Part 8: Other high speed devices & effects

Impact Ionisation

APDs

The IMPATT diode

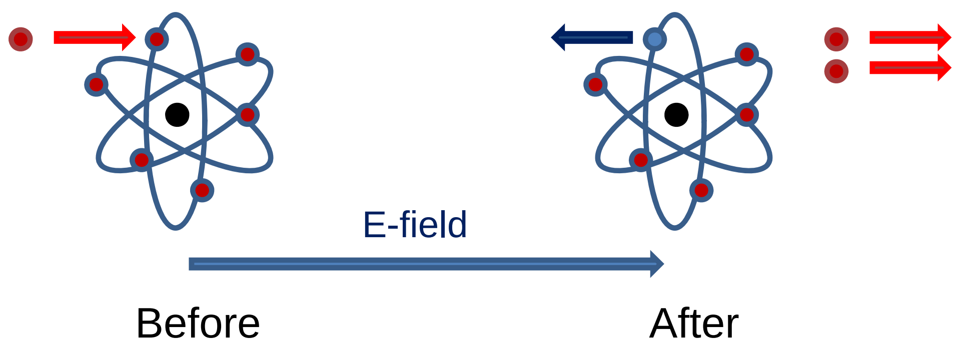
Quantum Mechanical tunnelling/ tunnel diode

Negative differential resistance devices

Impact ionisation

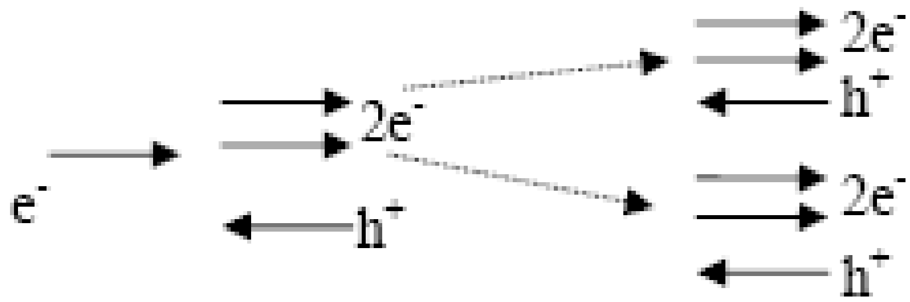
So far we have tended to consider devices which operate due to electron (or hole) drift in an electric field. These electrons may be scattered by the lattice, or by impurities, but otherwise do not interact with the material.

This is a reasonably good description of the transport under low Electric fields. However in a high fields ($>10^6 V.cm^{-1}$) electrons (& holes) can have sufficient kinetic energy to impact lattice atoms and 'ionise' them. Electrons are knocked out of their bound state (in the valence band) and are promoted to the conduction band. The vacating electron leaves behind a hole in the valence band.



Impact ionisation

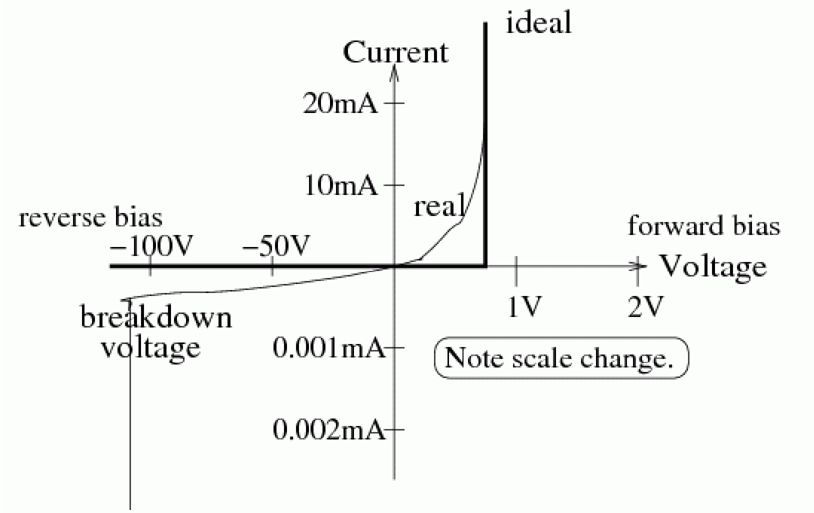
One impact ionising particle can therefore create 2 additional particles. These new carriers can then be further accelerated by the electric field to create further electron hole pairs. At sufficient fields **avalanche breakdown** can take place involving a large number of electron-hole pairs



Impact ionisation is a problem which limits the power output and speed of many devices. However it can also be exploited in in certain types of device (eg: IMPATT diode, avalanche photodiode)

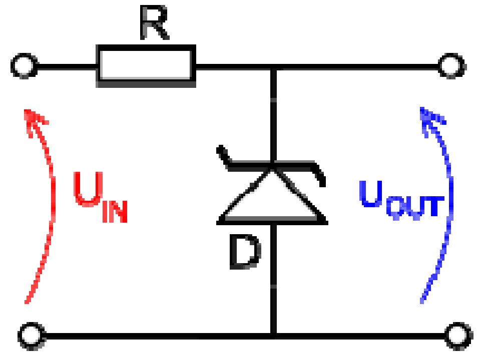
Impact ionisation

Impact ionisation is most commonly observed in the reverse breakdown of diodes at high negative bias.



Without regulation a high current pulse can be generated which will destroy the diode. However even in this case it has an application as a Zener diode (voltage regulator)

In Zener diodes the doping of the diode controls the breakdown field. By preparing a number of different dopings one can achieve a range of regulated voltages.



Impact ionisation

Impact ionisation is very important for high speed devices where the dimensions are very small (eg: 10s on nm). In such cases the Electric field values can be very high.

Impact ionisation if characterised by the ionisation coefficient of electrons and holes in a particular material.

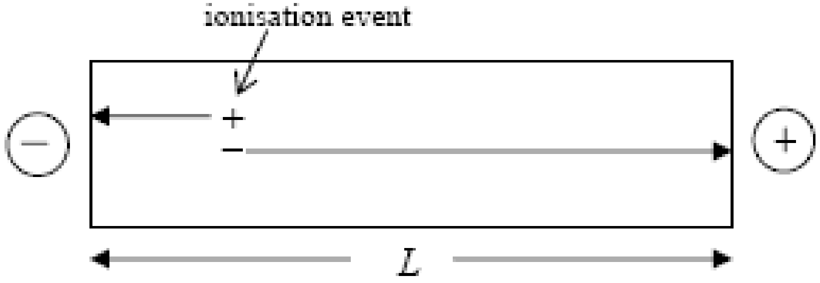
The ionisation coefficient is the probability of an ionising collision per unit length and is given the symbol α (E) for electrons and β(E) for holes

Sometimes α (E) $\approx\beta$(E) eg: GaAs, sometimes not.

Assume α (E) $\approx\beta$(E) and a constant E-field across a length, L

Consider that an ionisation event takes place somewhere in the device

Impact ionisation



No matter where the event takes place, the distance travelled by the electron plus that of the hole is = L

α. L new e-h pairs will be produced. Each of these will make another α. L new e-h pairs. This is a geometrical progression of the form: $1 + \alpha L(1 + \alpha L[1 + \alpha L\{1\ldots = 1 + (\alpha L)^2 + (\alpha L)^3 + (\alpha L)^4\ldots\ldots$

We call this term the Multiplication factor (M).

It has a well-known form: $$M = \frac{1}{1-\alpha L}$$

Impact ionisation

This is a rather simplistic model. For α varying with distance (more like the real situation) then

$$M = \frac{1}{1 - \int_0^L \alpha L.dx}$$

The ionisation coefficients α and β are strong functions of the Electric field as one might expect.

