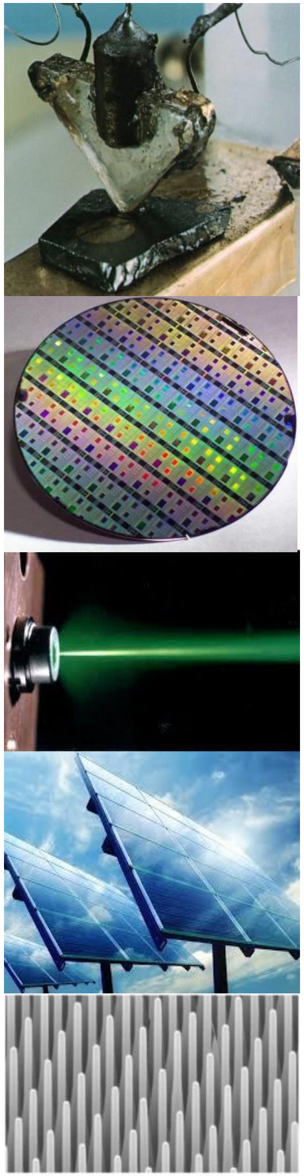


In the one-sided junction, because of the strong dependence of impact ionisation on electric field, most ionisation events are confined within $0<x<x_a$. This is simple to grow but the avalanche and transit properties are not so well controlled. It is difficult to confine the ionisation event positions.

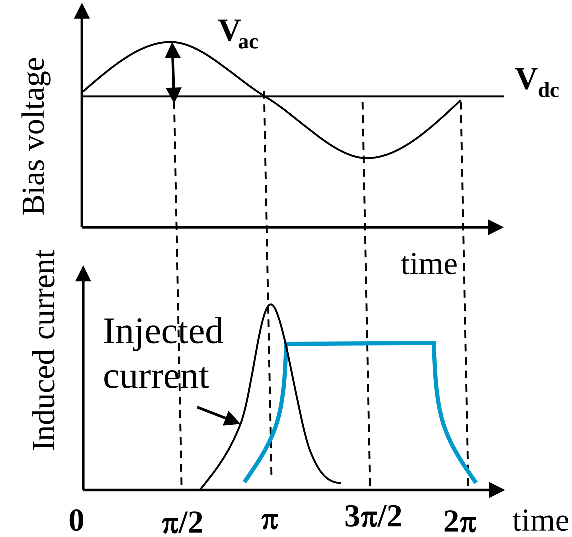
In the hi-lo structure, a moderately high doping N_1 is followed by a lower doping N_2. This provides a better confinement of avalanche events within the avalanche region x_a.

In the lo-hi-lo structure, a highly doped layer, n^+, is inserted between two low doping N_1 and N_2. This highly doped "field control layer" allows the electric to be kept high in the avalanche region but low in the drift region (to ensure no impact ionisation region). This provides very good control of avalanche and transit properties.

Operation frequency and efficiency



The avalanche built-up and decay times are usually much smaller than the transit time across the drift region. Otherwise there is a large phase noise. Therefore operation frequency is largely dominated by the transit time. The transit time is chosen to be one-half of the oscillation period.



$$\frac{W - x_a}{v_s} = \frac{1}{2 f_o}$$

$$f_o = \frac{v_s}{2(W - x_a)}$$

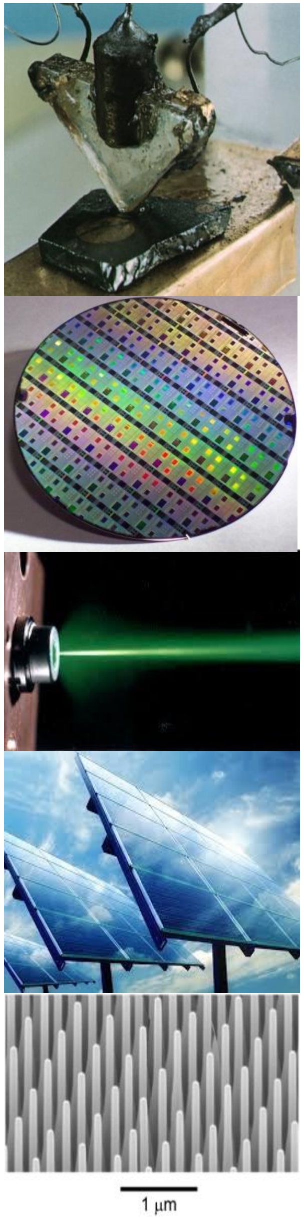
where v_s is the drift velocity. The dc input power is $P_{dc} = I_{dc} V_{dc}$

The ac output power is
$$P_{ac} = \frac{1}{2\pi} \int_0^{2\pi} I_{output}(\omega t) V_{ac} \sin(\omega t) d(\omega t)$$

The maximum power generating efficiency is
$$\eta = \frac{P_{ac}}{P_{dc}} = \frac{2.27}{\pi} \frac{V_{ac}}{V_{dc}}$$

If $V_{ac} = 0.5V_{dc}$, the efficiency is 36%. Examples of power generated by IMPATT diodes are 1W at 100 GHz with η=10% and 50 mW at 250 GHz with η=1%.

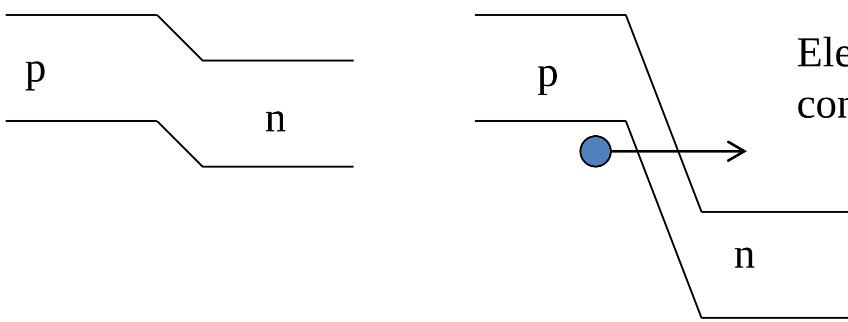
High frequency limitation



To operate at 1 THz, the drift region has to be very thin.

$$w - x_a = \frac{v_{sat}}{2(1\times10^{12})} = \frac{1\times10^{5}}{2\times10^{12}} = 50nm$$

Note that the avalanche region should be thin compare to the drift region for this estimate to be applicable. Therefore we may expect x_a and the field control layer to be much thinner than 50 nm. Accurate control of doping across a few nm of field control layer is very difficult. In addition if the avalanche region is below 50 nm, very high band to band tunnelling current will dominate making the IMPATT diode very noisy.

