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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!***

Resistivity
Sheet Resistance

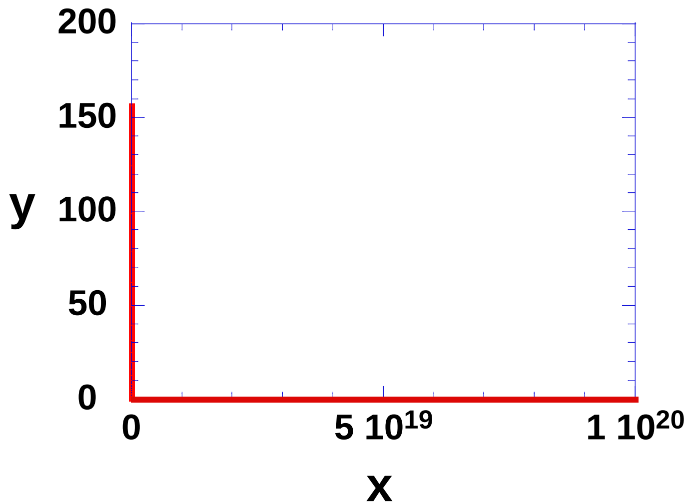
Four-point Probe
Semiconductor Resistivity

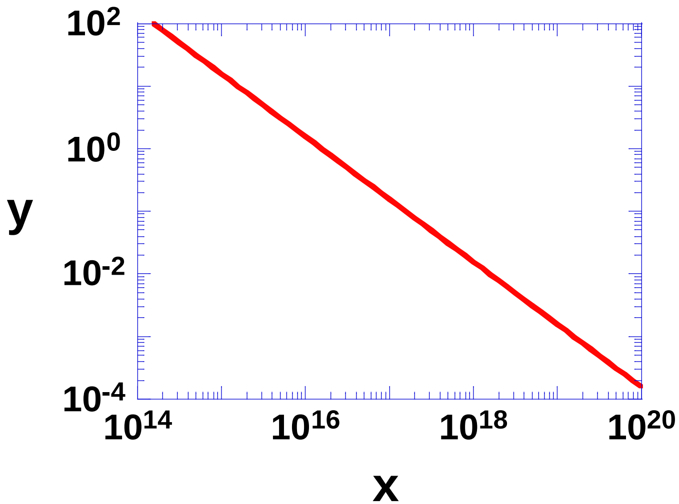
Wafer Mapping
van der Pauw
Eddy Current
Modulated Photoreflectance
Conductivity Type

Graphs and Plots

- When two variables, *e.g.*, resistivity and doping density, vary over many orders of magnitudes (decades) it is best to plot log - log

$$y = \frac{1}{6.4x10^{-17}x}$$



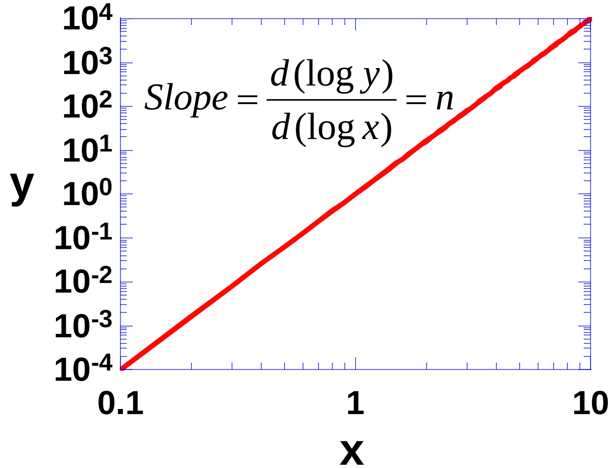


Graphs and Plots

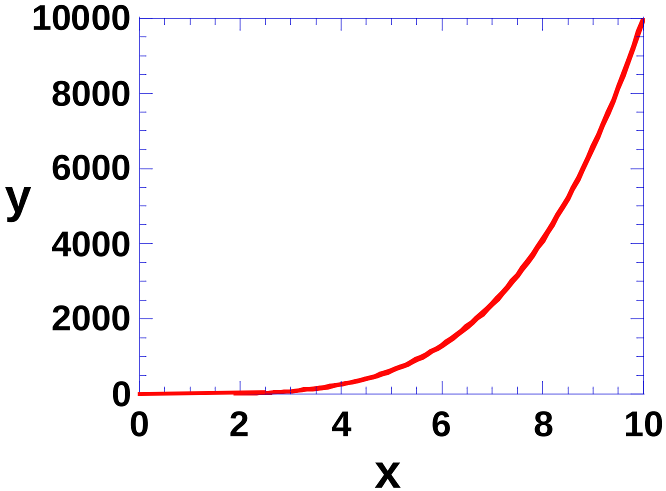
$y = x^n$

What is n?

Plotted on a Log Scale then Analyzed

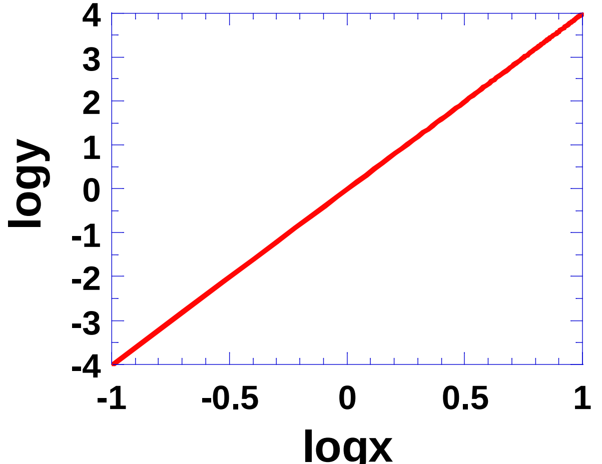


Plotted on a Linear Scale – Cannot be Analyzed



Take Log 1st then Plotted and Analyzed

$$y = x^n \quad \Rightarrow \log y = \log x^n = n \log x$$



Graphs and Plots: Example

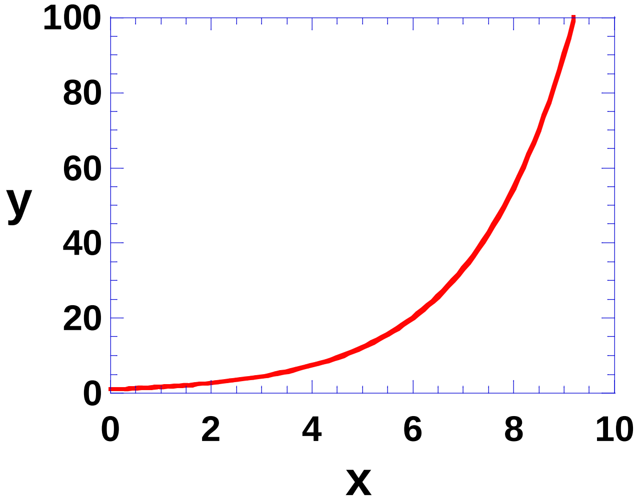
$$y = Ke^{x/x_1}$$

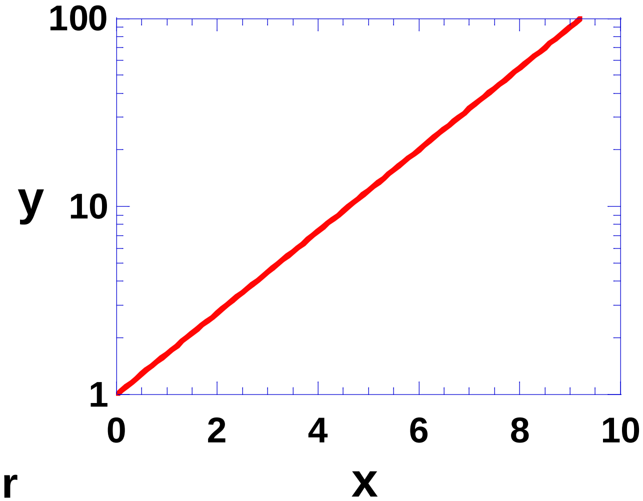
What are K and x_1?

