EEE337 Semiconductor Electronics
EEE348 Electronics and Devices
Carrier generation and recombination

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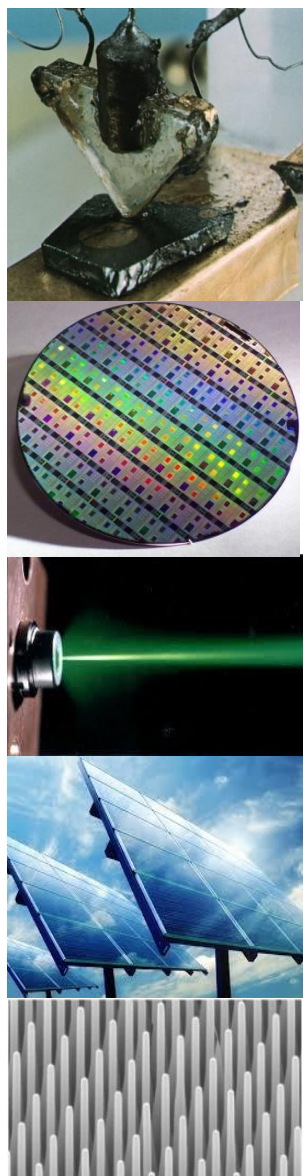
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Electrical Engineering, The University of Sheffield, UK

- Carrier generation
    - Temperature
    - Chemical
    - Optical
    - Electrical
- Recombination
    - SRH
    - Radiative
    - Auger

1 μm

What make semiconductor conducts?

Carrier concentration plays a critical role in determining how much current a semiconductor can conduct. At equilibrium (i.e no external excitations such as light, pressure or electric field), the electron concentration in the conduction band is

$$n = \int_{0}^{E_{top}} N(E)F(E)dE \qquad\qquad N(E) = 4\pi\left(\frac{2m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}}$$

$N(E)^*$ is the density of states (i.e, the density of allowed energy states per energy range per volume and $F(E)$ is the Fermi-Dirac distribution given by
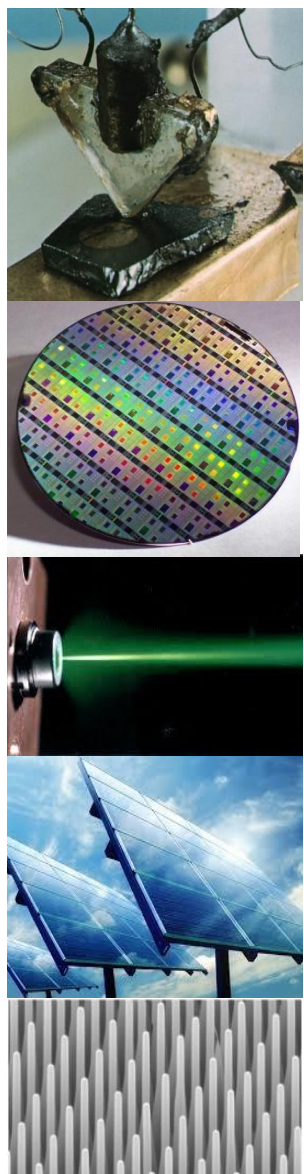
$$F(E) = \frac{1}{1+\exp\left(\dfrac{E-E_F}{kT}\right)}$$

E_F is the Fermi level corresponding to the probability of electron occupancy of 0.5. In an n-type semiconductor the Fermi level can be approximated by

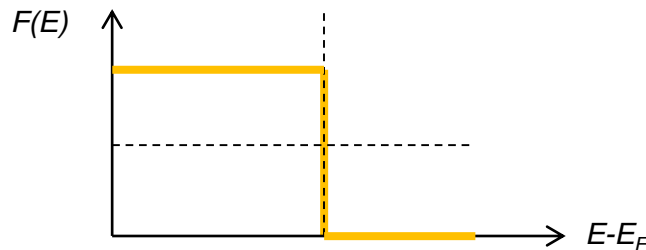$$E_F = E_C + kT\left[\ln\left(\frac{n}{N_C}\right) + \frac{1}{\sqrt{8}}\left(\frac{n}{N_C}\right)\right]$$

Where E_C is the conduction band, n is the electron concentration and N_c is the effective density of states in the conduction band.
What happens when T increases??

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1 µm

Carrier concentration

$$F(E) = \frac{1}{1 + \exp\left(\dfrac{E - E_F}{kT}\right)}$$

F(E)

If $(E-E_F) > 3kT$, $F(E) \sim e^{-(E-E_F)/kT}$
If $(E-E_F) < 3kT$, $F(E) \sim 1-e^{-(E-E_F)/kT}$

$E-E_F$

It can be shown (p.31-32, Sze and Lee) that the electron density (for non-degenerate semiconductors) is given by

$$n = N_C \exp\left[-\left(\frac{E_C - E_F}{kT}\right)\right]$$

Hole density is given by

$$p = N_V \exp\left[-\left(\frac{E_F - E_V}{kT}\right)\right]$$

$$n_i = \sqrt{np} = \sqrt{N_C N_V}\,\exp\left(-\frac{E_g}{2kT}\right)$$

$$E_g = E_c - E_V$$

At 300 K, N_C = 2.86×10^{19} cm^{-3} (Si), 4.7×10^{17} cm^{-3} (GaAs) and N_V = 2.66×10^{19} cm^{-3} (Si), 7.0×10^{18} cm^{-3} (GaAs)

