Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

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Hilary Term, TCD
10th of Feb '14

MAGNETISM & SPINTRONICS
Trinity College Dublin

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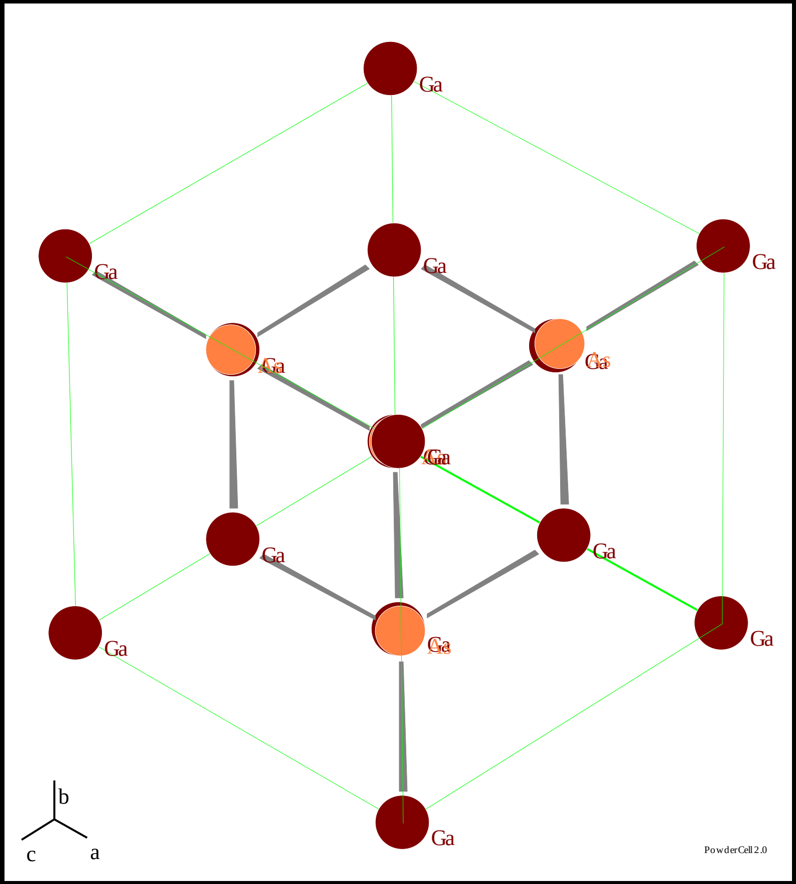
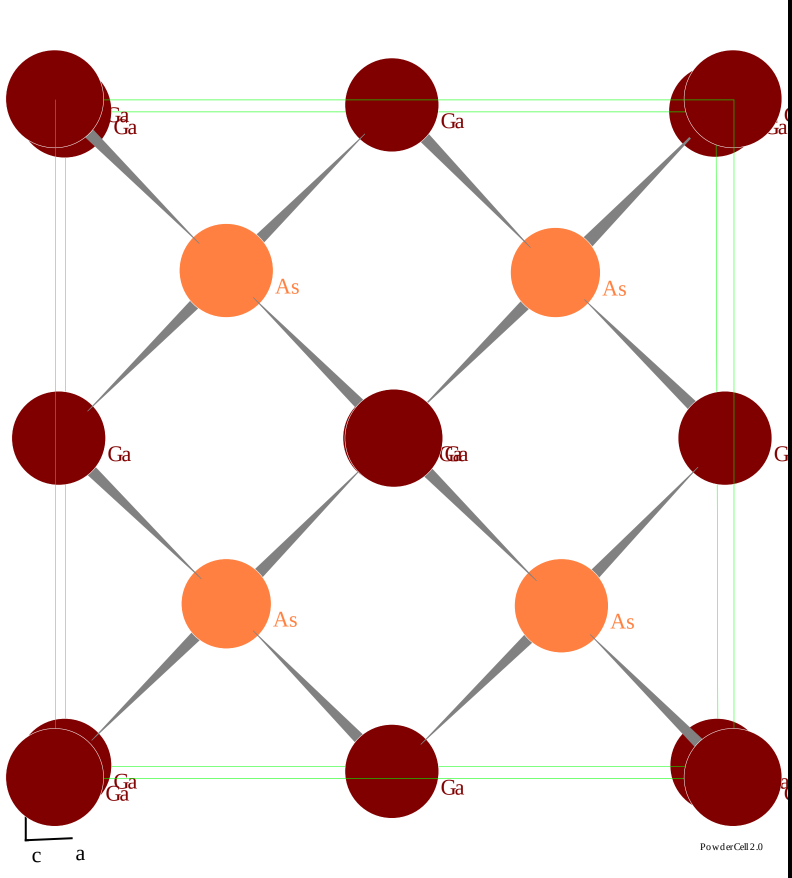
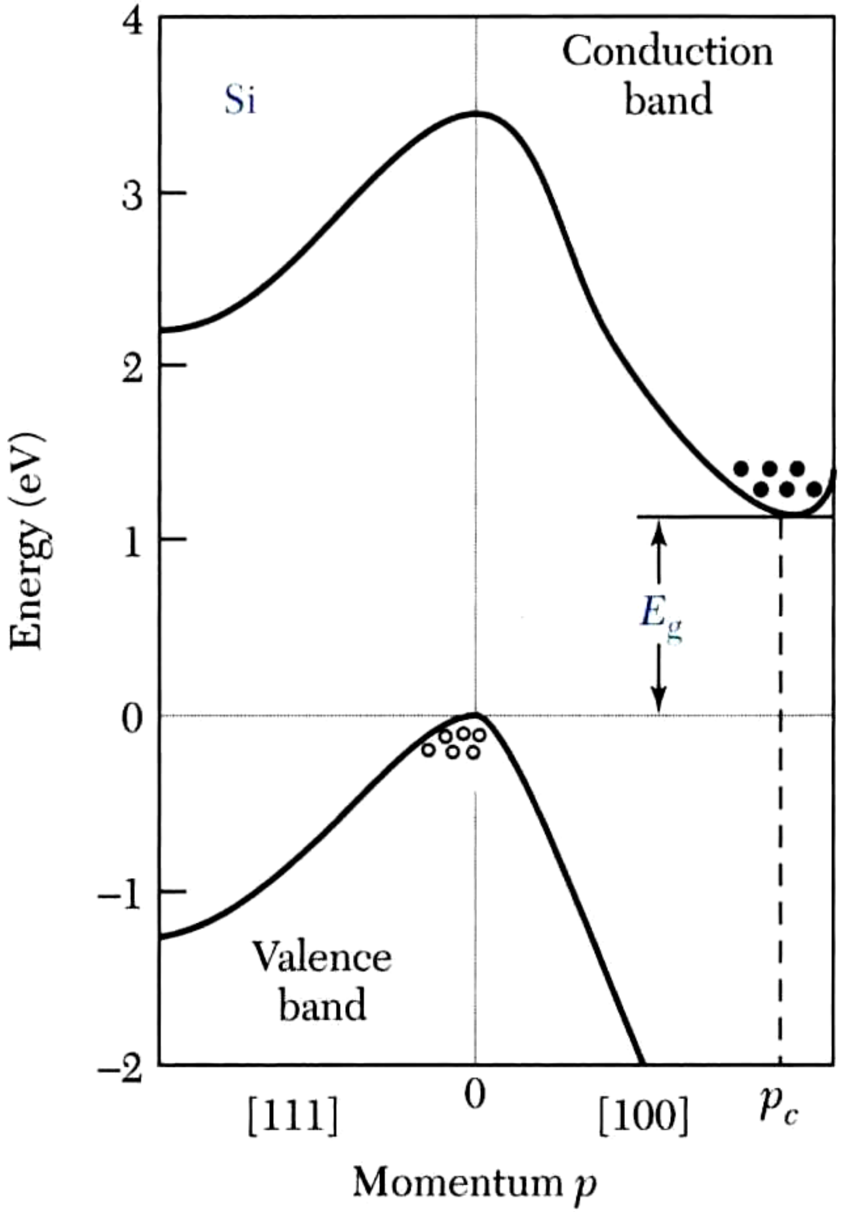
GaAs - Crystallographic Structure