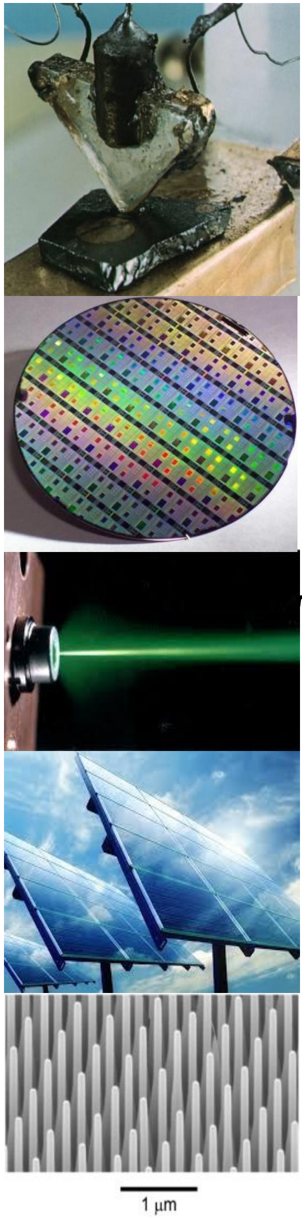


Electron tunnels from valence band to conduction band

0V

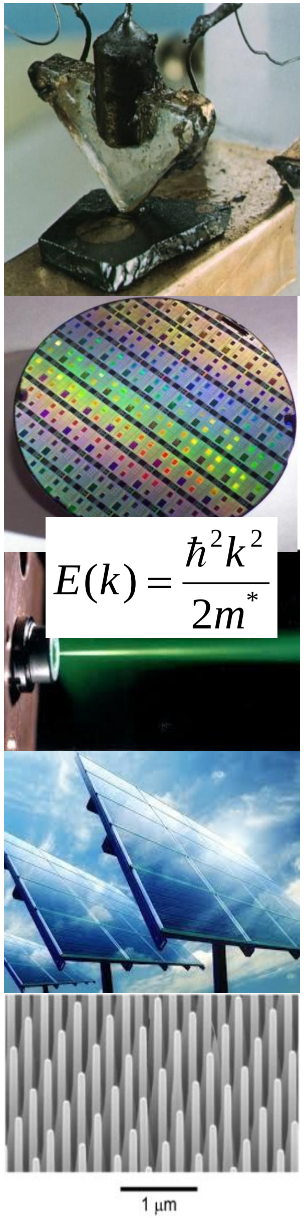
Large reverse bias

The University Of Sheffield.

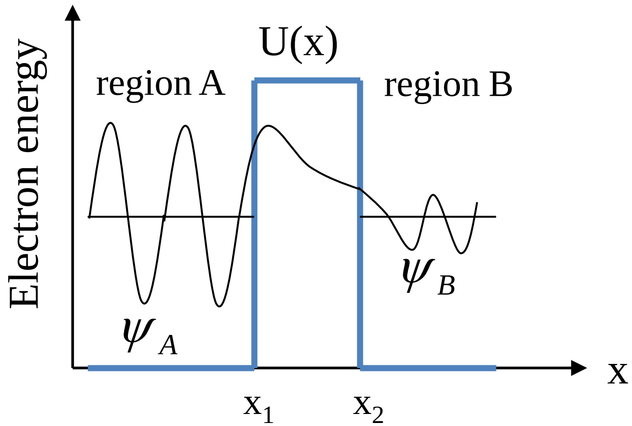


Tunnel Diode

Tunneling



$$E(k) = \frac{\hbar^2 k^2}{2m^*}$$

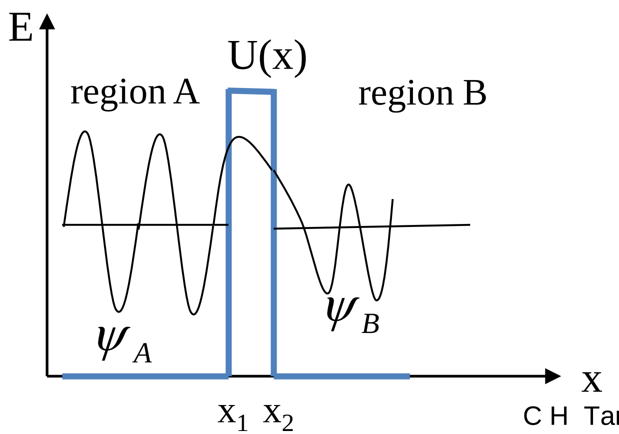


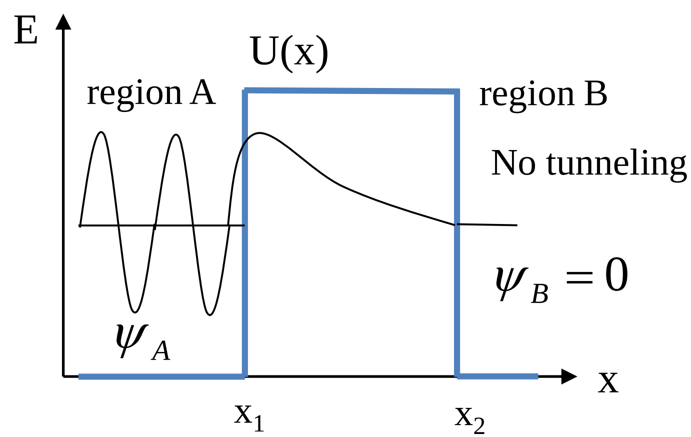
In classical mechanics only carriers with high energy can overcome the potential barrier defined by U(x). However in quantum mechanics, electron can be represented by its wavefunction. The wavefunction decays exponentially in the barrier, leading to a finite probability that the electron can tunnel through the barrier.

