Georgia Tech

ECE 4813

Semiconductor Device and Material Characterization

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As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, *Semiconductor Device and Materials Characterization*. ***Every serious microelectronics student should have a copy of this book!***

Doping

Plasma Resonance

Free Carrier Absorption

Infrared Spectroscopy

Photoluminescence

Hall Measurements

Magnetoresistance

Time of Flight

Plasma Resonance and Reflectivity Minimum

- ***Electron/hole plasmas are ensembles of free carriers that can, at certain frequencies, oscillate in concert as a group.***
- ***Such a plasma resonance exists whose frequency / wavelength (ν=c/λ) is determined by the free carrier density.***

$$\lambda_{plasma} = \frac{2\pi c}{q}\sqrt{\frac{K_s \varepsilon_O m^*}{n}}$$

- ***Good for p (or n) > ~10^{18} cm^{-3}***
- ***Since plasma resonances are hard to detect in practice, most of the time, free carrier densities are determined by empirical reflectivity minimums…***

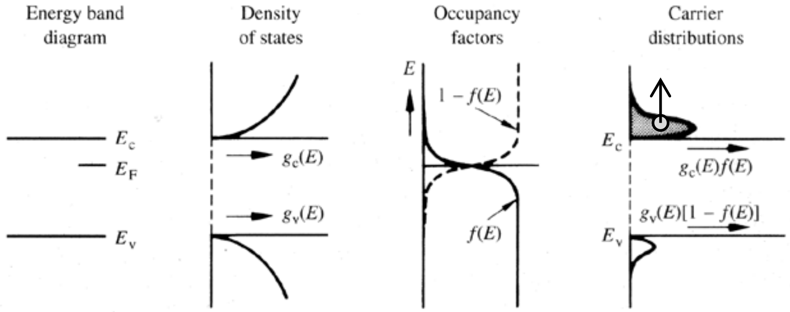
$$n = \left(A\lambda_{plasma} + B\right)^C$$

- ***… or free carrier absorption***

Free Carrier Absorption

- ***Free carrier absorption occurs within the conduction or valance band (not between).***
  - ***For example a conduction electron is absorbs an IR photon and is promoted into a higher energy state still inside the conduction band***

$$\alpha_{fc} = \frac{q^3 \lambda^2 p}{4\pi^2 \varepsilon_O c^3 n \left(m^*\right)^2 \mu_p}$$



(a) E_F above midgap

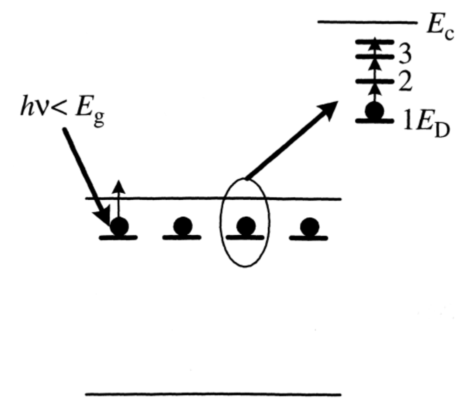
- ***In practice, empirical fitting is used***

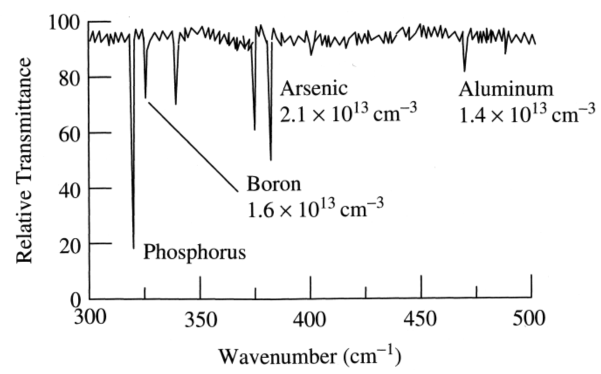
$$\alpha_{fc} = A\lambda^2 p$$

- ***Generally measured using Fourier Transmission Infrared (FTIR) Spectrometer***
- ***Good for p (or n) > ~10^{17} cm^{-3}***

Infrared Spectroscopy

- *Measures dopant concentrations (low temperature) and can be used at room temperature to measure free carrier absorption.*
- *Cryogenic temperatures are used to freeze carriers into their dopant ground state*
- *IR (very small energy) light is used to excite electrons/holes into their dopant “excited state” creating sharp absorption lines*
- *Absorption line intensity is calibrated to dopant density*

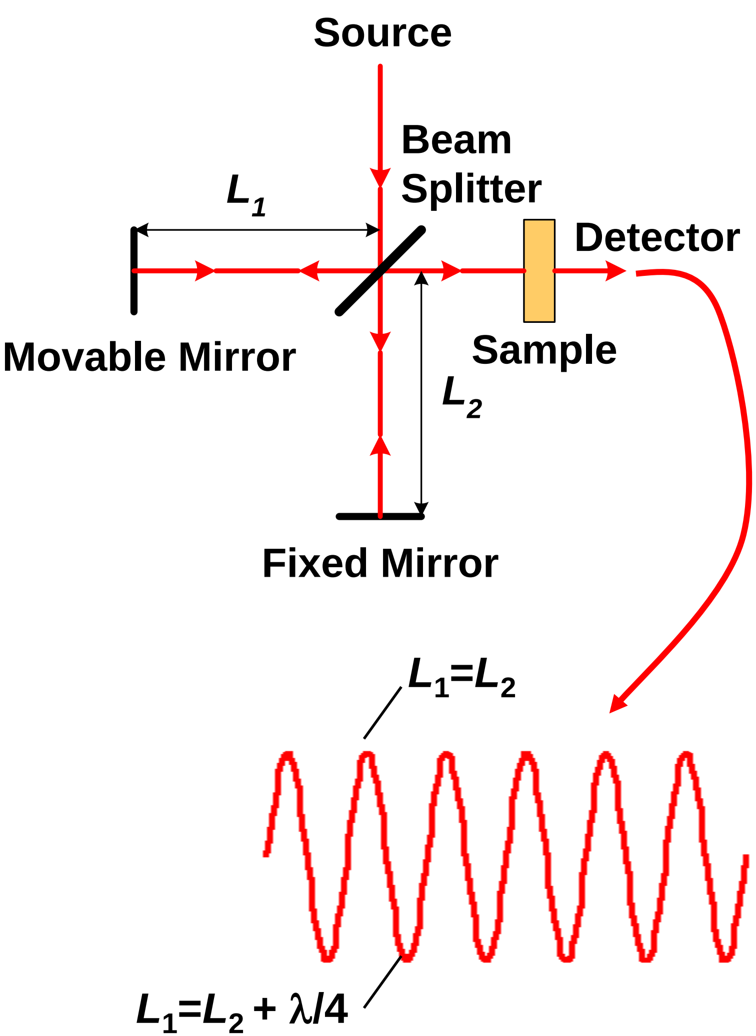




- *Good for N_A (or N_D) > ~10^{11} cm^{-3}*

Interferometer

- Let source be $\cos 2\pi f x$
  - f: frequency of light
  - x: movable mirror location
- $L_1 = L_2$
  - Constructive interference
  - Maximum detector output
- $L_1 = L_2 + \lambda/4$
  - Destructive interference
  - Zero detector output



