

Layer characterization

- **need to characterize the layers produced thus far**
 - **oxides**
 - thickness
 - dielectric constant / index of refraction
 - **doped layers**
 - junction depth
 - dopant concentrations
 - electrical resistance / carrier concentration

Thickness measurements

- **profilometry**
 - mechanically measure difference in height across a “step” on the surface
 - scanning “needle” traverses surface
 - Dektak, Tencor Alphastep
 - requirements:
 - must have step on surface
 - film must be hard enough that needle does not damage it
 - must be calibrated using known step height
 - precision / range
 - Alphastep specs:
 - profiling with 10\AA (1σ) or 0.1% repeatability
 - step height metrology below 50 nm to 300 μm

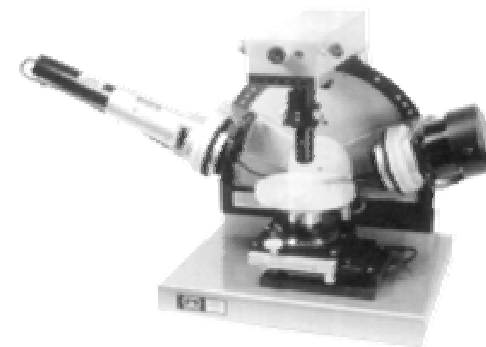
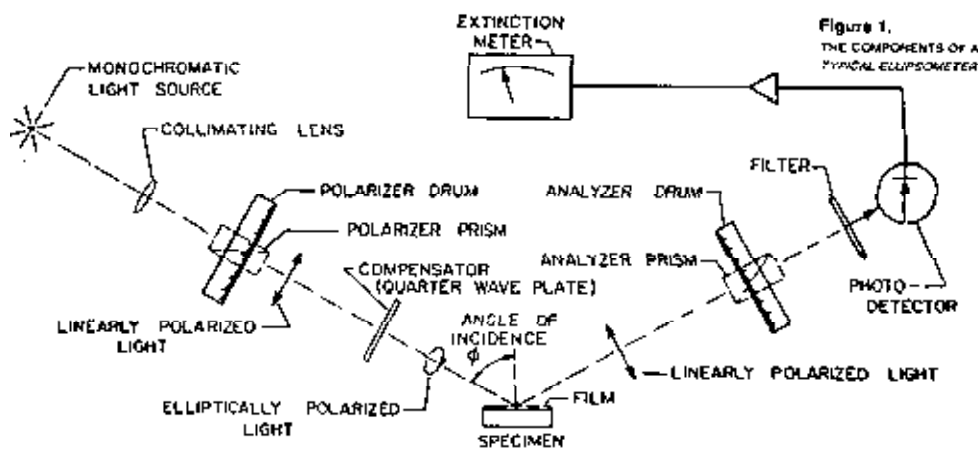


from <http://www.tencor.com/products/metrology/alpha-step500/AlphaStep500.pdf>

Transparent layer measurements

- **ellipsometry**

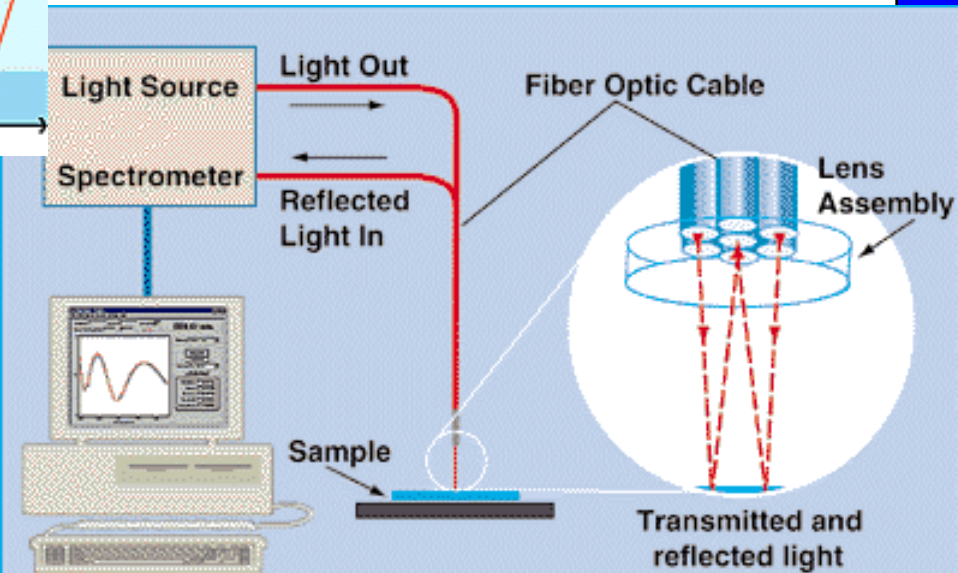
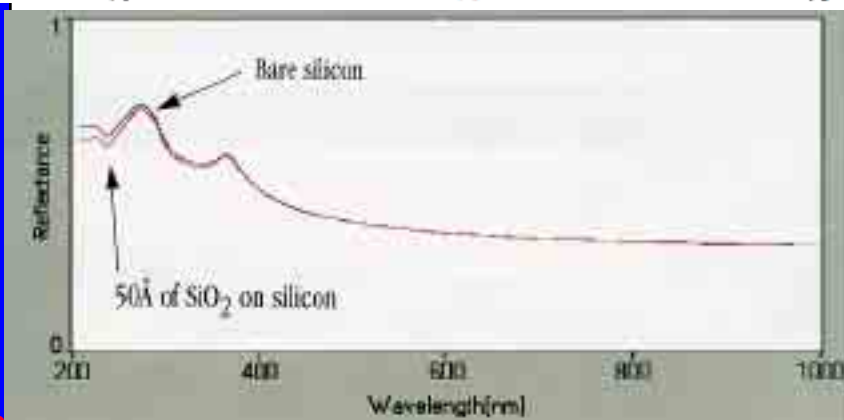
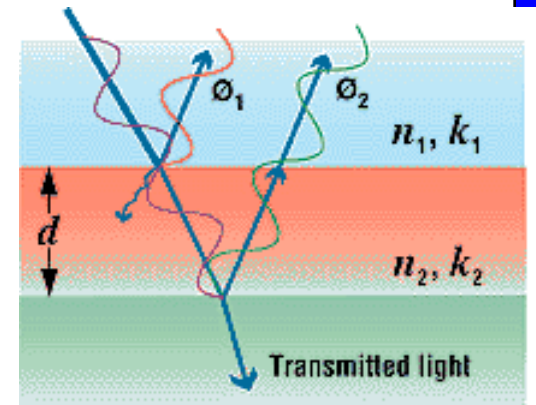
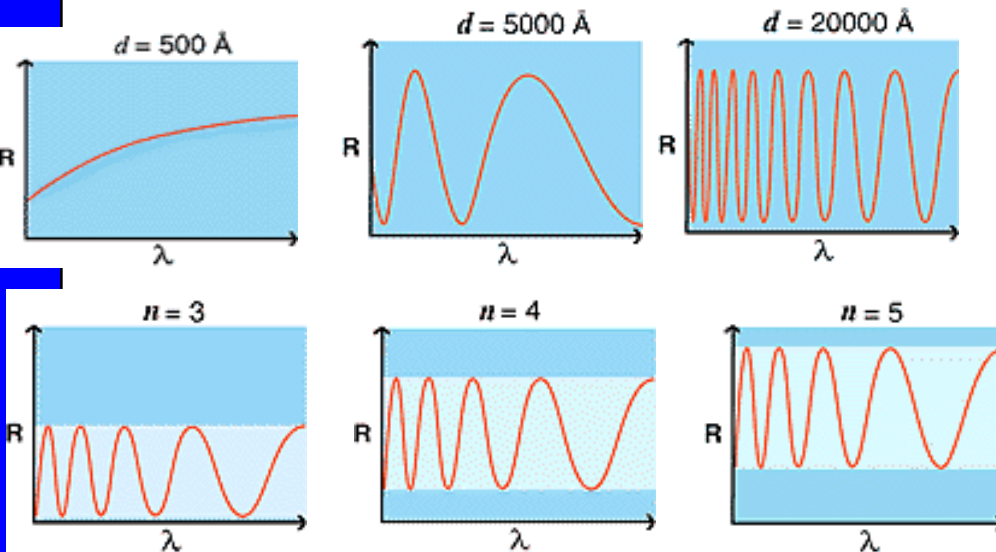
- uses elliptically polarized light incident at an angle on the sample
- state of polarization of reflected beam is dependent on
 - wavelength of illumination and angle of incidence
 - optical constants of the “substrate”
 - optical constants of “covering layer”
 - thickness of “covering layer”
- precision / range
 - can measure steps of down to somewhat less than 10 nm
 - periodicity creates ambiguity for thicknesses over several hundred nm