$$\ln y = \ln K + x/x_1; \ \log y = \log K + \frac{x/x_1}{\ln 10}$$

$$\left[recall \rightarrow \log y = \frac{\ln y}{\ln 10} \right]$$

$$Slope = \frac{d(\log y)}{dx} = \frac{1}{x_1 \ln 10} = \frac{1}{2.3 x_1}$$

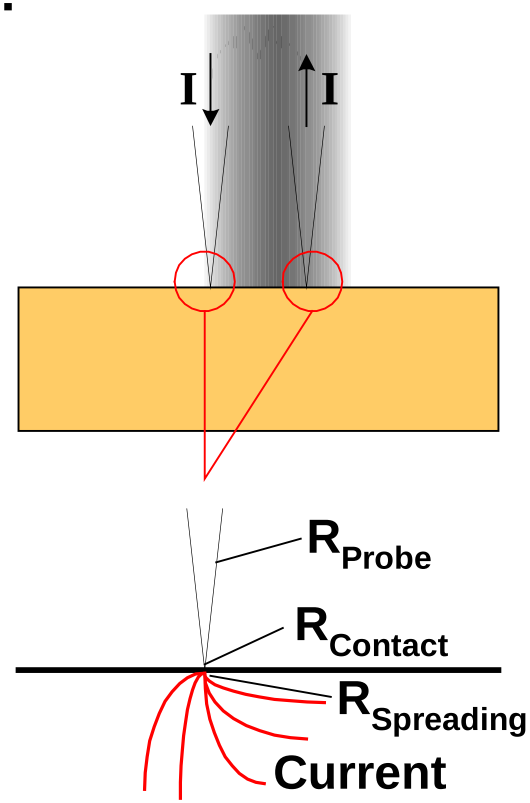


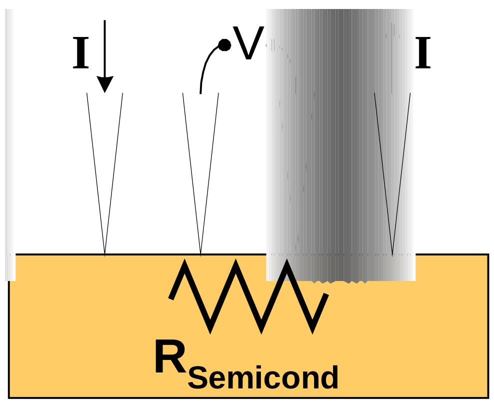


Taking Natural Log Scale makes Analysis easier but makes scales hard to read. Data is almost always presented in a Log10 basis.

Kelvin Measurements

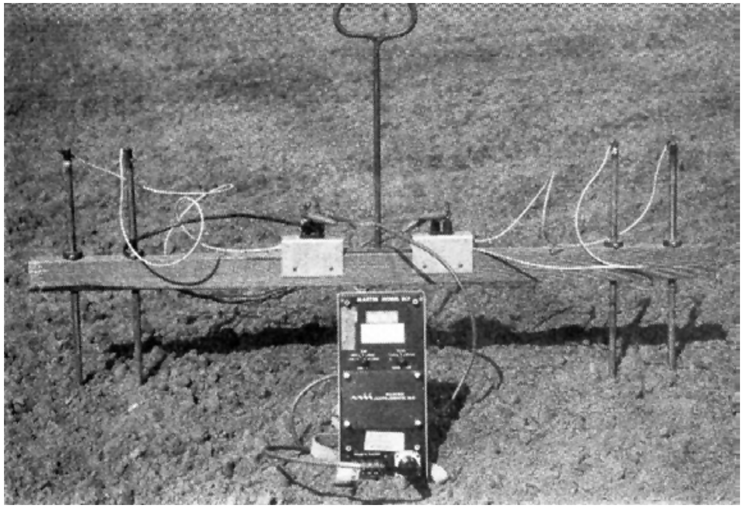
- Kelvin measurements refer to 4-probe measurements
- Two probes:
  - $2R_{Probe}+2R_{Contact}+2R_{Spreading}$
- Four probes:
  - $R_{Semicond}$

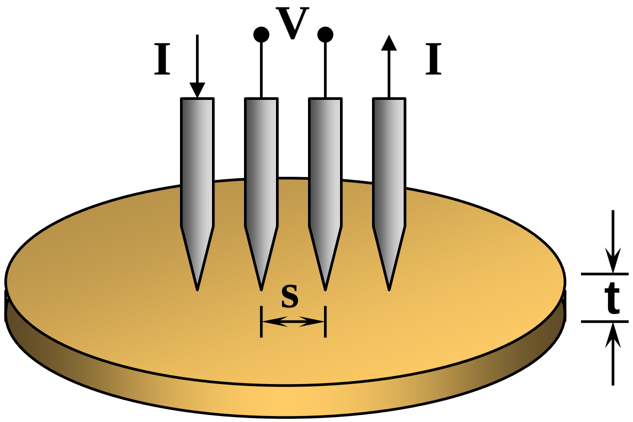




Four Point Probe

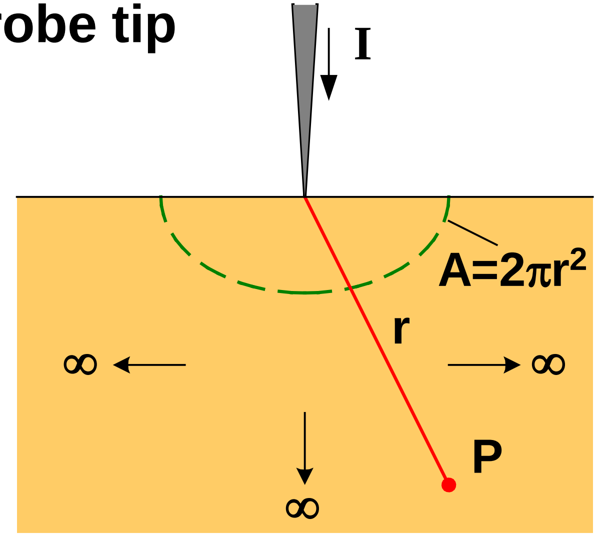
- The four point probe is used to determine the *resistivity* and *sheet resistance*



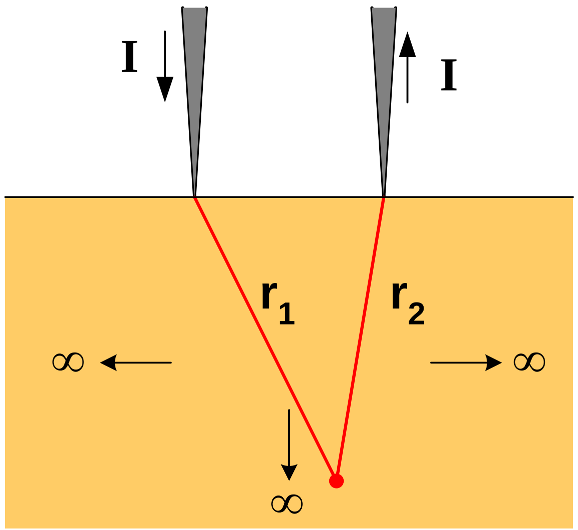


Four Point Probe

- Derivation of the basic four point probe equation
- Assumption: Current flows out radially from infinitesimal probe tip



Voltage Due to a Single Probe



Voltage Due to Two Probes

$$V = IR; \ \varepsilon = J\rho = -\frac{dV}{dr}; \ J = \frac{I}{A} = \frac{I}{2\pi r^2}$$