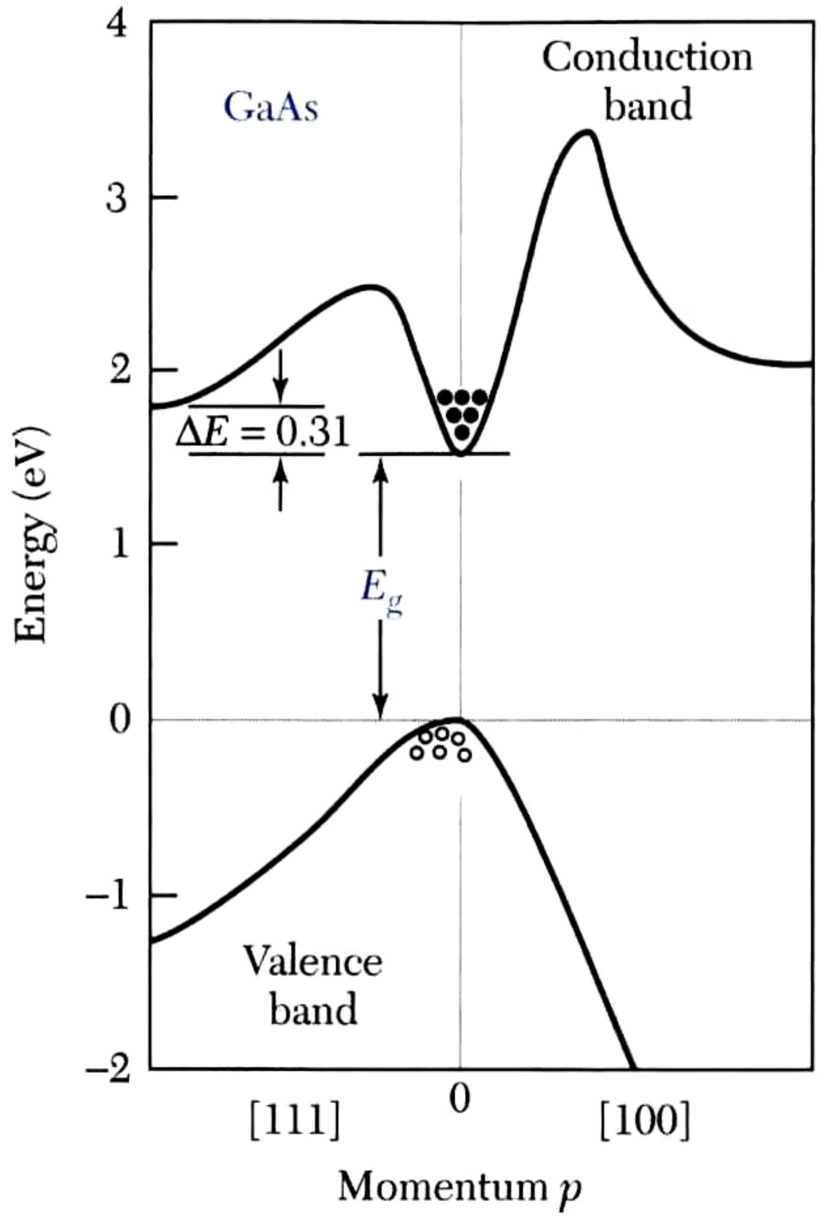




- Space group: 216, Setting 1, F-43m, *a* = 565.35 pm
- Ga (0, 0, 0), 4a; As (0.25, 0.25, 0.25), 4c
- $\rho = 8071$ kg.m^{-3}; $M = 144.645$ kg/kmol