Empirically it is found that $\alpha = \alpha_0 \exp\left[-b\left(\frac{E_0}{E^m}\right)\right]$ where m ~1-2

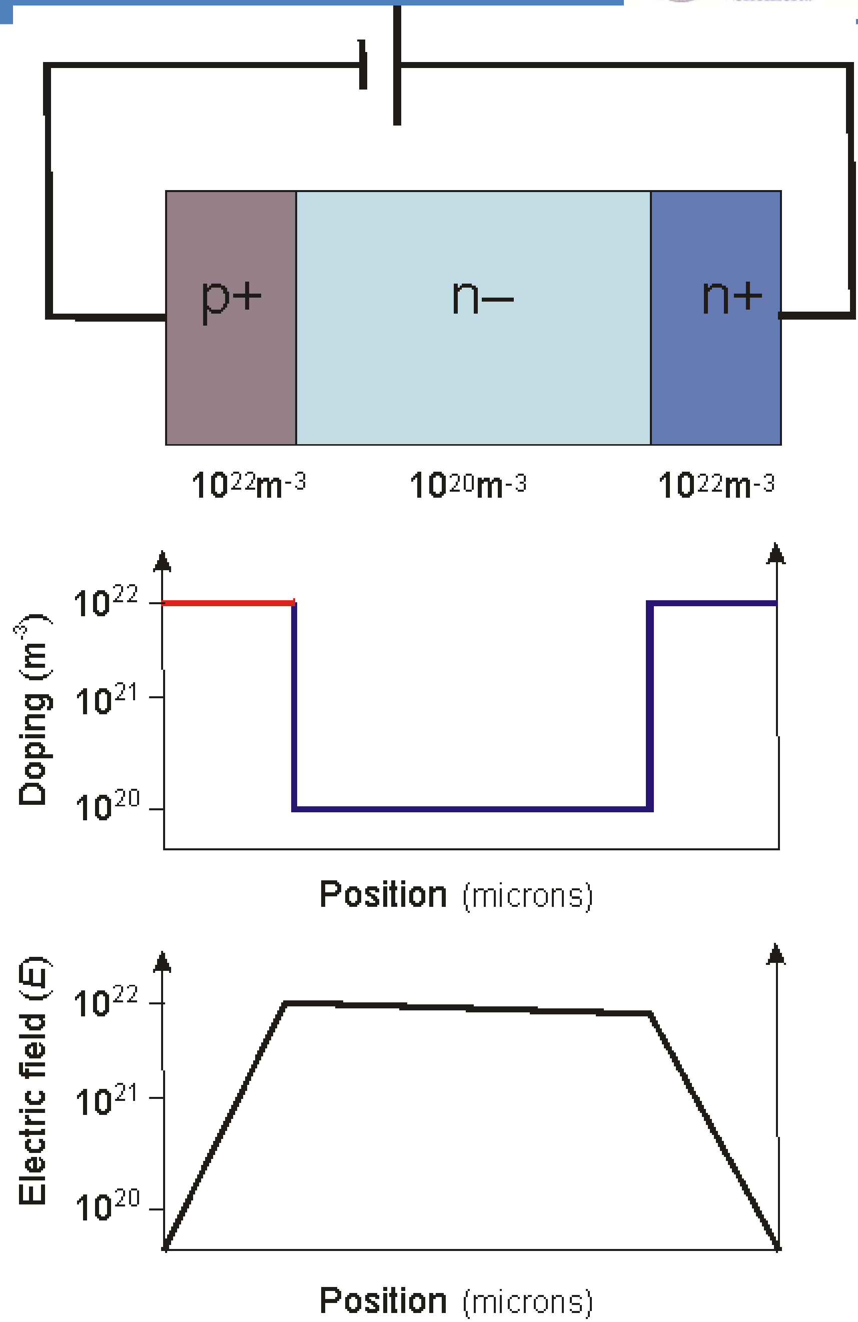
Where E_o and b are constants for a particular material

Avalanche breakdown condition occurs when M→∞, i.e: when $\int_0^L \alpha L = 1$

Impact ionisation

Example: p-i-n diode

(typically the i-region is not intrinsic but low background doped n^-type)



Carrier concentration goes from high p^+ to low n^- to high n^+

The E-field is given by Poisson equation

$$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon}$$

Rate of change of *E* is proportional to the charge density *ρ*

Impact ionisation

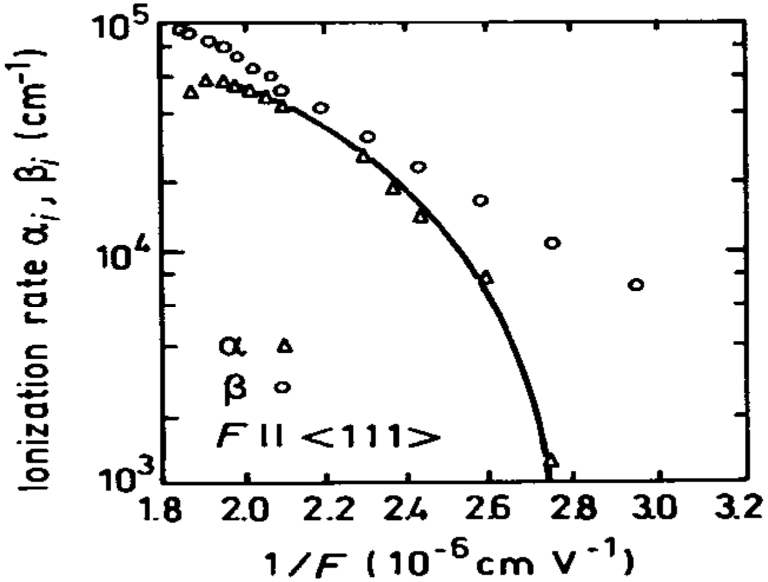
Assume the material is GaAs. The i-region is 1µm (=L)

Assume the field is constant across the low doped i-region

Breakdown occurs when $\int_0^L \alpha L = 1$ L= 10^{-4}cm so α = 10^4 cm^{-1}

From known data this corresponds to a field of about $4\text{x}10^5$V.cm^{-1}

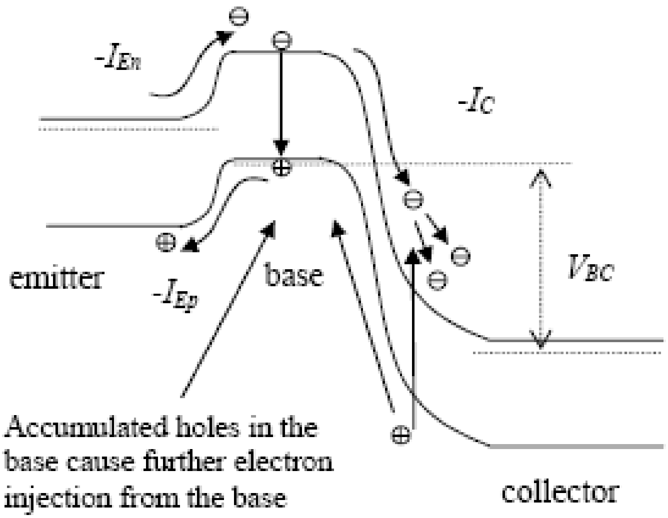
L=1µm = 10^{-4}cm, so V= 40V

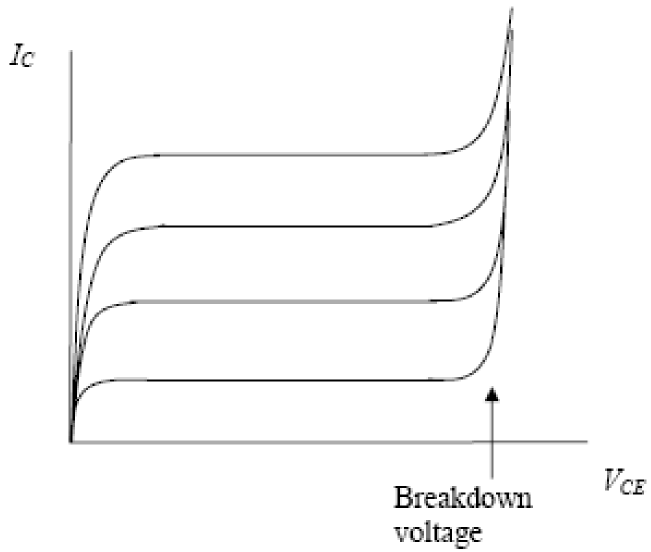


What about its effect on other devices?