<http://www.afep.cornell.edu/epl/index.html>

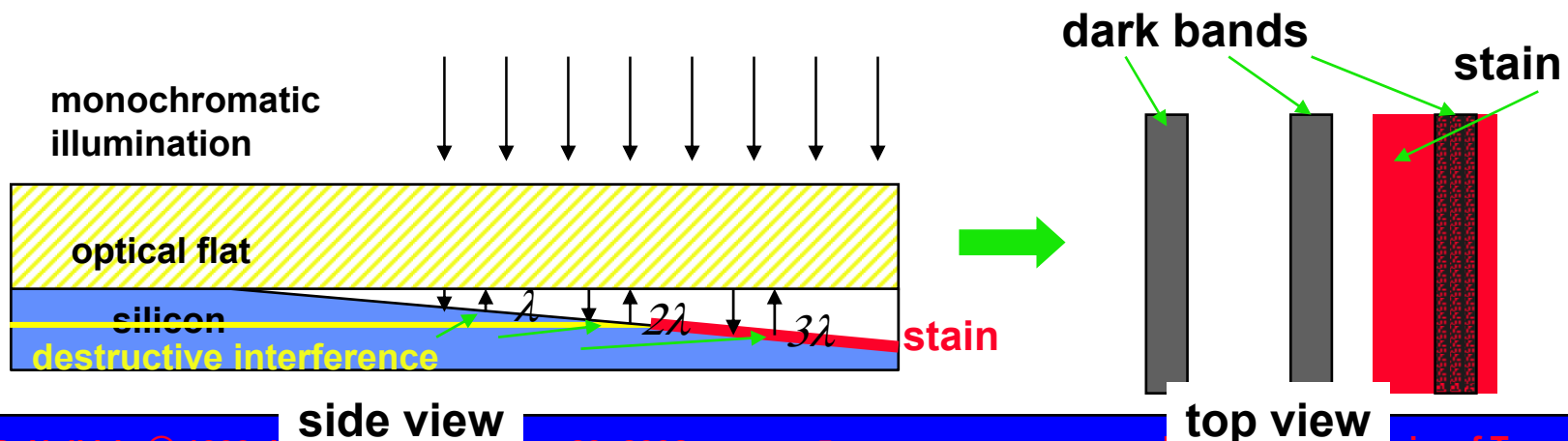
Transparent layer measurements

- spectroscopic reflectance
 - measure wavelength dependence of reflectivity



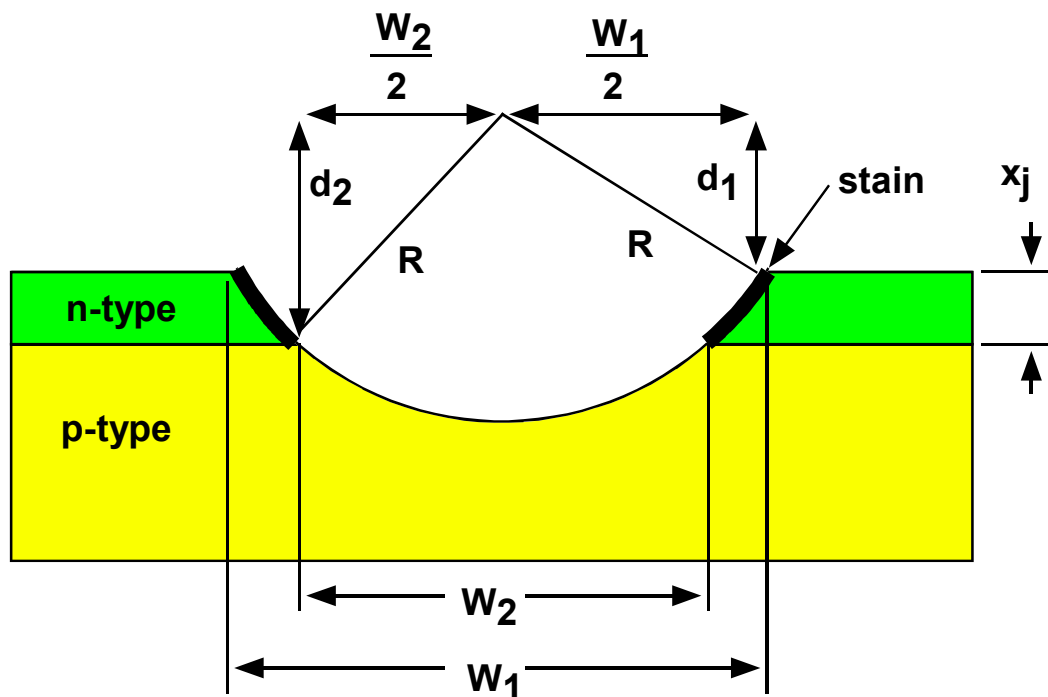
Junction depth measurements

- non-destructive techniques
 - film thickness gauge
 - use refractive index dependence on doping to do ellipsometry
 - weight gain method for epitaxial films
- junction exposing techniques
 - junction lapping
 - chemical stain used to “electroplate” one side of junction
 - when exposed to light p-n junction produces current that can drive chemical reaction on one side or other
 - interferometry used to measure gap



Junction groove technique

- grooving tool used to expose p-n junction
 - stain used to delineate junction
 - “electroplating” reaction used to coat either p or n side
 - measure lateral distances W_1 , W_2



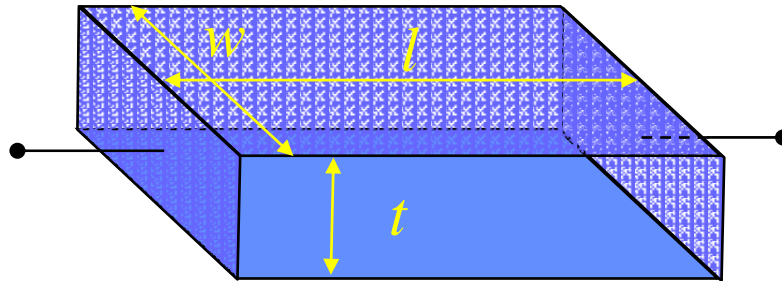
$$x_j = \sqrt{R^2 - \left(\frac{W_2}{2}\right)^2} - \sqrt{R^2 - \left(\frac{W_1}{2}\right)^2}$$

$$\approx \frac{(W_1/2)^2 - (W_2/2)^2}{2R}$$

Sheet resistance

- consider a block of uniform conducting material

$$R = \rho \cdot \frac{l}{t \cdot w}$$



- if the width and length are the same (i.e., it's a “square”)

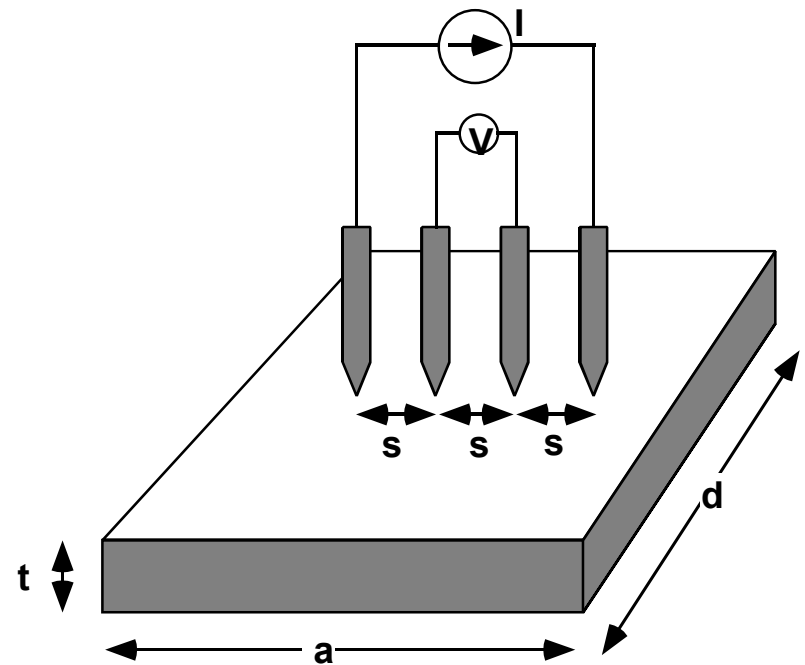
$$R_s = \rho \cdot \frac{l=w}{t \cdot w} = \frac{\rho}{t} \quad \text{or} \quad \rho = R_s \cdot t$$

- R_s is the “sheet resistance” of the material
- for a uniformly doped piece of semiconductor

$$\rho = \frac{1}{q \cdot \mu \cdot (n \text{ or } p)} \quad \Rightarrow \quad n \text{ or } p = \frac{1}{q \cdot \mu \cdot R_s \cdot t}$$

