Aalto University
School of Electrical
Engineering

S-69.4123 Postgraduate Course in Electron Physics I
Chapter 1: RESISTIVITY

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Contents

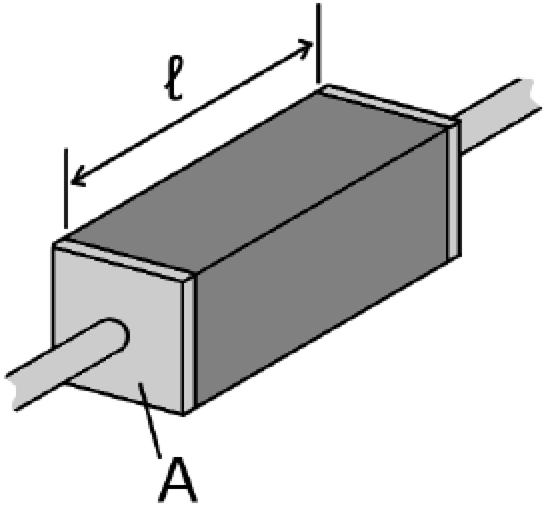
1. Introduction

- Resistivity

$$\rho = \frac{1}{q(n\mu_n + p\mu_p)}$$

- Resistance

$$R = \rho \frac{l}{A}$$

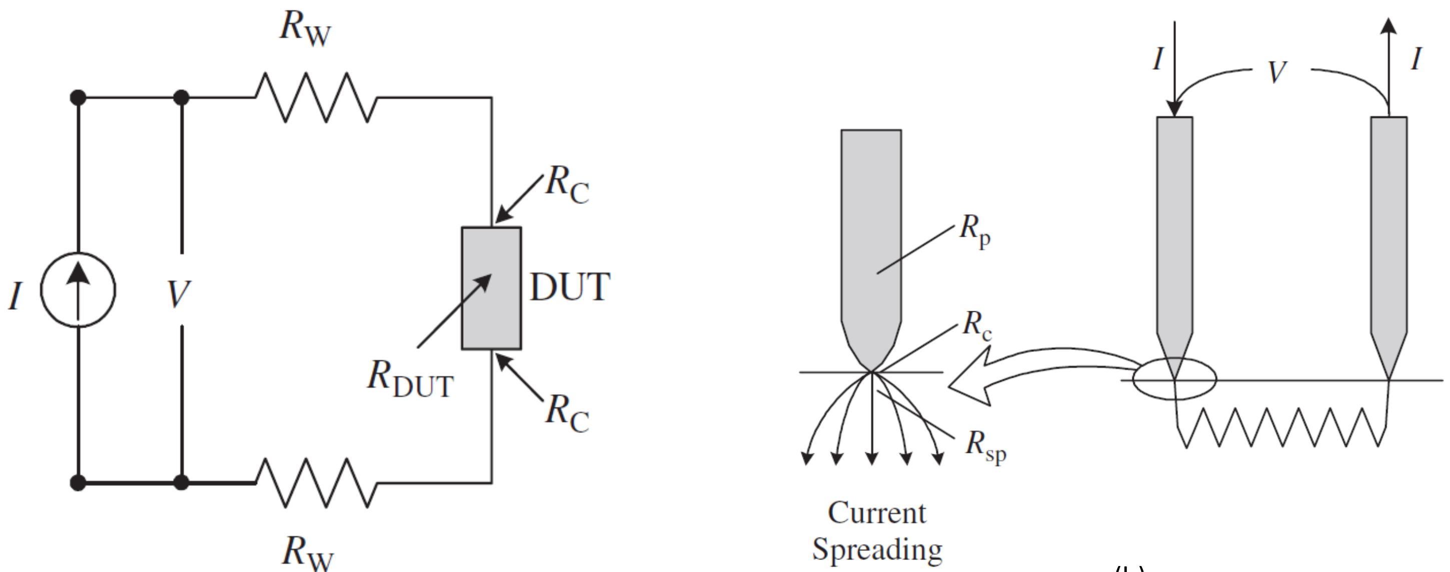


1. Resistivity

- Resistivity of epitaxially grown layer is generally very uniform
- Contributes to series resistance, capacitance, threshold voltage, hot carrier degradation in CMOS devices, etc.
- Usually n and p unknown, so other measuring methods required
- Can be divided into contactless, temporary contact and permanent contact methods

2. Two point probe

- Easier to implement but interpretation of the measured data is more difficult.