The tunnelling probability is given by

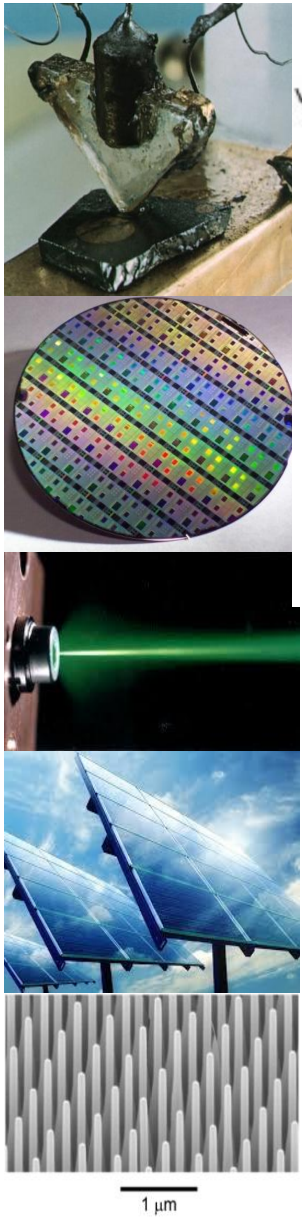
$$T_t = \frac{|\psi_B|^2}{|\psi_A|^2} \approx \exp\left(-2\int_{x_1}^{x_2} |\, k(x) \,|\, dx\right) \approx \exp\left\{-2\int_{x_1}^{x_2} \sqrt{\frac{2m^*}{\hbar^2}\left[U(x)-E\right]}dx\right\}$$

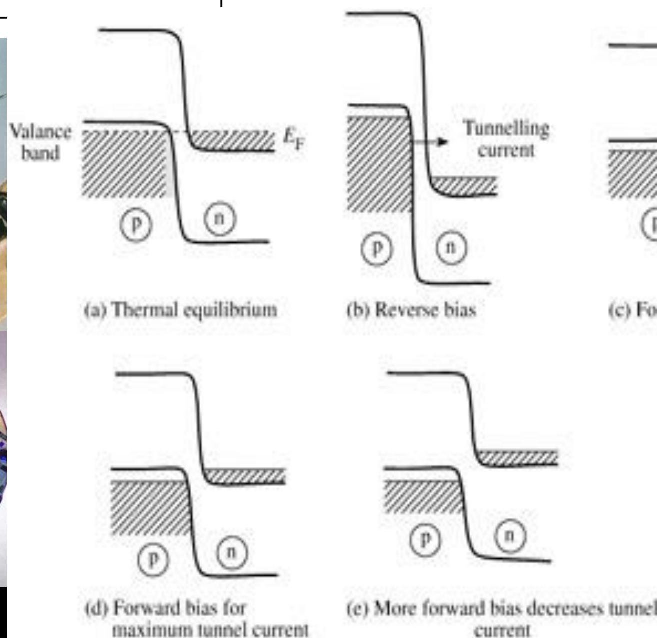
The tunnelling probability increases if the barrier is thin (x_2-x_1 is small) or the energy E is high and m* is small.

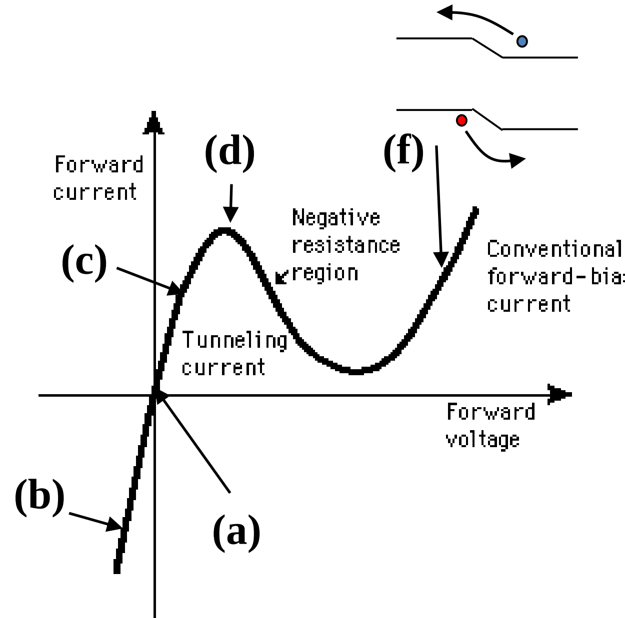




Tunneling







Shaded region represents occupied states in heavily doped $p^{++}n^{++}$ junction

(a) At 0V, the diode is at equilibrium. There is no electron (occupied state) above the Fermi level and no hole (empty state) below the Fermi level. Net tunnelling current is zero. Electrons are in the shaded region.

(b) When a reverse bias is applied, electron from p-side can tunnel to the empty states at the n-side. Tunneling current increases exponentially with increasing bias.

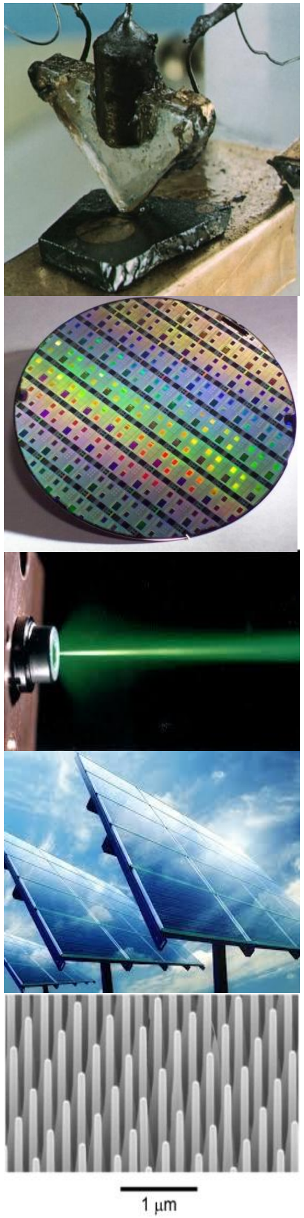
(c) Under a small forward bias, there exists a band of energies in which there are occupied states on the n-side and empty states on the p-side. So electrons can tunnel from n-side to p-side. Tunneling current increases with bias.