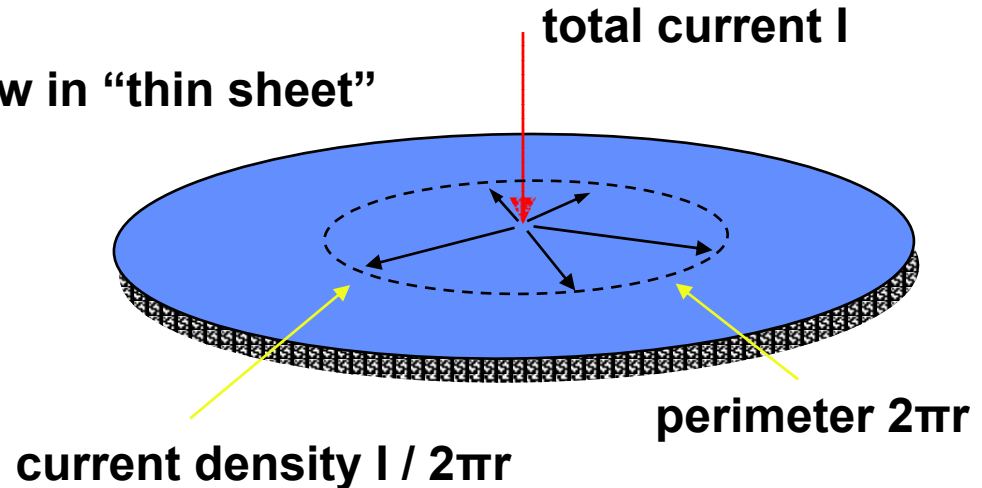
Sheet resistance measurements

- **problem: contact resistance can be VERY large**
 - use “four point” measurement
 - inject current through one pair of contacts, measure voltage across another pair
 - what is relation between I , V and resistance?



Sheet R from 4-point probe

- assume 2-d problem
 - geometry of current flow in “thin sheet”



- electric field/ current density relationship (Ohm's Law!)
 - for a single “source” have

$$\vec{E} = \vec{J}_{\text{sheet}} \cdot \rho_{\text{sheet}} = \frac{I \cdot \rho_{\text{sheet}}}{2\pi \cdot r} \hat{r}$$

- but in our four point geometry have two sources: one in, and one out!

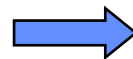
4-point probe

- probe geometry produces “dipole” distribution
- along x axis is simple:

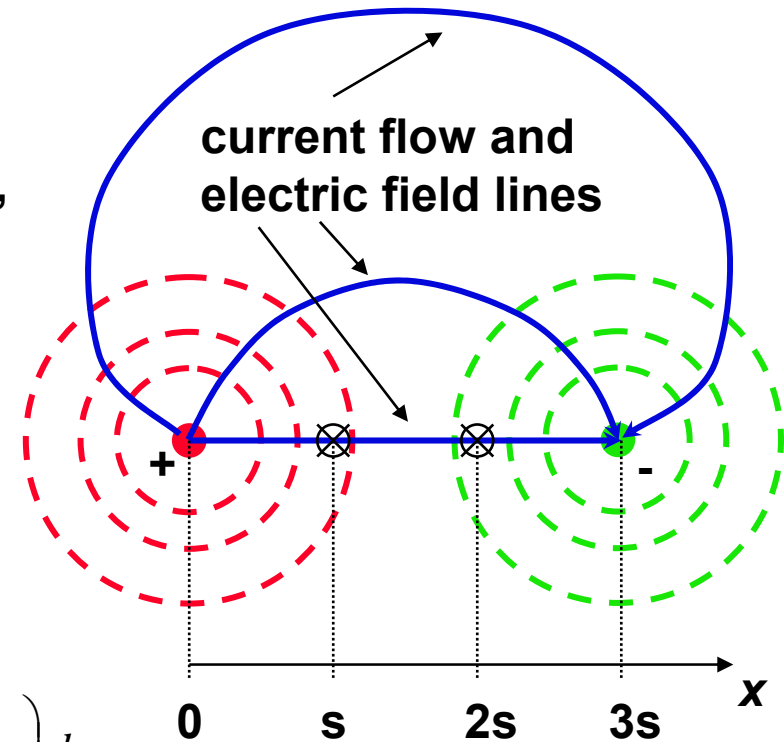
$$E_x = J_x \cdot \rho_{sheet} = \rho_{sheet} \cdot \left(\frac{I}{2\pi \cdot x} + \frac{I}{2\pi \cdot (3s-x)} \right)$$

- to get voltage integrate along field line

$$\begin{aligned} \Delta V &= \int_s^{2s} E_x dx = \int_s^{2s} \rho_{sheet} \cdot \left(\frac{I}{2\pi \cdot x} + \frac{I}{2\pi \cdot (3s-x)} \right) dx \\ &= \frac{\rho_{sheet} \cdot I}{2\pi} \left[\ln(x) \Big|_s^{2s} + \left(-\ln(3s-x) \Big|_s^{2s} \right) \right] \end{aligned}$$



$$\Delta V = \frac{\rho_{sheet} \cdot I}{2\pi} \cdot 2 \cdot \ln(2)$$

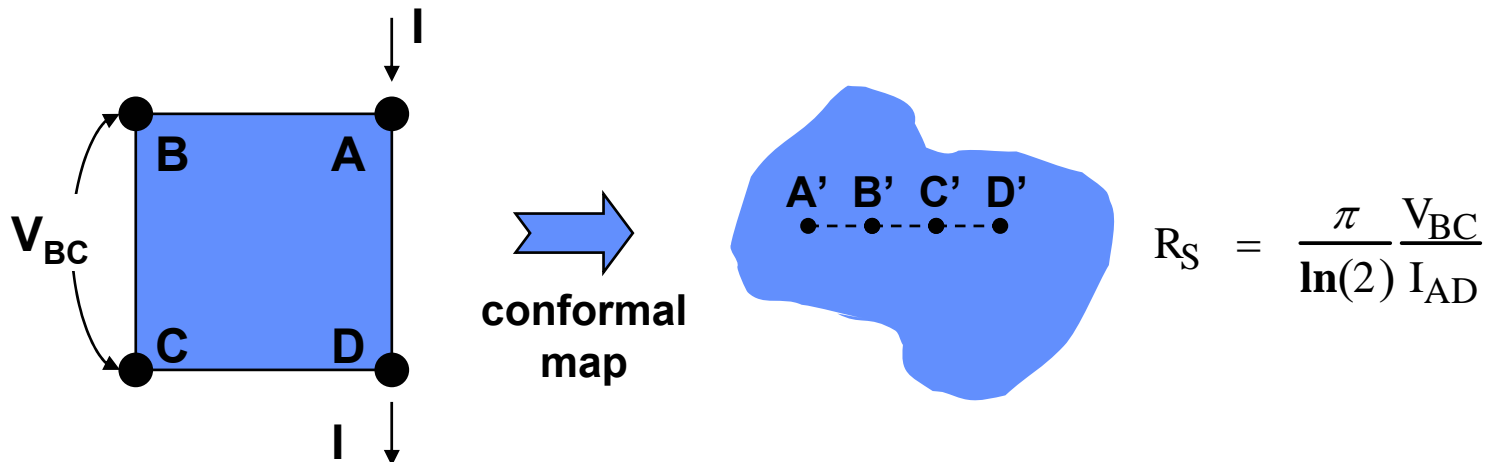


Final result for sheet R

- the relation between the voltage measured across the middle two probes and the current injected through the outer two probes is

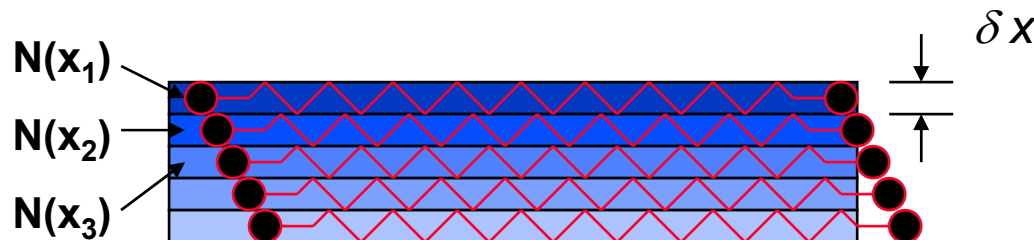
$$\rho_{\text{sheet}} = R_S = \frac{\pi}{\ln(2)} \frac{V}{I} \approx 4.54 \frac{V}{I}$$

- other probe geometries
 - for any bounded surface with current injected at one point on the perimeter and removed at another, the measurement of the voltage difference between any other two points on the perimeter is sufficient to determine the sheet resistance
 - Van der Pauw geometry: conducting square

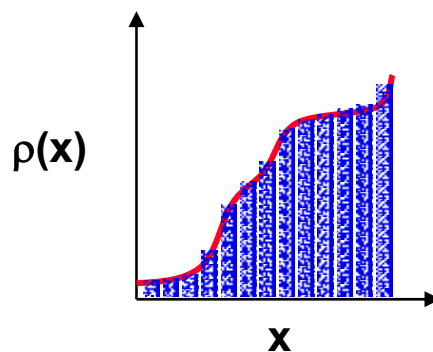
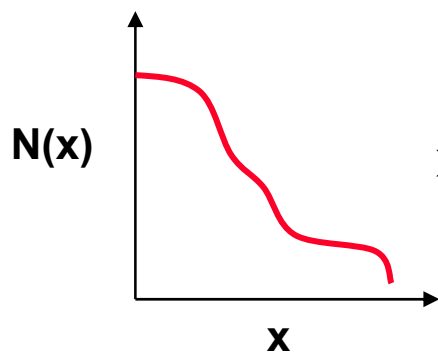