(a)

(b)

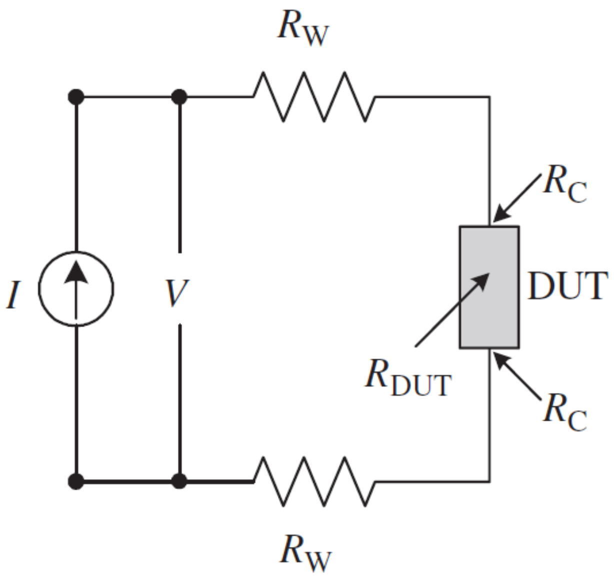
Fig: (a)Two-terminal resistance measurement arrangements (b) Two-point probe arrangement showing the probe resistance R_p, the contact resistance R_c, and the spreading resistance R_{sp}.

2. Two point probe

- Total resistance

$$R_T = V/I = 2R_W + 2R_C + R_{DUT}$$

- How to determine R_{DUT} ?



2. Four point probe

- Originally proposed by Wenner in 1916 to measure the earth's resistivity.
- Valdes adopted it for semiconductor wafer resistivity measurements in 1954
- Probes are generally collinear
- High impedance at voltage port ($Z_{in} \approx 10^{12}\ \Omega$)
- Voltage drop over R_w and R_c negligible.

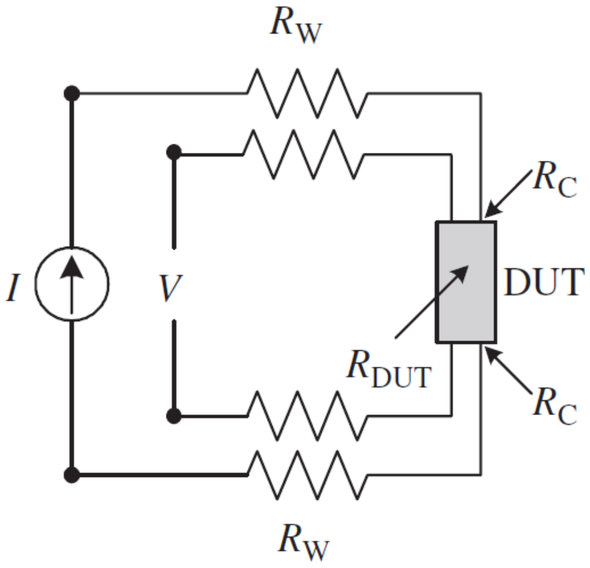


Fig: Four-terminal resistance measurement arrangements

2. Four point probe

- The most common method to determine resistivity
- Absolute measurement
- Used to provide standards for other measurements
- Also referred as Kelvin measurements