The intrinsic carrier concentration is $n_i^2 = np$, n_i = 9.65×10^9 cm^{-3} (Si) and 2.25×10^6 cm^{-3} (GaAs) at 300K. n_i determines the leakage current flowing in a photodiode and transistor and the short circuit current in solar cell.
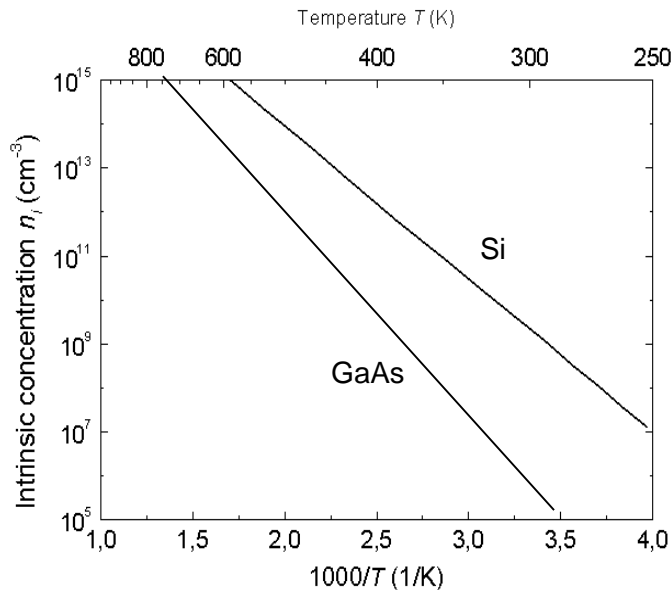
1 μm
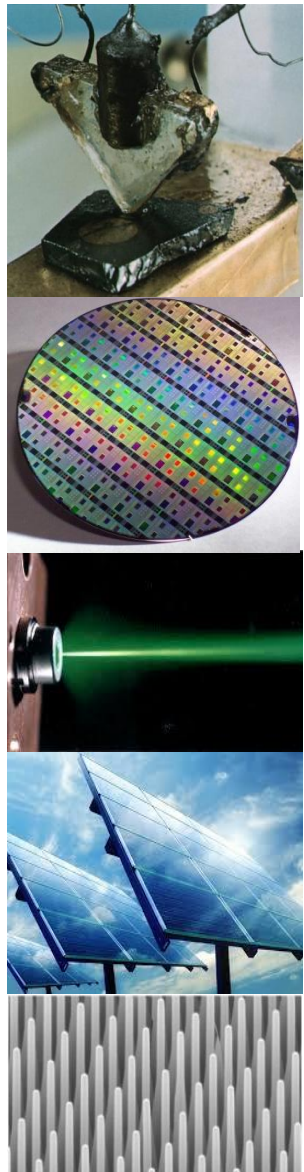
Increasing the carrier concentration

Factors influencing the carrier concentration
- **Temperature (as already discussed)**
- **Chemical (use of dopants to create pn diodes and transistors)**
- **Optical (exploited in solar cell and photodiodes)**
- **Electrical (exploited in avalanche photodiodes for optical communication and impatt diode for RF source)**

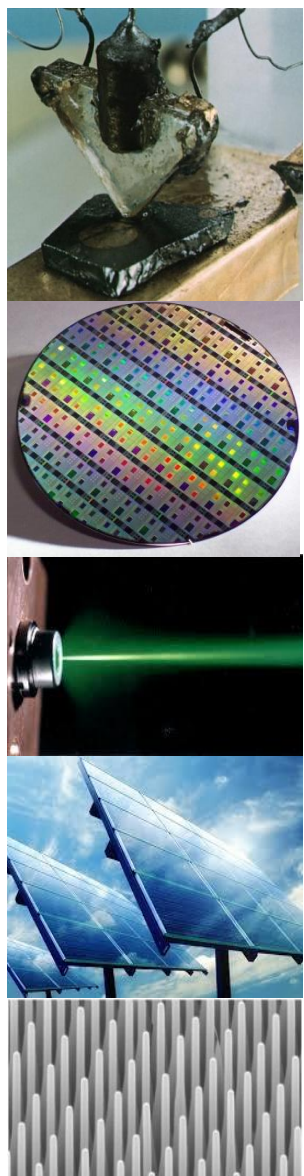$$n_i = \sqrt{np} = \sqrt{N_C N_V} \ \exp\left(-\frac{E_g}{2kT}\right)$$

The intrinsic carrier concentration is $n_i = 9.65 \times 10^9$ cm^{-3} (Si) but in metals the electron concentration is $\sim 10^{22}$ cm^{-3}. It can be seen that even at high temperature the number of electrons remains significantly lower than in metals, hence Si remains as a semiconductor (hence we can manipulate the current flow to make electronic devices).

Using temperature and bandgap to control the carrier concentration is not an attractive approach, so in practice chemical, optical and electrical methods are used.