(d) This corresponds to the maximum tunnelling probability to produce a peak current.

(e) As the forward bias is increase further the filled states on n-side and the empty states on p-side do not overlap. Hence the tunnelling current drops.

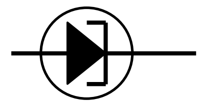
(f) At large forward bias, normal diffusion current dominates.

Tunnel diode

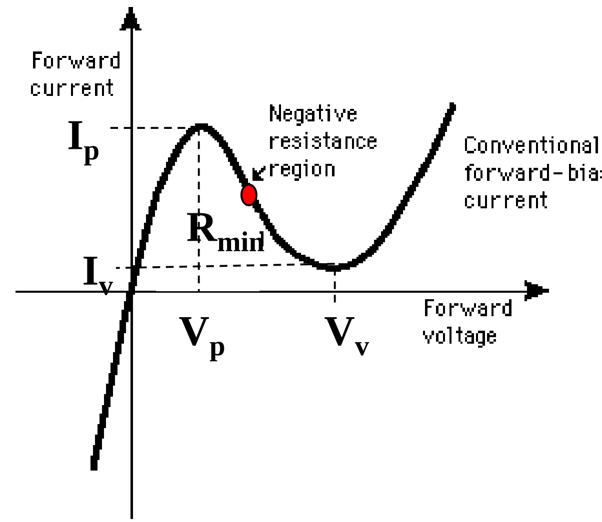


The tunnelling current can be fitted using

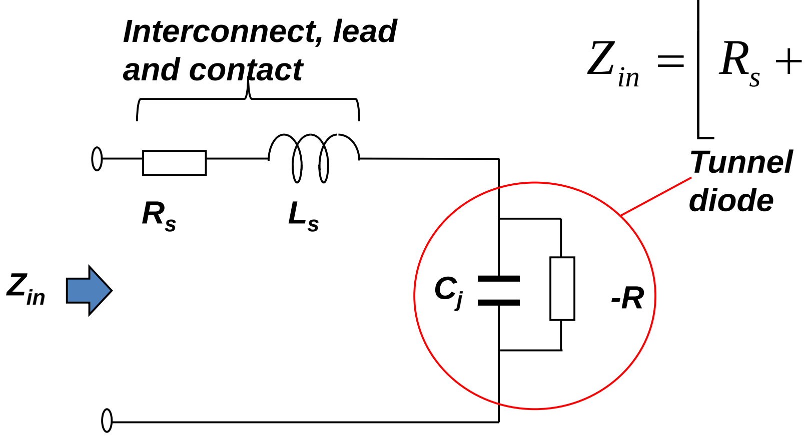
$$I_t = \frac{I_P V}{V_P} \exp\left(1 - \frac{V}{V_P}\right)$$

The symbol of a tunnel diode is 

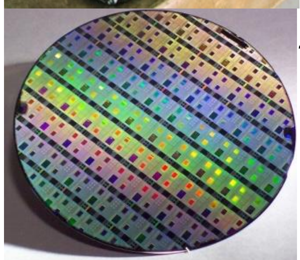
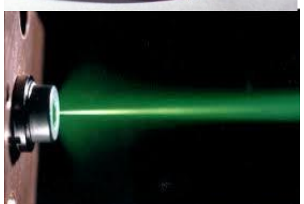
The magnitude of the negative resistance slope is determined by the peak tunnelling current, I_p and the valley current, I_v.

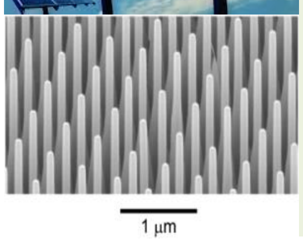


$$Z_{in} = \left[R_s + \frac{-R}{1+\left(\omega R C_j\right)^2}\right] + j\left[\omega L_s + \frac{-\omega C_j R^2}{1+\left(\omega R C_j\right)^2}\right]$$



Tunnel diode

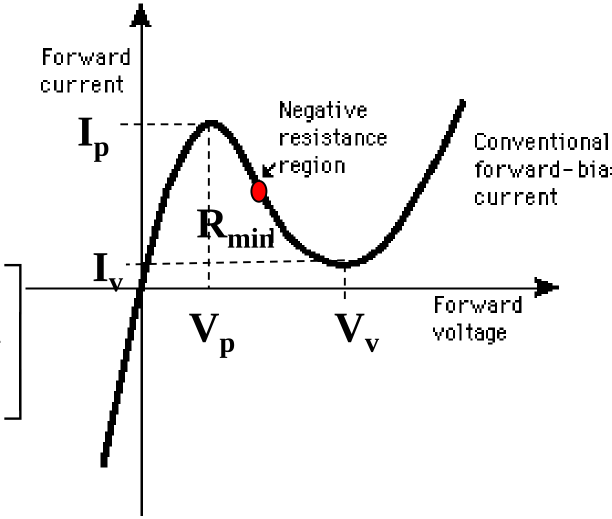






The minimum negative resistance is

$$R_{\min} = \frac{2V_P}{I_P}$$

$$Z_{in} = \left[R_s + \frac{-R}{1+(\omega R C_j)^2} \right] + j\left[\omega L_s + \frac{-\omega C_j R^2}{1+(\omega R C_j)^2} \right]$$



The resistive part of Z_{in} is zero at a frequency f_{r0}. Similarly the reactive part is zero at f_{rx}. These frequencies, specified at R_{min}, are

$$f_{r0} = \frac{1}{2\pi R C_j}\sqrt{\frac{R_{\min}}{R_s} - 1}$$

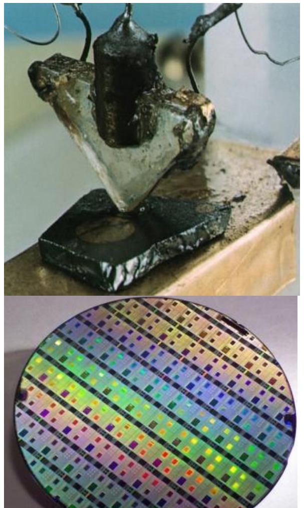
$$f_{rx} = \frac{1}{2\pi}\sqrt{\frac{1}{L_s C_j} - \frac{1}{(R_{\min} C_j)^2}}$$

