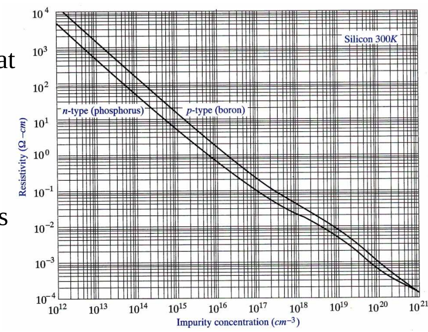
Conductivity and resistivity

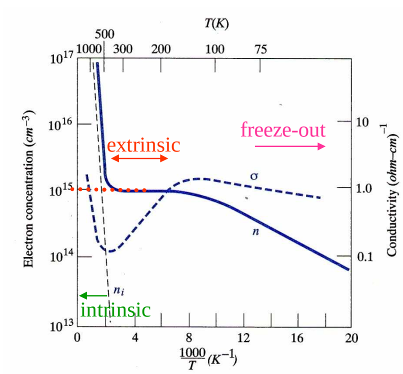
- From slide 15.3, and Ohm's Law $J_{drf} = e(\mu_e n + \mu_h p)E = \sigma E = E/\rho$
  where σ is conductivity, has units of ohm^{-1} cm^{-1}, and is a function of hole and electron concentrations and mobilities (ρ is resistivity, units: ohm.cm)
- Since mobilities are a function of impurity concentrations, then so is conductivity.
- The graph opposite shows resistivity plotted as function of impurity concentration for Si at 300K



- *E.g.*, consider a p-type semiconductor, with acceptor doping N_a ($N_d = 0$) in which $N_a >> n_i$. If we assume electron and hole mobilities are of the same order of magnitude then
  $$\sigma = e(\mu_e n + \mu_h p) \approx e\mu_h p$$
- If we also assume complete ionisation, then
  $$\sigma \cong e\mu_h N_a \cong 1/\rho$$
  i.e., The conductivity and resistivity of an extrinsic semiconductor are a function primarily of the majority charge carrier.

Conductivity

- Plot carrier concentration and conductivity against temperature →
- **Mid-temperature (extrinsic) range** - complete ionisation, and electron concentration remains essentially constant. The variation in conductivity is because mobility is a function of temperature – *i.e.* there is competition between μ_L and μ_I
- **At higher temperatures**, intrinsic carrier concentration, n_i begins to dominate the electron concentration and conductivity.
  $\sigma_i = e(\mu_e + \mu_h)n_i$ since $n = p = n_i$
- **At the lowest temperatures**, freeze-out begins to occur: electron concentration and conductivity decrease with decreasing temperature.
- **At room temperature**, phonon scattering dominates over ionised impurity scattering.



Silicon, $N_d = 10^{15}$ cm^{-3}

(This is a similar plot to that shown on slide 12.3 for *n* versus temperature.)

Velocity saturation

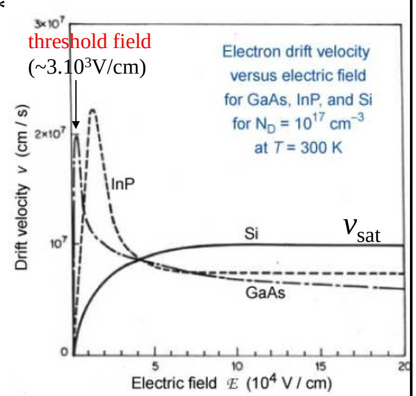
- So far, we've assumed $v_d = \mu E$, *i.e.* drift velocity will increase linearly with applied electric field.
- $v_{tot} = v_{th} + v_d$ (v_{th} is random thermal velocity)
- *e.g.* At room temperature, $v_{th} = 10^7$ cm s^{-1} for electrons in Si. $\left(\frac{1}{2} m v_{th} = \frac{3}{2} k_B T\right)$
- By comparison $\mu_e = 1350$ cm^2 V^{-1}s^{-1} apply 75 Vcm^{-1} → $v_d = 10^5$ cms^{-1} which is 1% of of thermal velocity.
  - This applied electric field does not appreciably alter the energy of the electron

- The linear relationship $v_d = \mu E$ breaks down when high fields are applied. When the carrier energy increases beyond the optical phonon energy, the probability of emitting an optical phonon increases abruptly.
- This mechanism causes the carrier velocity to saturate with increasing electric field. For carriers in silicon and other materials, which do not contain accessible higher bands, the velocity versus field relation increases monotonically.
- The analysis is more complex for materials such as GaAs and InP, which contain multiple closely spaced conduction band minima.