Relation between doping profile and resistance

- geometrically



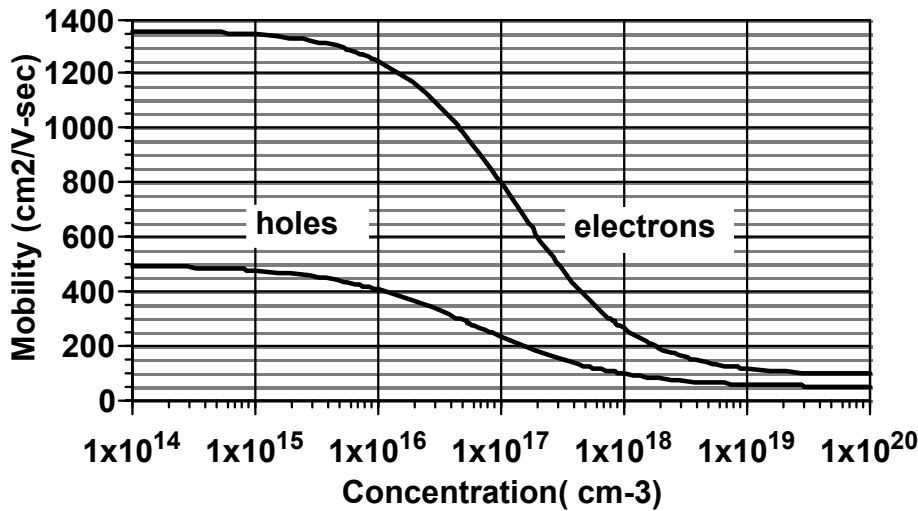
- $R_s \sim$ parallel sum of R's from each layer
 - $\delta R(x) = 1 / [q \cdot \mu(N) \cdot (\text{net carriers}) \cdot \delta x]$



$$R_s = \left[\int_0^{x_j} \underbrace{q \cdot \mu(N)}_{\sigma = 1/\rho} \cdot \overbrace{[N(x) - N_B]}^{\text{net carriers}} dx \right]^{-1}$$

- resistivity & mobility **are** functions of ionized impurity concentration

Mobility and resistivity for Si

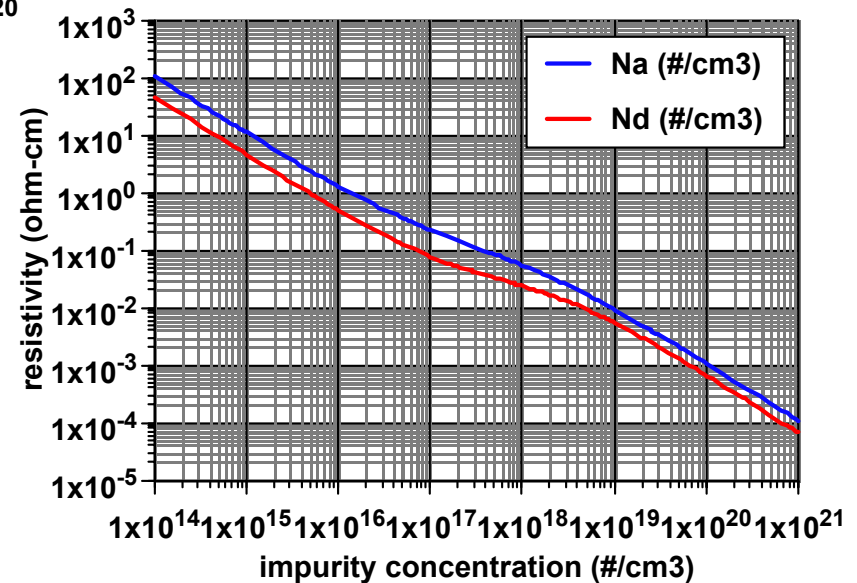


for silicon near room temp:

$$\mu_{electron}(N_D) \approx 92 + \frac{1360 - 92}{1 + \left(\frac{N_D}{1.3 \times 10^{17}}\right)^{0.91}}$$

$$\mu_{hole}(N_A) \approx 47.7 + \frac{495 - 47.7}{1 + \left(\frac{N_A}{6.3 \times 10^{16}}\right)^{0.76}}$$

$$\rho(n \text{ or } p) = \frac{1}{\sigma} = \frac{1}{q \cdot \mu \cdot (n \text{ or } p)}$$



Irvin Curves for Si

- note that the average resistivity is given by:

$$\bar{\rho} = (\bar{\sigma})^{-1} = \left(\frac{1}{\text{thickness}} \int_{\text{surface}}^{\text{thickness}} \sigma dx \right)^{-1} \quad \sigma = q \cdot \mu(n) \cdot n \quad n = N_D - N_B$$

$$\bar{\rho} = (\bar{\sigma})^{-1} = \left(\frac{1}{x_j} \right)^{-1} \underbrace{\left(\int_0^{x_j} q \cdot \mu \cdot (N_D - N_B) dx \right)^{-1}}_{R_S} = x_j \cdot R_S$$

- what can we say about the value of average resistivity??

$$\bar{\rho} = x_j \cdot R_S = \left(\frac{q}{x_j} \int_0^{x_j} \mu \cdot (N_D - N_B) dx \right)^{-1}$$

Irvin Curves for Si

- note that if you specify N_S , N_B , x_j , and the shape you have fully specified the exact doping profile!

- example: gaussian profile:
$$N(x, t) = \underbrace{\left(\frac{Q_o}{\sqrt{\pi D t}} \right)}_{N_S} \exp\left(- \left[\frac{x}{2\sqrt{D t}} \right]^2 \right)$$
- at the junction:

$$N_B = N_S \exp\left(- \left[\frac{x_j}{2\sqrt{D t}} \right]^2 \right) \quad \Rightarrow \quad (2\sqrt{D t})^2 = - \frac{(x_j)^2}{\ln(N_B/N_S)} = \frac{(x_j)^2}{\ln(N_S/N_B)}$$

$$\Rightarrow \quad N(x) = N_S \exp\left(- \frac{(x)^2}{(x_j)^2 / \ln(N_S/N_B)} \right)$$

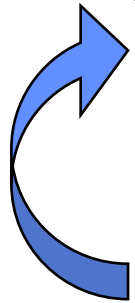
- can now do the sheet resistance integral since everything is known:

$$R_s = \left(q \int_0^{x_j} \mu \cdot \left\{ N_S \cdot \exp\left[- \frac{(x)^2}{(x_j)^2 / \ln(N_S/N_B)} \right] - N_B \right\} dx \right)^{-1}$$

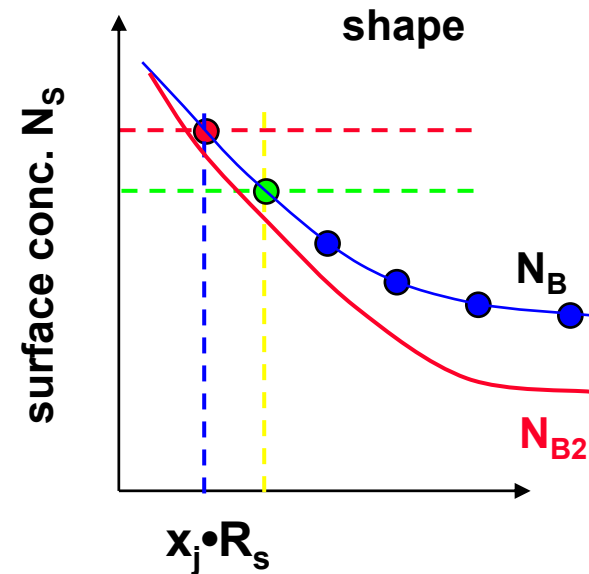
Irvin Curves for Si

- calculation process

- pick shape
- pick N_B , x_j
 - specify N_s
 - calculate sheet resistance R_s
 - find average resistivity = $x_j \cdot R_s$
 - graph
 - loop