Si and GaAs Band Structures

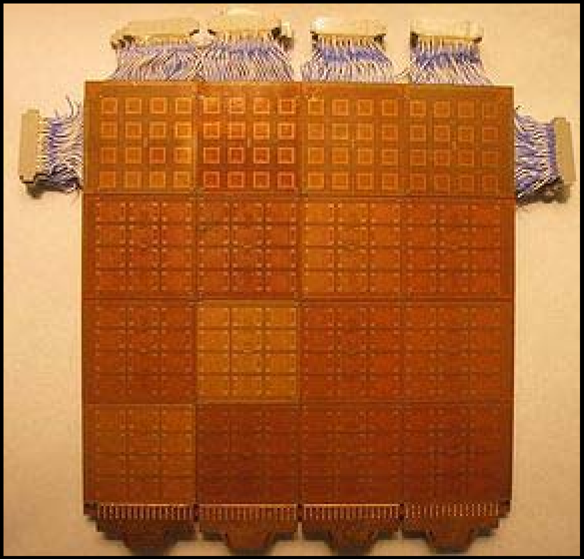


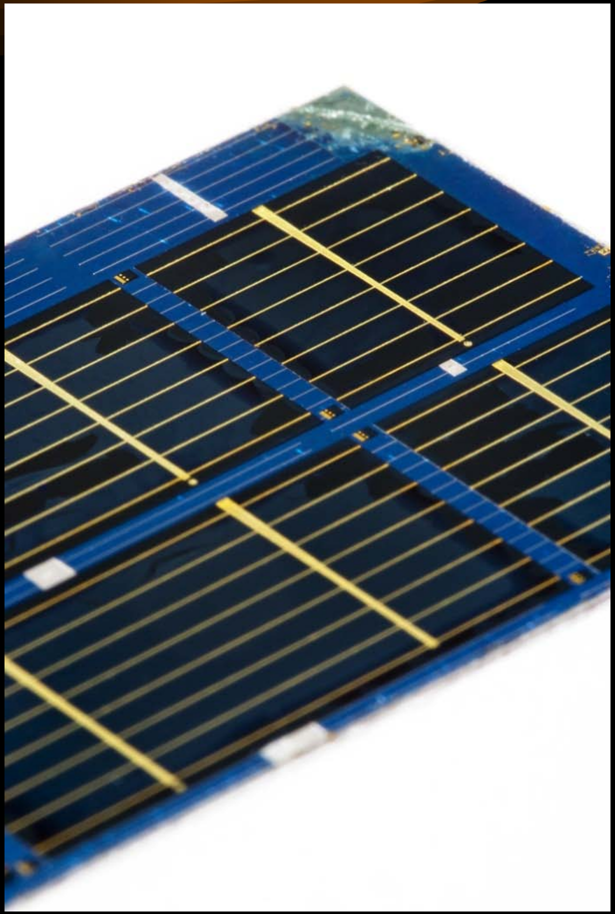


Comparison Si, Ge and GaAs

Properties at 300 K	**Si**	**Ge**	**GaAs**
Crystal structure	Diamond	Diamond	Zinc Blende
Group of symmetry	O_h^7 - Fd3m	O_h^7 - Fd3m	T_d^2 – F-43m
Number of atoms in 1 cm^3	$5\cdot10^{22}$	$4.4\cdot10^{22}$	$4.42\cdot10^{22}$
Debye temperature	640 K	374 K	360 K
Density	2.329 g cm^{-3}	5.3234 g cm^{-3}	5.32 g cm^{-3}
Dielectric constant	11.7	16.2	12.9
Effective electron masses m_l	0.98 m_o	1.6 m_o	0.063 m_o
Effective electron masses m_t	0.19 m_o	0.08 m_o	0.063 m_o
Effective hole masses m_h	0.49 m_o	0.33 m_o	0.51 m_o
Effective hole masses m_{lp}	0.16 m_o	0.043 m_o	0.082 m_o
Electron affinity	4.05 eV	4.0 eV	4.07 eV
Lattice constant	5.431 Å	5.658 Å	5.65325 Å
Band gap	1.12 eV	0.661 eV	1.424 eV
Optical phonon energy	0.063 eV	0.037 eV	0.035 eV