Impact ionisation

Transistor breakdown





High speed HBTs have thin collectors to reduce the capacitance. Avalanche breakdown can occur in the resulting high field collector region. Even worse, holes produced by the process move into the base and cause further injection of electrons from the emitter. As a result the output power of these devices can be severely limited

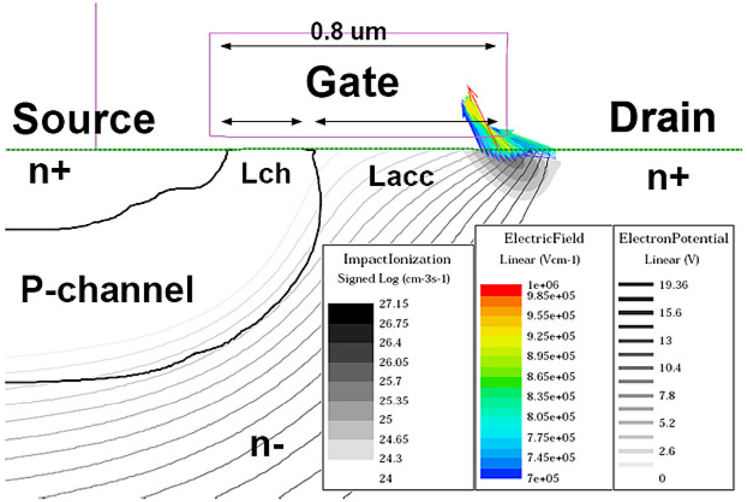
Impact ionisation

Transistors (of any type) therefore tend to show a very abrupt onset of avalanche breakdown. The collector current, including multiplication, is given by

$$I_C = \frac{M(1+h_{fe})}{1-(M-1).h_{fe}}$$

Avalanche breakdown is also an issue in field effect devices (MESFET, MOSFET) where large fields exist over short distances (10's on nm).

A particular problem for MOSFETs can be the formation of high electric field region between the drain and gate



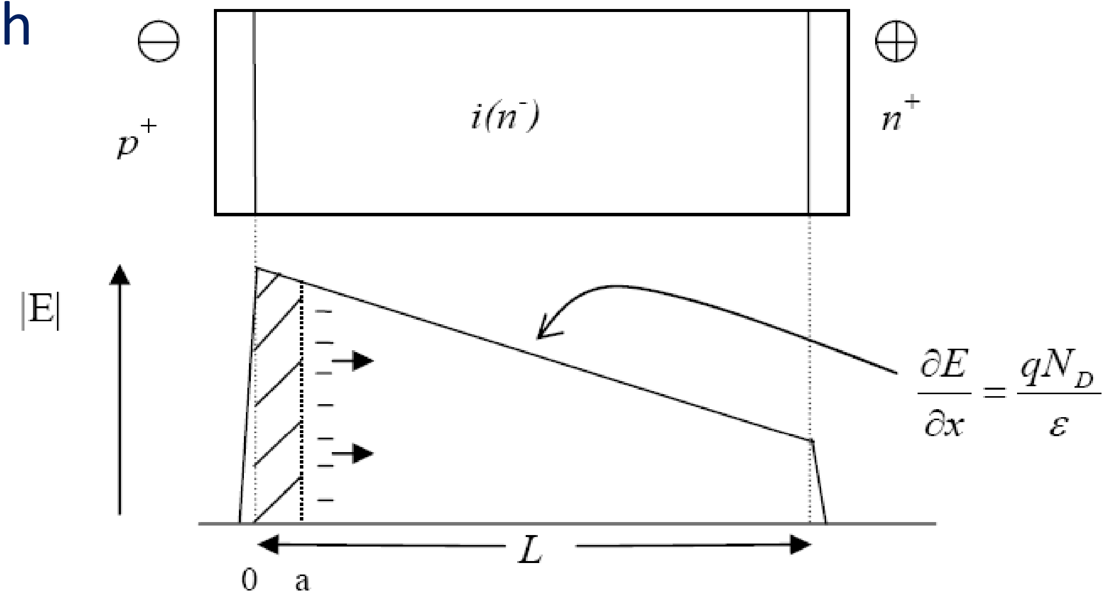
Impact ionisation

As well as a problem for device operation there are also devices which exploit impact ionisation

IMPATT diode (IMPact ionization **A**valanche **T**ransit-**T**ime)

Used as a microwave oscillator, found in low power RADAR systems (e.g: car collision avoidance)

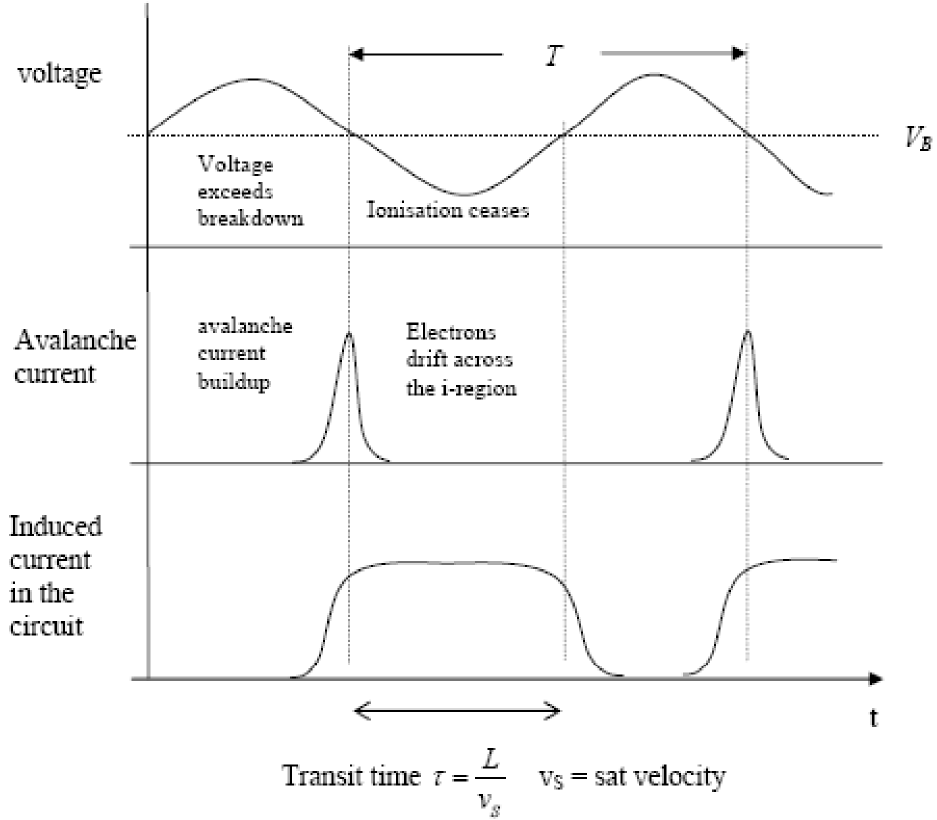
Breakdown occurs in the high field shaded region. The electrons and holes created drift through the rest of the intrinsic region causing a delay and a phase shift between the voltage and current.