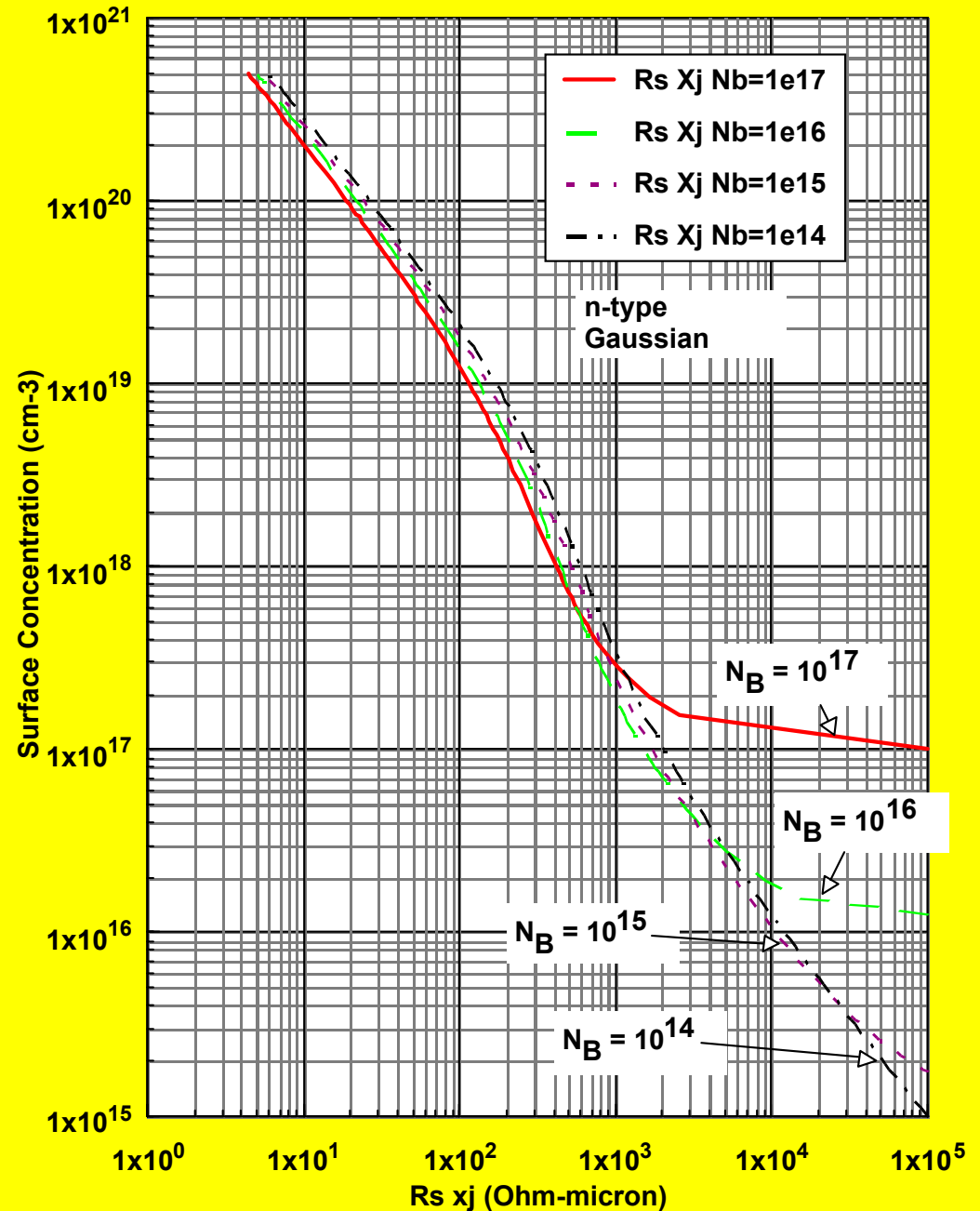


- repeat for new value of N_{B2}



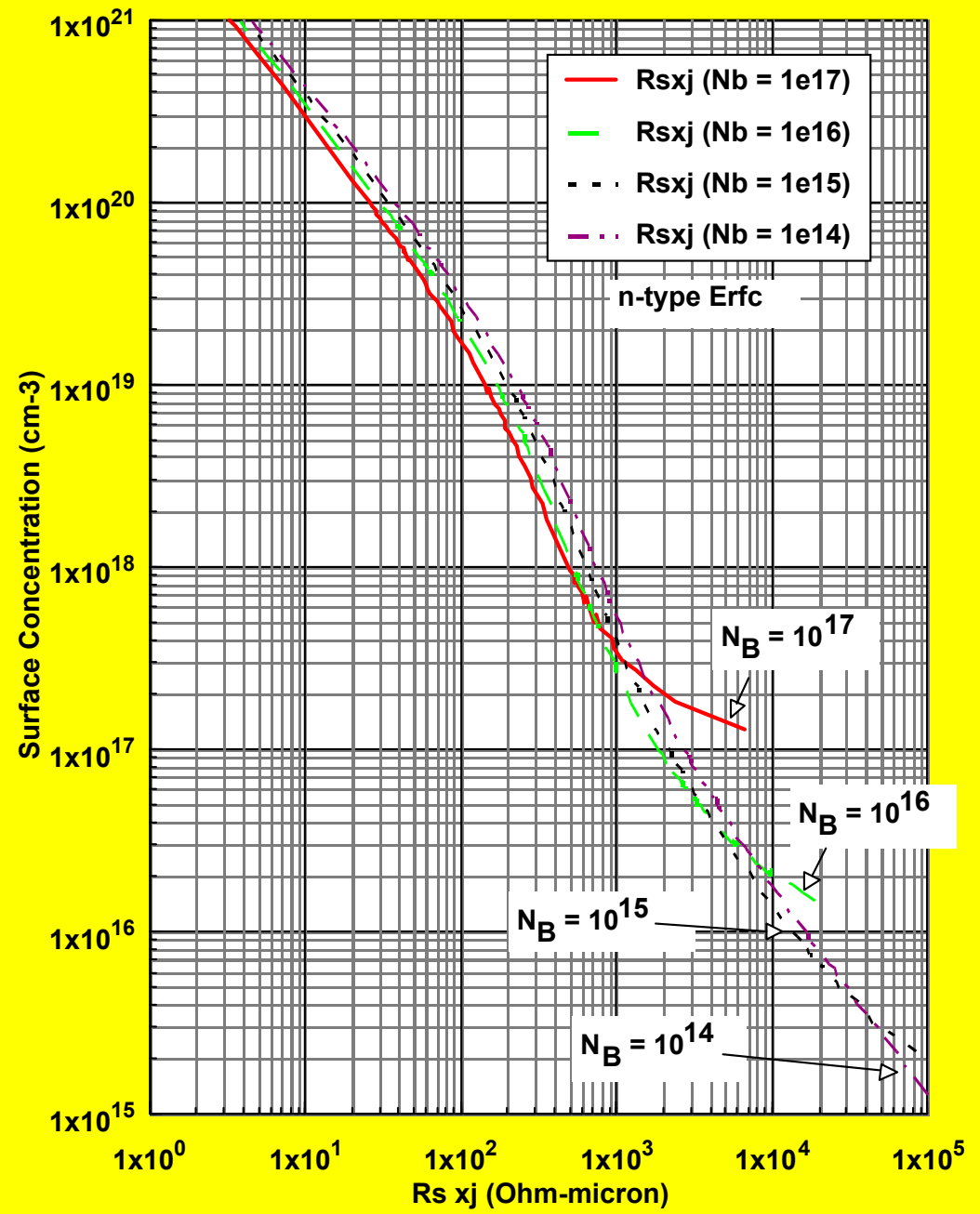
Irvin Curves for Si

carrier: electrons
shape: gaussian



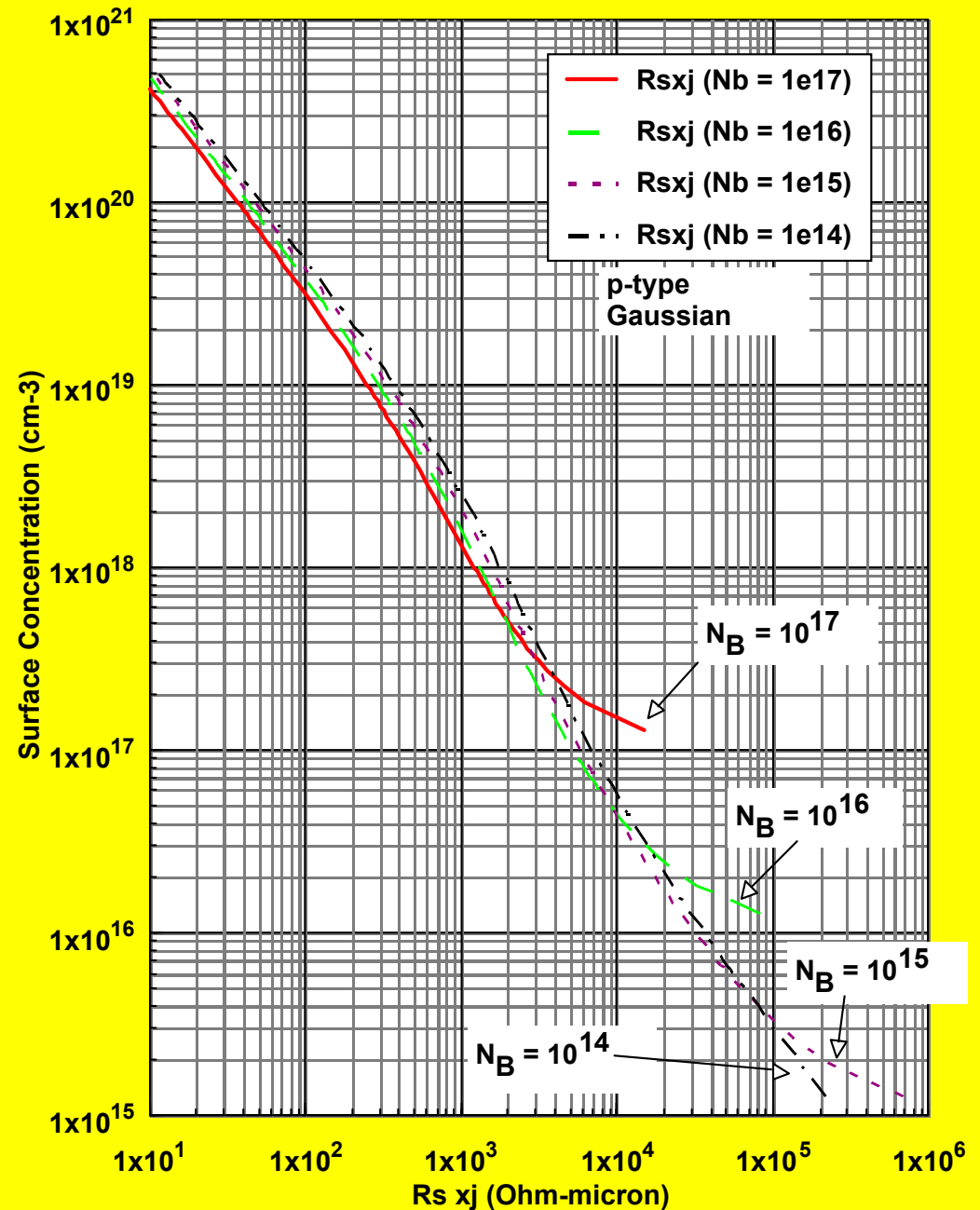
Irvin Curves for Si

carrier: electrons
shape: erfc



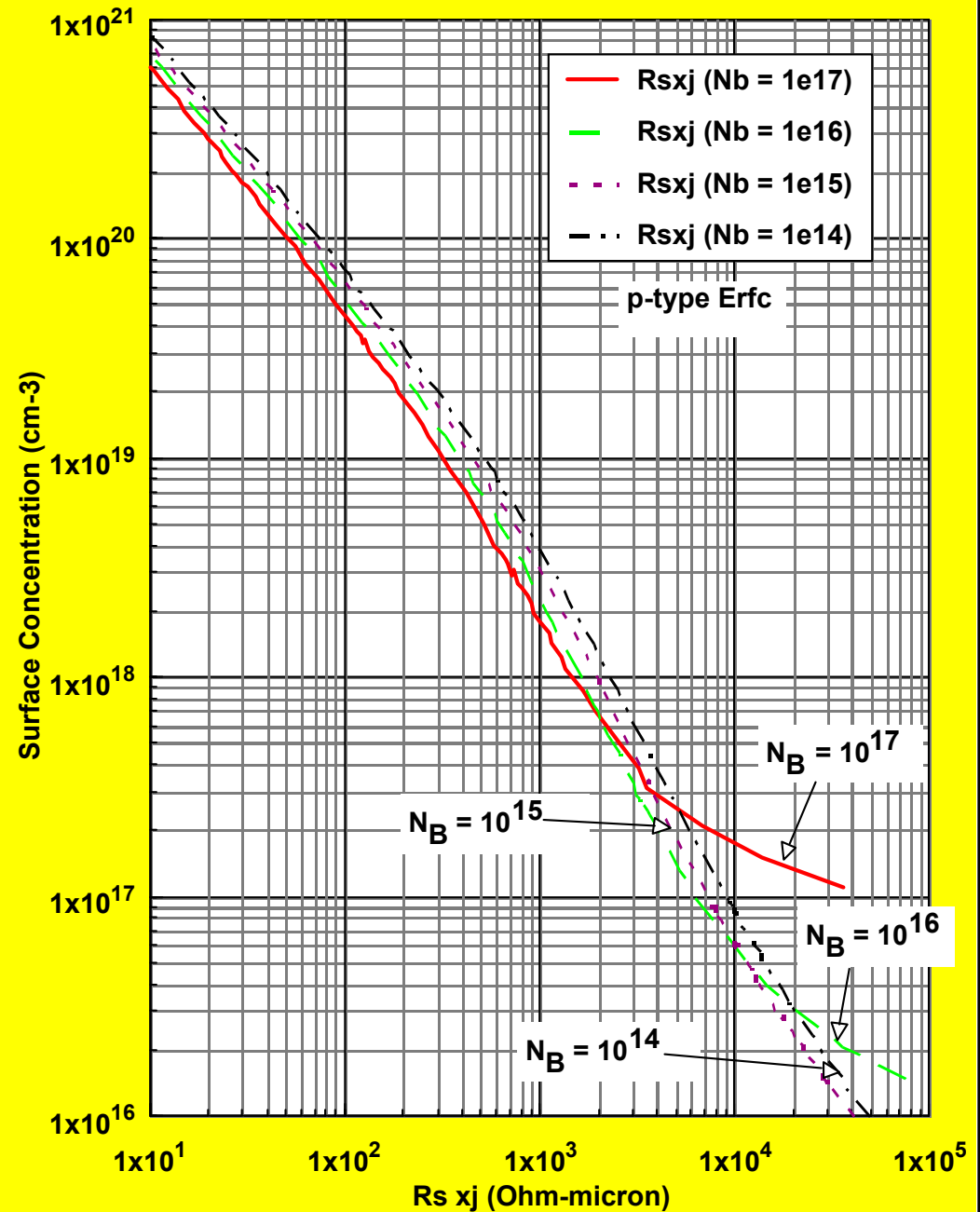
Irvin Curves for Si

carrier: holes
shape: gaussian



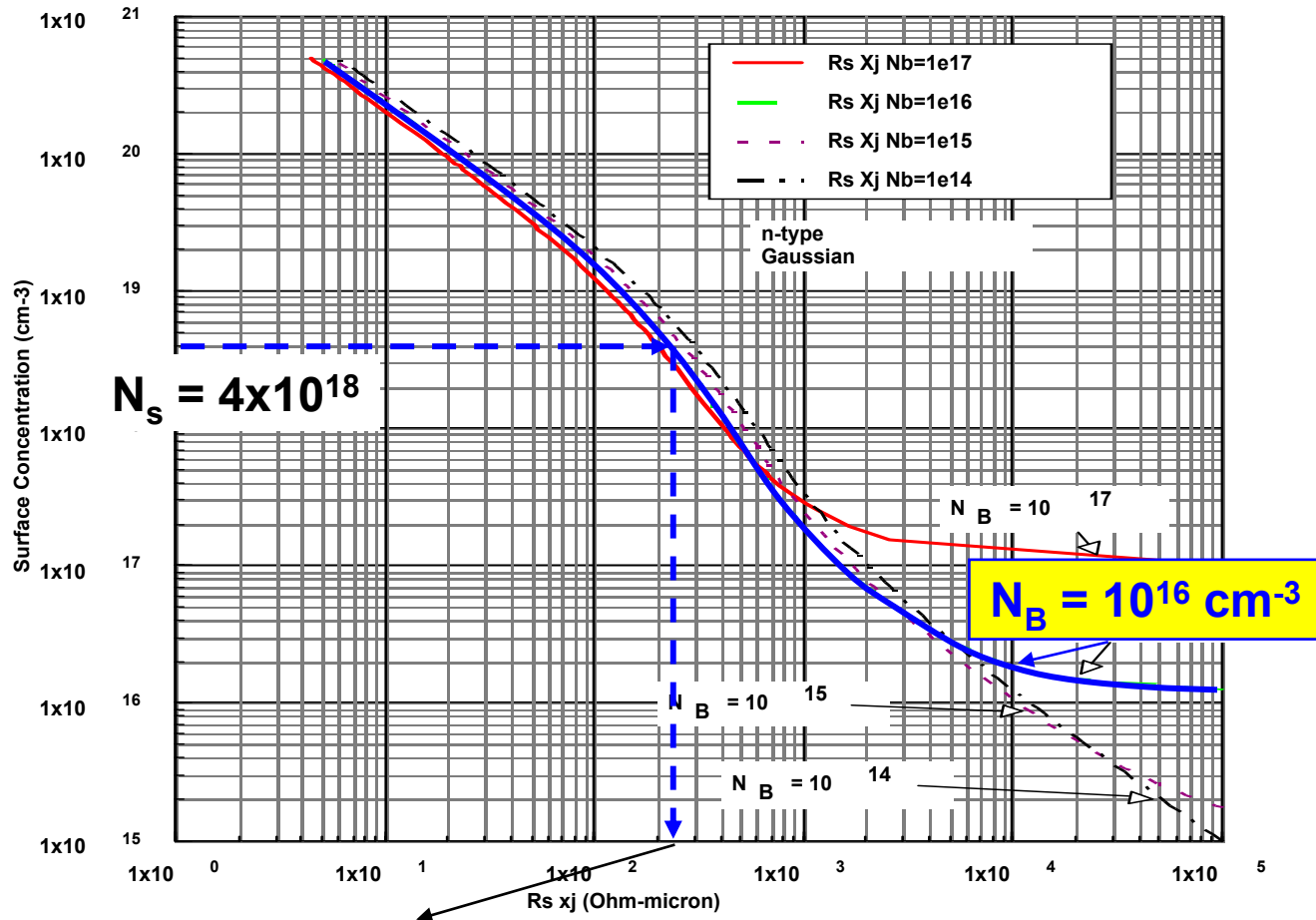
Irvin Curves for Si

carrier: holes
shape: erfc



Example: need to know three of: N_S , N_B , x_j , & R_S

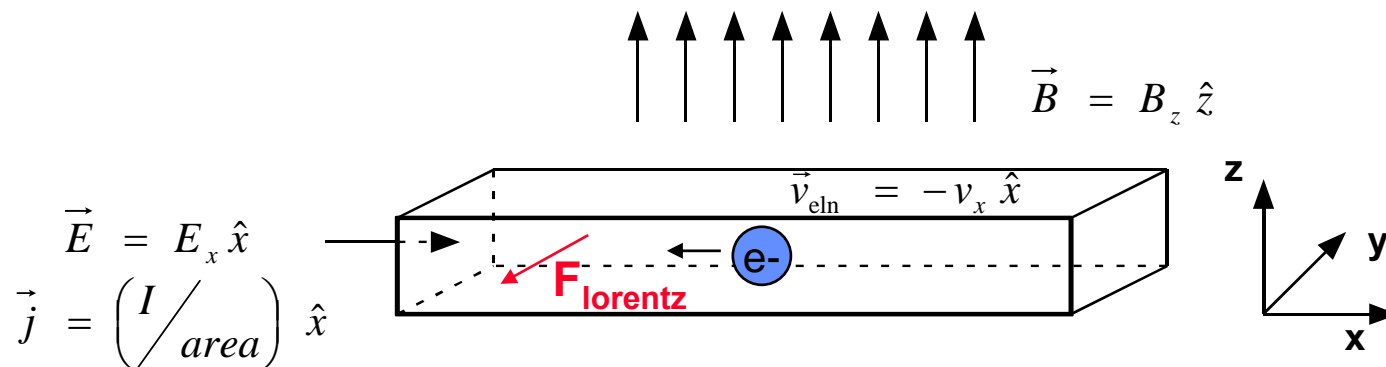
- n-type dopant, limited source (gaussian), $N_B = 10^{16} \text{ cm}^{-3}$



$R_S \cdot x_j \sim 2.2 \times 10^2 \text{ (ohm-micron)}$ for $N_S = 4 \times 10^{18}$ & $N_B = 10^{16} \text{ cm}^{-3}$

Hall measurements for carrier concentration

- example geometry, electrons as carriers



- if apply magnetic field to drifting carriers a Lorentz force is generated

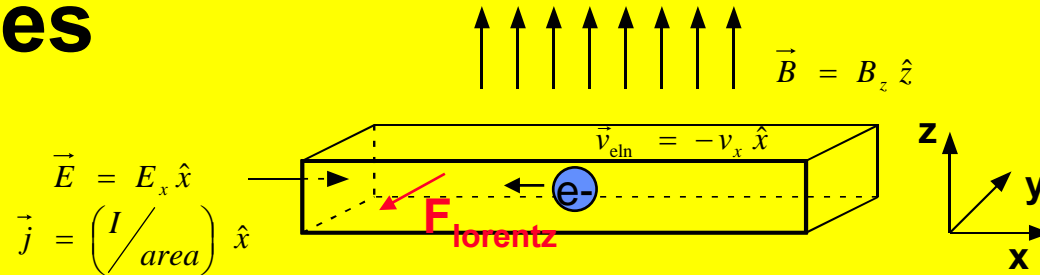
$$\vec{F} = \underbrace{q}_{\substack{+ : \text{holes} \\ - : \text{electrons}}} \cdot (\vec{E} + \vec{v} \times \vec{B})$$