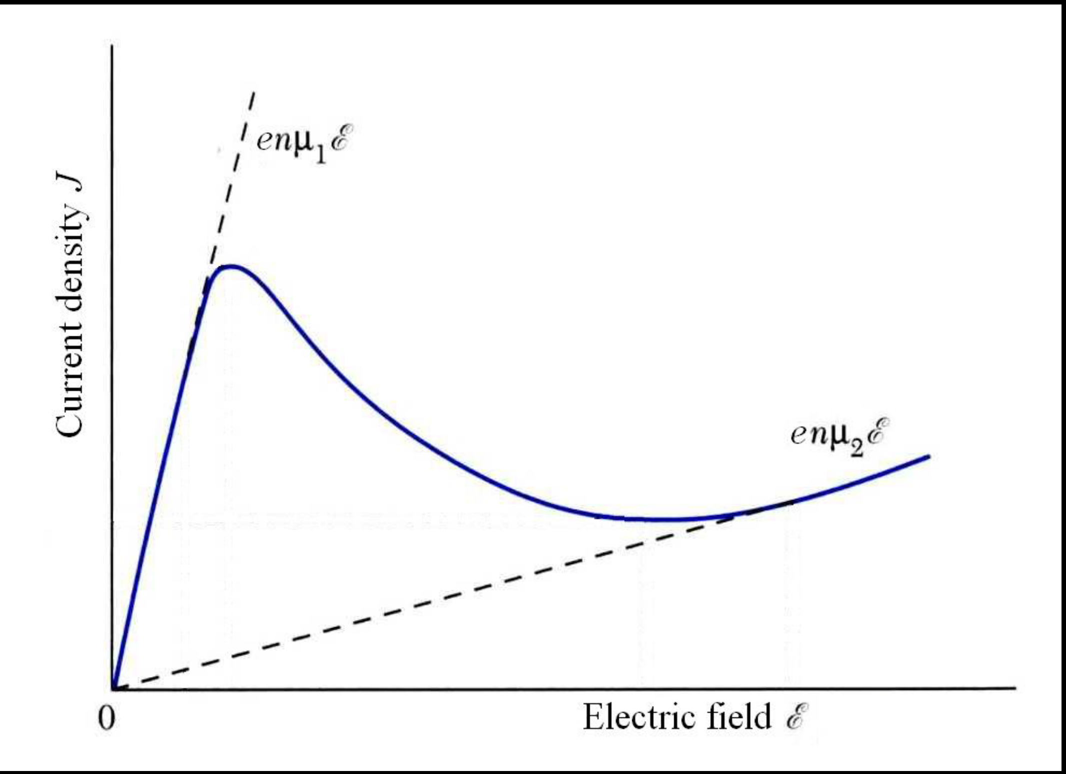
GaAs Uses





- High Speed Supercomputing
- Optoelectronics (both receivers and emitters)
- Microwave technology

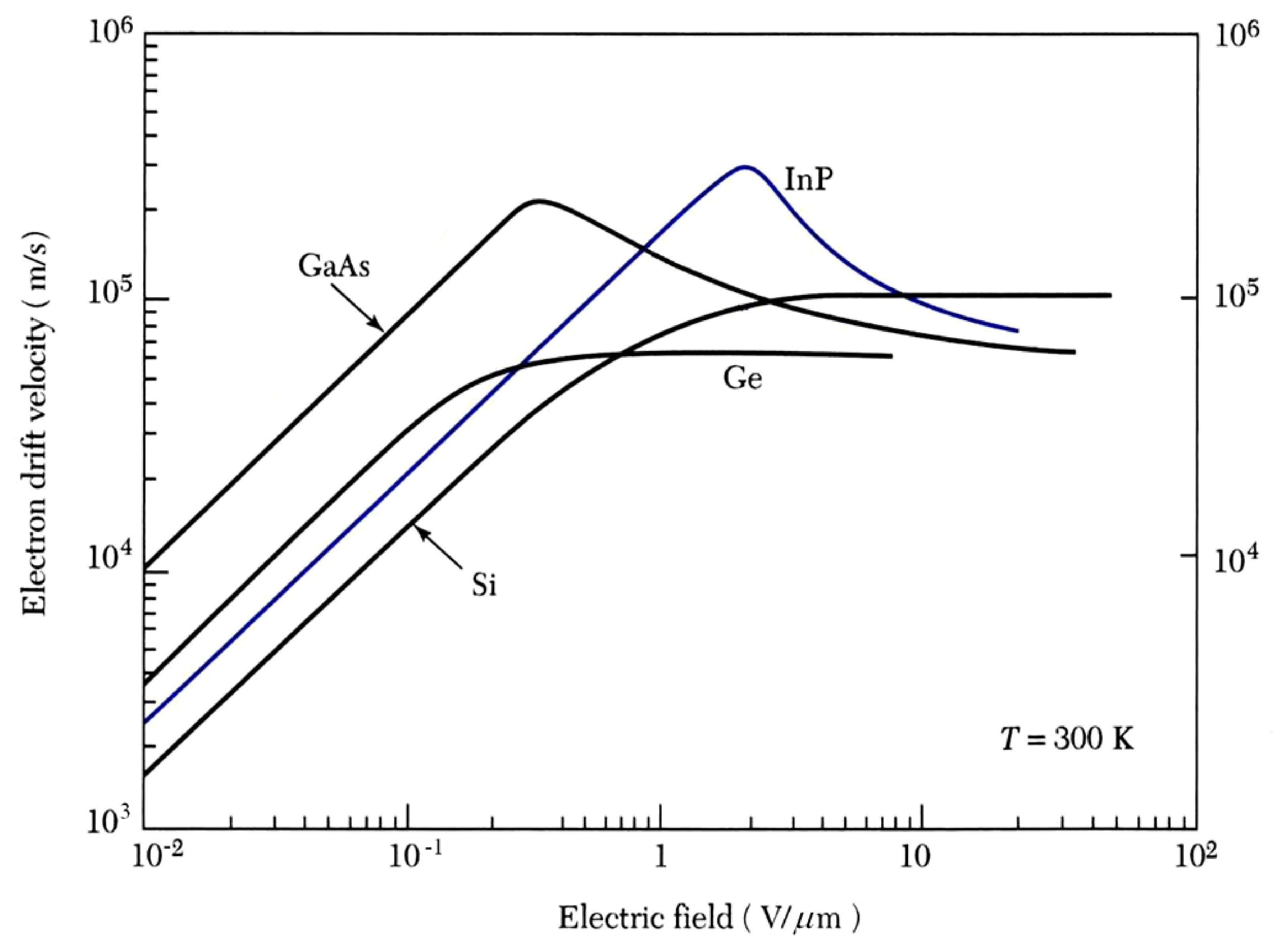
Low vs. High Electric Fields (GaAs)