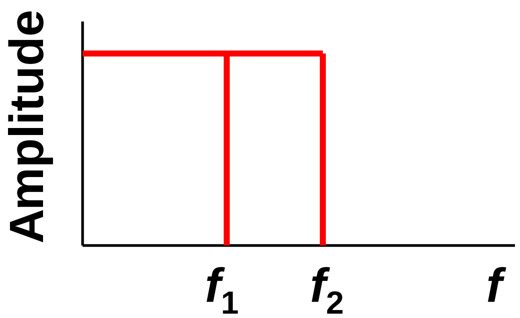
Fourier Transform Infrared Spectroscopy

- Fourier transform infrared spectroscopy (FTIR)

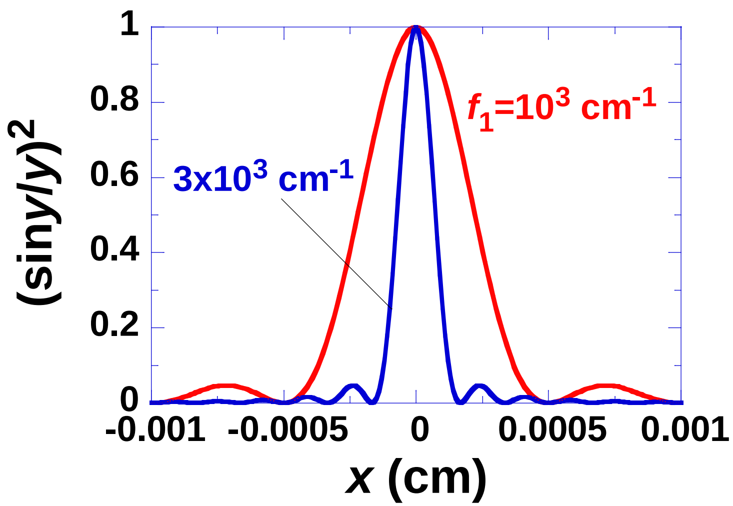
$$I(x) = B(f)[1 + \cos 2\pi x f] \qquad I(x) = \int_0^f B(f)[1 + \cos 2\pi x f]\,df$$

$$I(x) = \int_0^{f_1} A \cos 2\pi x f\, df = A f_1 \frac{\sin 2\pi x f_1}{2\pi x f_1}$$

$$B(f) = \int_{-\omega}^{\omega} I(x) \cos 2\pi x f\, dx$$



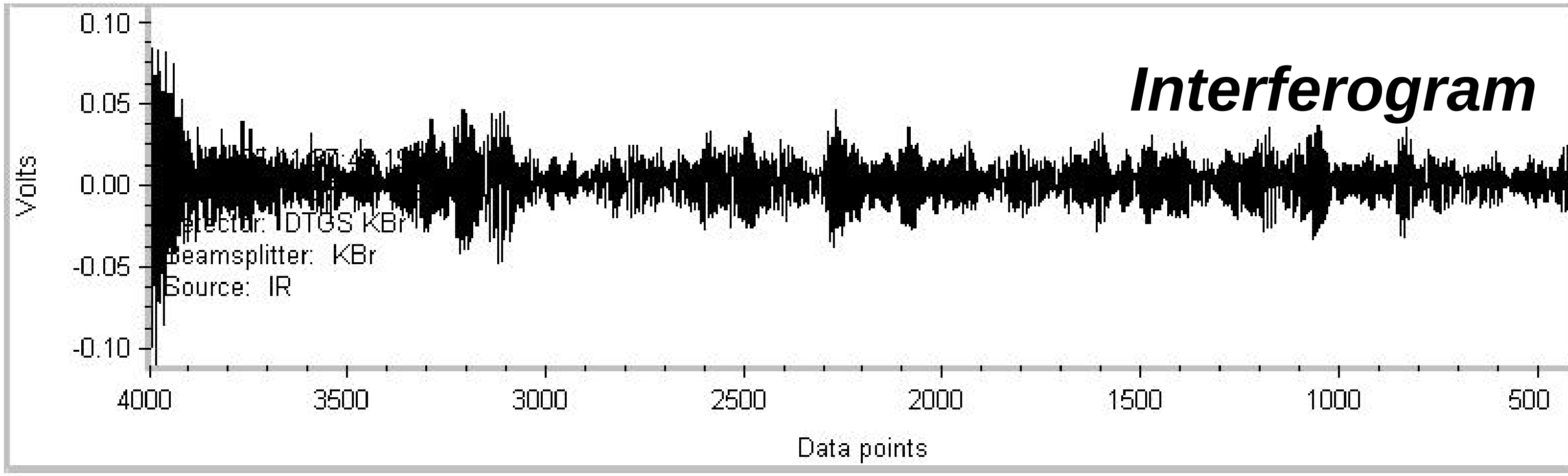
Spectrum

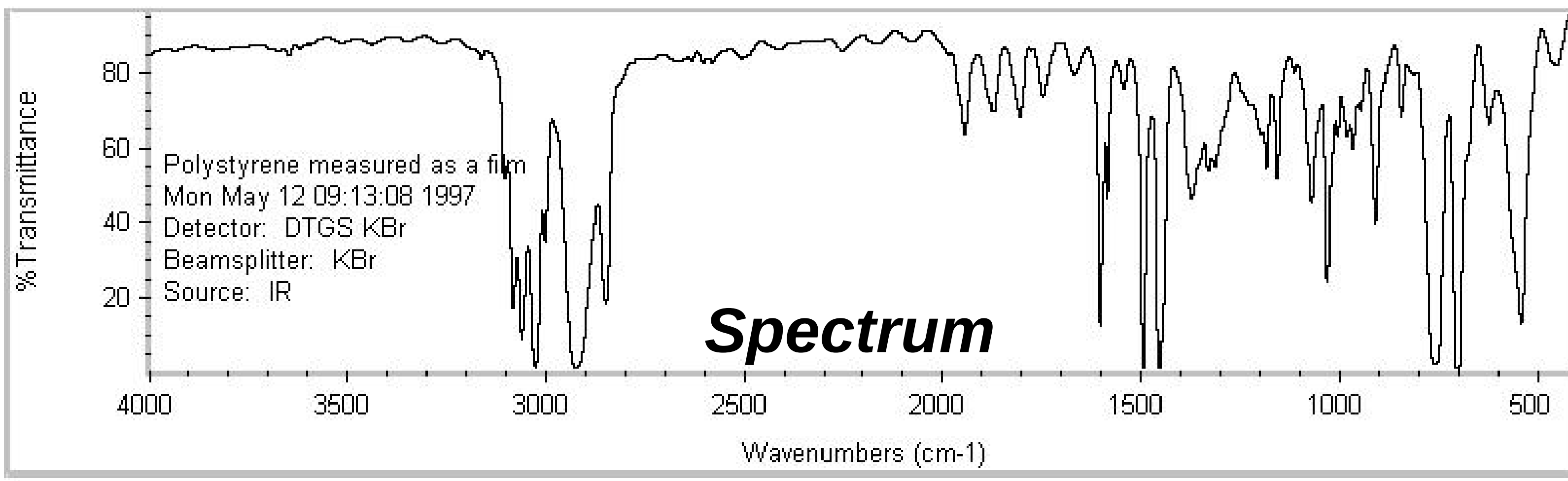


Interferogram

In a Fourier spectrum, frequency bandwidth determines resolution.