- note Lorentz force is proportional to velocity, direction depends on carrier type (sign of “q”)

$$\begin{aligned} \vec{F}_{\text{lorentz}} &= q \cdot (\vec{v}_{\text{electron}} \times \vec{B}) \\ &= q \cdot |v_x \cdot B_z| (-\hat{x} \times \hat{z}) \\ &= q \cdot |v_x \cdot B_z| \cdot (-(-\hat{y})) \\ &= -|q| \cdot |v_x \cdot B_z| \cdot \hat{y} \end{aligned}$$

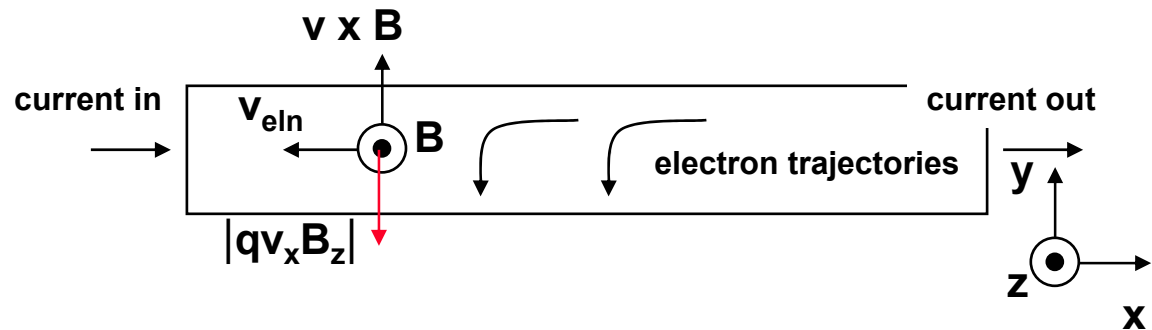
Lorentz forces

- side view again

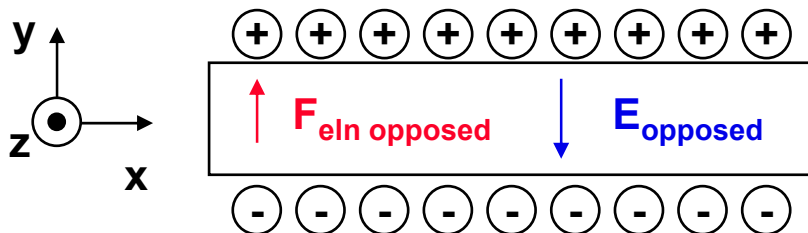


$$\vec{F}_{\text{lorentz}} = q \cdot (\vec{v}_{\text{electron}} \times \vec{B}) = - |q| \cdot |v_x \cdot B_z| \cdot \hat{y}$$

- top view of sample



- but since there are no contacts on the y faces of the sample no current can flow in y direction!



$$\vec{F}_{\text{opposed}} = - \vec{F}_{\text{lorentz}} = -(- |q| \cdot |v_x \cdot B_z|) \cdot \hat{y}$$

$$\vec{E}_{\text{opposed}}^{\text{electron}} = \vec{F}_{\text{opposed}} / q = -(|v_x^{\text{electron}} \cdot B_z|) \cdot \hat{y}$$

