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

\[ y = \frac{1}{6.4 \times 10^{-17} x} \]
Graphs and Plots

\[ y = x^n \]

What is \( n \)?

Plotted on a Linear Scale – Cannot be Analyzed

\[ \text{Slope} = \frac{d(\log y)}{d(\log x)} = n \]

Plotted on a Log Scale then Analyzed

Take Log 1\text{st} then Plotted and Analyzed

\[ y = x^n \quad \Rightarrow \quad \log y = \log x^n = n \log x \]
Graphs and Plots: Example

\[ y = Ke^{x/x_1} \]

What are K and \( x_1 \)?

\[
\ln y = \ln K + x / x_1; \quad \log y = \log K + \frac{x / x_1}{\ln 10}
\]

\[
\text{[recall } \log y = \frac{\ln y}{\ln 10} \text{]}
\]

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

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:
  - $2R_{\text{Probe}} + 2R_{\text{Contact}} + 2R_{\text{Spreading}}$
- Four probes:
  - $R_{\text{Semicond}}$
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

\[ V = lR; \quad \varepsilon = J\rho = -\frac{dV}{dr}; \quad J = \frac{l}{A} = \frac{l}{2\pi r^2} \]

\[ \int_0^V dV = -\frac{l\rho}{2\pi} \int_0^\infty \frac{dr}{r^2} \Rightarrow V = \frac{l\rho}{2\pi r} \]

Voltage Due to a Single Probe

Voltage Due to Two Probes

\[ V = \frac{l\rho}{2\pi r_1} - \frac{l\rho}{2\pi r_2} \]

\[ V = \frac{l\rho}{2\pi \left( \frac{1}{r_1} - \frac{1}{r_2} \right)} \]
Four Point Probe

- For four *in-line* probes

\[
V_2 = \frac{l\rho}{2\pi} \left( \frac{1}{s} - \frac{1}{2s} \right); \quad V_3 = \frac{l\rho}{2\pi} \left( \frac{1}{2s} - \frac{1}{s} \right)
\]

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

\[
\rho = 2\pi s \frac{V}{l} \quad \Omega - cm
\]
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

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

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

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

ECE 4813 Dr. Alan Doolittle
Resistivity

Resistivity ($\Omega \cdot$cm)

Dopant Density (cm$^{-3}$)

Boron

Phosphorus

Dopant Density (cm$^{-3}$)

Resistivity ($\Omega \cdot$cm)

$n$-GaP

$p$-GaP

$p$-Ge

$n$-Ge

$n$-GaAs
Thin Layers

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

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

Usually $t \ll s$

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

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

$$\rho = 2\pi s \frac{t/s}{2 \ln 2} \frac{V}{l} = \frac{\pi}{\ln 2} t \frac{V}{l} = 4.532 t \frac{V}{l}$$
What Is Sheet Resistance?

- The resistance between the contacts is

\[ R = \frac{\rho L}{A} = \frac{\rho}{t} \frac{L}{W} \text{ ohms} \]

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

\[ R = (R_{sh}) \times (\text{number of squares}) \text{ [ohms]} \]

- 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

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

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

\[
R_a = \left( \frac{V_{f23} + V_{r23}}{I_{f14} + I_{r14}} \right) \quad \quad R_b = \left( \frac{V_{f24} + V_{r24}}{I_{f13} + I_{r13}} \right)
\]
# Wafer Mapping

## TABLE 1.1  Mapping Techniques for Ion Implantation Uniformity Measurements.

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Wafer Maps

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

**Si-doped Al**

\[ R_{sh,av} = 80.6 \text{ m}\Omega/\text{square} \]

1% Contours

**Epitaxial Si**

\[ R_{sh,av} = 18.5 \text{ k}\Omega/\text{square} \]

1% Contours

**B-implanted Si**

\[ R_{sh,av} = 98.5 \text{ }\Omega/\text{square} \]

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 $L$.

**Uniformly doped:**

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

**Non-uniformly doped:**

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

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

\[
\rho = \frac{\pi t}{\ln 2} F \left( \frac{R_{12,34} + R_{23,41}}{2} \right); \quad R_{12,34} = \frac{V_{34}}{I_{12}}; \quad R_{23,41} = \frac{V_{41}}{I_{23}}
\]
van der Pauw Measurements

- $F$ function is determined from

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

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 SiO₂ 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.

\[ R_{sh} = \rho / t \]

Line Width

- **Greek Cross**

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

- Cross bridge test structure

\[ R_{sh} = \frac{\pi}{\ln(2)} \frac{V_{12}}{I_{65}} ; \quad R_{\text{line}} = \frac{V_{54}}{I_{13}} = R_{sh} \frac{L}{W} \quad \Rightarrow \quad W = R_{sh} \left( \frac{L}{R_{\text{line}}} \right) \]

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
Using Leibniz's theorem:

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

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

\[
R_{sh} = \frac{1}{t} \int_0^x \sigma dx \Rightarrow \frac{d(1/R_{sh})}{dx} = -\sigma = -\frac{1}{\rho}
\]
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**: $t = \frac{\rho_{metal}}{R_{sh}}$, measure metal sheet resistance $R_{sh}$, know metal resistivity $\rho_{metal}$
Four Point Probe / Eddy Current

**Four Point Probe:**

1 µm Aluminum

\[ R_{sh,av} = 3.023 \times 10^{-2} \ \Omega/\text{square} \]

Std. Dev. = 1.413%

200 Å Titanium

\[ R_{sh,av} = 62.904 \ \Omega/\text{square} \]

Std. Dev. = 2.548%

**Eddy Current:**

\[ R_{sh,av} = 3.024 \times 10^{-2} \ \Omega/\text{square} \]

Std. Dev. = 1.459%

\[ R_{sh,av} = 62.560 \ \Omega/\text{square} \]

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: \( V_{\text{hot}} > 0 \)
  - For \( p \)-type: \( V_{\text{hot}} < 0 \)

- **Thermoelectric power**
  \[ J_n = \mu_n n dE_{F_n} / dx - q\mu_n n P_n dT / dx \]
  - When you are at \( \sim \)open circuit (i.e. measuring voltage)
    \[ J_n \equiv 0 \Rightarrow dE_{F_n} / dx = qP_n dT / dx \]
  \( P_n \) is differential thermoelectric power (<0)
Warnings

- **Hot Probe - Warnings:**
  - Works for $\sim 10^{-3}$ to $\sim 10^3$ ohm-cm
  - Above $\sim 10^3$ 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!**

\[
I = I_o \left( e^{\frac{qV}{kT}} - 1 \right)
\]

\[
I \sim I_o \left( \frac{qV}{kT} \right) \text{ for } V \ll \left( \frac{qV}{kT} \right)
\]
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?