Interferogram - Spectrum

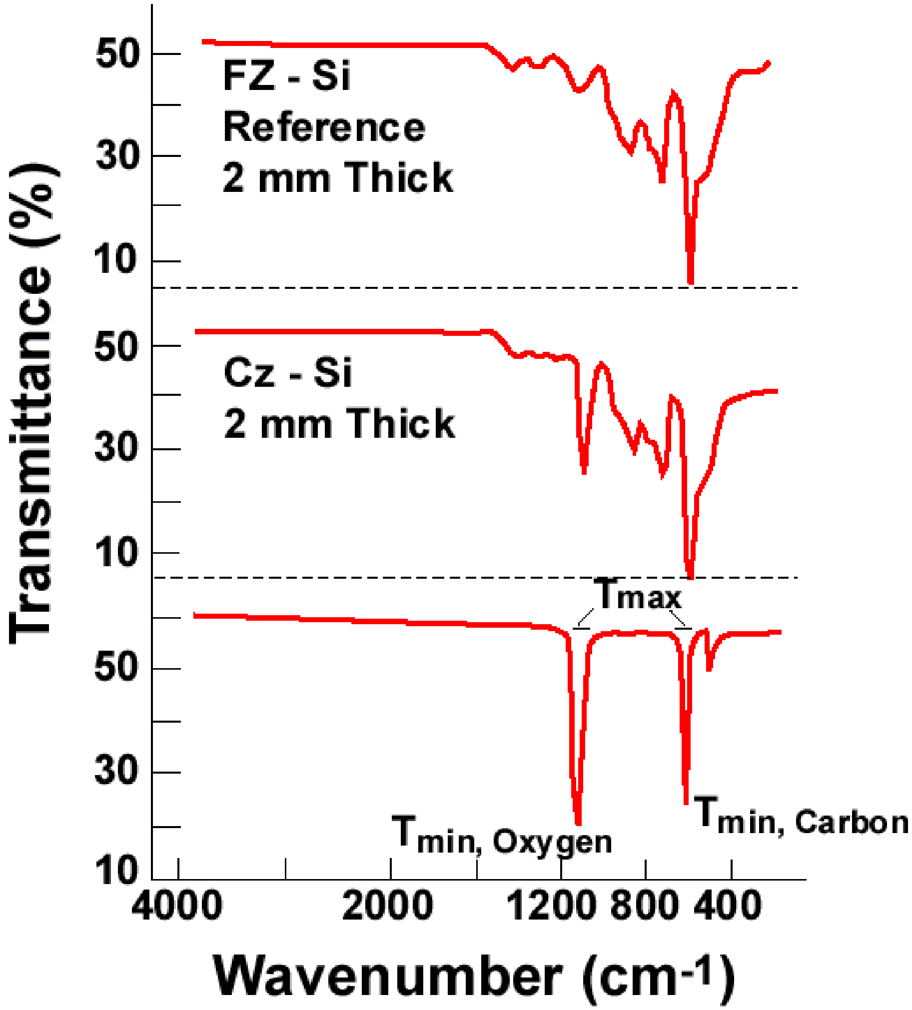




www.chem.orst.edu/ch361-464/ch362/irinstrs.htm

FTIR Applications

- Determine oxygen and carbon density by transmission dip



Mobilities

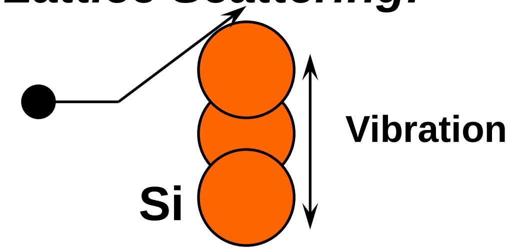
- ***Conductivity*** **Mobility:** $\mu_p = 1/qp\rho$
  - **Majority carrier mobility; need carrier concentration and resistivity**
- ***Drift*** **Mobility:** $\mu_p = v_d/\varepsilon$
  - **Minority carrier mobility**
  - **Need drift velocity and electric field (Haynes-Shockley experiment)**
- ***Hall*** **Mobility:** $\mu_H = R_H/\rho$
  - **Need Hall measurement**
  - **Hall mobility does not necessarily equal conductivity mobility**
- ***MOSFET*** **Mobility:**
  - **MOSFET mobility lowest, carriers are scattered at the Si-SiO_2 interface**
  - **Interface is microscopically rough**

Mobility

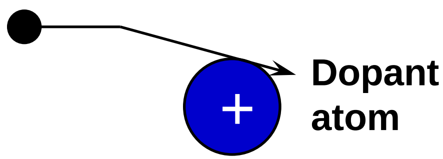
- Electron/hole mobility is a measure of carrier scattering in the semiconductor
  - Lattice scattering
    - Silicon atoms
  - Ionized impurity scattering
    - Dopant atoms
  - Interface scattering
    - Surface roughness at SiO_2/Si interface
    - Polar scattering
- Silicon bulk
  - $\mu_n \approx 3\ \mu_p$
  - MOSFET mobility (effective mobility) ≈ 0.3 bulk mobility

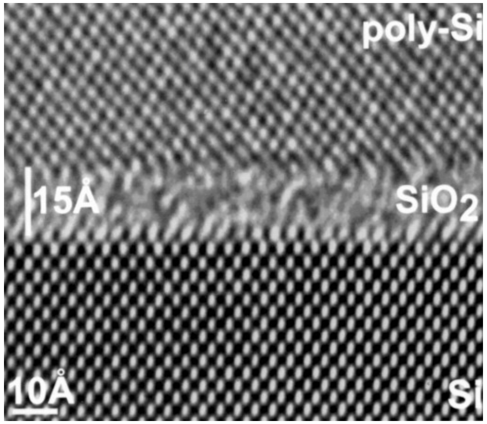
$$\frac{1}{\mu} = \frac{1}{\mu_l} + \frac{1}{\mu_i} + \frac{1}{\mu_s}$$

Lattice Scattering:



Ionized Impurity Scattering:



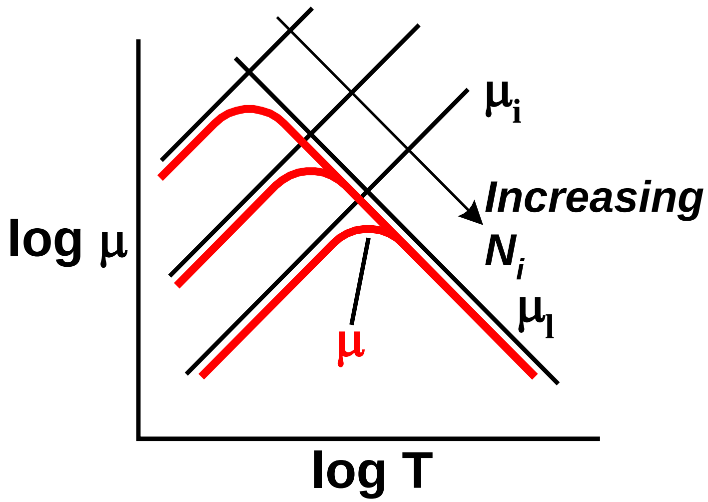


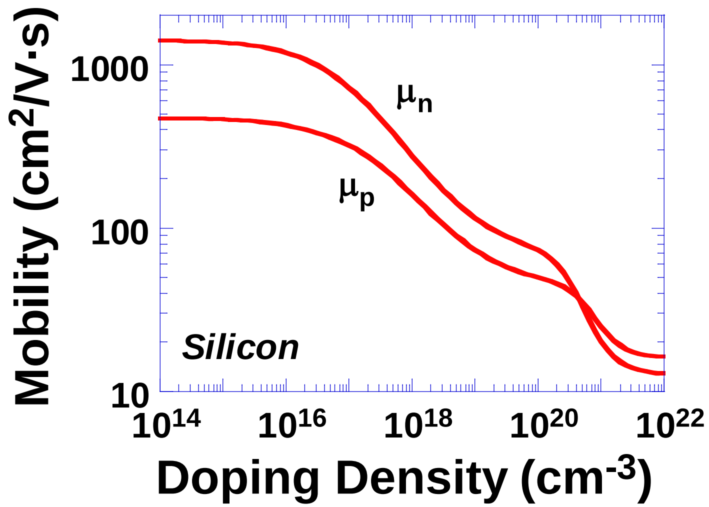
Courtesy of M.A. Gribelyuk, IBM.

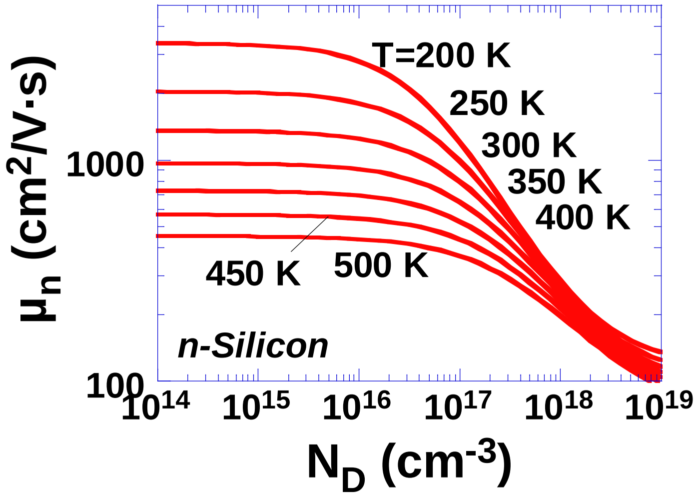
Mobilities

- **For bulk semiconductors, lattice and ionized impurity scattering dominate the mobility**

$$\mu_l = T^{-1.5}; \mu_i = \frac{T^{1.5}}{N_i}$$



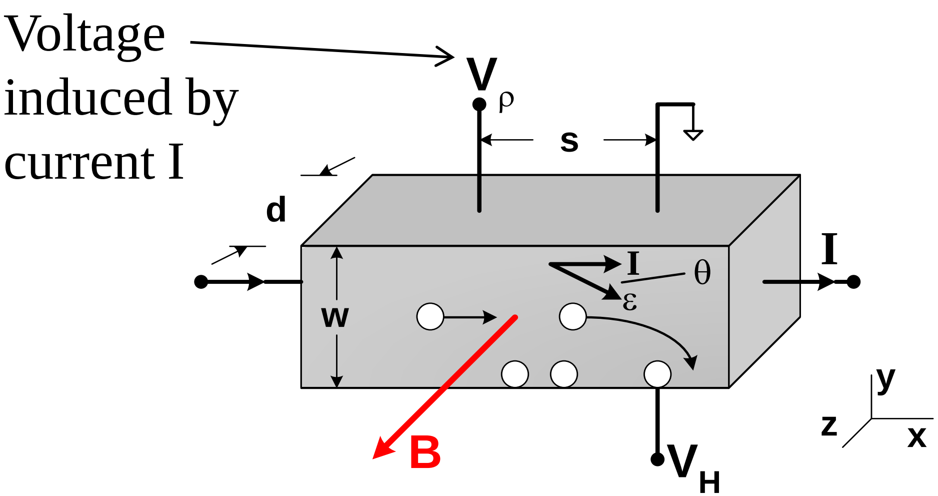




“Simple” Hall Effect

- Hall effect is commonly used during the development of new semiconductor material
- Resistivity, carrier concentration AND mobility can all be determined simultaneously
- Lorentz Force – deflection of free carriers by an applied magnetic field
- Temperature dependent Hall is very powerful and can elucidate scattering mechanisms (plotting mobility vs T^a), and determine dopant activation energies
  - Compensated Dopant Freeze out regime – Arrhenius slope results in E_A
  - Uncompensated Dopant Freeze out regime – Arrhenius slope results in $E_A/2$
  - At moderate temperatures, $p \sim (N_A - N_D)$
  - At elevated temperatures, $p \sim n_i$

“Simple” Hall Effect



Lorentz Force

$$\vec{F} = q(\vec{\varepsilon} + \vec{v} \times \vec{B})$$

$$I = qApv_x = qwdpv_x$$

In steady state, the magnetic force is balanced by the induced electric field

$$\varepsilon_y = Bv_x = \frac{BI}{qwdp}$$

Hall voltage

$$\int_0^{V_H} dV = V_H = -\int_w^0 \varepsilon_y dy = -\int_w^0 \frac{BI}{qwdp} dy = \frac{BI}{qdp}$$

$$R_H = \frac{dV_H}{BI}$$

Hall coefficient [m³/C or cm³/C]

"Simple" Hall Effect

- **Resistivity is simply found from the voltage drop along the length (no magnetic field),**

$$\rho = \frac{dw}{s}\frac{V_\rho}{I}$$

- **Carrier density** $p = \frac{r}{qR_H}; \quad n = -\frac{r}{qR_H}$

(*r* ~ 1 - 2, Hall scattering factor)

- **Mobility**

$$p = \frac{r}{qR_H}$$

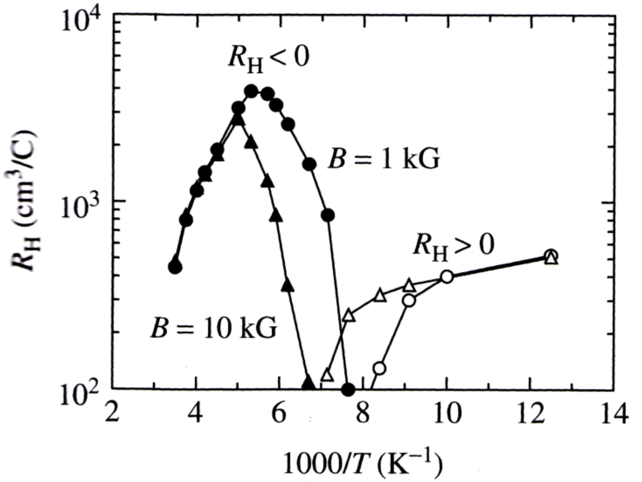
$$q\mu_p p = \sigma = \frac{r\mu_p}{R_H} = \frac{\mu_H}{R_H}$$

$$\mu_H = \left|\sigma R_H\right| = r\mu_p$$

Detailed Hall Effect

- **The Hall Coefficient for both electrons and holes present in the same material is in general:**

$$R_H = r\left(\frac{\left(p-\left(\frac{\mu_n}{\mu_p}\right)^2 n\right)+(\mu_n B)^2(p-n)}{q\left[\left(p+\left(\frac{\mu_n}{\mu_p}\right)n\right)^2+(\mu_n B)^2(p-n)^2\right]}\right)$$