2. Four versus two point probe

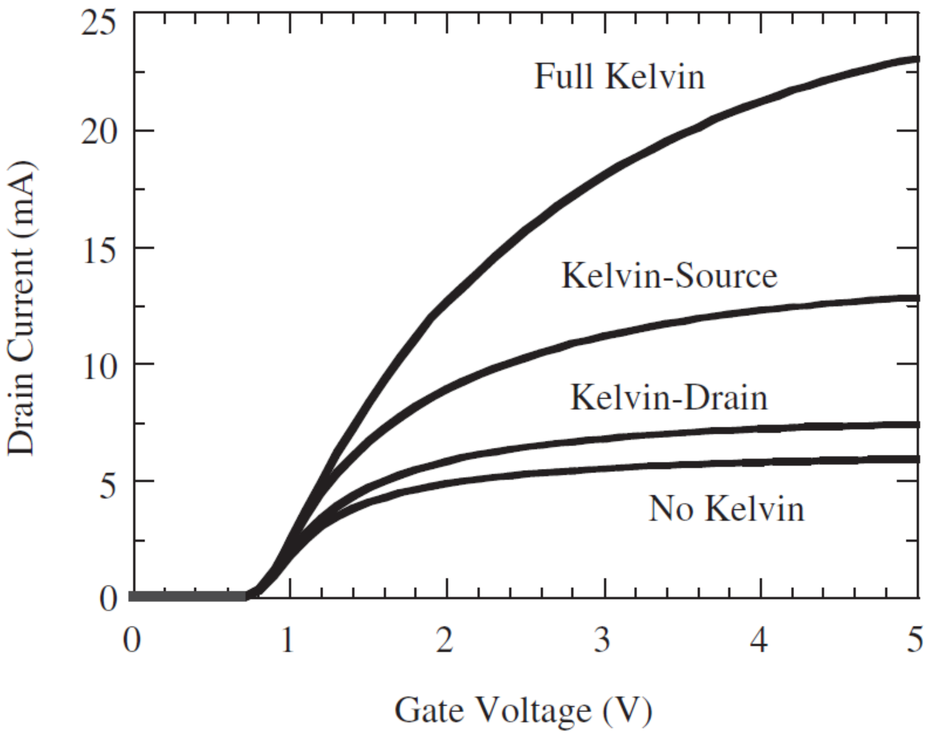


Fig. Effect of contact resistance on MOSFET drain current

2. Resistivity in four probe setup

- Electric field

$$E = J\rho = -\frac{dV}{dr}$$

- Current density

$$J = \frac{I}{2\pi r^2}$$

- The voltage at point P

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

$$V = \frac{I\rho}{2\pi r}$$

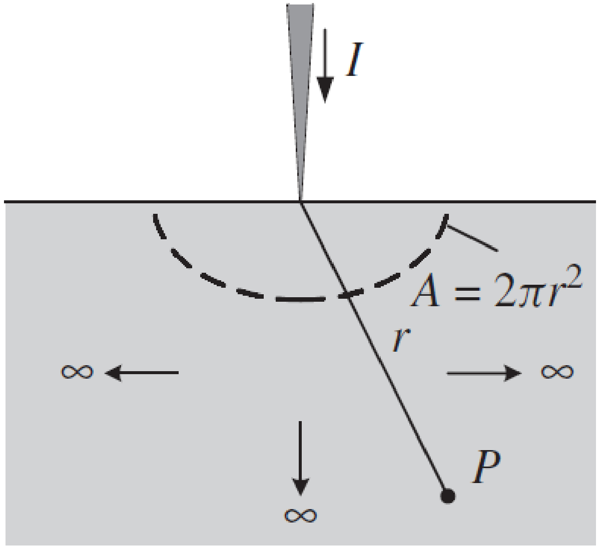


Fig: one-point probe

2. Resistivity in four probe setup

- Voltage across two point probe

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

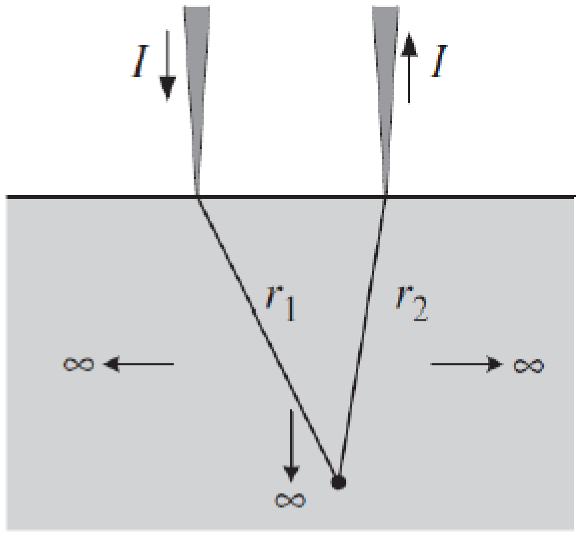


Fig: two-point probe

2. Resistivity in four probe setup

$$V_2 = \frac{I\rho}{2\pi}\left(\frac{1}{s_1} - \frac{1}{s_2 + s_3}\right)$$

$$V_3 = \frac{I\rho}{2\pi}\left(\frac{1}{s_1 + s_2} - \frac{1}{s_3}\right)$$

$$V = V_2 - V_3$$

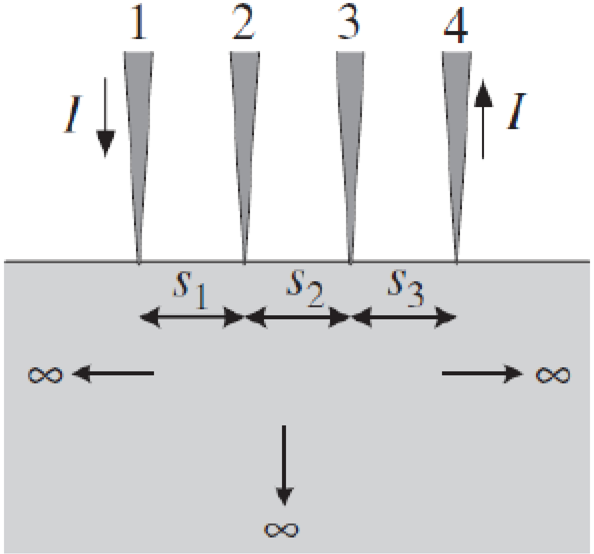


Fig: Four-point probe

$$\rho = \frac{2\pi}{1/s_1 - 1/(s_1 + s_2) - 1/(s_2 + s_3) - 1/s_3}\frac{V}{I}$$

2. Resistivity in four probe setup

For $s_1=s_2=s_3=s$

$$\rho = 2\pi s \frac{V}{I}$$

However, wafers are finite in lateral and vertical directions. arbitrarily shaped sample the resistivity is given by

$$\rho = 2\pi s F \frac{V}{I}$$

For samples thicker than the probe spacing, correction are no longer adequate due to interactions between thickness and edge effects.

2. Correction Factors

- F can be expressed for collinear probes with equal probe spacing s

$$F=F_1F_2F_3$$

- Sample thickness: F_1
- Lateral sample dimensions: F_2
- Probe placement relative to the edges: F_3

2. Correction for sample thickness

- Non-conductive bottom

$$F_{11} = \frac{t/s}{2\ln\left[\sinh(t/s)/\sinh(t/2s)\right]}$$

- Conductive bottom

$$F_{12} = \frac{t/s}{2\ln\left[\cosh(t/s)/\cosh(t/2s)\right]}$$

- Thin samples

$$F_{11} = \frac{t/s}{2\ln(2)} \qquad (t \leq s/2)$$

- Most four-point probe measurements are made with insulating bottom boundaries.