The operating frequency is usually chosen such that

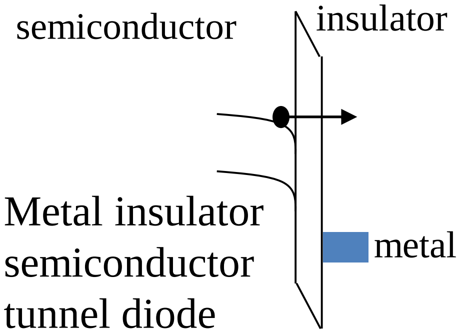
$$f_o << f_{r0} < f_{rx}$$

Since tunnelling process is very fast (not limited by transit time or carrier velocity), the operating frequency is limited by the diode capacitance C_j. Tunnel diodes are used if very high speed (to THz) switch, oscillator and other circuit functions but has relatively low current operation as tunnelling does not supply high current.

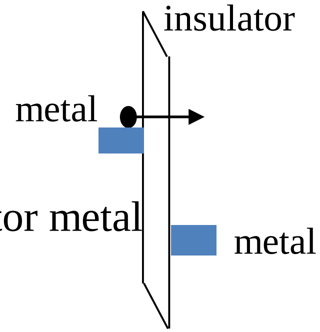
Tunnel diode



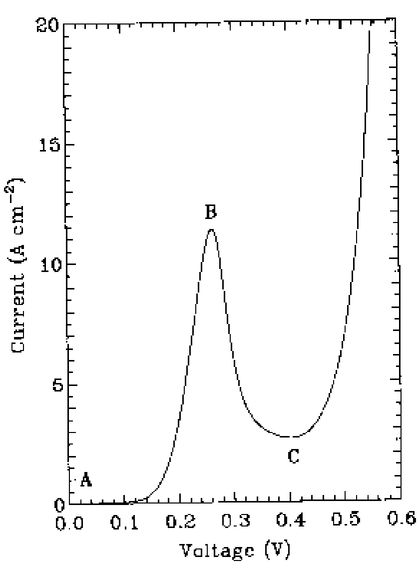
In addition to the simple tunnel diode constructed using a pn diode, there are other configuration of tunnel diodes such as

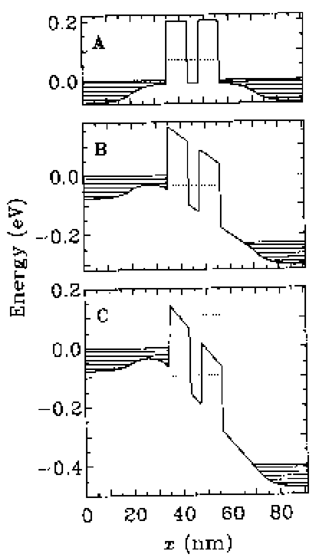


Metal insulator semiconductor tunnel diode



Metal insulator metal tunnel diode



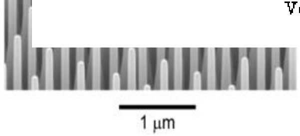


Resonant tunnelling diode

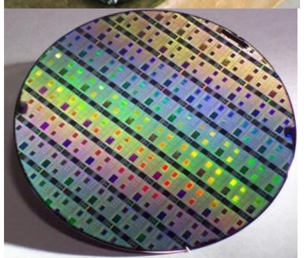
A) Current is low as electrons are blocked by the barrier.

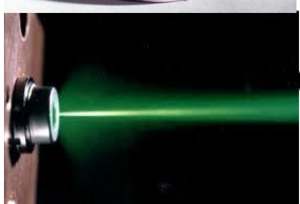
B) As the bias is increased, the band is tilted. Electrons from the left can tunnel to the state in the quantum well and then to the empty states on the right. Current increases.

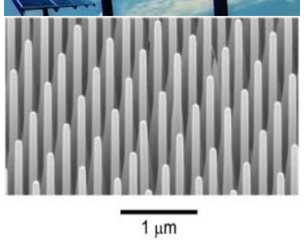
C) At higher bias, the state in the quantum well is no longer aligned with the occupied states, so tunnelling reduces and the current drops.



The University Of Sheffield.





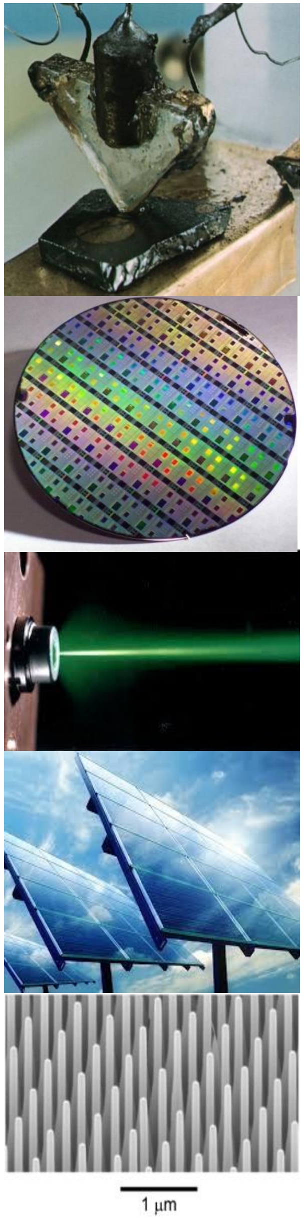


Gunn Diode

The University Of Sheffield.