Detailed Hall Effect

- **The Hall Coefficient is in general:**

$$R_H = r\left(\frac{\left(p-\left(\frac{\mu_n}{\mu_p}\right)^2 n\right)+(\mu_n B)^2(p-n)}{q\left[\left(p+\left(\frac{\mu_n}{\mu_p}\right)n\right)^2+(\mu_n B)^2(p-n)^2\right]}\right)$$

- **At low fields ($B<<1/\mu_n$)…**

$$R_H = \frac{r\left(p-\left(\frac{\mu_n}{\mu_p}\right)^2 n\right)}{q\left(p+\left(\frac{\mu_n}{\mu_p}\right)n\right)^2} \approx \frac{r}{qp} \quad or \quad -\frac{r}{qn}$$

$$r = \frac{\langle \tau^2 \rangle}{\langle \tau \rangle^2} \quad \text{where } \tau \text{ is the mean time between collisions}$$

- **And at high fields ($B>>1/\mu_n$)…**

$$R_H = \frac{r}{q(p-n)}$$

Two Layer Hall Effect

- Sometimes, a semiconductor has two different conduction layers (surface inversion, fermi-level pinning, substrate layers, n-p junctions or p+/n or n+/n layers)
- The Hall coefficient is then a weighted sum of both layers and can be either positive or negative leading to confusion (shown for the low B field limit):

$$R_H = R_{H1}\left(\frac{t_1}{t_{total}}\right)\left(\frac{\sigma_1}{\sigma}\right)^2 + R_{H2}\left(\frac{t_2}{t_{total}}\right)\left(\frac{\sigma_2}{\sigma}\right)^2$$

$$where \quad \sigma = \left(\frac{t_1}{t_{total}}\right)\sigma_1 + \left(\frac{t_2}{t_{total}}\right)\sigma_2$$

$$and \quad t_{total} = t_1 + t_2$$

Two Layer Hall Effect (more detail)

- **The Hall coefficient is then a weighted sum of both layers and can be either positive or negative leading to confusion:**

$$R_H = \left(\frac{t_{total}\left[\left(R_{H1}\sigma_1^2 t_1 + R_{H2}\sigma_2^2 t_2\right) + R_{H1}\sigma_1^2 R_{H2}\sigma_2^2\left(R_{H1}t_2 + R_{H2}t_1\right)B^2\right]}{\left(\sigma_1 t_1 + \sigma_2 t_2\right)^2 + \sigma_1^2\sigma_2^2\left(R_{H1}t_2 + R_{H2}t_1\right)B^2} \right)$$

Low B Field

High B Field

$$R_H = R_{H1}\left(\frac{t_1}{t_{total}}\right)\left(\frac{\sigma_1}{\sigma}\right)^2 + R_{H2}\left(\frac{t_2}{t_{total}}\right)\left(\frac{\sigma_2}{\sigma}\right)^2$$

$$where \quad \sigma = \left(\frac{t_1}{t_{total}}\right)\sigma_1 + \left(\frac{t_2}{t_{total}}\right)\sigma_2$$

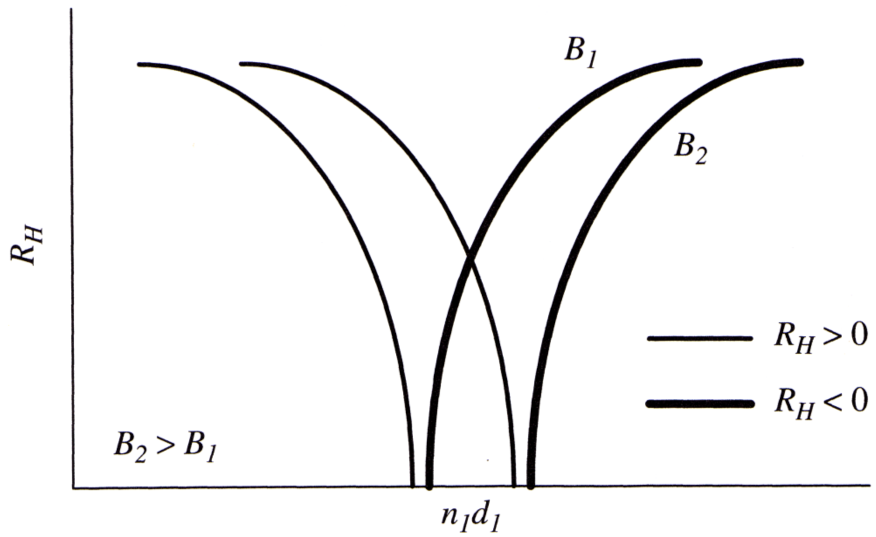
$$and \quad t_{total} = t_1 + t_2$$

$$R_H = \left(\frac{R_{H1}R_{H2}t_{total}}{R_{H1}t_2 + R_{H2}t_1}\right)$$

Two Layer Hall Effect (more detail)

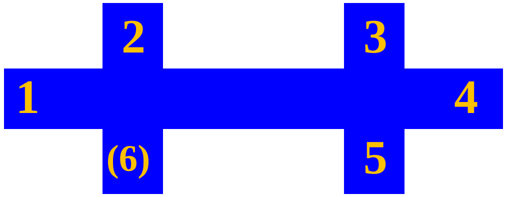
- The Hall coefficient is then a weighted sum of both layers and can be either positive or negative leading to confusion (generally):

$$R_H = \left(\frac{t_{total}\left[\left(R_{H1}\sigma_1^2 t_1 + R_{H2}\sigma_2^2 t_2\right) + R_{H1}\sigma_1^2 R_{H2}\sigma_2^2\left(R_{H1}t_2 + R_{H2}t_1\right)B^2\right]}{\left(\sigma_1 t_1 + \sigma_2 t_2\right)^2 + \sigma_1^2\sigma_2^2\left(R_{H1}t_2 + R_{H2}t_1\right)B^2} \right)$$

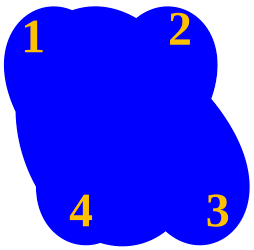


Hall Effect Measurements

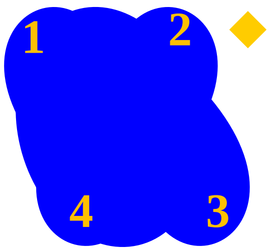
- Two approaches:
  - Hall Bar (5 or 6 contacts)