Negative Differential Resistance

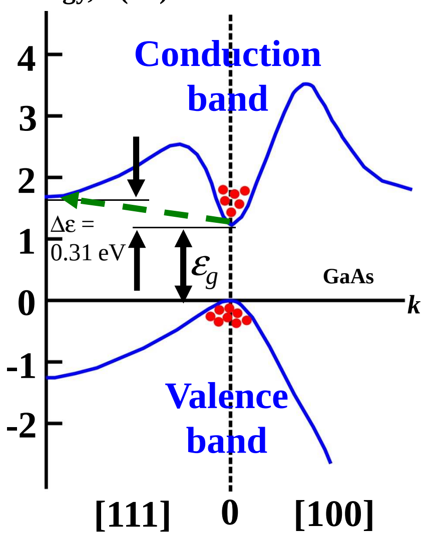
- As a first approximation $v_{sat} = \sqrt{2\varepsilon_{phonon}/m^*}$
- i.e., Materials with a small m* and high optical phonon energy are more likely to have a high v_{sat}. Materials with multiple band minima can have a rather low v_{sat}, relative to the peak velocity, if the carriers in the higher minima have a larger m*.,

- Now consider GaAs
  - low E: v_d, E linear, $\mu \sim 8500$ cm^2 V^{-1}s^{-1}
  - as field increased, v_d peaks, then decreases
  - negative slope of represents a negative differential mobility
- *i.e.* over certain voltage ranges, current is a decreasing function of the voltage.



Note, even in this NDR region the static resistance of the circuit element is positive, whereas the slope of the resistance curve is negative (Ohms law not obeyed).

Negative Differential Resistance



- At CB minimum [Γ], $m_e^* = 0.067m_e$ → large mobility (8500 cm^{2}V^{-1}s^{-1}) $\left(\mu_e = \frac{e\tau_{ce}}{m_e^*}\right)$
- Because of their high mobility, electrons are easily accelerated by a strong E-field, and scattered into the satellite valley (L).
- Here $m_e^* = 0.55m_e$ and effective density of states is much higher
- This larger m^* yields a smaller mobility, and the inter-valley transfer results in a decreasing average drift velocity with electric field (negative differential mobility).
- This is called the **GUNN effect** – useful for producing oscillators (signal generators and power supplies)

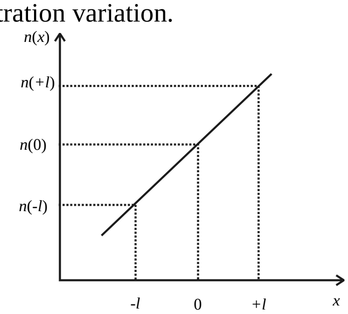
http://www.st-andrews.ac.uk/~www_pa/Scots_Guide/RadCom/part5/page1.html

Neaman p692

http://www.nhn.ou.edu/~johnson/Education/Juniorlab/Microwave/Gunn%20Effect.pdf

Diffusion

- Particles flow from region of high concentration to region of low concentration – **diffusion current.**
- Simplified analysis – assume 1D electron concentration variation.
- We will calculate the current (J) by considering the net flow of electrons per unit time passing across the x = 0 plane.
- l is the mean-free path of an electron, *i.e.* the average distance travelled between collisions, $l = v_{th}\tau_{ce}$.



- Thus, one half of the electrons at $x = -l$ will be travelling to the right, and one half of the electrons at $x = +l$ will be travelling to the left, and both groups will cross the x = 0 plane.

Diffusion

- Hence, $J = -e\left[\tfrac{1}{2}n(-l)v_{th} - \tfrac{1}{2}n(+l)v_{th}\right] = \tfrac{-ev_{th}}{2}\left[n(-l) - n(+l)\right]$

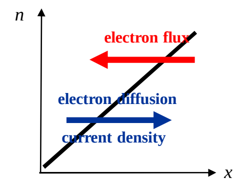
- Using a Taylor expansion around $x = 0$, keeping only first two terms:

$$J = \tfrac{-ev_{th}}{2}\left\{\left[n(0) - l\tfrac{dn}{dx}\right] - \left[n(0) + l\tfrac{dn}{dx}\right]\right\}$$
$$= +ev_{th}l\tfrac{dn}{dx}$$

- *i.e.* electron diffusion current is proportional to density gradient of electron concentration where the conventional current density is in *x*-direction.

- The diffusion current is also written as

$$J_{e,x,dif} = eD_e\frac{dn}{dx}$$



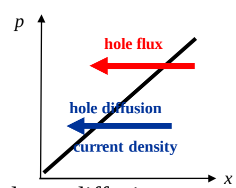
where D_e is the **electron diffusion coefficient** ($cm^2\ s^{-1}$)

$$D = v_{th}\,l$$

Diffusion

- Since holes are positively charged, then the conventional diffusion current density is in the negative *x*-direction:

$$J_{hx,dif} = -eD_h\frac{dp}{dx}$$



- where D_h is the **hole diffusion coefficient.**

- Therefore **total current density** is made up of two drift and two diffusion terms…

$$J = en\mu_e E_x + ep\mu_h E_x + eD_e\frac{dn}{dx} - eD_h\frac{dp}{dx} \qquad \text{(in 1D)}$$

- **Mobility** gives an indication of how well a carrier moves in a semiconductor due to the force of an electric field.
- **Diffusion coefficient** gives an indication of how well a carrier moves in a semiconductor as a result of a density gradient.
- But these two terms are not independent parameters:

  the **Einstein relation** relates the two…