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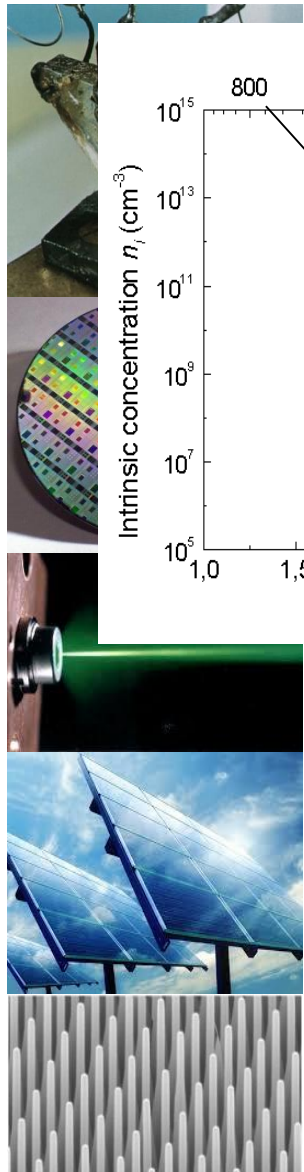
Chemical generation (Doping)
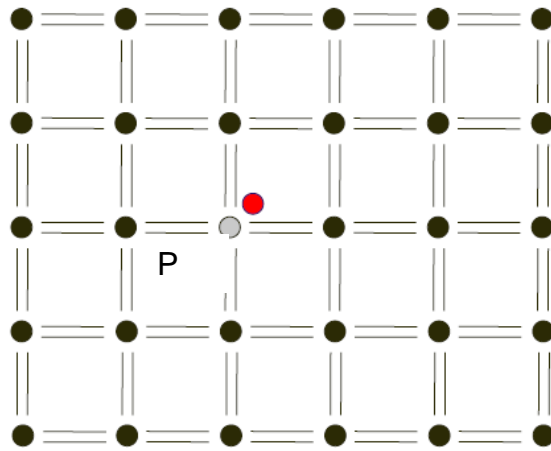
The addition of a Group V (phosphorus) to Group IV (Si) creates a free electron that is not bonded. Likewise a Group III (Boron) element creates an additional hole. Boron and Phosphorus are important in Si because they have low ionization energy ~ 45meV and they have similar atomic mass to Si so that they can be incorporated without too much disruption to the Si crystal. Hence at room temperature there is a high proportional of ionised carriers. The dopant atoms are usually incorporated during epitaxial growth, ion implantation (very high energy ions implanted directly into the semiconductor) or high temperature diffusion.

If a Si wafer is doped with P concentration of 10^{15} cm^{-3}. Find the carrier concentration and Fermi level at room temperature.
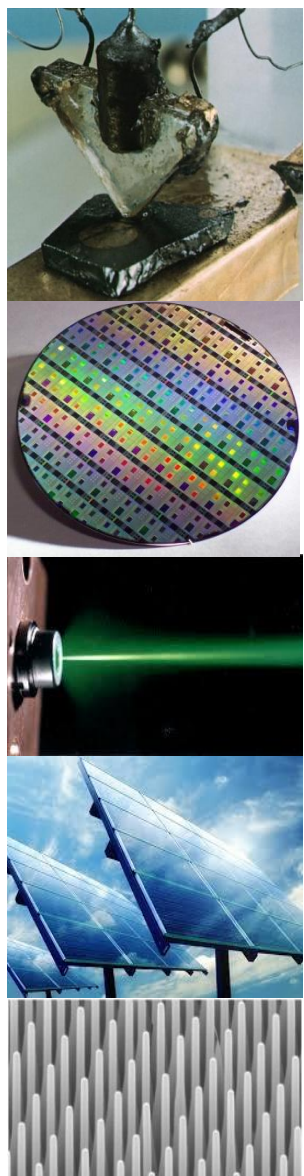
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1 µm

Fermi Level

The Fermi level can be approximated using the Joyce-Dixon approximation

$$E_F = E_C + kT\left[\ln\left(\frac{n}{N_C}\right) + \frac{1}{\sqrt{8}}\left(\frac{n}{N_C}\right)\right] \qquad E_F = E_V - kT\left[\ln\left(\frac{p}{N_V}\right) + \frac{1}{\sqrt{8}}\left(\frac{p}{N_V}\right)\right]$$

For n-type

For p-type

1 µm

Chemical generation (Doping)

Suggest suitable p and n-type dopants for GaAs.

Group IV (Si) into Group III (Ga) to produce n-type.
Group II (Be) into Group V (As) to produce p-type.

What happens when the doping concentration is high?

If the doping concentration (e.g, $>>10^{19}$ cm^{-3} in Si and $>>10^{17}$ cm^{-3} in GaAs) is higher than the density of states, the Fermi level will be above E_C or below E_V. In this case we have a degenerate semiconductor.

What happens if the doping concentration approaches 10^{22} cm^{-3}?