Impact ionisation

The avalanche injects an additional charge of Q per cycle. The induced current $=Qv_{sat}/L$

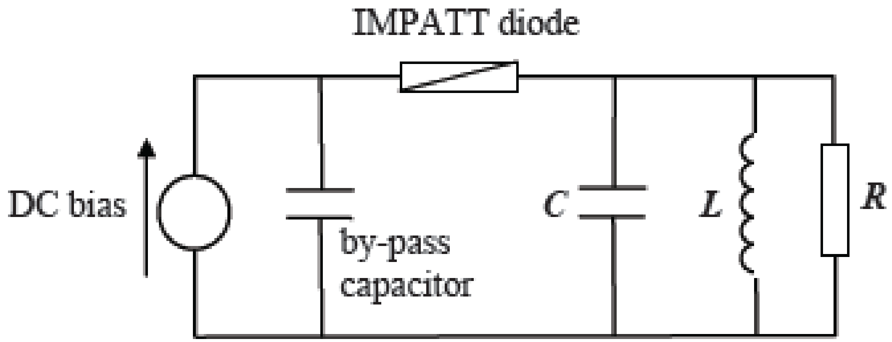
If we apply a sinusoidal voltage with a peak just above the breakdown voltage V_B then avalanche breakdown takes place on part of the cycle. There is a delay (~90^o) before the avalanche current reaches its maximum. The ionised carriers then drift through the i-region with a transit time $\tau = L/V_{sat}$



Impact ionisation

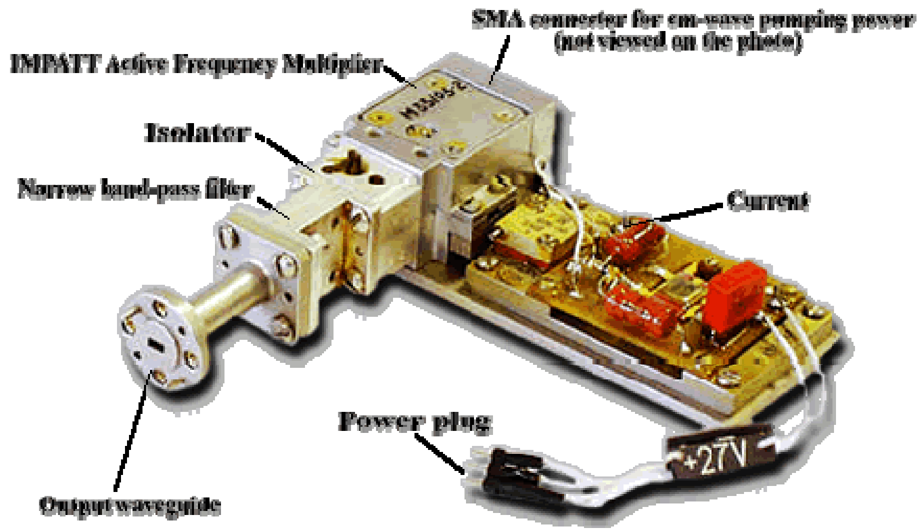
The resulting up to 180°C phase change between voltage and current in the external circuit develops oscillations. These can be tuned by an external LR circuit. The maximum power will be obtained when $f = 1/2\tau$

The by-pass capacitor is able to provide the oscillator current. RF power is drawn from the DC bias supply



IMPATT diodes provide simple and cheap oscillators for a range of microwave applications. Efficiencies of 15% for Si and 20% for GaAs devices has been demonstrated and oscillation frequencies up to 500GHz are possible.

Impact ionisation



IMPATT diodes are often at the heart of many Radar systems

A variation on the IMPATT is the TRAPATT (TRApped, Plasma Avalanche Triggered Transit diode)
This operates on a similar principle but uses a very high current pulse to create a localised plasma which then screens the field (self-extinguishing). The separation and drift of the electrons and holes are then driven by a very much smaller field. TRAPATT devices can provide efficiencies of up to 60%.

One problem of these devices is they are intrinsically very noisy due to the statistics of the avalanche process

Impact ionisation

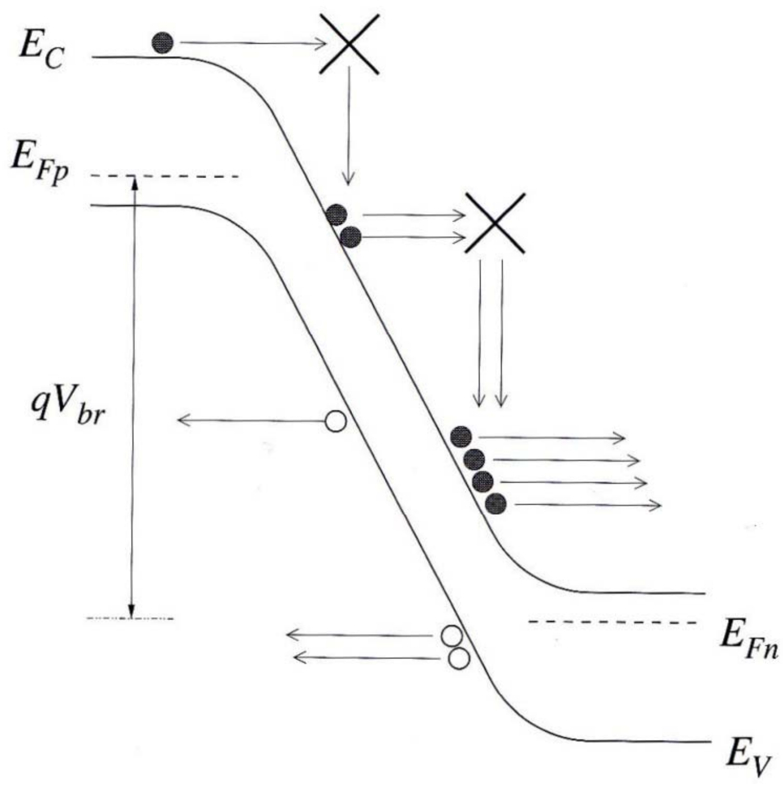
Avalanche Photodiode (APD)

This is a type of photodetector used in fiber optic communications, with a capability for both high speed and high gain.

The APD is a reverse biased p-n diode operated just below the breakdown voltage

Absorbed photons create excess electron-hole pairs which undergo ionisation events

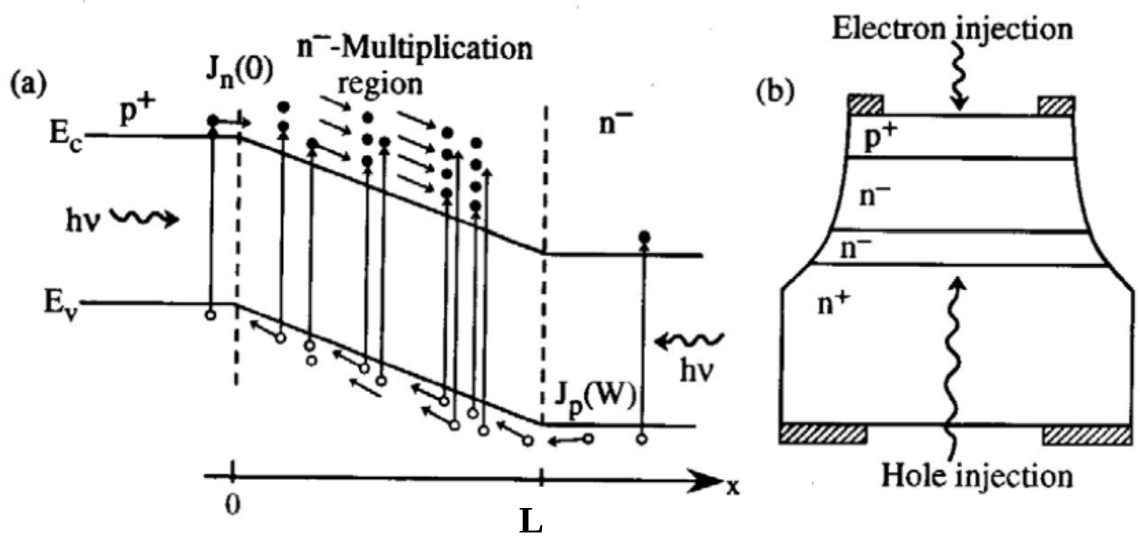
Multiplication occurs and result in a current gain ~ 10^3 or higher. As a result APDs are highly sensitive and can even detect single photons