Hall effect continued

- in summary, application of “transverse” magnetic field induces an electric field in the other transverse direction

$$E_y = (v_x \cdot B_z) = \mp (|v_x \cdot B_z|)$$

– - electrons

– + holes

- define the Hall coefficient to be

$$R_H = \frac{\overbrace{E_y}^{\text{measured}}}{\underbrace{j_x}_{\text{external}} \cdot \underbrace{B_z}_{\text{external}}} = \frac{v_x}{j_x}$$

- using a simple “drift” model we have

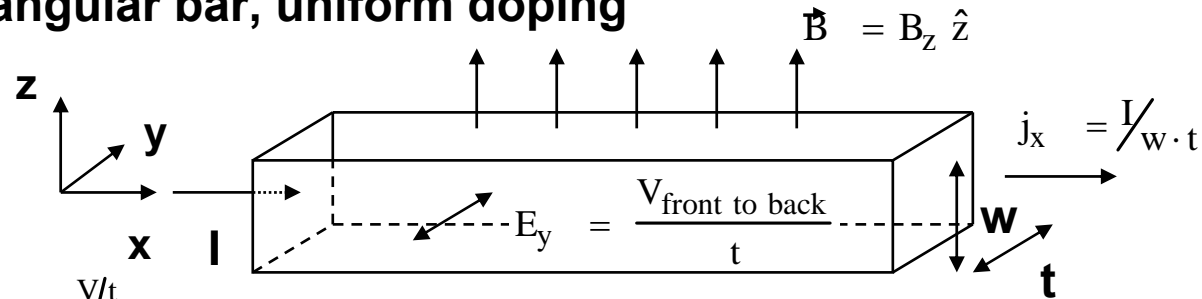
$$j_x = \underbrace{q}_{\substack{-: \text{electrons} \\ +: \text{holes}}} \cdot (n \text{ or } p) \cdot \underbrace{v_x}_{\substack{-: \text{electrons} \\ +: \text{holes}}}$$

$$\Rightarrow R_H = \frac{v_x}{\underbrace{q}_{\substack{-: \text{electrons} \\ +: \text{holes}}} \cdot (n \text{ or } p) \cdot v_x} = \frac{1}{q \cdot (n \text{ or } p)} \Rightarrow$$

$$\begin{cases} \text{if } -, \text{ then } n \text{ type} \\ \text{if } +, \text{ then } p \text{ type} \end{cases} \left\{ \begin{array}{l} n \\ p \end{array} \right. = \frac{1}{|q \cdot R_H|}$$