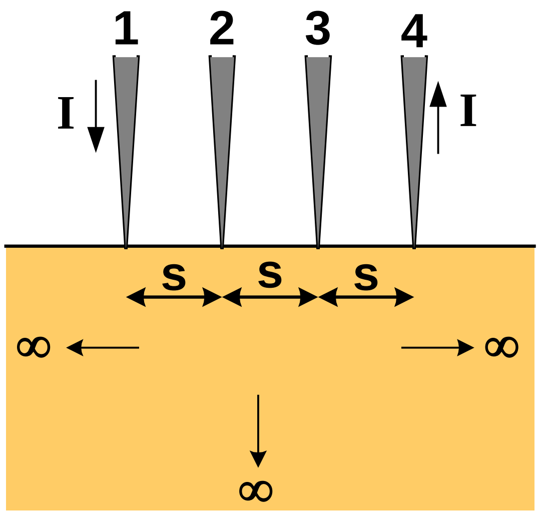
$$\int_0^V dV = -\frac{I\rho}{2\pi}\int_\infty^r \frac{dr}{r^2} \Rightarrow \boxed{V = \frac{I\rho}{2\pi r}}$$

$$V = \frac{I\rho}{2\pi r_1} - \frac{I\rho}{2\pi r_2}$$

$$V = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

Four Point Probe

- For four *in-line* probes



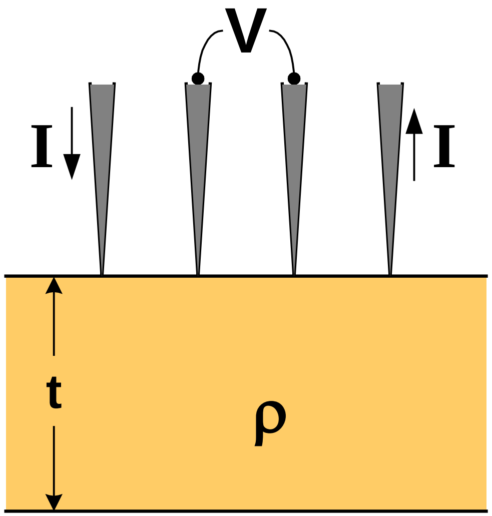
$$V_2 = \frac{I\rho}{2\pi}\left(\frac{1}{s} - \frac{1}{2s}\right);\ V_3 = \frac{I\rho}{2\pi}\left(\frac{1}{2s} - \frac{1}{s}\right)$$

$$V = V_{23} = V_2 - V_3 = \frac{I\rho}{2\pi}\left(\frac{1}{s} - \frac{1}{2s} - \frac{1}{2s} + \frac{1}{s}\right) = \frac{I\rho}{2\pi s}$$

$$\rho = 2\pi s \frac{V}{I} \quad \Omega - cm$$

Four Point Probe

- **Since wafers are not infinite in extent, need to correct for**
  - **Conducting/non-conducting bottom boundary**
  - **Wafer thickness**
  - **Nearness to wafer edge**
  - **Wafer size**



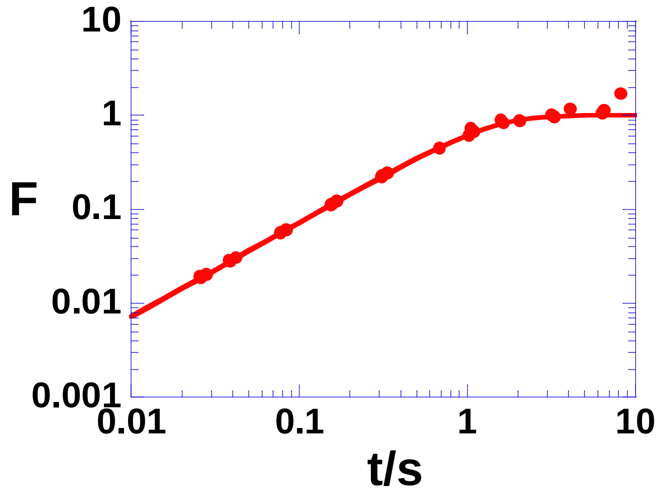
- **For *non-conducting* bottom surface boundary**

F=$F_1F_2F_3$

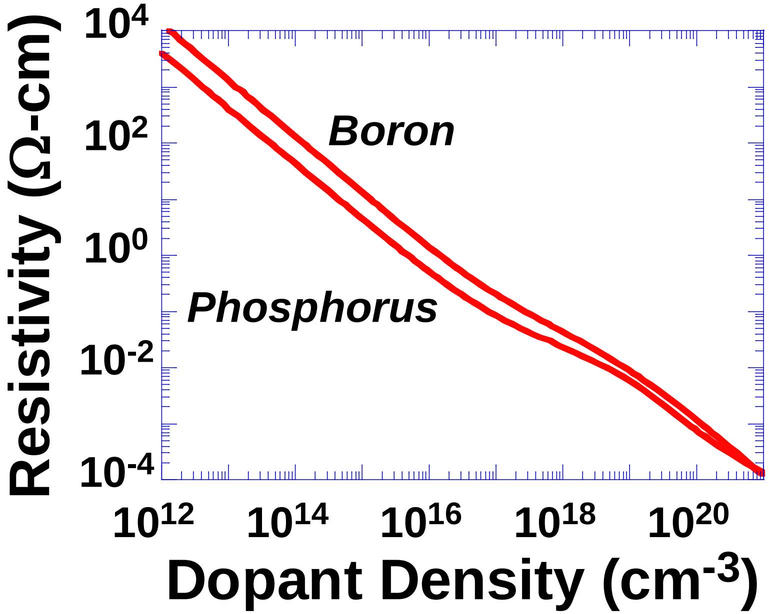
- F_1 corrects the sample thickness
- F_2 corrects the lateral dimensions (F_2 ~1if wafer size is ~40 times S)
- F_3 corrects the probe to edge (d) placement errors (~1 if d>2S)

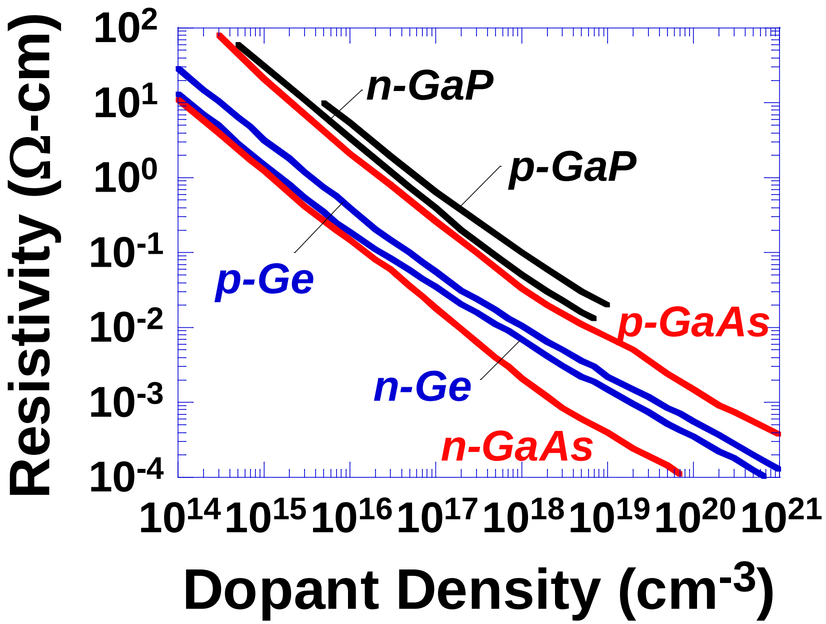
$$\rho = 2\pi s F \frac{V}{I} (\Omega \cdot cm)$$

$$F_1 = \frac{t/s}{2\ln[\sinh(t/s)/\sinh(t/2s)]}$$



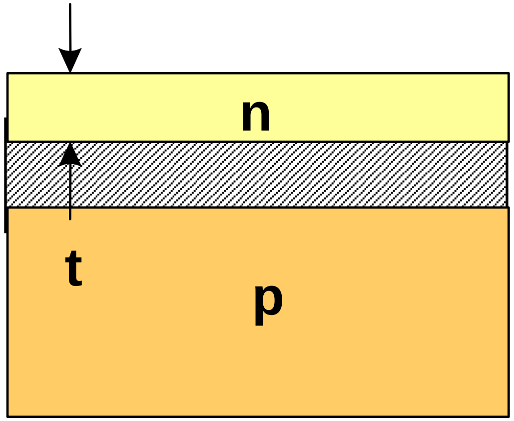
Resistivity





Thin Layers

- Consider a thin film on an insulator
  - Metal layer on insulator
  - Poly-Si layer on insulator
  - *n* on *p* or *p* on *n*