Impact ionisation

Simple p-i-n APD

Lets assume only electrons involved in the multiplication



Change in current in the Multiplication region

$$\frac{\partial I_n}{\partial x} = \alpha_n I_n(x)$$

Electron ionisation coefficient

The solution to this is $I_n(x) = I_n(0)e^{\alpha_n x}$

Multiplication factor

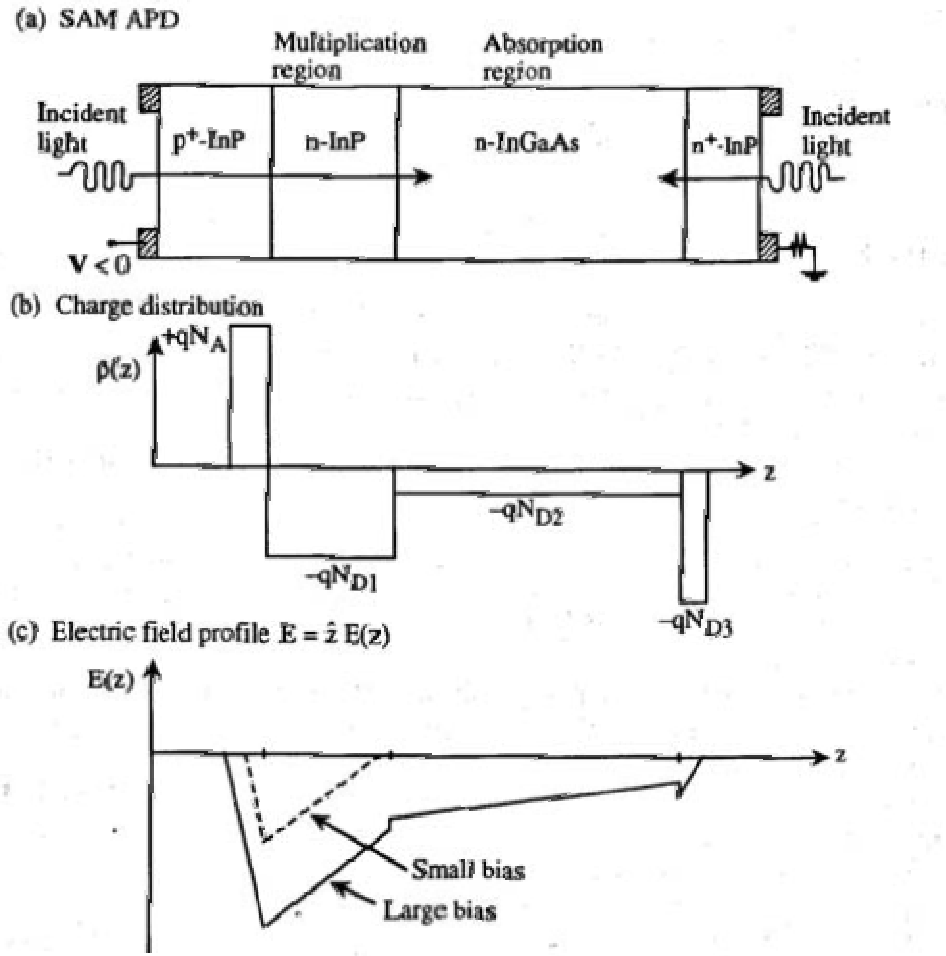
$$M_n = \frac{I_n(L)}{I_n(0)} = e^{\alpha_n W}$$

Impact ionisation

Separate Absorption and Multiplication Region Avalanche Photodiode (SAM-APD)

This is a more advanced design in which light is absorbed in one region and the resulting carriers are multiplied in another region

The structure can control the relative effects of different α and β values



Impact ionisation

If both electrons and holes present (more realistic)

Electron current
$$\frac{\partial I_n(x)}{\partial x} = \alpha_n I_n(x) + \beta_p I_p(x)$$

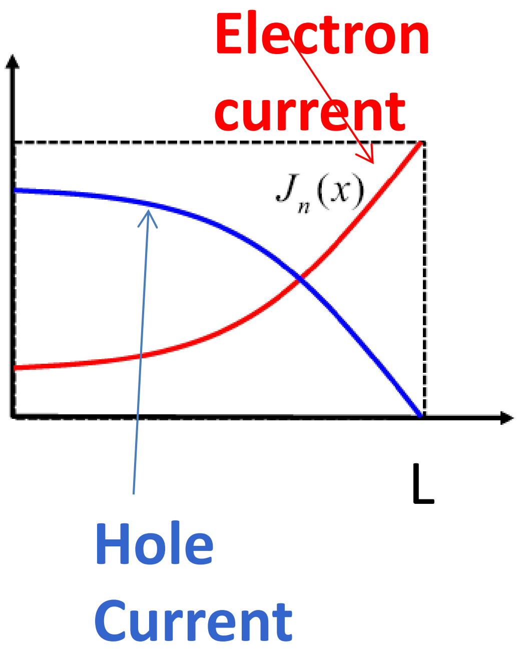
Hole current
$$-\frac{\partial I_p(x)}{\partial x} = \alpha_n I_n(x) + \beta_p I_p(x)$$

Total current
$$I = I_n(x) + I_p(x)$$

also
$$\frac{\partial(I_n(x) + I_p(x))}{\partial x} = 0$$

via complex maths

Multiplication
$$M = \frac{\alpha_n - \beta_p}{\alpha_n e^{-(\alpha_n - \beta_p)L} - \beta_p}$$



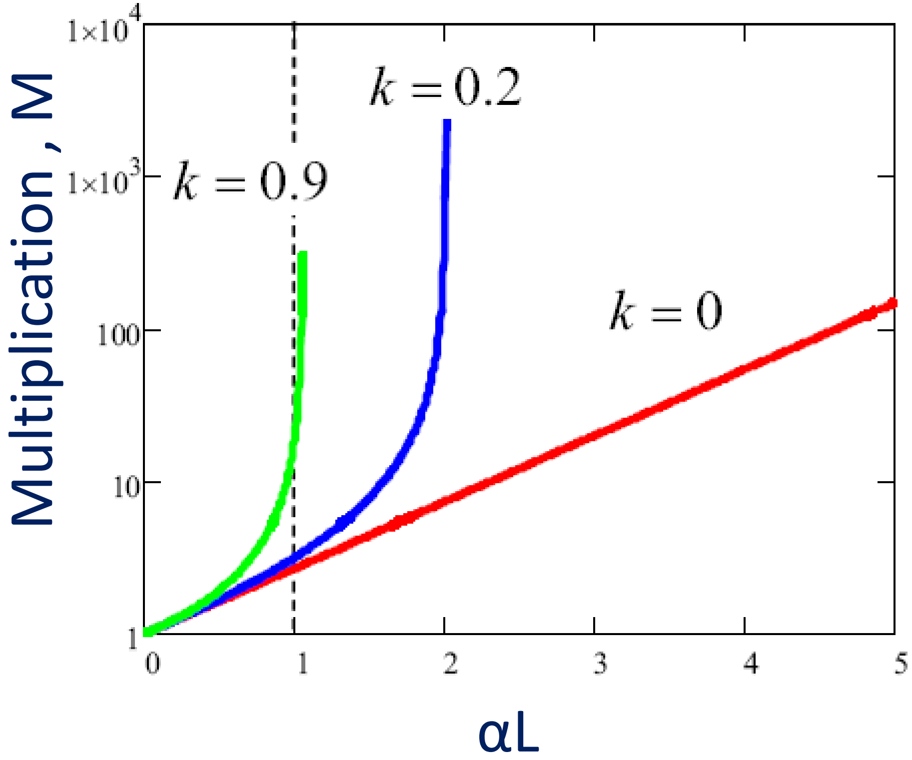
Impact ionisation

Define $k = \dfrac{\beta_p}{\alpha_n}$ *k*- ratio of hole to electron ionisation coefficients