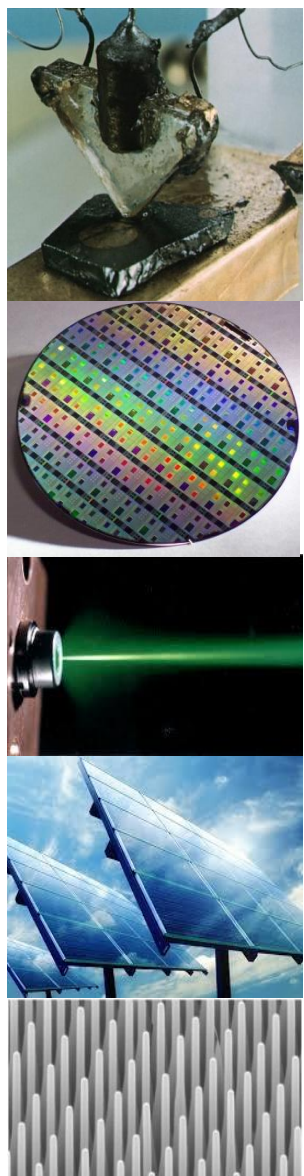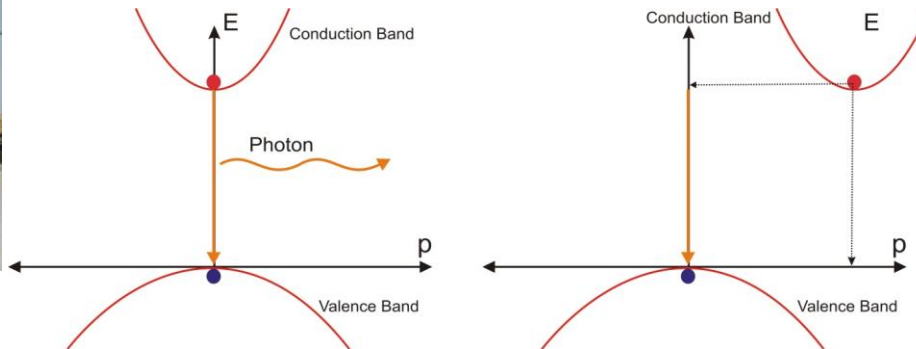Since there are 10^{22} atoms/cm^3 the high concentration of "foreign" atoms will form alloy with the host atoms. The band structure will change and usually defects are generated since the foreign and host atoms usually do not form lattice matched alloys.
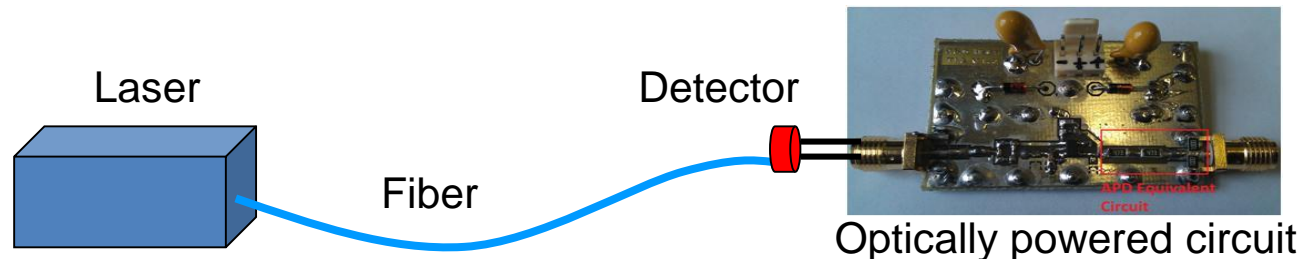
1 μm
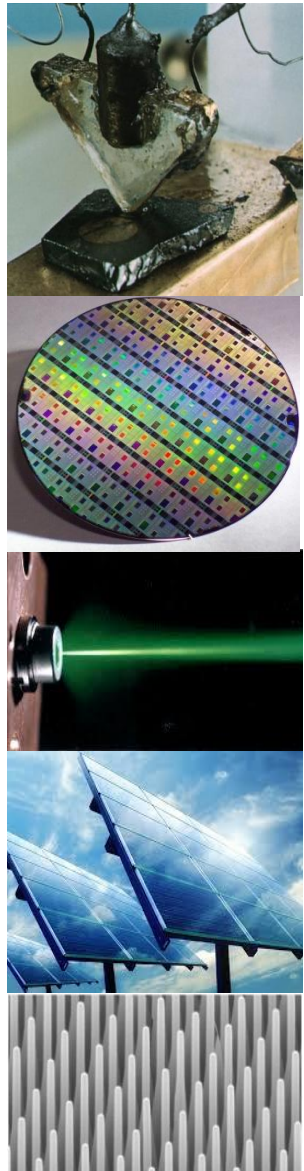
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Although Si is not as efficient as GaAs, its low cost and high quality allows it to dominate the solar cell market.

Conservation of energy and momentum is necessary. Therefore in indirect semiconductors, the absorption of an optical photon also involves phonons to satisfy the momentum conservation. Therefore a direct band gap semiconductor has a higher optical absorption coefficient (i,e requires a thinner layer to convert all the incident light into electron-hole pairs).
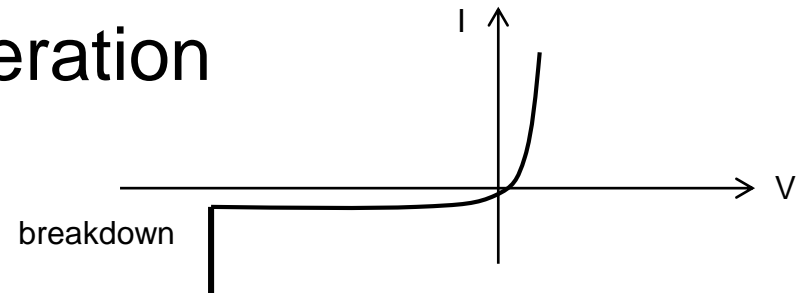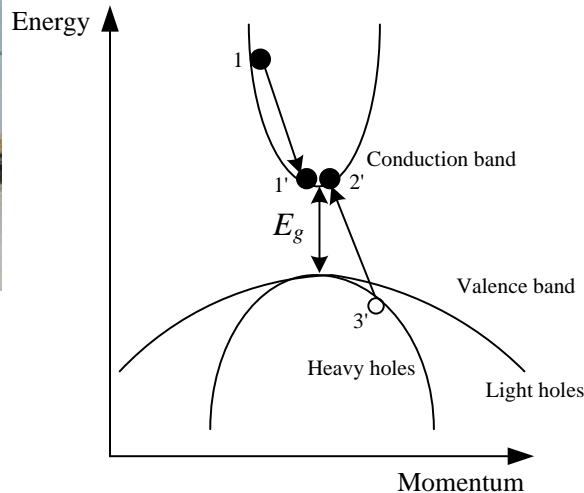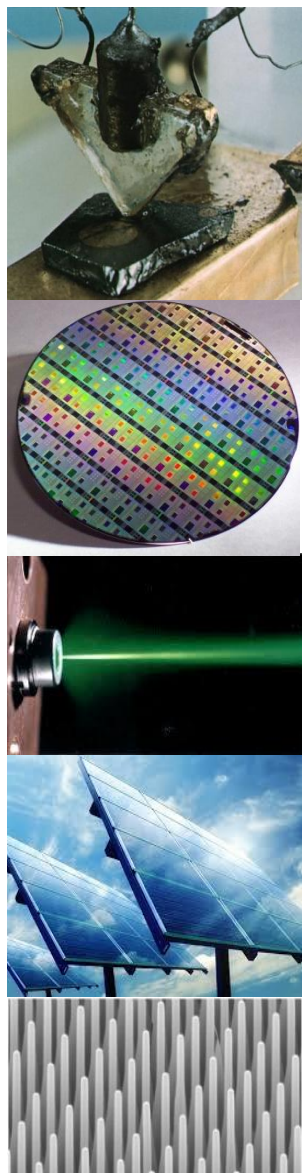
This optical process is the underlying principles of solar cells and photodiodes. Maximizing absorption is key in efficient solar cell and optically power circuit/module.