- The electron velocity $v(= \mu\mathscr{E})$ begins to *fall* as $\mathscr{E}$ increases further!
- The fall continues until at very high $\mathscr{E}$ all the electrons are in the upper valley of lower mobility (μ_2, say).
- In all devices considered so far (that could be made from GaAs), only the lower valley is occupied because $\Delta E >> k_B T = 0.025$ eV, at room temperature and the electric fields $\mathscr{E}$ are relatively low, so the mobility (μ_1, say) stays high.
- When $\mathscr{E} > 0.3$ V μm^{-1}, the electron energy gain from $\mathscr{E}$ between scattering events is large enough to enable some electrons to transfer into the upper valley.

Transport in High Electric Fields

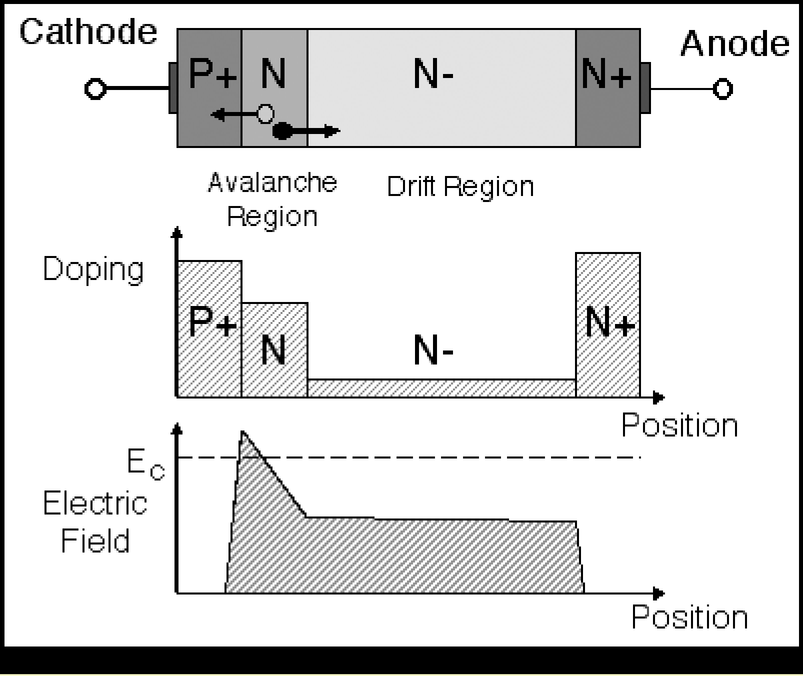
Mobility at low fields (cm^2/V.s)