$$F_1 = \frac{t/s}{2\ln\left[\sinh(t/s)/\sinh(t/2s)\right]}$$

Usually $t \ll s$

Recall $\sinh x \cong x$ for $x \ll 1$

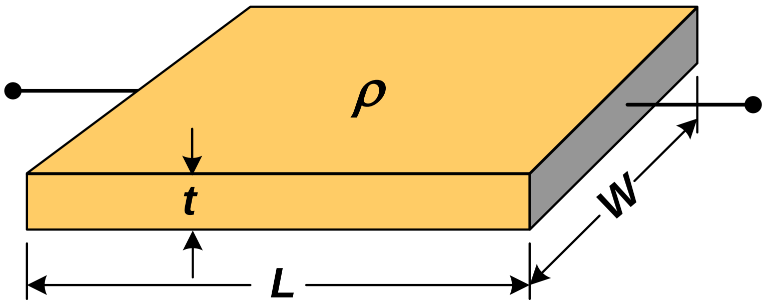
$$\therefore \; F_1 \approx \frac{t/s}{2\ln(2)}$$

$$\rho = 2\pi s \frac{t/s}{2\ln 2}\frac{V}{I} = \frac{\pi}{\ln 2} t \frac{V}{I} = 4.532 t \frac{V}{I}$$

What Is Sheet Resistance?

- The resistance between the contacts is

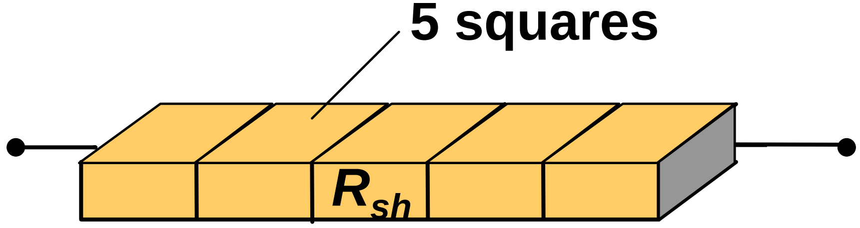
$$R = \frac{\rho L}{A} = \frac{\rho}{t}\frac{L}{W} \quad ohms$$



- *L/W* has no units
- ρ/*t should* have units of *ohms*
- But . . . $R \neq \rho/t$!
- Sheet resistance $R_{sh} = \rho/t$ (*ohms/square)*

$$R = (R_{sh})\, x\, (number\, of\, squares)\; [ohms]$$

- Resistance independent of the size of the square



Sheet Resistance

$$\rho = \frac{\pi}{\ln 2} t \frac{V}{I}$$

- **Frequently you do not know *t*.**
  - **Ion implanted layer**
  - **Diffused layer**
  - **Metal film**
  - **Poly-Si layers**
- **Define *sheet resistance* R_{sh}**
- **For uniformly-doped layer**

$$R_{sh} = \frac{\rho}{t} = \frac{1}{\sigma t} = \frac{\pi}{\ln 2} \frac{V}{I}$$

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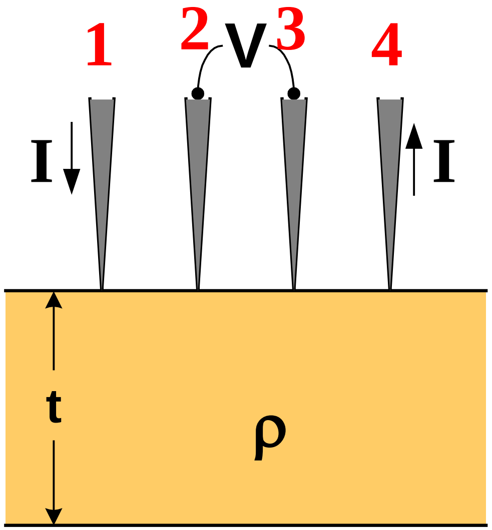
Dual Configuration (or Switched Configuration)

- **Measurement 1: Current in 1 & out 4 and voltage measured on 2 and 3. Directions then reversed.**
- ***Measurement 2: Current in 1 & out 3 and voltage measured on 2 and 4.*** **Directions then reversed.**
- ***Advantages:***
  - ***Probes can be oriented in any direction (no need to be parallel or perpendicular to the wafer radius or edges)***
  - ***Lateral dimensions no longer needed***
  - ***Self-correcting for changes in probe spacing***

$$R_{SH} = -14.696 + 25.173\frac{R_a}{R_b} - 7.872\left(\frac{R_a}{R_b}\right)^2$$

$$R_a = \left(\frac{\frac{V_{f23}}{I_{f14}} + \frac{V_{r23}}{I_{r14}}}{2}\right) \qquad R_b = \left(\frac{\frac{V_{f24}}{I_{f13}} + \frac{V_{r24}}{I_{r13}}}{2}\right)$$



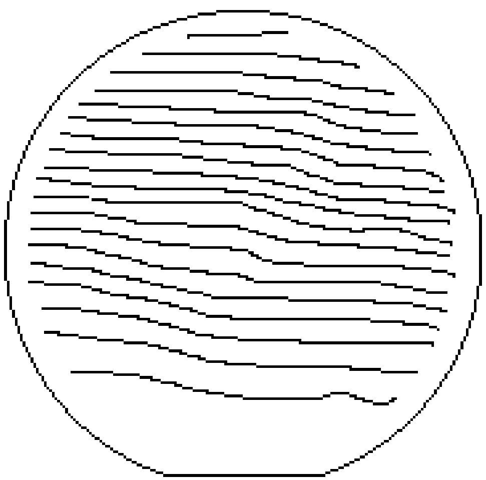
Wafer Mapping

TABLE 1.1 Mapping Techniques for Ion Implantation Uniformity Measurements.

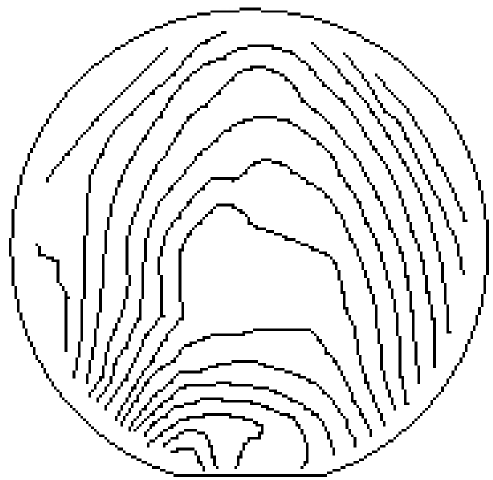
	Four-Point Probe	Double Implant	Spreading Resistance	Modulated Photoreflectance	Optical Densitometry
Type	Electrical	Electrical	Electrical	Optical	Optical
Measurement	Sheet Resistance	Crystal Damage	Spreading Resistance	Crystal Damage	Polymer Damage
Resolution (μm)	3000	3000	5	1	3000
Species	Active	Active, Inactive	Active	Inactive	Inactive
Dose Range (cm^{-2})	$10^{12}-10^{15}$	$10^{11}-10^{14}$	$10^{11}-10^{15}$	$10^{11}-10^{15}$	$10^{11}-10^{13}$
Results	Direct	Calibration	Calibration	Calibration	Calibration
Relaxation	Minor	Serious	Minor	Serious	Serious
Requires	Anneal	Initial Implant	Anneal		Measure before and after