  - Van der Pauw configuration
    - Based on Conformal mapping theory
    - Contacts assumed point sources
    - Uniform thickness
    - Cannot contain isolated (interior) holes



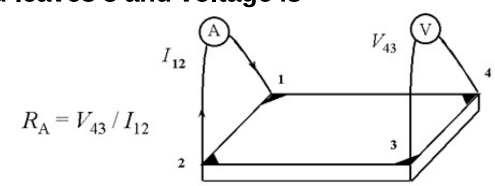
Hall Effect Measurements

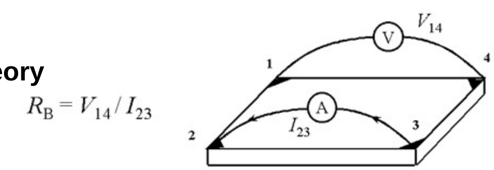


◆ Van der Pauw configuration

- **Measure resistivity first by "perimeter measurements"…**
  - Example: determine $R_{12,34}$ where current goes in 1 and leaves 2 and voltage is measured between terminals 3 and 4. Next determine $R_{23,14}$ where current goes in 2 and leaves 3 and voltage is measured between terminals 1 and 4.
  - Use:

$$\rho = \left(\frac{\pi t}{\ln(2)}\right)\left(\frac{R_{12,34} + R_{23,14}}{2}\right)F$$

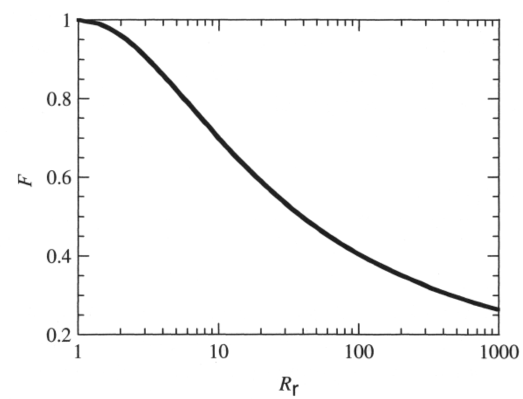




  - …where F is a symmetry term derived from conformal mapping theory
  - F is determined from:

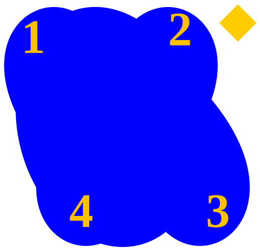
$$\left(\frac{R_r - 1}{R_r + 1}\right) = \frac{F}{\ln(2)} \cosh^{-1}\left(\frac{e^{\left(\frac{\ln(2)}{F}\right)}}{2}\right)$$

$$where \quad R_r = \frac{R_{12,34}}{R_{23,14}}$$

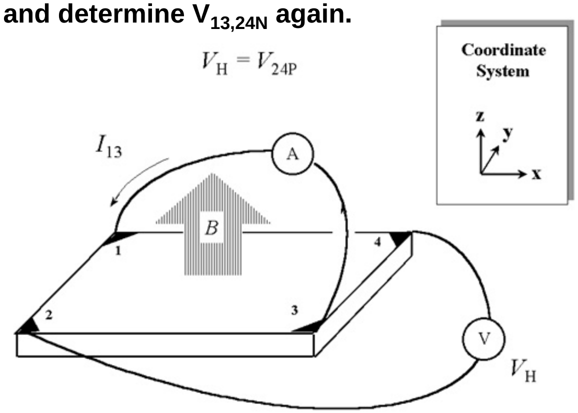


Differs some from your text. For details see http://www.nist.gov/pml/semiconductor/hall_resistivity.cfm

Hall Effect Measurements



- Van der Pauw configuration
  - Now measure the Hall voltage using "Crossing configurations"
    - Example: Apply the magnetic field and determine $V_{13,24P}$ where current goes in 1 and leaves 3 and voltage is measured between terminals 2 and 4. Next reverse the field and determine $V_{13,24N}$ again.
    - To find the sheet concentration (#/cm²) use:



$$\rho \propto \left(\frac{IB}{q\left(V_{13,24P} + V_{13,24N}\right)} \right)$$

- …where we have intentionally left out the proportionality constant
- In reality, 8 resistivity and eight hall voltage measurements are made to reduce contact related offset voltage errors resulting in an equation that is of the form:

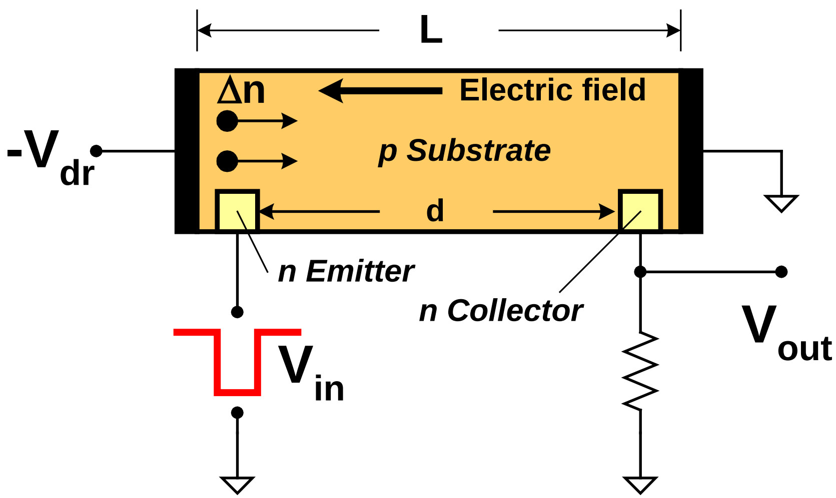
$$\rho = \left(\frac{\left(8x10^{-8}\right)IB}{q\left[\left(V_{13,24P} - V_{13,24N}\right) + \left(V_{31,42P} - V_{31,42N}\right) + \left(V_{42,13P} - V_{42,13N}\right) + \left(V_{24,31P} - V_{24,13N}\right)\right]} \right)$$

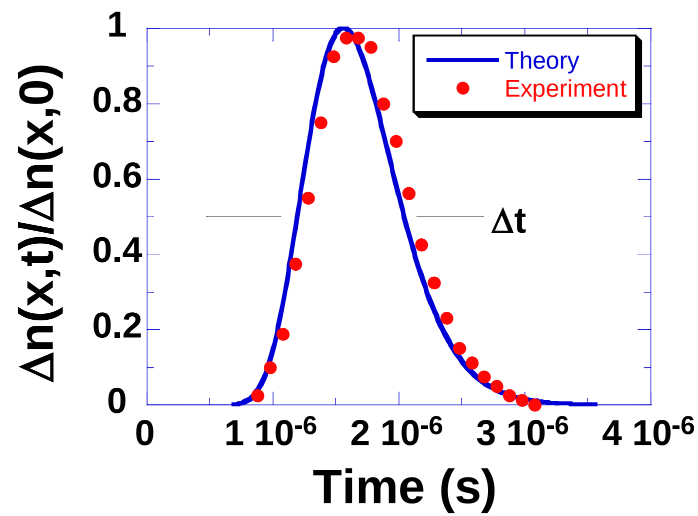
- See text for important sample geometry considerations (if ignored, significant error can result)