Summary of Hall & R_s measurements

- Hall measurement gives the carrier concentration
 - for rectangular bar, uniform doping



$$R_H = \frac{\frac{V/t}{\underbrace{j_x}_{I/(w \cdot t)}} \cdot \underbrace{B_z}_{\text{measured}}}{\underbrace{B_z}_{\text{measured}}} = \frac{V}{I} \cdot \frac{w}{B_z} \quad \Rightarrow \quad n \text{ or } p = \left| \frac{I \cdot B_z}{q \cdot V_{\text{Hall}}} \right| \cdot \frac{1}{w}$$

- resistance gives mobility • concentration product
- combination of R and R_H gives mobility

$$R = \frac{\rho \cdot l}{t \cdot w} = \frac{1}{q \cdot (\mu \cdot n)} \cdot \frac{l}{t \cdot w}$$

- for non-uniformly doped layers can still get “sheet” parameters
 - essentially integral averages of μ and n

Other profiling methods

- “beam” techniques
 - electron
 - LEED (low energy electron diffraction): structure
 - SEM: imaging of topology
 - AES (Auger spectroscopy): composition (look at energy spectrum of emitted electrons)
 - ion
 - SIMS (secondary ion mass spectroscopy): bombard sample with ions, look at mass of “sputtered” atoms
 - RBS (Rutherford back-scattering): high energy (MeV) He bombardment, look at energy spectrum of back-scattered He
- electrical
 - spreading resistance, layer stripping
 - measure sheet R as function of removed material
 - capacitance-voltage measurements
 - use depletion as function of applied voltage to infer carrier profiles

SIMS

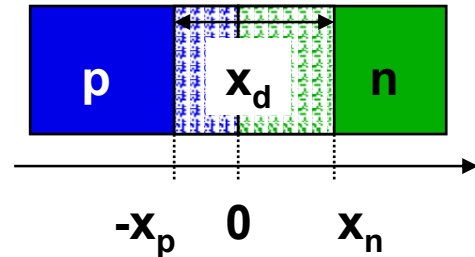
- material is “sand-blasted”
 - depth information from time and sputtering rate
- secondary-ion yields vary with incident ion mass and energy
 - standards required to calibrate SIMS measurements
- good for measurement of “low” concentrations of impurities

element	primary ion	detected ion	detection limit
B	O_2^+	$^{11}B^+$	$10^{15} /cm^3$
P	Cs^+	$^{31}P^-$	$10^{16} /cm^3$
As	Cs^+	$^{75}As^-$	$10^{16} /cm^3$
Na	O_2^+	$^{23}Na^+$	$10^{14} /cm^3$
Fe	O_2^+	$^{56}Fe^+$	$10^{17} /cm^3$
Cu	O_2^+	$^{63}Cu^+$	$10^{16} /cm^3$
Al	O_2^+	$^{27}Al^+$	$10^{15} /cm^3$

adapted from
Sze, 2nd ed.,
p. 542

C-V profiling

- consider p-n junction or Schottky contact



- reverse bias produces depletion layer, width function of doping profile and applied bias

- measure capacitance
$$C_{\text{unit area}} = \frac{dQ}{dV} = \frac{\epsilon_s}{x_d}$$

- solve Poisson's eq. for applied voltage to get (for p-n junction, assumes $n = N_D$, $p = N_A$):

$$N_D(x_n) = - \frac{C^3}{\epsilon_s \cdot q \cdot \frac{dC}{dV}} \left(1 + \frac{N_D(x_n)}{N_A(-x_p)} \right)$$

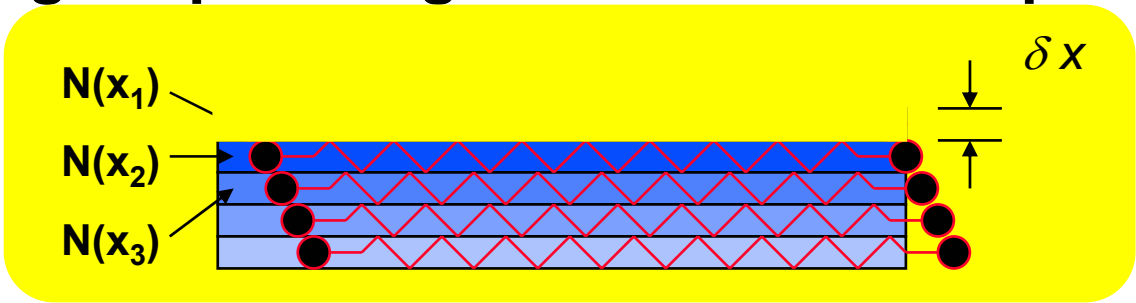
- for p⁺-n (“one-sided”) junction simplifies to

$$N_D(x_n) = - \frac{C^3}{\epsilon_s \cdot q \cdot \frac{dC}{dV}}$$

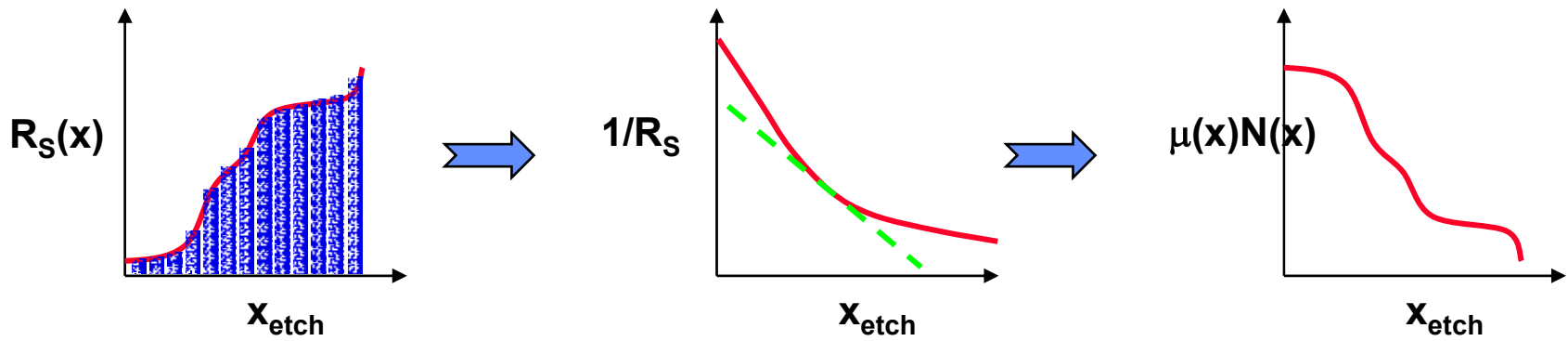
- can only profile on lightly-doped side of junction

“Layer stripping” / spreading resistance techniques

- geometrically



- sequentially remove “surface” layer, then measure R_S



$$(R_S)^{-1} = \int_0^{x_j} \underbrace{q \cdot \mu(N)}_{\sigma = 1/\rho} \cdot \overbrace{[N(x) - N_B]}^{\text{netcarriers}} dx \quad \Rightarrow \quad q \cdot \mu(x_{etch}) \cdot [N(x_{etch}) - N_B] \cdot \delta x = \{1/R_S(x_{etch})\} - \{1/R_S(x_{etch} + \delta x)\}$$

$$\mu(x_{etch}) \cdot [N(x_{etch}) - N_B] = -\frac{1}{q} \cdot \frac{[\{1/R_S(x_{etch} + \delta x)\} - \{1/R_S(x_{etch})\}]}{\delta x}$$

- slope of $1/R_S$ curve gives μN product

$$\mu(x_{etch}) \cdot [N(x_{etch}) - N_B] = -\frac{1}{q} \cdot \frac{\partial \{1/R_S(x_{etch})\}}{\partial x}$$

Deposited thin films

- **need to be able to add materials “on top” of silicon**
 - both conductors and insulators
- **deposition methods**
 - physical vapor deposition (PVD)
 - thermal evaporation
 - sputtering
 - chemical vapor deposition (CVD)
- **general requirements**
 - good electrical characteristics
 - free from pin-holes, cracks
 - low stress
 - good adhesion
 - chemical compatibility
 - with both layer “below” and “above”
 - at room temperature and under deposition conditions