Optically powered circuit

http://lasermotive.com/technology/power-over-fiber/

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Electrical generation

Energy

Conduction band

1

1' 2'

E_g

Valence band

3'

Heavy holes

Light holes

Momentum

I

V

breakdown

Extremely high security data transmission using single photon

Secret Digital Key Exchange Using Quantum Key Distribution

TOSHIBA

TOSHIBA

Single Photons

1
0
1
1
0
0
1
0
1

Secret Digital Key

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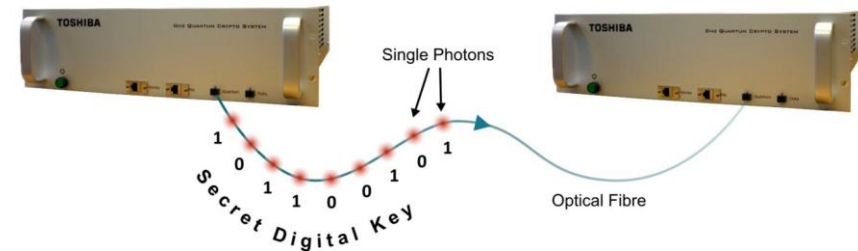
When operated close to the reverse breakdown voltage a high energy electron can collide with a lattice atom to promote an electron from VB to CB. Since a hole is also produced, we have a new electron-hole pair.

This impact ionization process is utilized to provide internal gain in avalanche photodiodes that are routinely used in optical fiber network and quantum key distribution .

Impact ionization is also important in Impatt diode which is one of the most important semiconductor devices used for generation of RF signals as high as 100-150 GHz.

1 µm

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Recombination

We have discussed briefly how the band structure is derived and methods to increase carrier concentration.
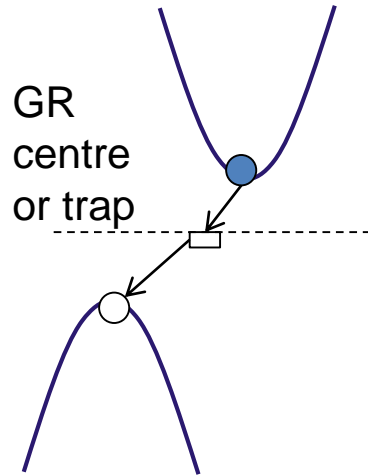How about mechanisms that can reduce carrier concentration? Can you suggest the three most important recombination process in semiconductor?

- Generation-recombination centre recombination
- Band to band (radiative) recombination
- Auger recombination
- Surface recombination

Generation-recombination (GR) centre

GR centre or trap
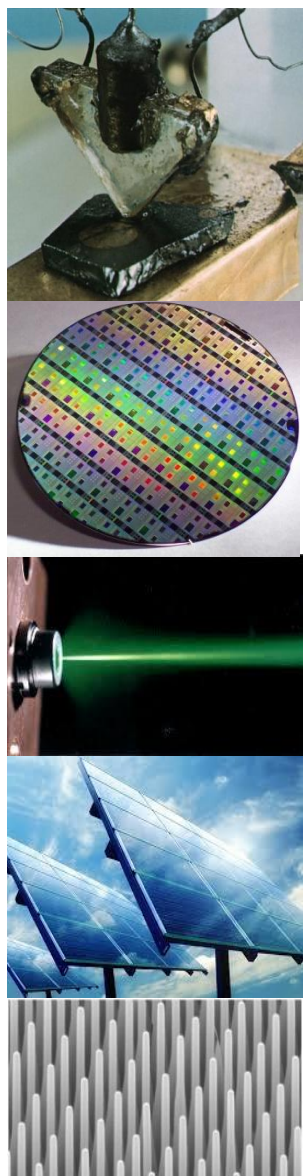
Semiconductor crystals are not perfect. Missing atoms, faults in atom stacking and presence of impurity atom will all introduce disturbance to the perfect periodicity that give rise to the band structure. These defects introduce energy levels in the energy gap.

Unlike the fixed energy levels introduced by donors and acceptors, the energy levels due to traps are distributed across the bandgap, allowing recombination process to take place "step by step". Each step involves fewer phonons than that required for band to band transition.

The so called midgap trap is most effective recombination centre as it can capture both hole and electron. The GR centre recombination is also sometimes known as **Shockley-Read-Hall (SRH)** recombination.

For low and moderate doping concentration, this is the dominant recombination process in relatively wide bandgap semiconductors such as Si, and most significant non-radiative recombination in direct bandgap materials such as GaAs.