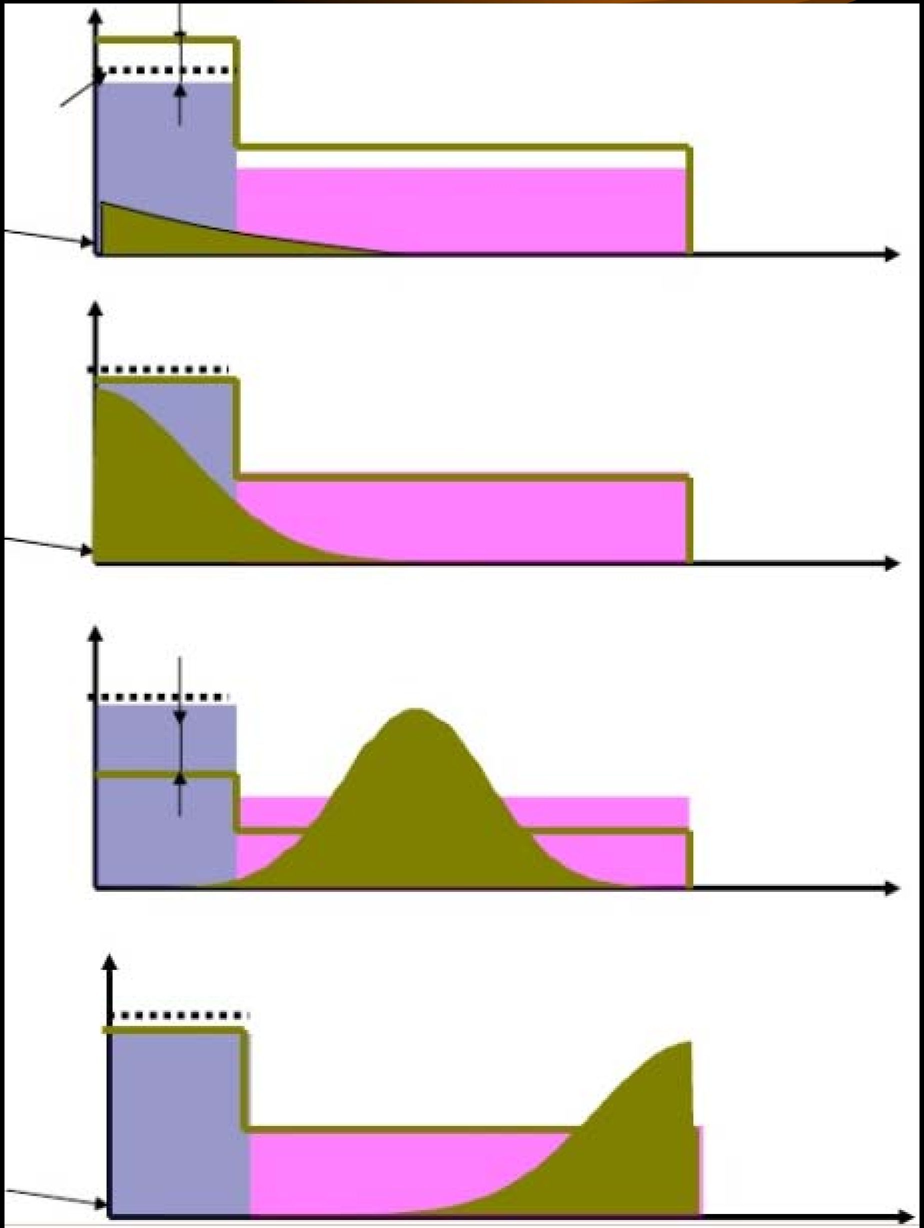


Negative Differential Resistance

- In contrast to Si and Ge, GaAs (like InP) shows a region of negative differential mobility $\mathrm{d}v/\mathrm{d}\mathcal{E}$ ($\sim -0.2\ \mathrm{m^2\ V^{-1}\ s^{-1}}$), i.e. negative differential (small-signal) resistance $\mathrm{d}V/\mathrm{d}I$.
- Any device (or circuit) which shows negative *dV/dI* is unstable, and spontaneously breaks into electrical oscillations when operated in such a region.
- This is exploited in the IMPact ionisation Avalanche Transit Time *IMPATT* diode (not considered in detail here) and the *Gunn* device (Transferred Electron Device or TED, 1963), among others. Both of these can be exploited to convert d.c. power into microwave oscillations, with an appropriate voltage bias.
- The possibility of exploiting the band structure of GaAs for d.c./microwave conversion was predicted before the Gunn device was first developed. Remember the note on Esaki tunnel diodes from the historic introduction.

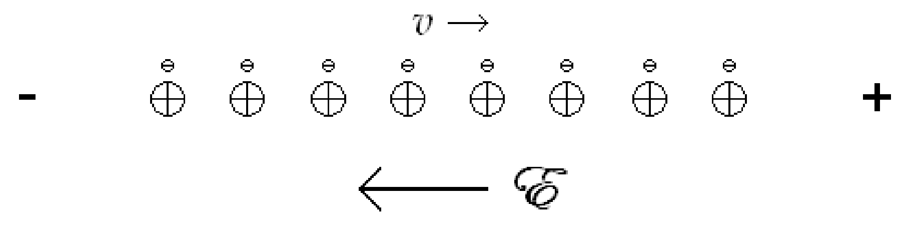
IMPATT Diodes – In Dynamics



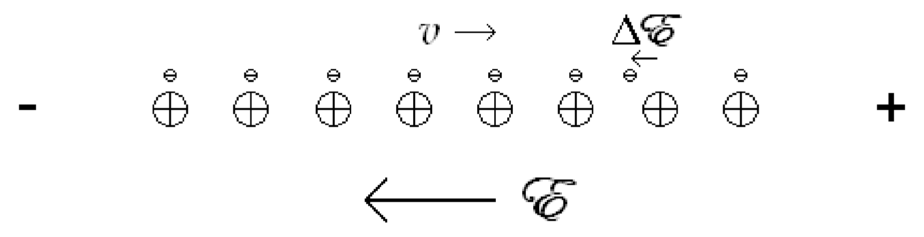


- Originally suggested by W. T Read (1958) . Created later in Si, GaAs, etc.
- Avalanche is produced semi-stochastically by impact ionisation
- The transit time through the N-region determines the frequency
- d*V*/d*I* is lower during propagation
- High power and high phase noise!

The Gunn Diode - Basics



- Within a simple 1D picture of an *n*-type semiconductor with one quasi-electron per ionized donor site (and periodic, homogeneous distribution of the donor sites – implications to be explained later) there is a close to perfect local neutrality at small electric fields. This is the ‘unperturbed’ situation of homogenous carrier drift.