Differs some from your text. For details see http://www.nist.gov/pml/semiconductor/hall_resistivity.cfm

Haynes - Shockley Experiment

- **Allows *mobility*, *diffusion constant*, and *minority carrier lifetime* to be determined**

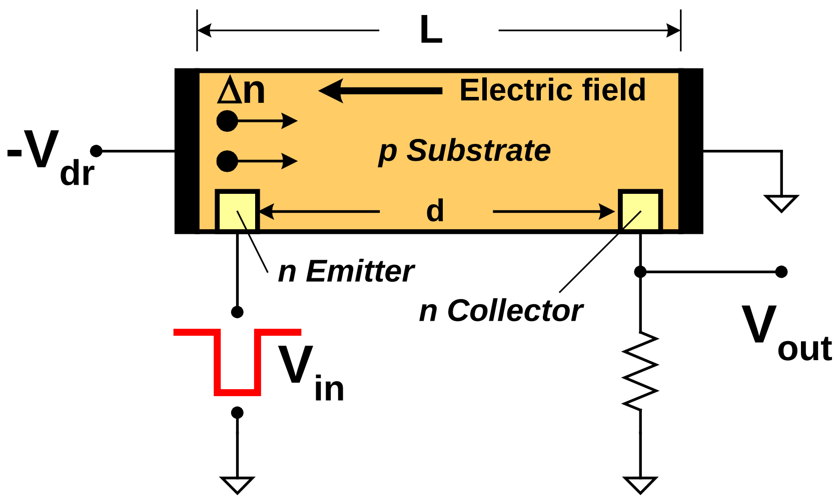


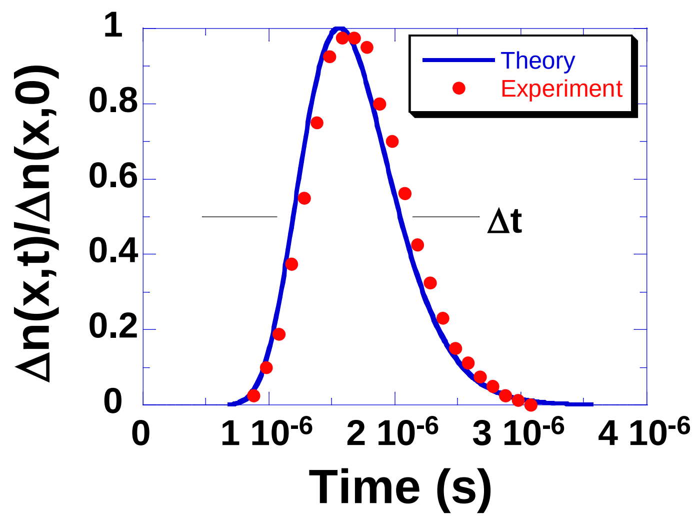


$$\Delta n(x,t) = \frac{N}{\sqrt{4\pi D_n t}} e^{\left(-\frac{(x-vt)^2}{4D_n t}-\frac{t}{\tau_n}\right)}$$

Haynes - Shockley Experiment

- Allows ***mobility***, ***diffusion constant***, and ***minority carrier lifetime*** to be determined



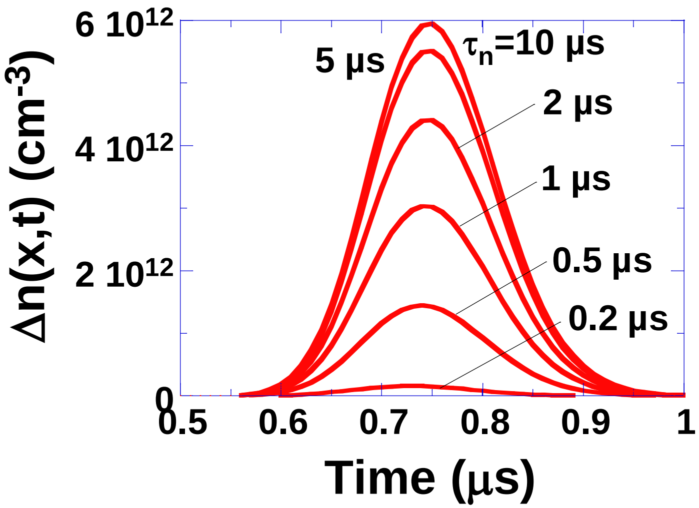


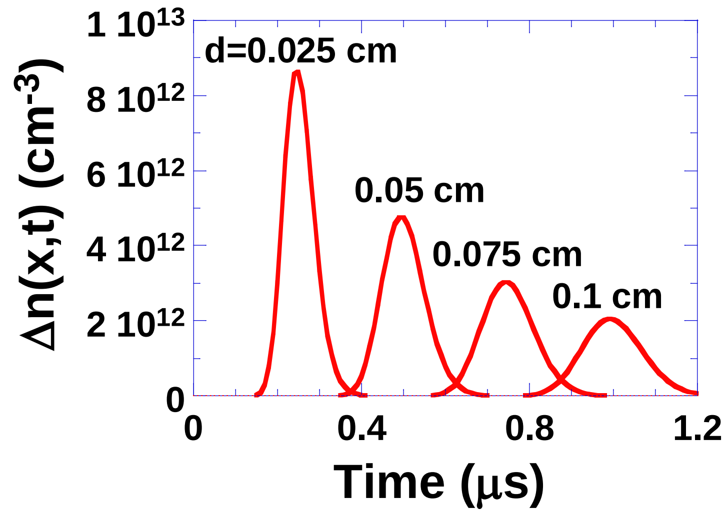
- If at least two lengths and two times are measured, the FWHM of the time plot, Δt can be used to…

$$t_d = d / v_{drift}; \quad \mu_n = \frac{d}{\varepsilon t_d}; \quad D_n = \frac{(d\Delta t)^2}{16 t_d^3 \ln 2}; \quad \tau_n = \frac{t_{d2} - t_{d1}}{\ln(V_{out1}/V_{out2}) - 0.5\ln(t_{d2}/t_{d1})}$$

Haynes – Shockley Experiment

$$\Delta n(x,t) = \frac{N}{\sqrt{4\pi D_n t}} \exp\left(-\frac{(x - vt)^2}{4D_n t} - \frac{t}{\tau_n} \right)$$