1 μm

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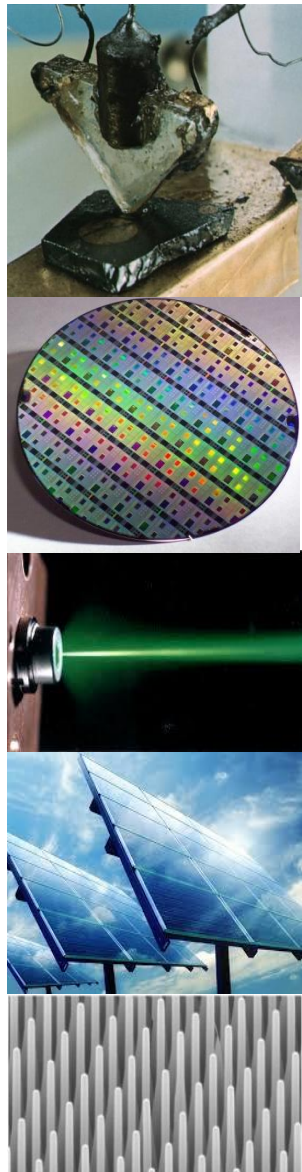
Generation-recombination (GR) centre

We note that the recombination process depends on electron, hole and trap density. However the main rate limiting factor is the capture of the minority carrier in the material. For instance in a p-type material, the minority electron will limit the recombination rate which can be described by
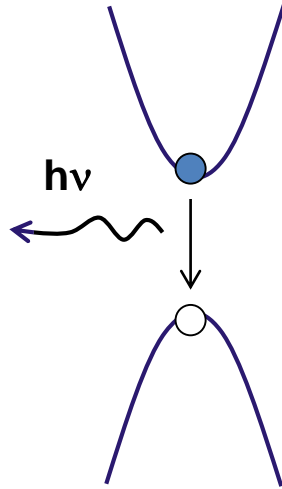
$$R_{GR} = rN_T n = An$$

r is a temperature dependent constant, N_T is the trap density and A is the trap-dependent recombination coefficient with a unit of s^{-1}.

1 μm

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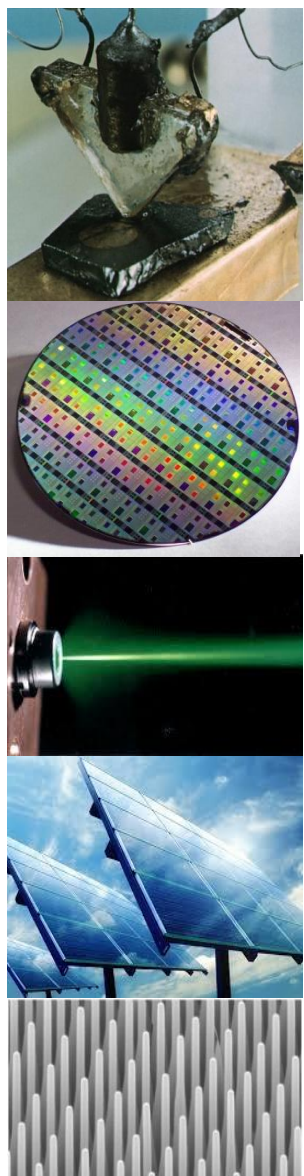
Radiative recombination

This process is the inverse of optical generation. The energy lost when an electron in CB recombines with a hole in VB is converted to a photon. Phonons are not involved. If the transition rely on phonon, a large number of phonons that are emitted simultaneuosly will be required. Hence the probability of creating a photon is much higher than energy dissipation through phonons in direct bandgap material like GaAs. Not surprisingly lasers are made from direct bandgap semiconductors such as GaAs and GaN.
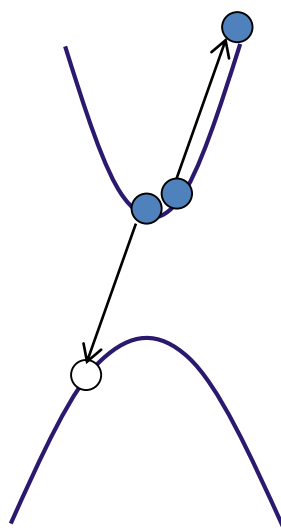
hν

The recombination rate is given by $$R_{rad} = Bnp$$

where B is the radiative recombination coefficient, n and p are the electron and hole concentrations, respectively. For GaAs B~ 10^{-10}cm^{3}s^{-1} and Si ~ 10^{-14}cm^{3}s^{-1}. Radiative recombination is weak in indirect bandgap materials because of the need to converse momentum by involving phonons.

1 µm
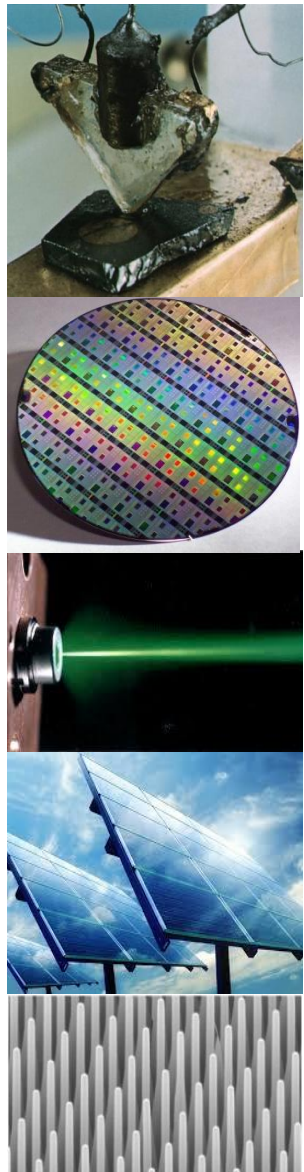
Auger recombination

This process is the inverse impact ionization. The energy and momentum produced by the electron-hole recombination resulted in a hot electron (or hole). The hot electron will subsequently dissipate the energy as heat via phonon emission.