Wafer Maps

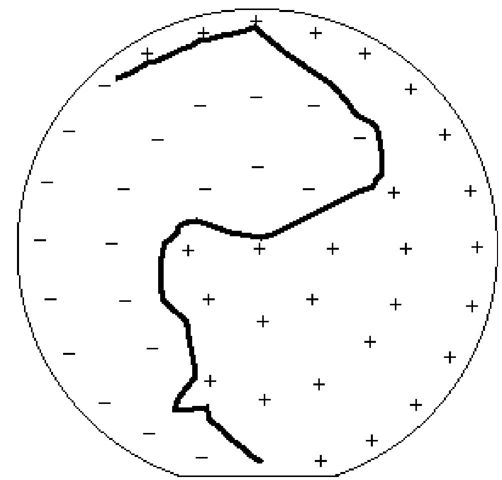
- **Measure sheet resistance; generate and plot contour maps (lines of equal sheet resistance)**



Si-doped Al
$R_{sh,av}$ = 80.6 mΩ/square
1% Contours



Epitaxial Si
$R_{sh,av}$ = 18.5 kΩ/square
1% Contours

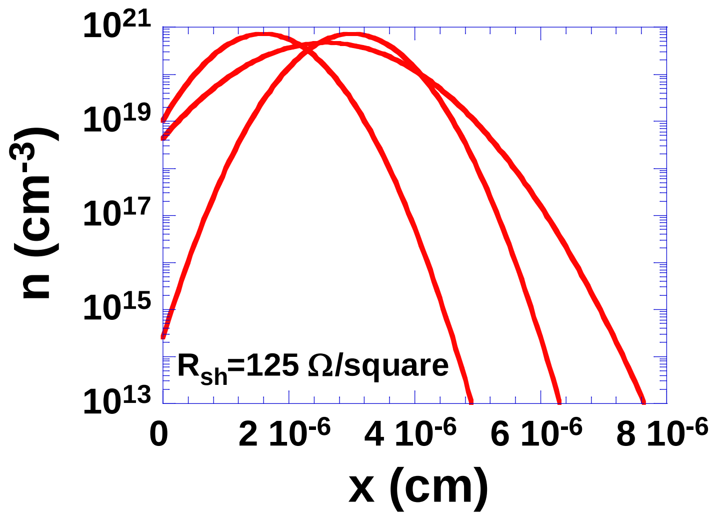


B-implanted Si
$R_{sh,av}$ = 98.5 Ω/square
1% Contours

Sheet Resistance

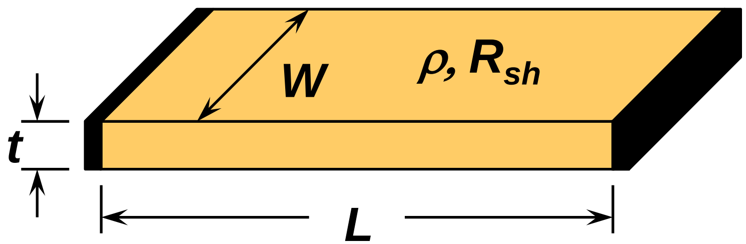
- For *non-uniformly* doped layers

$$R_{sh} = \frac{1}{\int_0^t \sigma\, dx} = \frac{1}{q\int_0^t n\mu_n dx}$$



Sheet Resistance

- **Sheet resistance R_{sh} depends on the total number of implanted or diffused impurities and on the layer thickness**



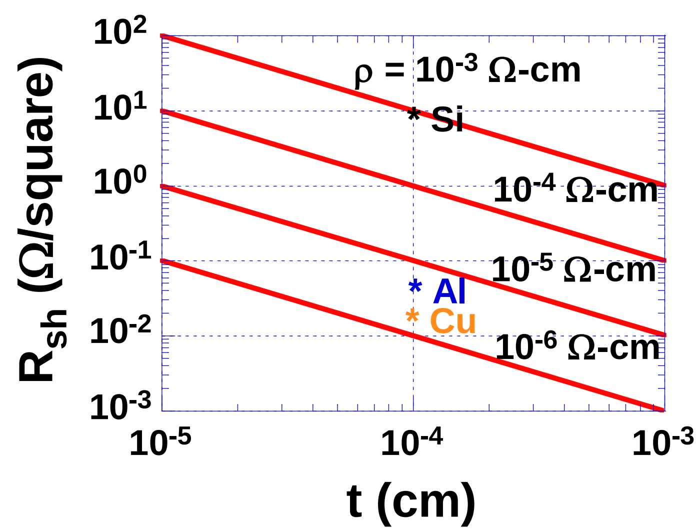
$$R = \frac{R_{sh} L}{W} \; Ohms$$

Uniformly doped:

$$R_{sh} = \frac{\rho}{t} = \frac{1}{\sigma t} = \frac{1}{q n \mu_n t} \; Ohms/square$$

Non-uniformly doped:

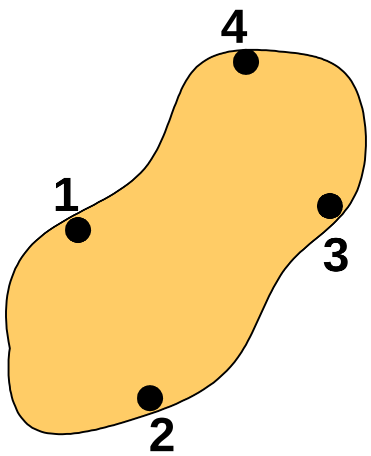
$$R_{sh} = \frac{1}{q \int_0^t n \mu_n dx} \; Ohms/square$$



van der Pauw Measurements

- Instead of a four-point probe, one can use an arbitrarily shaped sample
  - Current flows through two adjacent contacts
  - Voltage is measured across the other two contacts

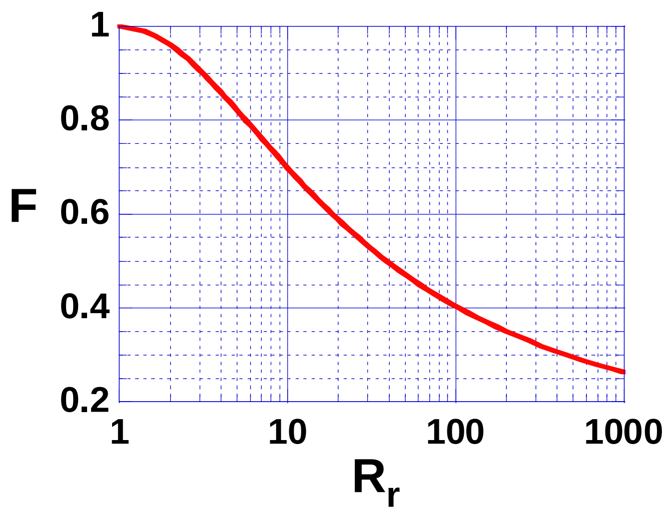
$$\rho = \frac{\pi t}{\ln 2} F\left(\frac{R_{12,34} + R_{23,41}}{2}\right); \; R_{12,34} = \frac{V_{34}}{I_{12}}; \; R_{23,41} = \frac{V_{41}}{I_{23}}$$

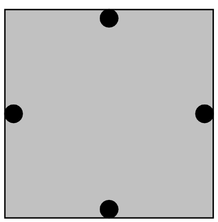


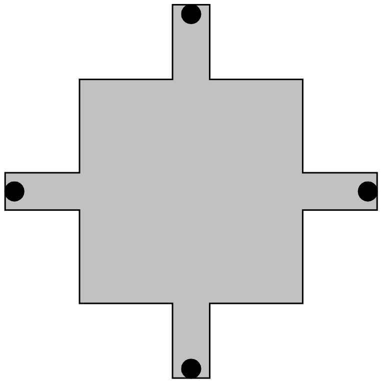
van der Pauw Measurements

- *F* function is determined from

$$\frac{R_r - 1}{R_r + 1} = \frac{F}{\ln 2}\cosh^{-1}\left(\frac{\exp(\ln 2 / F)}{2}\right) \qquad R_r = \frac{R_{12,34}}{R_{23,41}}$$