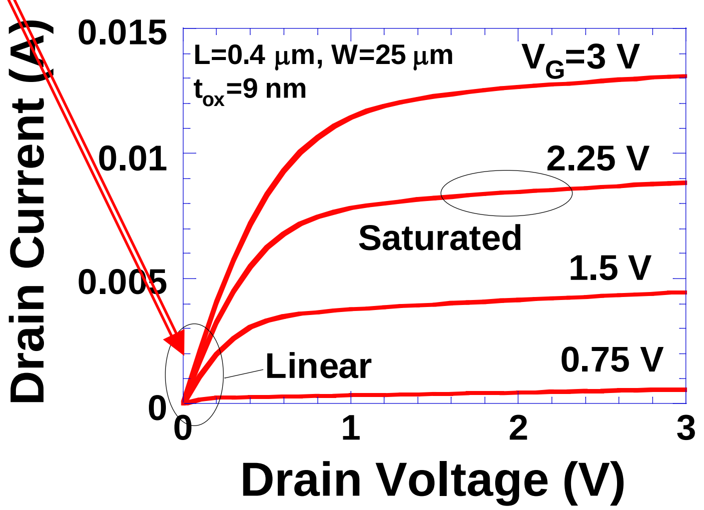
MOSFET *Effective* Mobility

- **Effective mobility determined from drain current – drain voltage characteristics**
- **The MOSFET drain current for small V_D (50 - 100 mV) is**

$$I_D = (W/L)\mu_{eff} Q_N V_D \approx (W/L)\mu_{eff} C_{ox}(V_G - V_T)V_D$$

- **Determine $g_d = \Delta I_D / \Delta V_D$ for low V_D**
- **Solve for μ_{eff}**

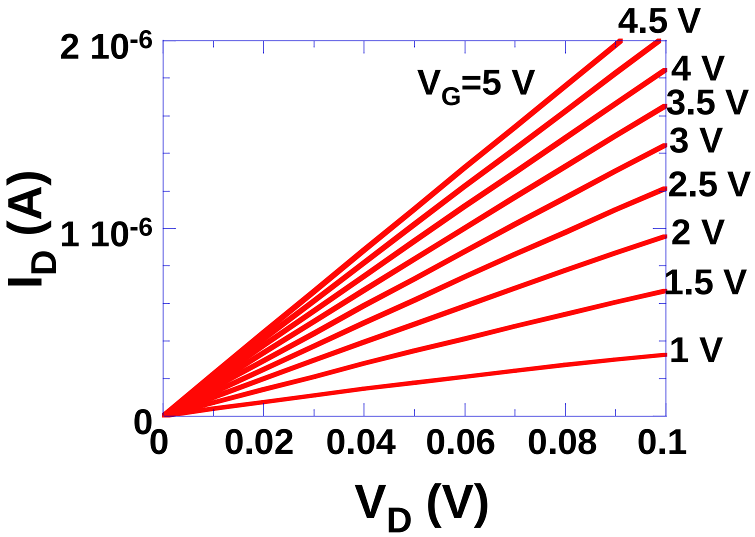
$$\mu_{eff} = \frac{L g_d}{W Q_N} \approx \frac{L g_d}{W C_{ox}(V_G - V_T)}$$

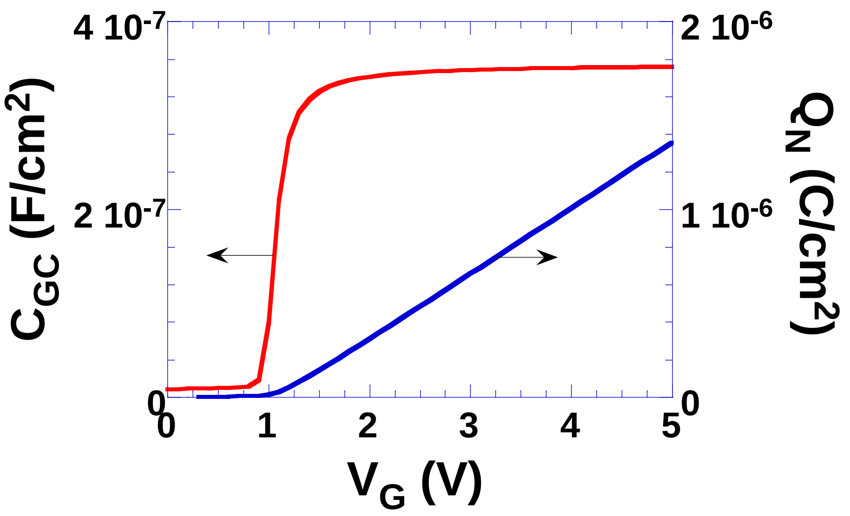


- **Need g_d, Q_N, V_T**

MOSFET *Effective* Mobility

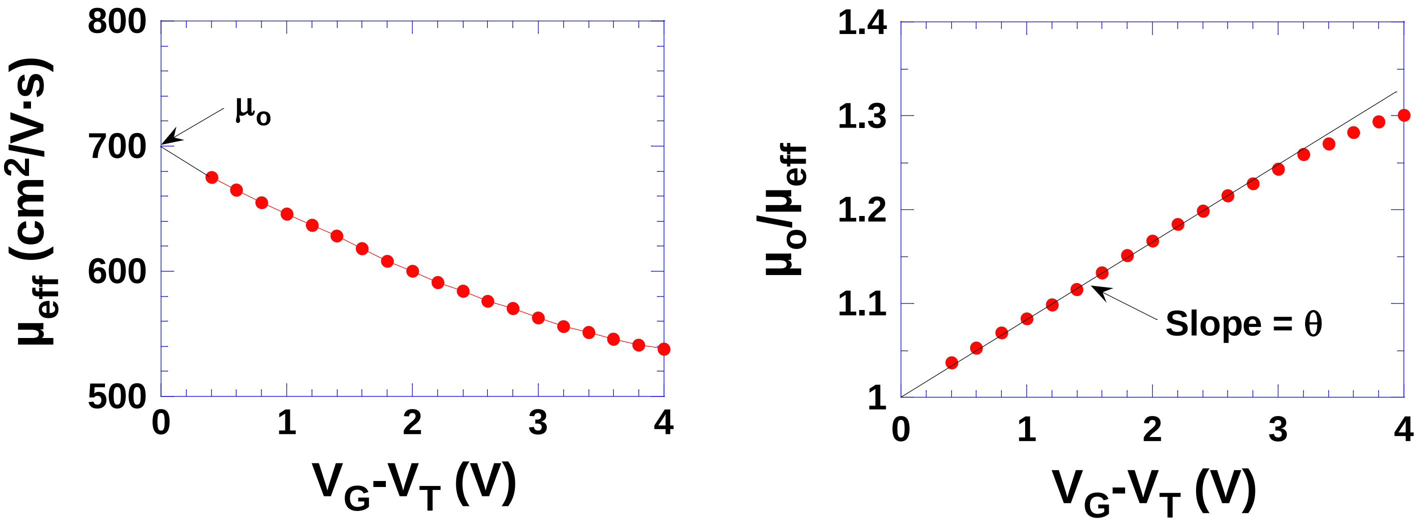
- I_D-$V_D \Rightarrow g_d$; C_{GC}-$V_G \Rightarrow Q_N$; I_D-$V_G \Rightarrow V_T$





$$Q_N = \int_{-\infty}^{V_G} C_{GC}\,dV_G$$

MOSFET *Effective* Mobility



$$\mu_{eff} = \frac{\mu_o}{1+\theta(V_G - V_T)}$$

μ_o = low-field mobility; θ = mobility degradation factor

Review Questions

- What are the different mobilities?
- Why is the MOS effective mobility less than the bulk mobility?
- How is μ_{eff} most commonly determined?
- Why does the Hall mobility differ from the conductivity mobility
- How does a Hall mobility measurement work?
- How does the Haynes-Shockley experiment work?
- What is determined with the Haynes-Shockley experiment ?
- For what is the time-of-flight technique used?