Multiplication $M_n = \dfrac{1-k}{e^{-(1-k)\alpha_n L} - k}$

Multiplication is always higher with higher electron ionisation coefficients and longer distances

When both electrons and holes cause ionising events then the multiplication is even higher and when α≈β (electron and hole coefficients the same) then k=1 and M is at its highest



Impact ionisation

Device Speed

Response time = multiplication time (τ_m)+ transit time (τ_t)

$$\tau_r = \frac{M_n kL}{V_e} + \frac{L}{V_h} \approx \frac{M_e kW}{V_e}$$

For large M, L/V_h is not significant.
Therefore $\tau_r \approx \tau_m$

Gain-bandwidth product (important figure of merit)

G x BW

$$= M_n . \frac{1}{2\pi\tau_m} = M_n . \frac{1}{2\pi} . \frac{\nu_e}{M_n kL} = \frac{\nu_e}{2\pi kL}$$

V_e is the electron saturation velocity, which is constant for a particular material. Therefore for a high GBW product a low k and a short length would be preferred. However k cannot be too low of the gain will be compromised. There is a trade off between M and the bandwidth.

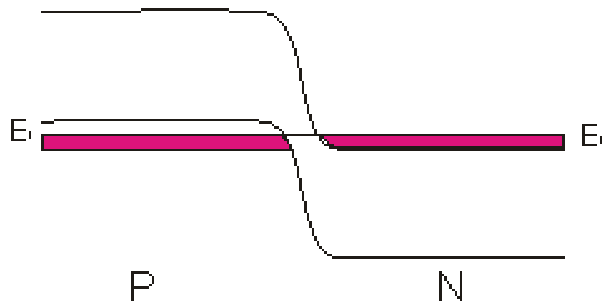
Impact ionisation

Some typical characteristics for optical communication devices

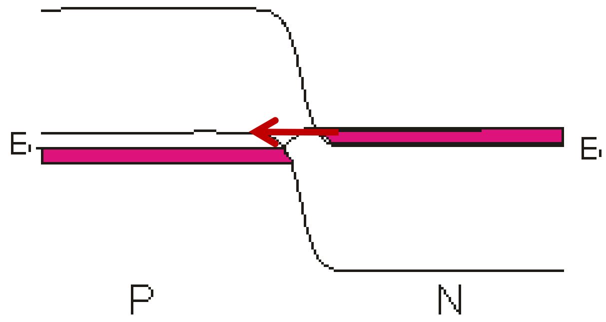
Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
	Active area			55		um
R	Responsivity	λ=1310nm, M=1	0.7	0.8	-	A/W
		λ=1550nm, M=1	0.8	0.9	-	
Vb	Breakdown voltage	Id=10uA	40	50	60	V
Id	Dark current	V_r=0.9Vb		10	50	nA
C	Capacitance	f=1MHz, Vr=0.9Vb		0.38	0.5	pF
Mmax	Maximum multiplication factor	λ=1310nm,1550nm, Ipo=2uA, Vr=V@Id=1uA	25			
fc	Cutoff frequency	M=10	2.0			GHz
	Temperature coefficient of Vb		0.09			V/℃

Tunnel diode

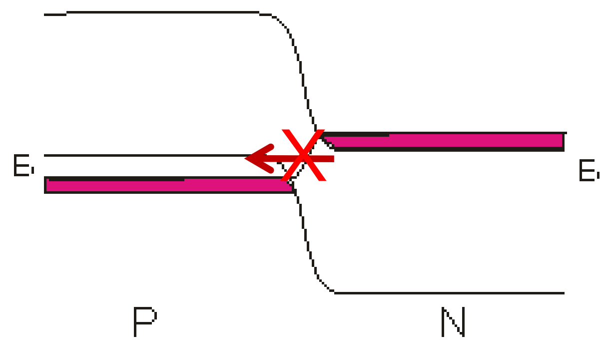
Consider a pn junction at equilibrium. The Fermi level is constant and there is no current flow



Now apply a small forward bias. It is still difficult for electrons to overcome the junction barrier. However there is a possibility that electrons in n-type can tunnel through the depletion region into to adjacent empty states if the depletion region is very thin.



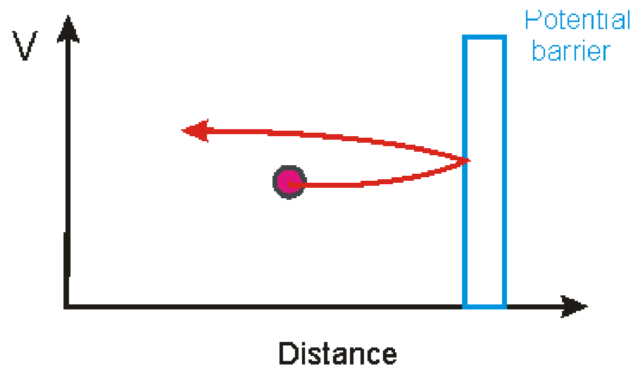
Increase the bias further and the electron current stops; there are no longer any adjacent states



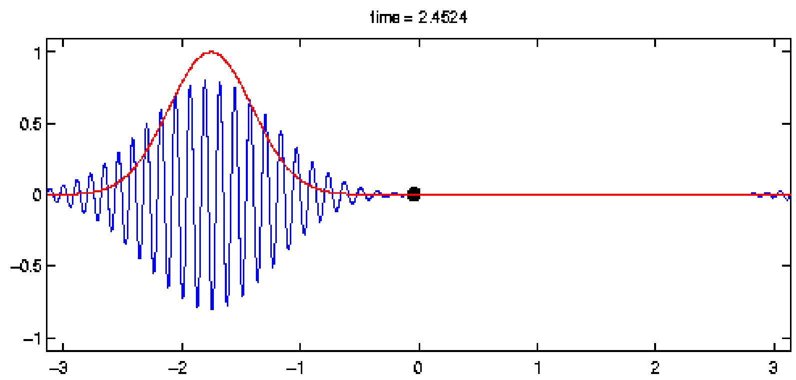
Tunnel diode

Quantum mechanics allows for electrons to ‘tunnel’ through a barrier and appear on the other side if states are available.