Auger recombination is very important in emitter of solar cell, space-charge region of LEDs and base of HBTs. Because it involves electron and hole, the rate is given by
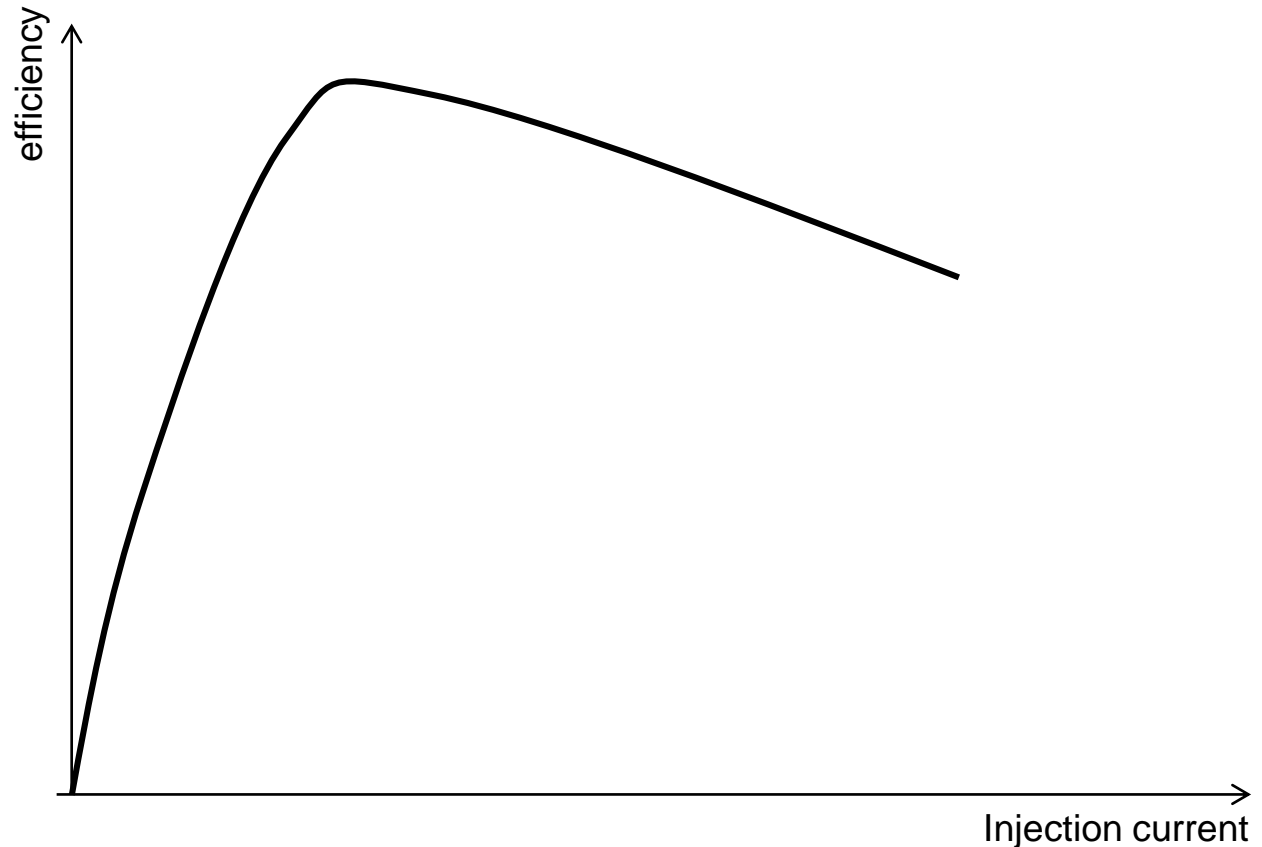
$$R_{Aug} = Cn^2 p + Dp^2 n$$

C and D are Auger recombination coefficients in $cm^6 s^{-1}$.