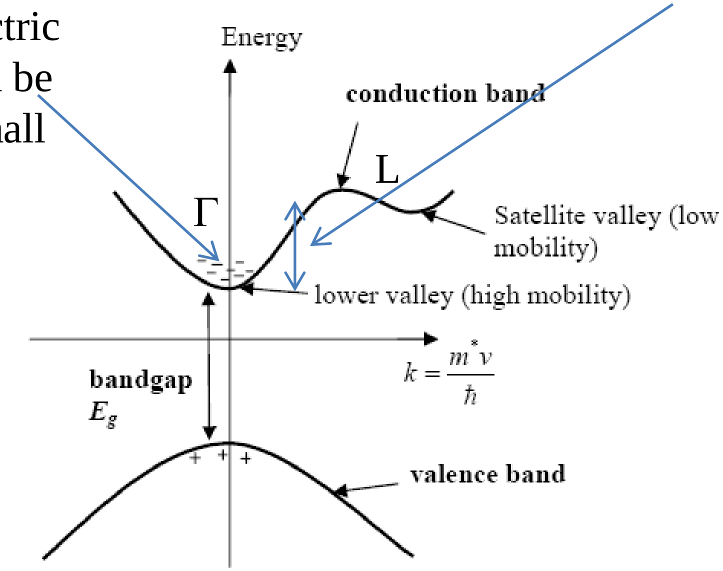
Gunn diode

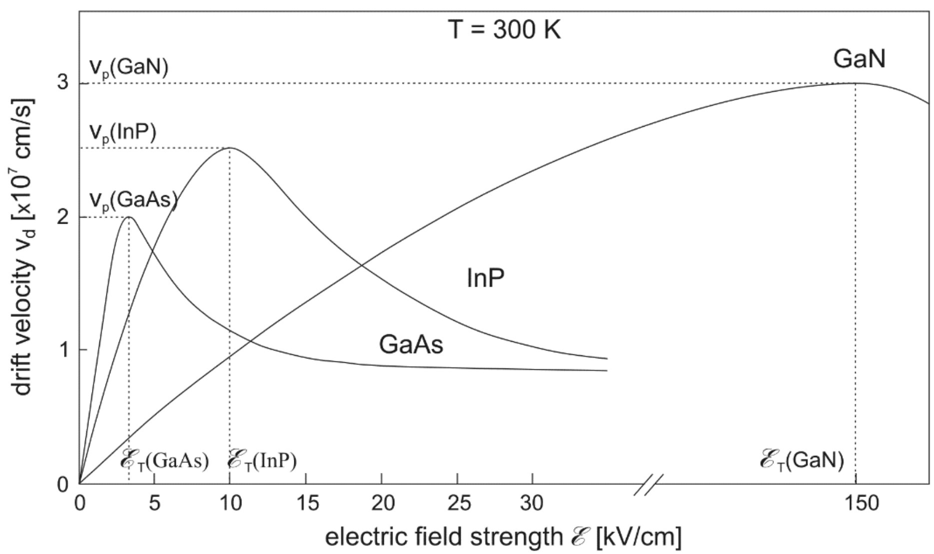
Valley separation energy should be smaller than bandgap to prevent impact ionisation before transfer to satellite valley. In GaAs this is 0.3 eV which is much smaller than energy required for impact ionization (>1.42 eV)



In the absence of electric field electrons should be in low valley with small effective mass.

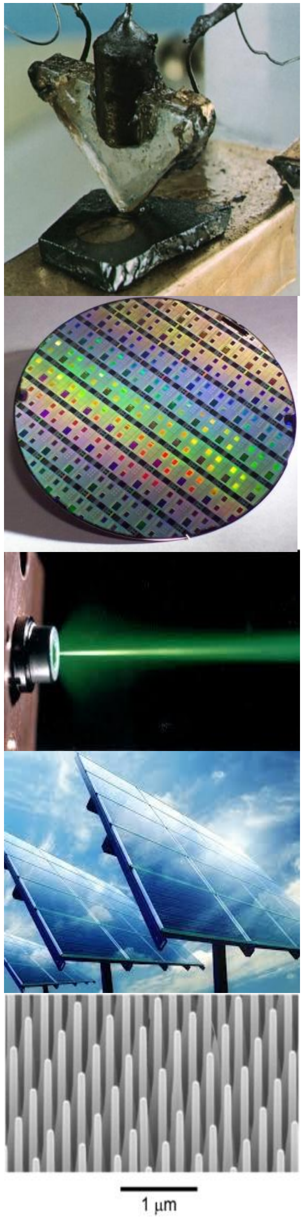
In GaAs the m* in Γ and L valleys are $0.067m_o$ and $0.55m_o$



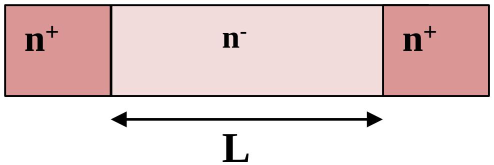


GaAs and InP are important materials for Gunn diode.

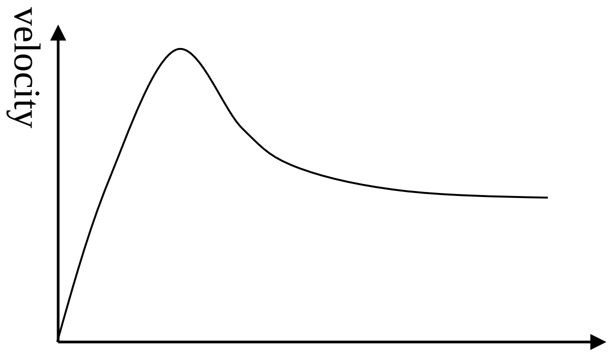
Gunn diode



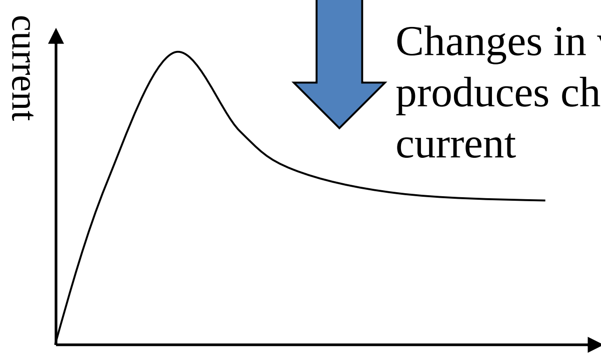
A simple Gunn diode is constructed using a lowly doped n, sandwiched between two highly doped n^+ layers. layerby The current density is contributed by drift and diffusion currents.