In a classical electrodynamics electrons are seen as particles and there is no penetration through a potential barrier

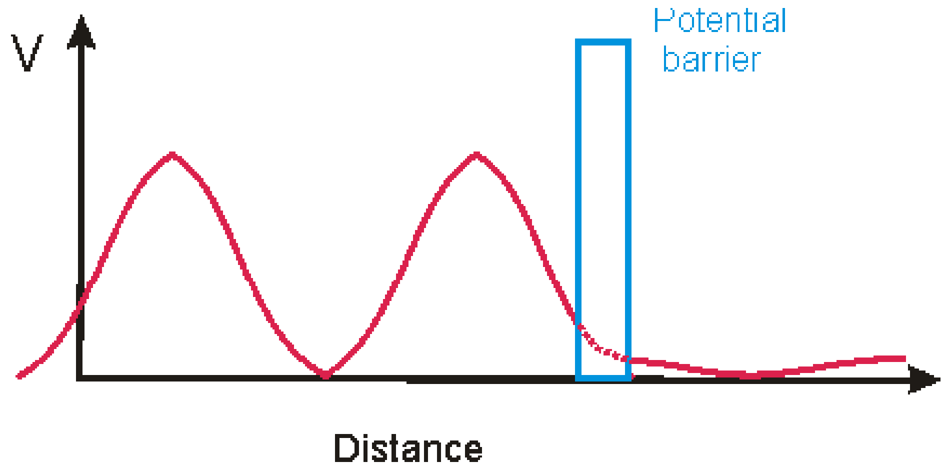


In quantum mechanics however electrons are consider as probability waves (wavepackets). They have no fixed position, only probabilities of being at a certain place and a certain time. (Heisenberg uncertainty principle operates)



Tunnel diode

In quantum electronics there is a finite chance of electrons passing through a potential barrier, such at that which exists in the depletion region of a pn diode

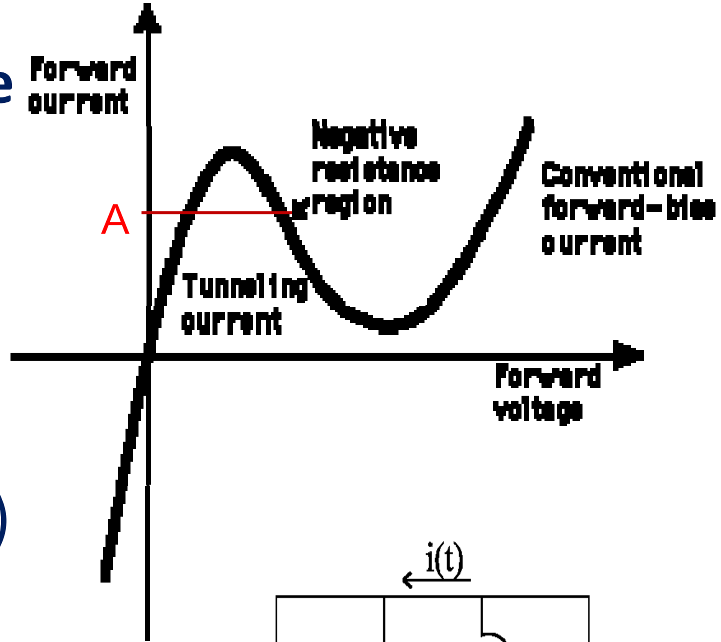


The tunnelling current is extremely small but becomes exponentially stronger as the barrier thickness is reduced. For the pn diode we can create a narrow depletion region by heavy n and p doping on both sides

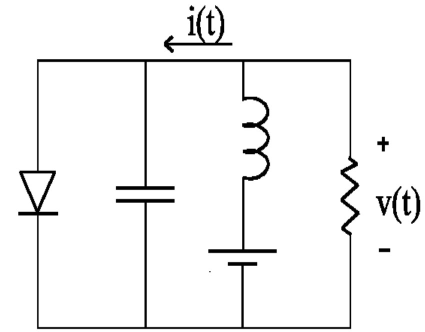
A small voltage of either polarity can then provide a small current. As the voltage is increased the number of states diminishes and the tunnel current stops. Eventually the normal current mechanisms come into play.

Tunnel diode

The response leads to an unusual **negative differential resistance (NDR)** characteristic



Operation at point A is unstable- device will oscillate in voltage at a very high frequency (tunnelling rate very fast- ~ 1ps)



The external circuit is very similar to that for the IMPATT diode. Applications of the tunnel diode include high speed microwave oscillators and amplifiers

This is a high speed, low noise device. However it suffers due to the small tunnelling current and is therefore restricted to low power applications

Quantum Mechanical Tunnelling

Quantum mechanical tunnelling through the gate dielectric (which might otherwise be thought of as a perfect insulator is becoming more and more of a problem as CMOS scales down into the 10's of nm regime.

The tunnelling current in through the gate dielectric has been observed to follow the relationship

$$I_{tn} \propto \frac{\sqrt{m_{eff,ox}}}{\epsilon_{r,ox}\,\phi_b}.exp\left(-K\phi_b^{3/2}\Big/E\right)$$

where $m_{eff,ox}$ is the dielectric electron effective mass, Φ_b is the silicon/oxide barrier height in eV (determined by the electron affinity), $\epsilon_{r,ox}$ is the relative permittivity of the oxide a E is the magnitude of the electric field across the oxide. K is a constant ≈ $1x10^8$.

Quantum Mechanical Tunnelling

One of the great achievements of CMOS in recent years has bee the replacement of SiO_2 gate dielectric with the 'high-k' material HfO_2

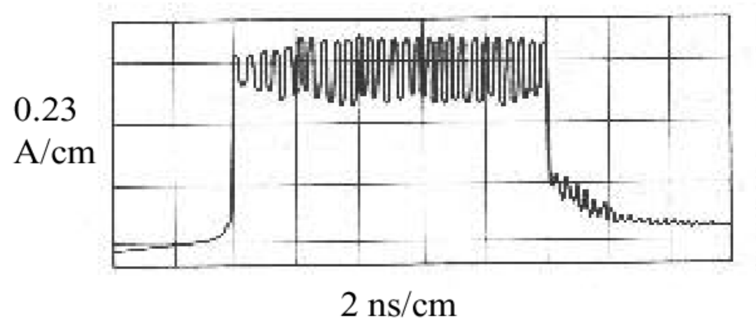
	SI	SIO_2	HFO_2
BAND GAP (EV)	1.12	9.0	6.8
RELATIVE PERMITTIVITY, ϵ_R	11.9	3.9	25
ELECTRON AFFINITY, Φ (EV)	4.1	0.95	2.0
EFFECTIVE MASS, M* (M_O)	0.26	0.55	0.11

The main advantage of HfO_2 comes from its very high relative permittivity (over 6 times higher than that of SiO_2). It also offers a substantially lower electron effective mass. Its lower electron affinity does lead to a lower barrier height for this material, but this is entirely offset by the gains made elsewhere.

