# Outline

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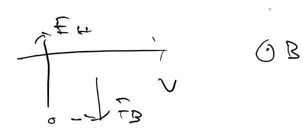
Why study?
- Hall effect in general allows determination of carrier types (ie electrons in metals, p vs n type)
- For semiconductor can determine mobility of carriers which is important for industrial application

Background

**Band Theory**
- Discrete energy levels of single atom overlap and form bands as atoms move closer together (Pauli exclusion principle)
- Band gaps come from periodicity of lattice potential leading to forbidden region
  - (to be specific mention at BZ wavefunction can be centered at lattice sites or shifted resulting in splitting of energy levels)
- Valence band is highest filled at T=0
- Conduction band is next band up
  - Metal has fermi energy (highest filled energy level) within band
  - Insulator/semiconductor has filled valence band (difference is size of gap, usually define semiconductors with gap ~1.5eV ie on order kT)

For holes




**Semiconductors**
- Can be doped by replacing small fraction of atoms with donor or acceptor atoms (which either give electrons or take resulting in holes)
  - N type vs p type
- Extrinsic region where doped carriers dominate, intrinsic where electrons ~= holes

**Hall effect**
- Lorentz force, draw picture of forces
- Steady state forces equal

$F = pev(sd)$ $\quad J = \frac{I}{(sd)} = pev$ $\quad F_H = -vB_z$

$$R_H = \frac{F_H}{J_x B_z} = \frac{-vB_z}{pev\,B_z} = \frac{-1}{pe}$$

if had $e^-$ would be $R_H = \frac{1}{ne}$

- More accurately if both hole and electron carriers get:
- Note: defined slightly different than write up, get extra negative sign

$$R_H = \frac{\mu_h^2 p - \mu_e^2 n}{e(\mu_h p + \mu_e n)^2}$$

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- Melissanos reference

**Van der Pauw Technique**
- More accurate measurement method than standard measurements which introduce errors in what is being measured
  - If needed to explain essentially start with infinite plane apply current, measure voltage at four points, can conformally map to any slab with no holes
- Uses four probes at ends of material (draw picture of square with corners shaded)
- Transresistance defined as R_AB_CD = V_CD/I_AB
  - Can also take reverse as consistency check and for averaging
- Can find resistivity from

$$\rho = \frac{\pi d}{ln(2)} \cdot \frac{(R_{AB,CD} + R_{AD,CB})}{2} \cdot f\left(\frac{R_{AB,CD}}{R_{AD,CB}}\right)$$

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$$R_H = \frac{E}{JB} = \frac{-V/d}{\frac{I}{ds} B} = \frac{-Vs}{IB} = \frac{-Rs}{B}$$

- Where f(x) = *1/cosh(ln(x)/2.403)* (derived for us)
- Hall coefficient from R_AC,BD and R_BD,CA where average is used as R_t and **R_H = -V*s/(I*B) = -R_t*s/B**
  - s=thickness , 1.5mm

**Experiment**
- Germanium sample (10mm x 10mm x 1.5mm) in cryostat cooled by liquid nitrogen
- Electrometer-measures voltage
- Sourcemeter-applies current
- Gaussmeter-measures B field
- Electromagnet-applies B Field
- Temperature controller-measures and controls sample temperature
- Gold box-controlled by labview to take measurements every 5K
- Cool germanium to ~90K, take measurements for positive, negative, and zero B field every 5K up to 350K

**Results:**
- Shown for .5 mA current and 5000 Gauss field
- Calculated hall coefficient, resistivity, conductivity, hole concentration, hole mobility

From hall coefficient being negative, know p type. Sign of Bfield doesn't matter because hall voltage sign flips with B field

We see 'hall coefficient inversion' since in general u_e>u_h and from complete equation above R_h switches signs when n>(u_h/u_e)^2 p (occurs in intrinsic region) **at 272K**

At room T: R**_H = .011 m^3/C, resistivity = .868 ohm*m**

From resistivity curve can easily switch from extrinsic to intrinsic. At **243K** w/ resistivity = 9.03 ohm*m

In general for intrinsic semiconductor increased temperature decreases resistivity as electrons excited to conduction band. So region of decreasing resistivity is intrinsic other is extrinsic.

notice difference in resistivity between when magnetic field is on (magnetoresistance) and normal resistance. Makes sense that with magnetic field resistance decreases. Not all particles at same speed such that transverse motion is nonzero (ie E != vB for all v). Thus there is an increased trajectory taken by particle reducing the mean free path in the net direction of current. This decreases the resistance.

Resistivity increases in extrinsic region because with increasing temperature the mobility decreases seen in that figure. Resistivity is inversely proportional to mobility so get that curve.

Mobility decreases because the time between thermal collisions decrease with increasing temperature, and mobility is proportional to that time

Mobility/concentration curves go negative because of invalid assumption that R_H still = 1/ep in intrinsic region (remember hall coefficient inversion)

In extrinsic region **2.33*10^19 (1/m^3) holes-**saturated; saturation T defined by gap separation of acceptor level from valence band

Find mobility through equation on right assuming n=0

Can fit extrinsic region mobility to power law aT^-c and get **c= 1.763** compared to theoretical 1.5 (ref Melissanos)

Theoretical value comes from considering avg velocity picked up in mean free time

Also lattice vibrations affect carrier scattering decreasing mean free path

In extrinsic region **2.33*10^19 (1/m^3) holes-**saturated; saturation T defined by gap separation of acceptor level from valence band

From equation on right, we fit resistance in extrinsic region to power law and get gT^f, f=1.94.

Extrapolating to inversion point T=272K and substituting into b get **b=1.4** ie at the inversion point the electron mobility is 1.4 times the hole mobility which is close to other observations.

$$R_H = \frac{\mu_h^2 p - \mu_e^2 n}{e(\mu_h p + \mu_e n)^2}$$

For $n \sim 0$ in extrinsic

$$R_H = \frac{1}{ep}$$

or $p = \frac{1}{eR_H}$

$$\mu_H = \frac{1}{\rho e p}$$

$$\frac{1}{\rho} = e \cdot (n\mu_e + p\mu_h)$$

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at $R_H = 0$ $\quad nb^2 = p$ $\quad b = \frac{\mu_e}{\mu_h}$

in intrinsic region $p = N_a + n$

$N_a =$ saturated holes in extrinsic

$$n = \frac{N_a}{b^2 - 1}$$

also know $\sigma_0 = e[\mu_e n + \mu_h(N_a + n)]$

$T_0 =$ inversion $= 272$ K

$\sigma_e(T = T_0) = e\,\mu_h N_a$ (since $n = 0$)

$\mu_h(T)$ can be extrapolated to $T_0$

$$\frac{\sigma_0}{\sigma_e(T = T_0)} = \frac{N_a + n(1+b)}{N_a} \rightarrow b = \frac{R_e(T_0)}{R_e(T_0) - R_0}$$