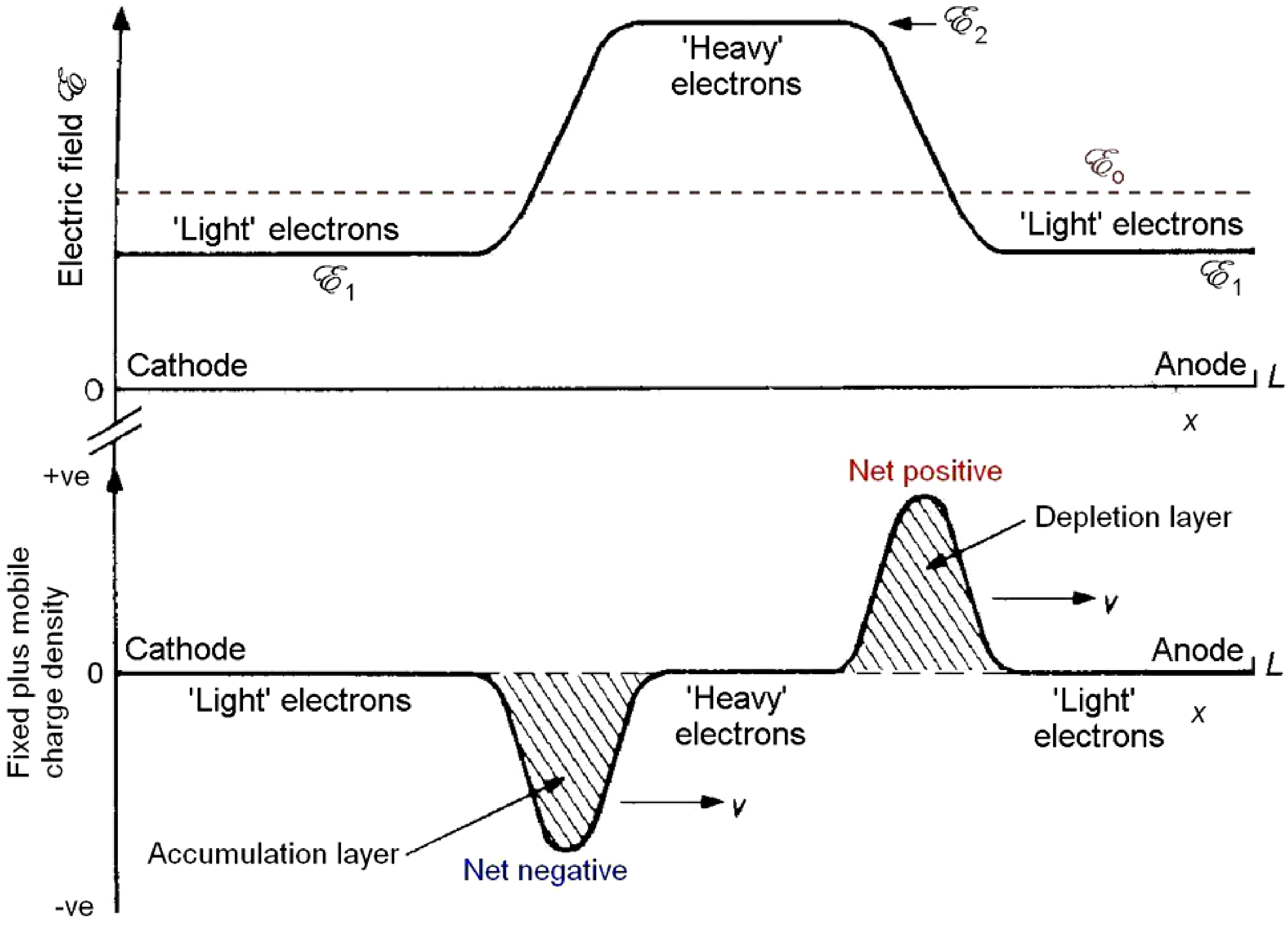


- If, due to local perturbations, an electron lags behind the crowd, an instability can be created at high enough electric field.
- Normally, any fluctuation of the charge distribution would be smeared away on the time scale of momentum scattering ~ ps – i.e. The ‘defector’ will be accelerated by the additional electric field $\Delta\mathcal{E}$ to match with the rest of the crowd.

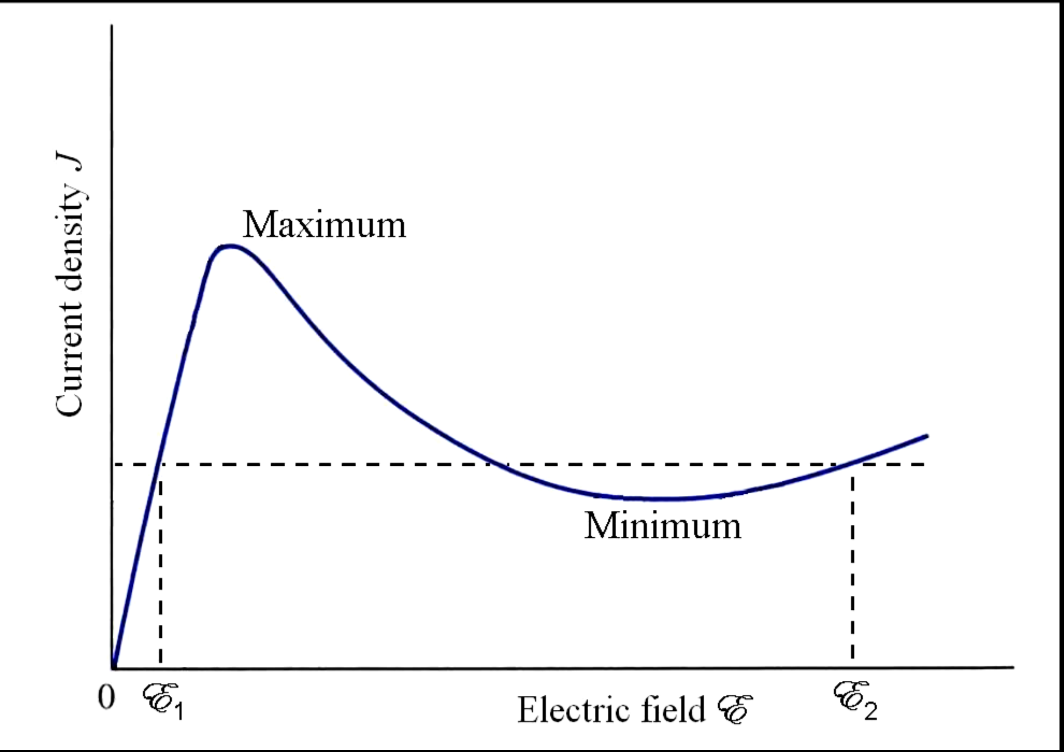
Gunn Diode – Domain Formation

- If the semiconductor can be biased in a region where $dv/d\mathscr{E} < 0$, as in a Gunn device, this electron (together with others) slows down and lags behind even more.
- This causes the space charge perturbation to grow on a time scale of a few ps.
- A full analysis shows that a dipole space-charge domain can be formed, containing donors depleted of electrons followed by an cloud of drifting electrons with mobility μ_n and effective mass m^* = values (because of the extra electric field) for the *upper*, satellite conduction band valley, i.e. μ_n is low ($=\mu_2$) and m^* high.
- Obviously, the domain will grow and propagate until it is ‘expelled’ from the device. Thus, the physical length of the active region will be an important parameter setting the frequency of the generated microwave oscillations.