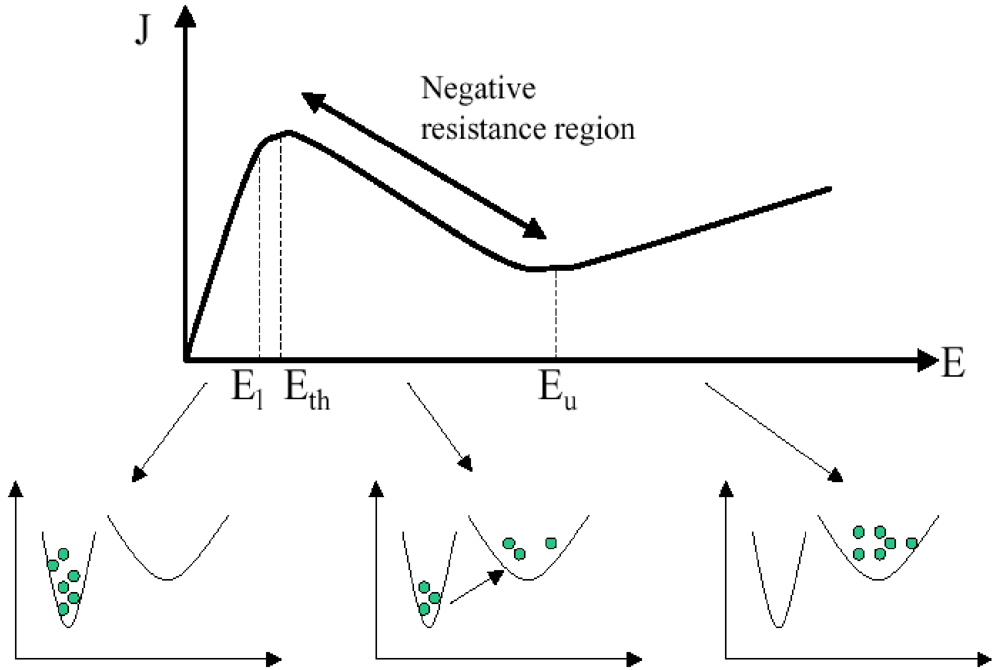
Other NDR devices

Gunn diode

The Gunn effect was observed in GaAs at very high fields in the 1970's



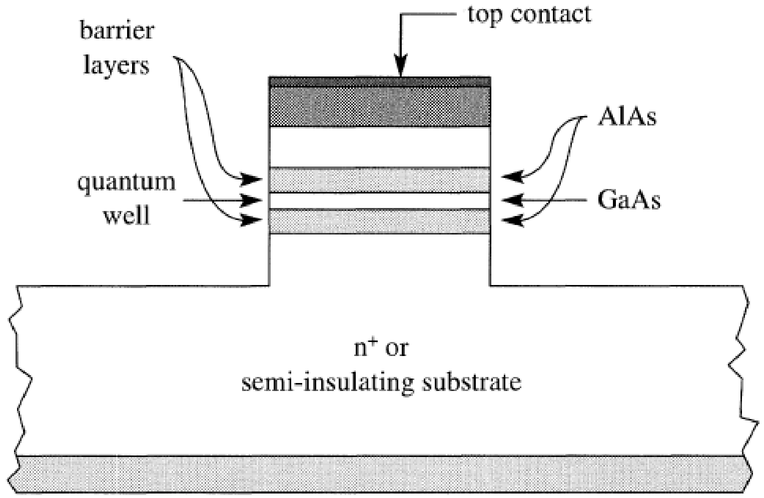
GaAs has two closely spaced valleys in the conduction band. At high fields electrons can become scattered into a higher order band.



This band has a much higher effective mass (much lower mobility)

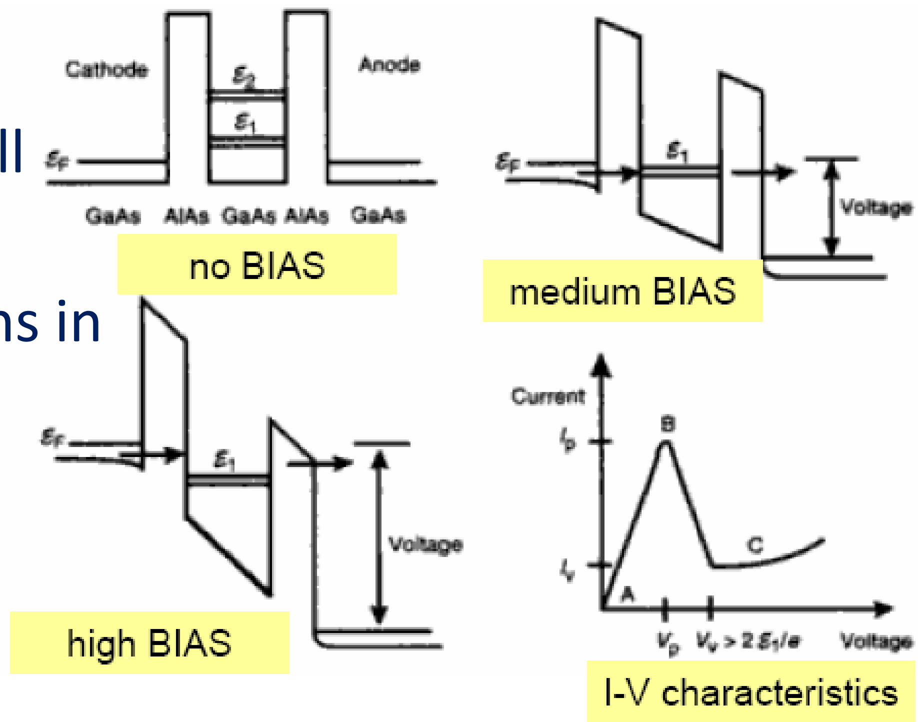
Other NDR devices

The **Resonant tunnelling diode (RTD)** uses heterojunctions and is produced by epitaxial growth techniques.



In the RTD a quantum well is formed between two wide gap barriers. At zero bias there are different energy levels in the well and outside the well

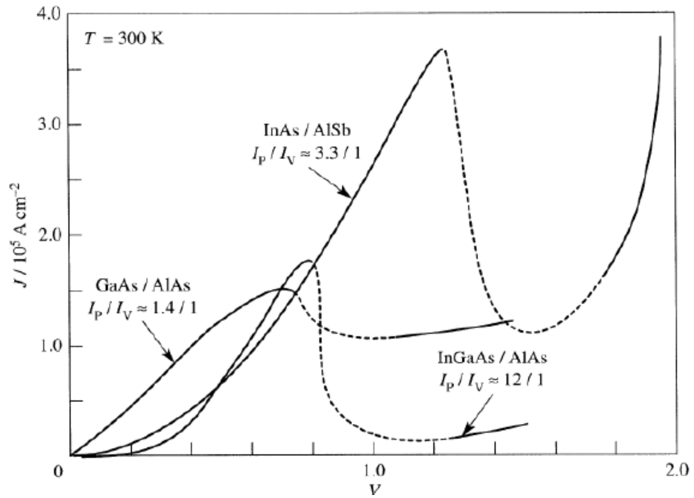
At higher bias, however, electrons in the cathode can align with the energy states in the QW and tunnelling can occur.

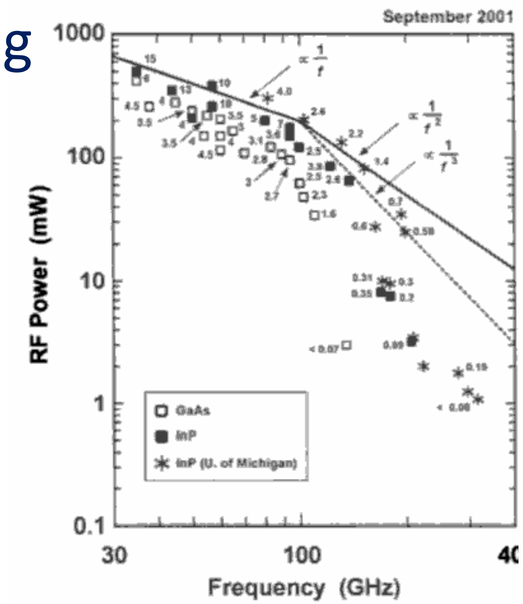


Other NDR devices

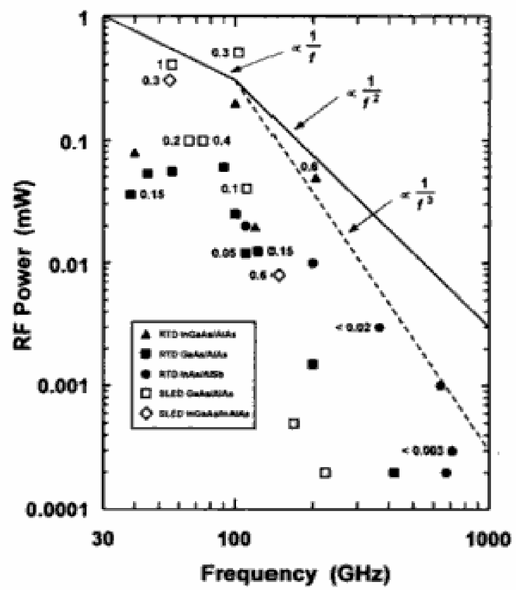
The RTD can give very sharp NDR ‘resonances’ and can support sub ps operation. It is intrinsically a very low power device, as opposed the Gunn diode which has much better power handling capabilities.

However the RTD has the ultimate capability for high speed (approaching 1THz)





Gunn diode



Resonant tunnelling diode