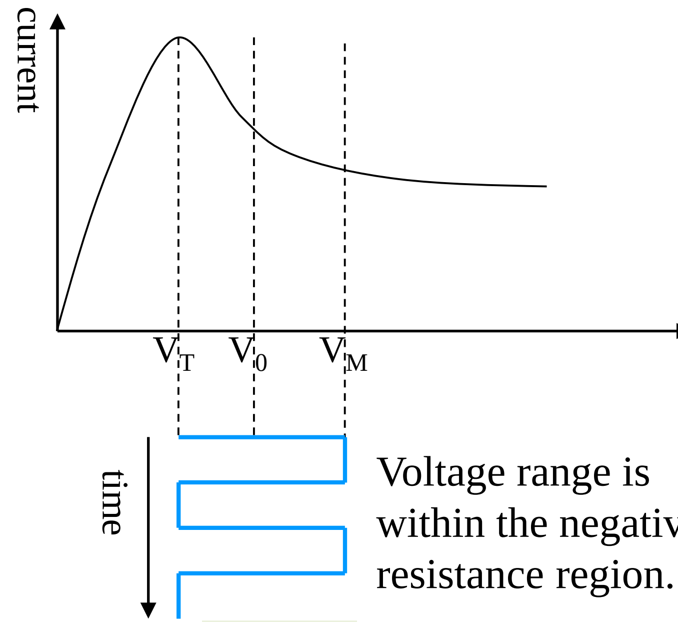


$$J = qn_o \mu E + qD\frac{\partial n}{\partial x}$$



Changes in velocity produces changes in current





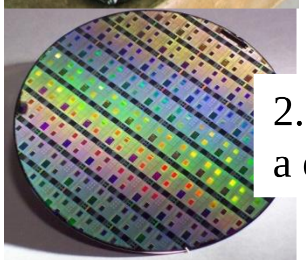
Voltage range is within the negative resistance region.