1 µm

Efficiency in LEDs


efficiency

Injection current
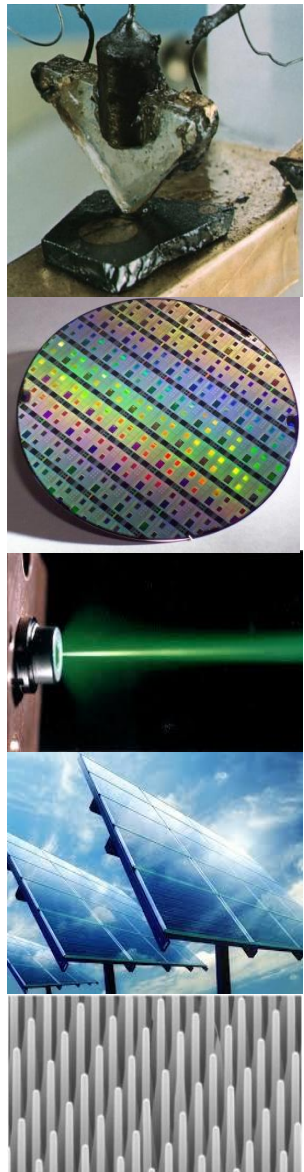
Consider a low defect density pin LED. The quantum emission is dependent on the recombination process. The process that explains the so-called droop effect is not completely verified. Many different contributions (including Auger) have been discussed. The typical efficiency curve for an LED is shown. Suggest the recombination process involved.
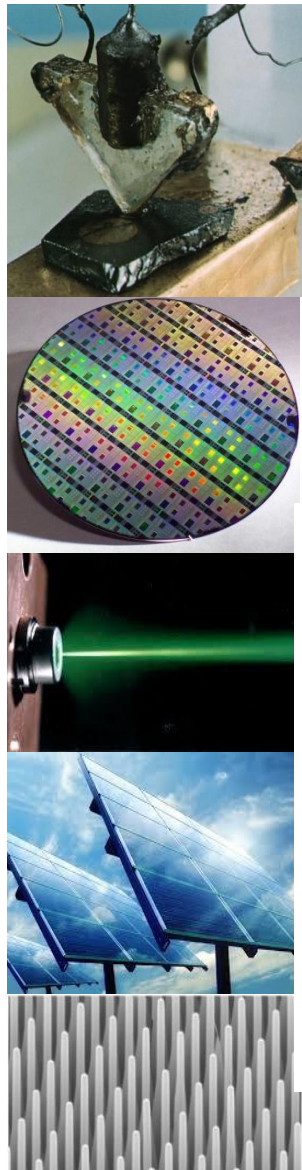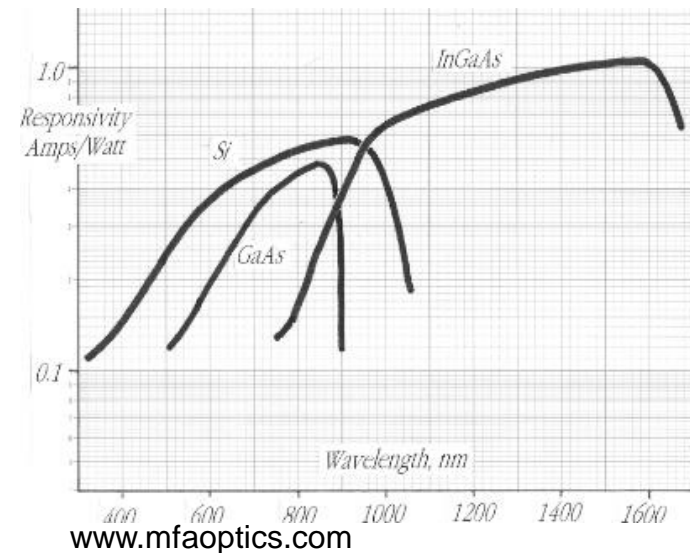
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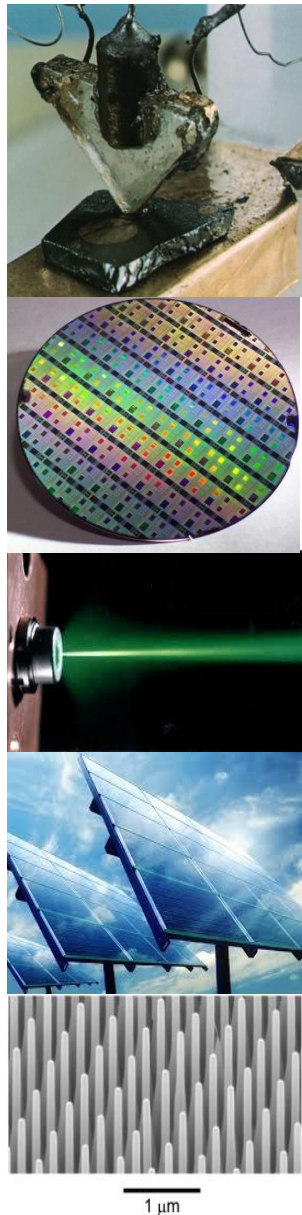
Surface recombination
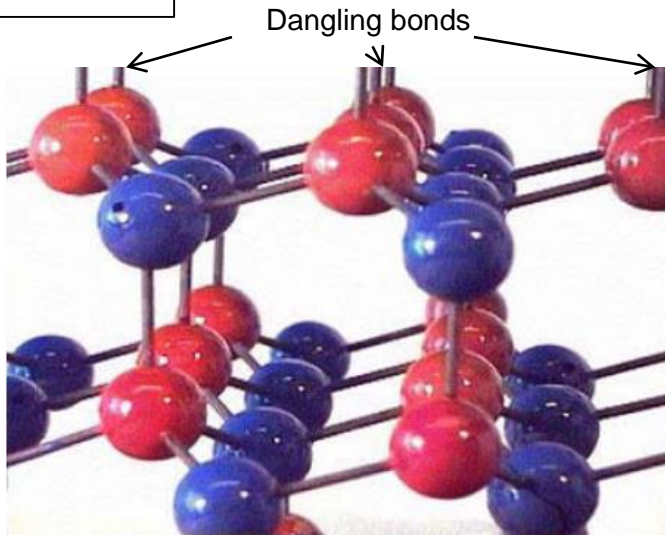
Dangling bonds

The abrupt discontinuities at the surface dangling bonds that create a large number of localized energy states or generation-recombination centres. These are called surface states. In order to characterise the rate of recombination the surface recombination velocity is introduced.

Minimizing surface recombination is the key success of SiO_2/Si that makes Si such a great material for MOSFET. In solar cell and photodetectors it is extremely important to ensure that carriers generated by light absorption do not recombine at the surface. Hence the surface recombination limits the quantum efficiency of solar cell and photodetectors at short wavelengths.

Responsivity Amps/Watt

InGaAs

Si

GaAs

1.0

0.1

Wavelength, nm

400   600   800   1000   1200   1400   1600

www.mfaoptics.com

1 µm

Surface recombination

The surface recombination rate is given by

Hole concentration at the surface

Hole concentration in n-type

$$R_{surf} = v_{th}\sigma_p N_{st}(p_s - p_{no})$$

Thermal velocity

Constant describing the effectiveness of the recombination centres

Surface recombination centre concentration

The surface recombination velocity is given by

$$S_{lr} = v_{th}\sigma_p N_{st}$$

In addition to limiting the quantum efficiency surface recombination is also a primary source of generation-recombination leakage currents in photodiodes and transistors. In this case the leakage current is usually proportional to the device perimeter. On the other hand leakage current originating from defects within the bulk semiconductors is proportional to the device area. Therefore successful termination of dangling bond is important for solar cell, photodiodes and transistors.

1 µm