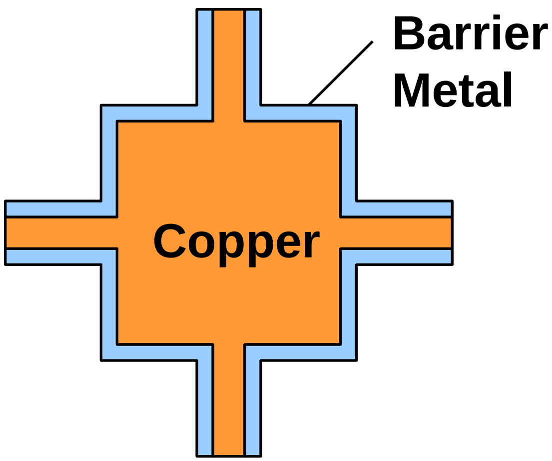


For symmetrical samples, *e.g.*, circles or squares, *F* = 1

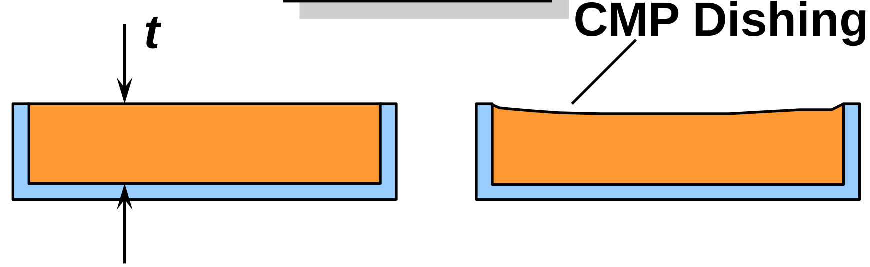
$$\rho = \frac{\pi t}{\ln 2} R_{12,34} ; R_{sh} = \frac{\pi}{\ln 2} R_{12,34}$$

Precautions

- **For copper metallization barrier layers are used to prevent Cu from diffusing into SiO_2 or Si**
- **Barrier layers have negligible effect on sheet resistance R_{sh} measurement of thick conductor films**
- **Chemical-mechanical polishing (CMP) *dishing* does affect R_{sh} measurements**



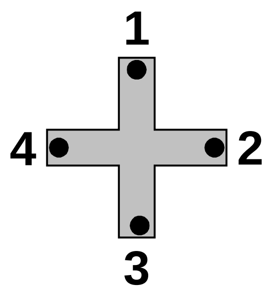
$$R_{sh} = \rho / t$$



T. Turner, "Cu-Linewidth Resistivity Measurements," *Solid State Technol*. **43**, 89-96, April 2000

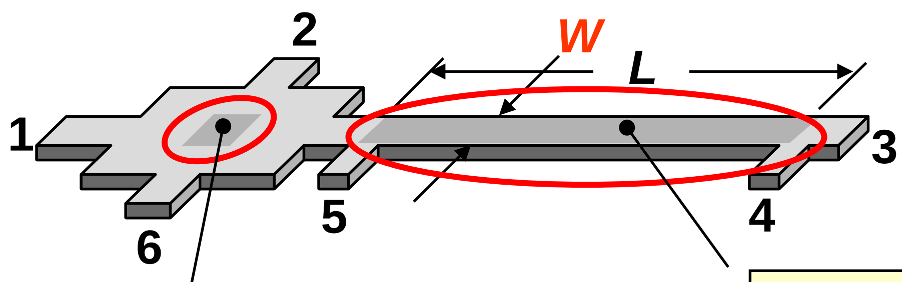
Line Width

- Greek Cross



$$R_{sh} = \frac{\pi}{\ln 2}\frac{V_{34}}{I_{12}}$$

- Cross bridge test structure

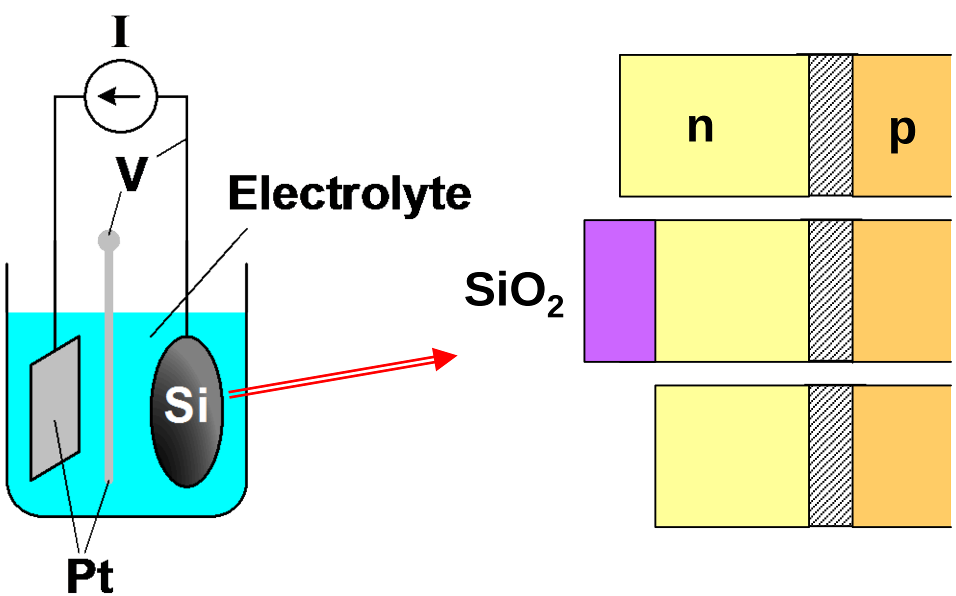


$$R_{sh} = \frac{\pi}{\ln(2)}\frac{V_{12}}{I_{65}};\ R_{line} = \frac{V_{54}}{I_{13}} = R_{sh}\frac{L}{W} \Rightarrow W = R_{sh}\frac{L}{R_{line}}$$

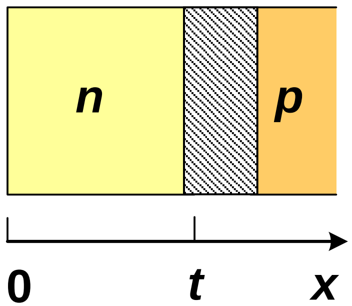
Used to determine line width *W*

Anodic Oxidation / van der Pauw

- Place wafer into electrolyte
- Apply constant current, measure voltage
- Oxide grown anodically at room temperature
- Oxide growth consumes Si
- When oxide is etched, Si is removed
- Measure sheet resistance