Charge and Field Distributions



Notes on Domain Formation



- The higher electric field would itself stabilize to a value close to the minimum of the *J* vs. $\mathscr{E}$ curve in a sufficiently long device.
- The integral of the electric field distribution must be = applied bias.
- The areas enclosed by each region in the lower plot, i.e. the total charges in each layer, are equal.
- The net charge density in the positive depletion layer ≤ the charge density qN_d due to the ionised donors.
- The values of the electric field $\mathscr{E}_1$ and $\mathscr{E}_2$ outside and inside the domain (top plot, black solid line) stabilise in the way depicted on the plot of *J* vs. $\mathscr{E}$, i.e. *J* inside the domain = *J* outside.

Domain Nucleation and Growth

- The domain nucleates at the cathode, and grows to the structure shown while drifting through the GaAs thickness *L* to the anode; the process then repeats itself.
- The main frequency of the signal induced in the external circuit would be approximately *v*/*L*, where *v* = domain velocity.
- This velocity can be estimated roughly from $v = \mu_2 \mathscr{E}_2 \approx 0.02 \times 5.10^6 \approx 10^5$ m s^{-1} (as expected), where $\mathscr{E}_2 \approx$ field near the minimum in *J vs* $\mathscr{E}$.
- The GaAs thickness *L* must be large enough to allow significant domain space-charge growth while the domain is travelling from cathode to anode. The power conversion efficiency of the device depends on the magnitude of the dynamic differential resistance, which in turn depends on the domain size. If the domain is not allowed to grow – the efficiency will be low – i.e. efficiency would drop for short devices.

Domain Growth and Propagation

- The *dielectric relaxation* (*growth*) *time* τ_r in any material is the exponential time constant for decay (growth) of space charge (i.e. within a linear approximation for the recombination or generation rates).
- It can be shown that $\tau_\mathrm{r} \approx \varepsilon_0 \varepsilon_\mathrm{r} \rho = \dfrac{\varepsilon_0 \varepsilon_\mathrm{r}}{\sigma}$, where $\varepsilon_r = 12$ for GaAs and σ = conductivity.
- It can be easily shown that this expression for τ_r is the same as the *RC* time constant of a parallel-plate capacitor containing a leaky dielectric of permittivity ε_r and conductivity σ.
- The relevant conductivity here is $\sigma(\mathscr{E}) = nq\mu(\mathscr{E})$, where, in the case of domain growth, the appropriate value for the mobility μ is the negative differential mobility $\mu_\mathrm{d} = \mathrm{d}v/\mathrm{d}\mathscr{E} \approx -0.2\ \mathrm{m}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$.
- The relevant carrier concentration n ~ the equilibrium value ~ donor density N_d.

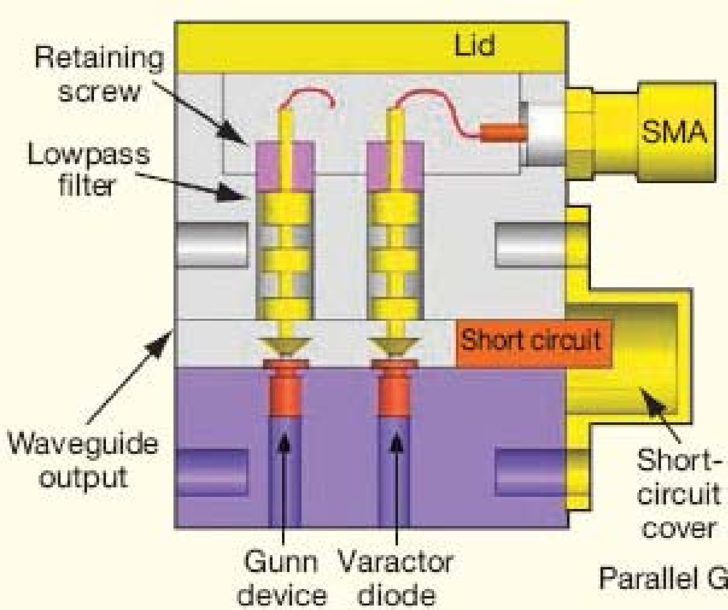
Operation Frequency and Performance

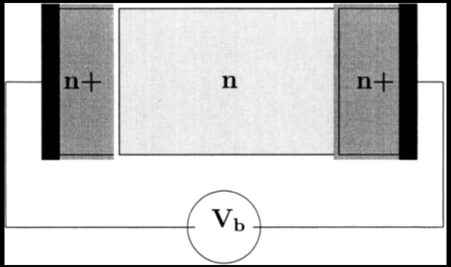
- In order to achieve significant space charge growth:

$$\frac{\text{Domain transit time}}{\text{Dielectric growth time}} = \frac{L / v}{\tau_r} \gg 1$$

- Values of N_D for GaAs are typically 10^{21} m^{-3}, so L can be as low as 10 μm, giving an oscillation frequency v/L of 10 GHz.
- Performance figures for the best Gunn devices:

0.5 W	at 30	GHz	with 15% efficiency
0.2 W	at 100	GHz	with 7 % efficiency
70 mW	at 150	GHz	with 1 % efficiency





Thanks and Acknowledgements

Thank You Very Much for Your Attention!