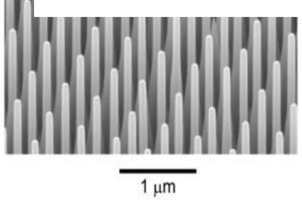
The transit time frequency is

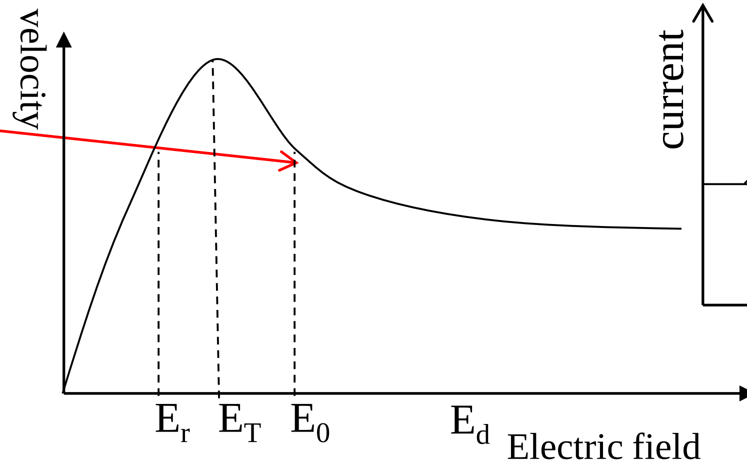
$$f = \frac{v_d}{L}$$

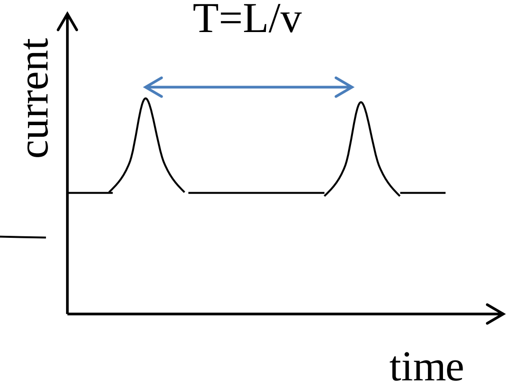
Gunn diode

Oscillation can also be produced by change of carrier concentration



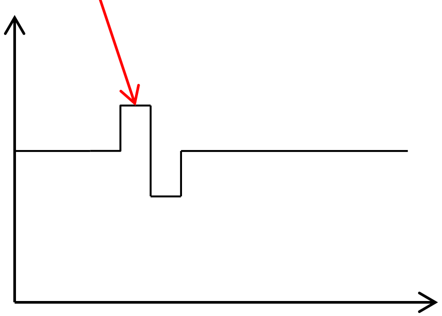


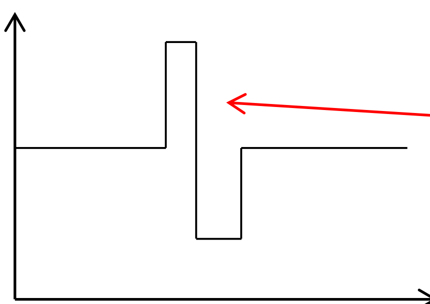




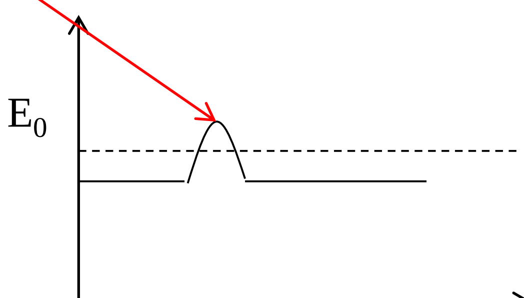
1.Bias device at NDR region, E_0

2. Instability induced by a dipole of domain.

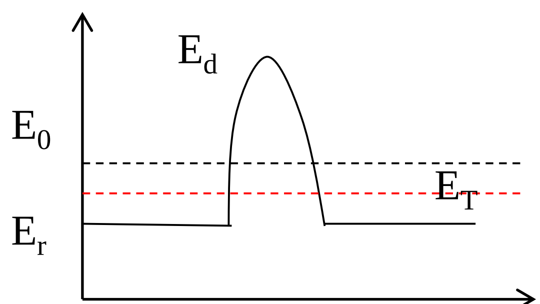




3. Dipole sets up higher electric field. Electrons at higher field slow down.

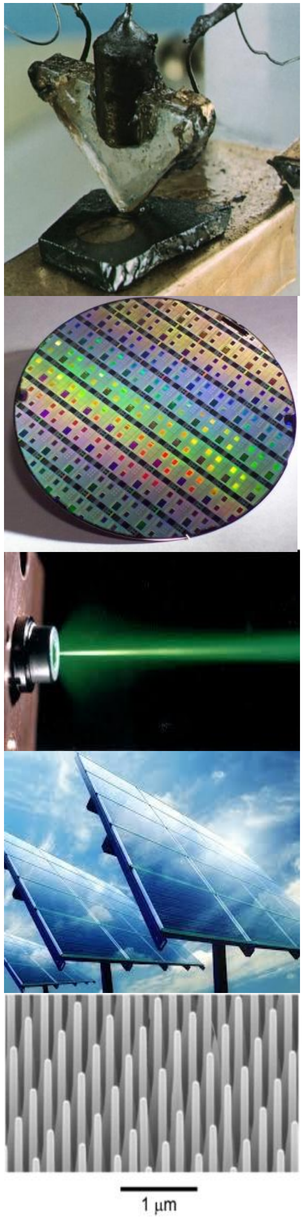


4. Electrons behind and ahead travel at higher velocity, making the dipole larger.



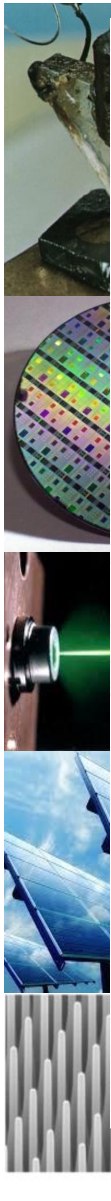
5. Domain stabilizes, current peaks as field swings pass E_T.

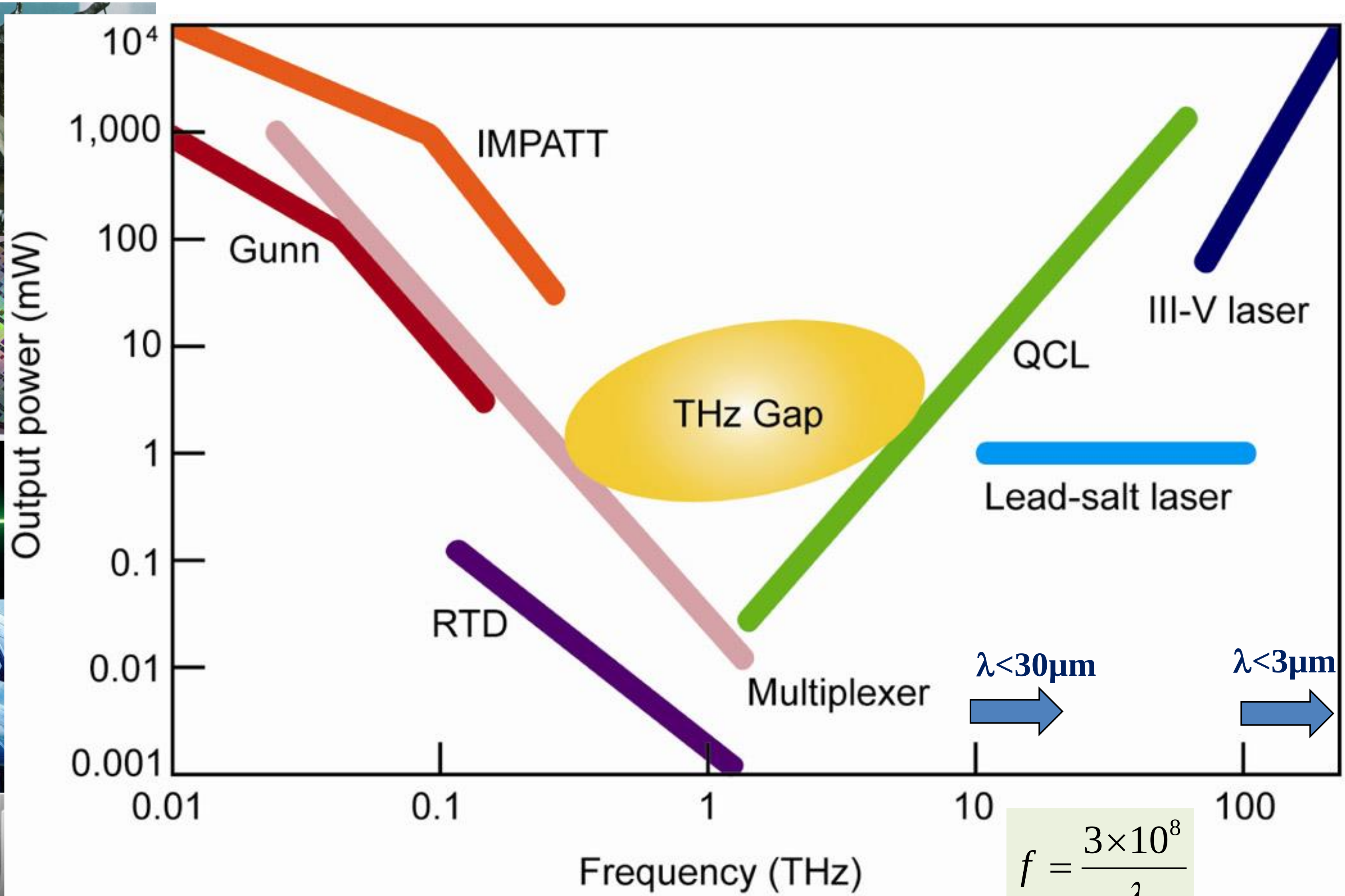
Gunn diode



- Use n^+in^+ structure
- Can deliver power of 0.5 W at 30 GHz, 70mW at 150 GHz.
- Lower power than IMPATT but also lower noise too.
- Operation will depends on doping profile, length of active region, contact characteristics, operating bias and types of circuits.

Power and frequency comparison





$$f = \frac{3\times10^{8}}{\lambda}$$