Anodic Oxidation / van der Pauw

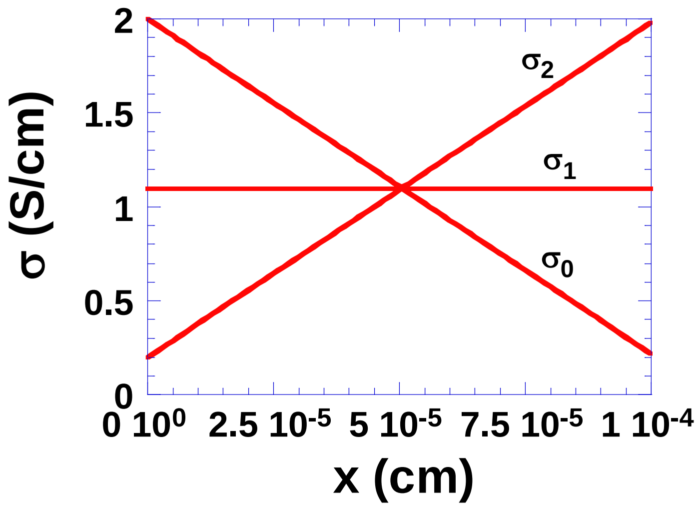


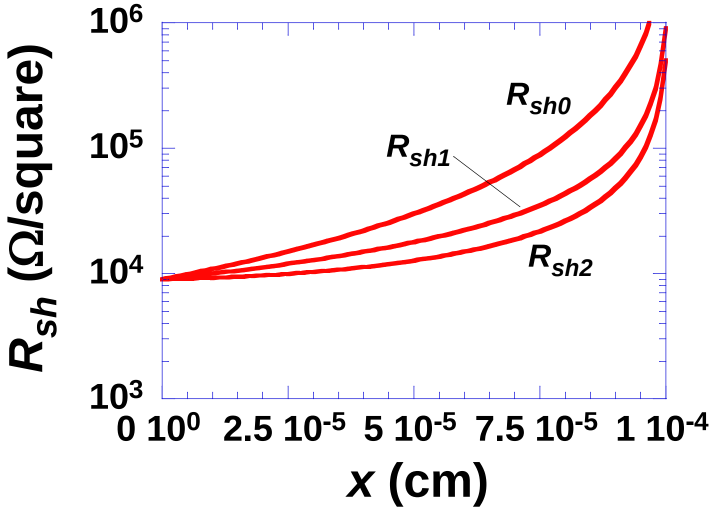
$$R_{sh}=\frac{1}{\int_x^t \sigma dx}\Rightarrow \frac{d(1/R_{sh})}{dx}=-\sigma=-\frac{1}{\rho}$$

Using Leibniz's theorem:

$$\left[\frac{d}{dc}\int_a^b f(x)dx = f(b)\frac{\partial b}{\partial c}-f(a)\frac{\partial a}{\partial c}\right]$$

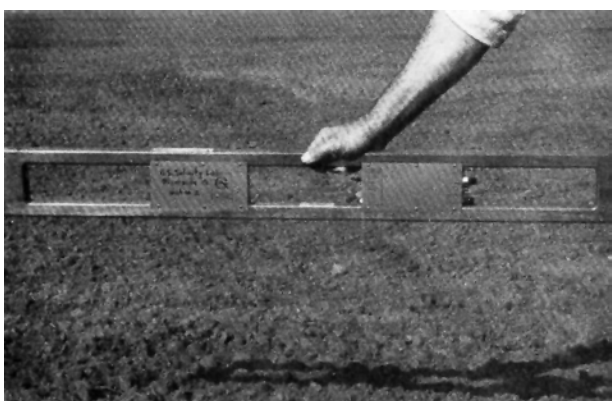
$$\rho(x)=-\frac{1}{d(1/R_{sh})/dx}=\left[\frac{1}{R_{sh}^2}\frac{dR_{sh}}{dx}\right]^{-1}$$

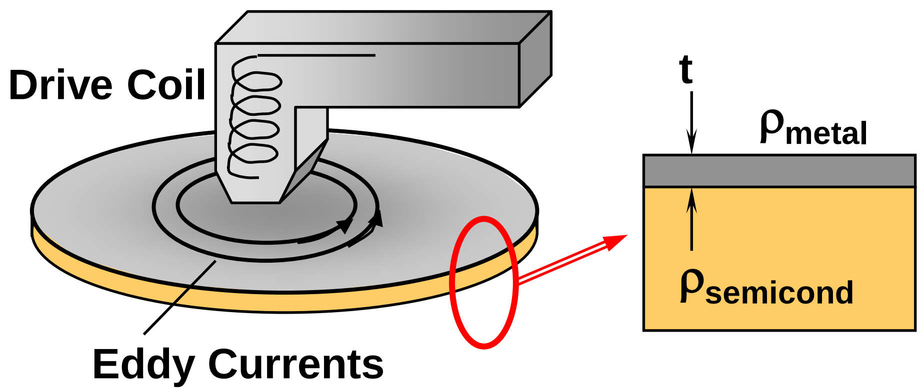




Eddy Current - Contactless

- **An oscillating circuit induces time-varying magnetic fields leading to *eddy currents* in the wafer ⇒ resulting loss is proportional to the *sheet resistance* R_{sh}**
  - ***Sheet resistance***
  - ***Conductor thickness*: $t = \rho_{metal} / R_{sh}$, measure metal sheet resistance R_{sh}, know metal resistivity ρ_{metal}**

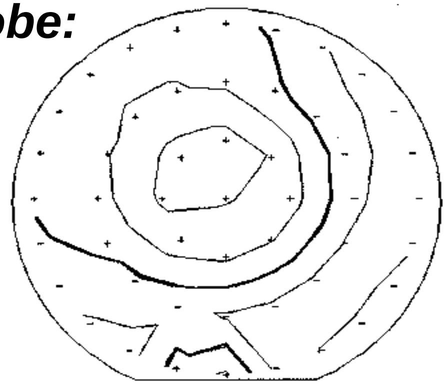




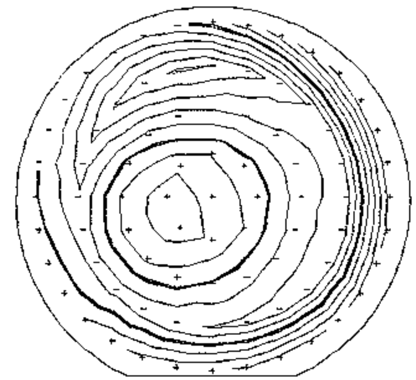
Four Point Probe / Eddy Current

Four Point Probe:

1 μm Aluminum



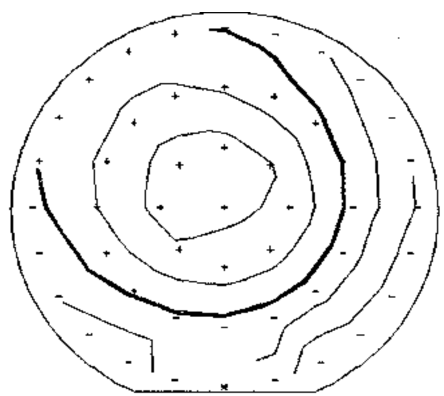
$R_{sh,av}$ = 3.023x10^{-2} Ω/square
Std. Dev. = 1.413%



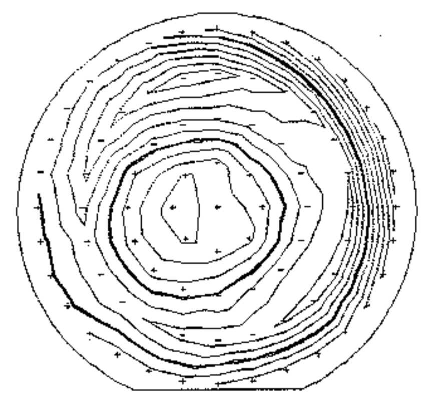
200 Å Titanium

$R_{sh,av}$ = 62.904 Ω/square
Std. Dev. = 2.548%

Eddy Current:



$R_{sh,av}$ = 3.024x10^{-2} Ω/square
Std. Dev. = 1.459%

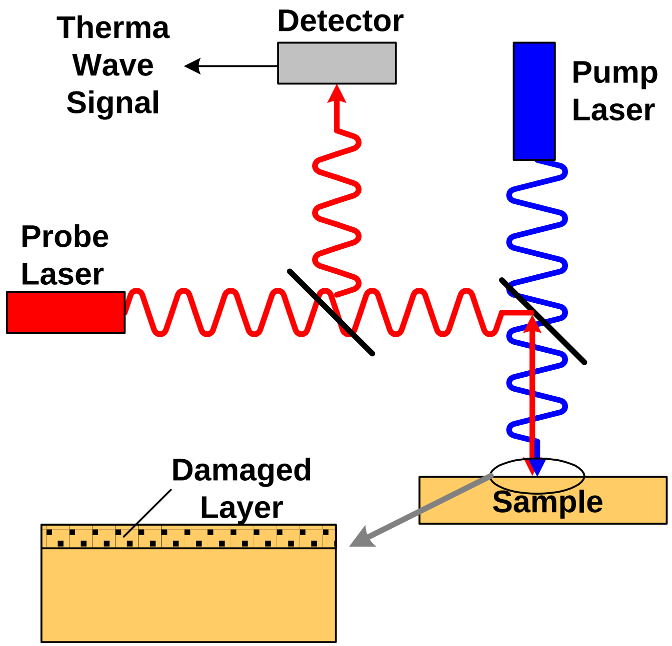


$R_{sh,av}$ = 62.560 Ω/square
Std. Dev. = 2.94%

Figures courtesy of
W. Johnson, KLA-Tencor

Modulated Photoreflectance

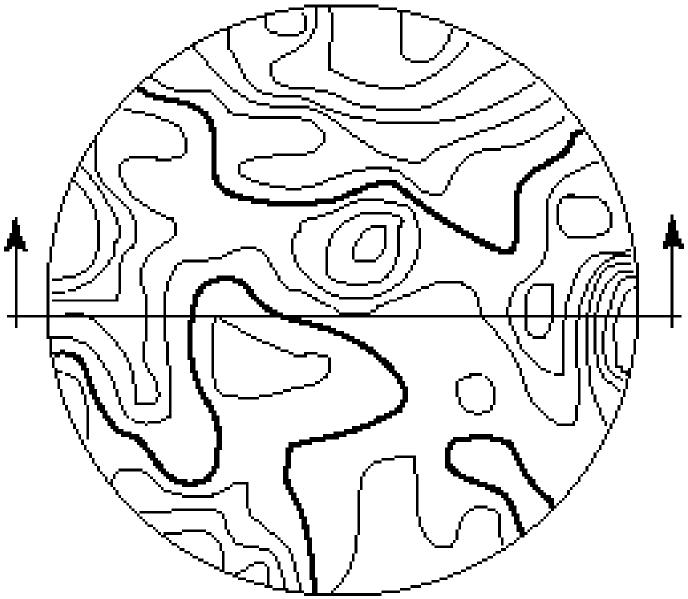
- **Pump laser heats semiconductor locally ⇒ small reflectivity change of the wafer ⇒ measured by the probe beam**
- **Ion-implanted samples:**
  - **No post-implant annealing required**
  - **Signal ~ implant dose**
  - **High spatial resolution (few μm)**
  - **Can measure implanted patterns**
  - **Bare and oxidized wafers**
  - **Non-contact, non-destructive**

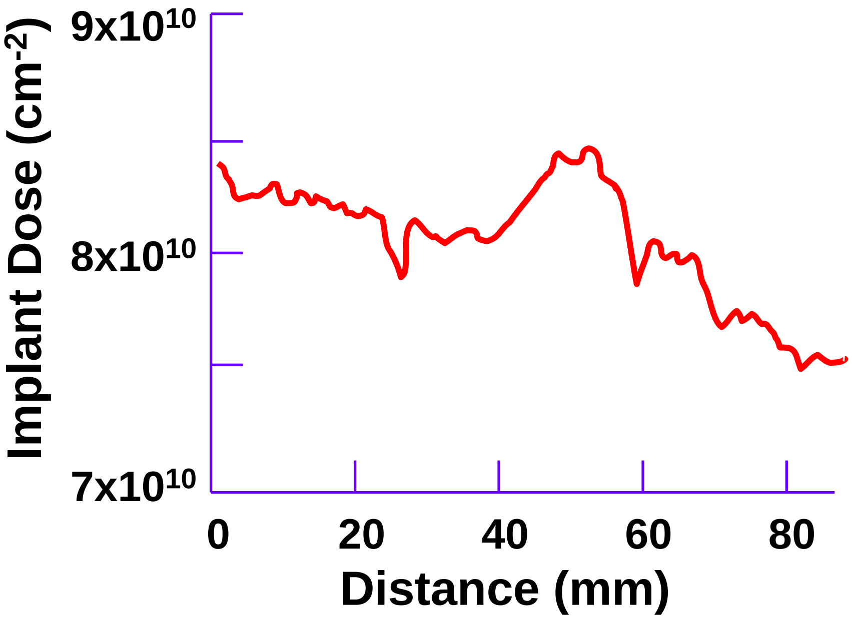


…also known as ThermaWave

http://www.thermawave.com

Modulated Photoreflectance





B in Si, 30 keV, $8x10^{10}$ cm^{-2}, contour intervals: 1%

Courtesy A.M. Tello, Xerox Microelectronics Center

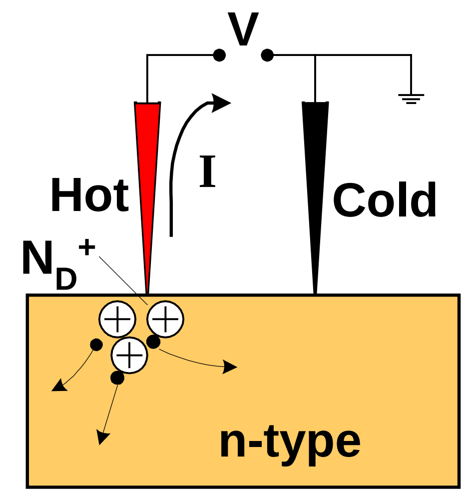
Conductivity Type

- **Hot Probe**

$$v_{th} = \sqrt{\frac{3kT}{m^*}} \sim \sqrt{T}$$

Where v_{th} is the thermal velocity of the carrier

  - **Electrons move away from hot probe**
  - **Positive donor ions left behind**
  - **For *n*-type: $V_{hot} > 0$**
  - **For *p*-type: $V_{hot} < 0$**

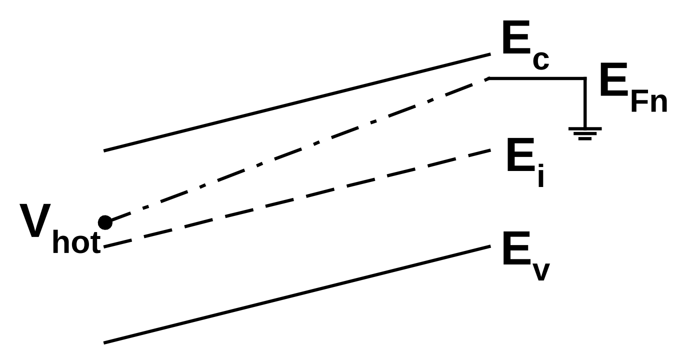


- **Thermoelectric power**

$$J_n = \mu_n n dE_{Fn}/dx - q\mu_n n P_n dT/dx$$

- **When you are at ~open circuit (i.e measuring voltage)**

$$J_n \cong 0 \Rightarrow dE_{Fn}/dx = qP_n dT/dx$$



P_n is differential thermoelectric power (<0)

Warnings

- Hot Probe - Warnings:
  - Works for ~10^{-3} to ~10^{3} ohm-cm
  - Above ~10^{3} ohm-cm, p-type will likely read as n-type (due to you actually measuring $n\mu_n$ and $p\mu_p$ not n and p)
  - High resistivity materials need very high input impedance voltmeter (electrometer type).

- Resistivity Warnings:
  - Watch out for surface depletion
    - Especially serious in compound semiconductors
  - Thermal variations due to drive currents
    - Follow NIST standards for power levels
  - Fermi-level pinned surfaces (InN for example)
  - Whenever possible, keep drive voltages small (V<kT/q) so contact non-linearities are not important. Otherwise ***CHECK CONTACT LINEARITY!***

$$I = I_O\left(e^{\left(\frac{qV}{kT}\right)} - 1\right)$$

$$I \sim I_O\left(\frac{qV}{kT}\right) \text{for V} << \left(\frac{qV}{kT}\right)$$

Review Questions

- What is the best way to plot power law data?
- What is the best way to plot exponential data?
- Why is a four-point probe better than a two-point probe?
- Why is resistivity inversely proportional to doping density?
- What is an important application of wafer mapping?
- Why is a four-point probe better than a two-point probe?
- Why is sheet resistance commonly used to describe thin films?
- What is the main advantage of Eddy current measurements?
- What are advantages and disadvantages of the modulated photoreflectance (therma wave) technique?