2. Correction for sample thickness

F_{11} = Non-conductive bottom correction factor

F_{12} =conductive bottom correction factor

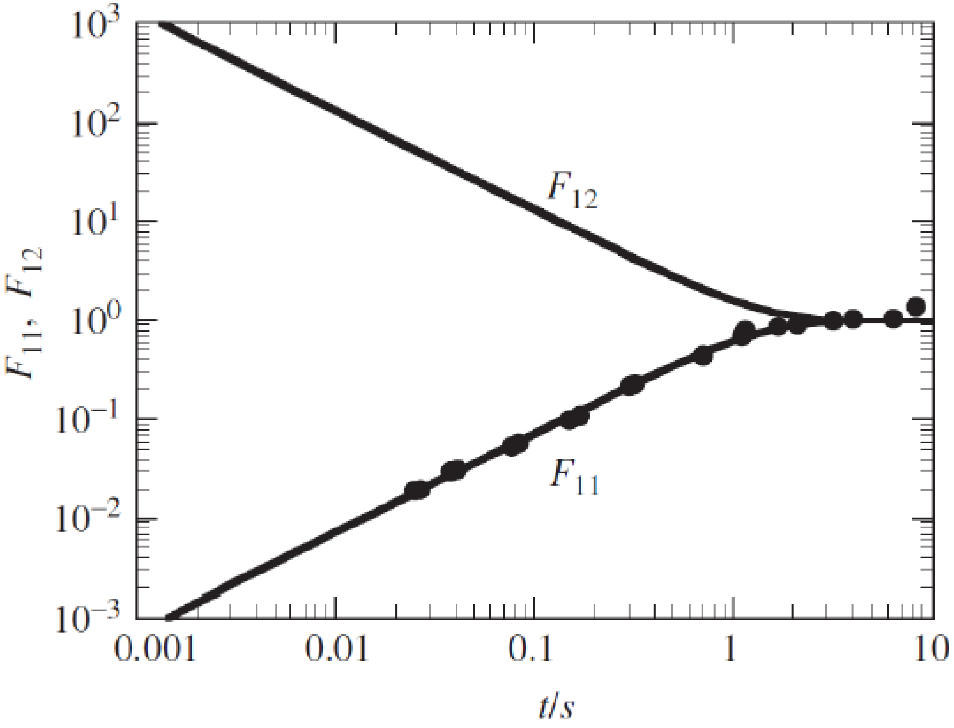


Fig. Wafer thickness correction factors versus normalized wafer thickness; t is the wafer thickness, s the probe spacing

2. Correction for sample thickness

- If F_2=F_3=1 i.e for very thin samples

$$\rho = \frac{\pi t}{\ln(2)} \frac{V}{I} \approx 4.532\, t \frac{V}{I}$$

- Sheet resistance for uniform doping

$$R_{sh} = \frac{\rho}{t} \approx 4.532 \frac{V}{I}$$

- Non-uniform doping

$$R_{sh} = \frac{1}{\int_0^t \sigma(x)dx} = \frac{1}{q \int_0^t \left[n(x)\mu_n(x) + p(x)\mu_p(x)\right] dx}$$

2. Correction for sample size

For circular wafers of diameter D, the correction factor F_2

$$F_2 = \frac{\ln(2)}{\ln(2) + \ln\left([(D/s)^2 + 3]/[(D/s)^2 - 3]\right)}$$

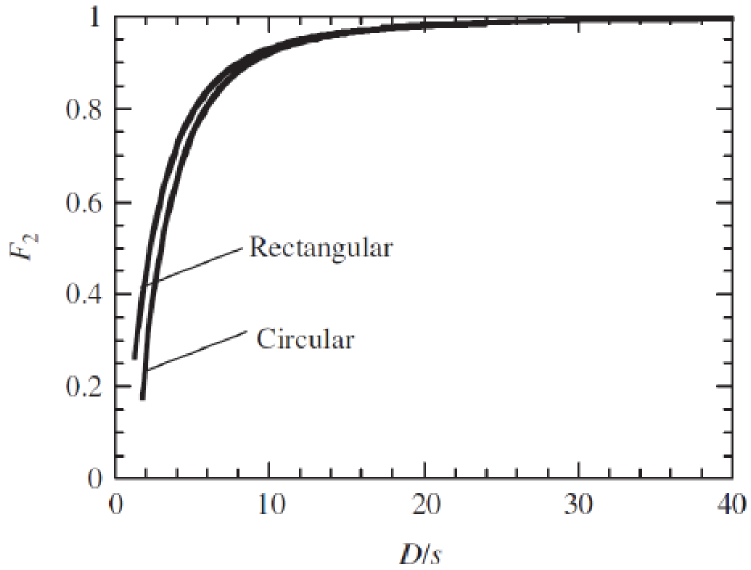


Fig: Wafer diameter correction factors versus normalized wafer diameter. For circular wafers: D = wafer diameter; for rectangular samples: D = sample width, s = probe spacing

2. Boundary proximity corrections

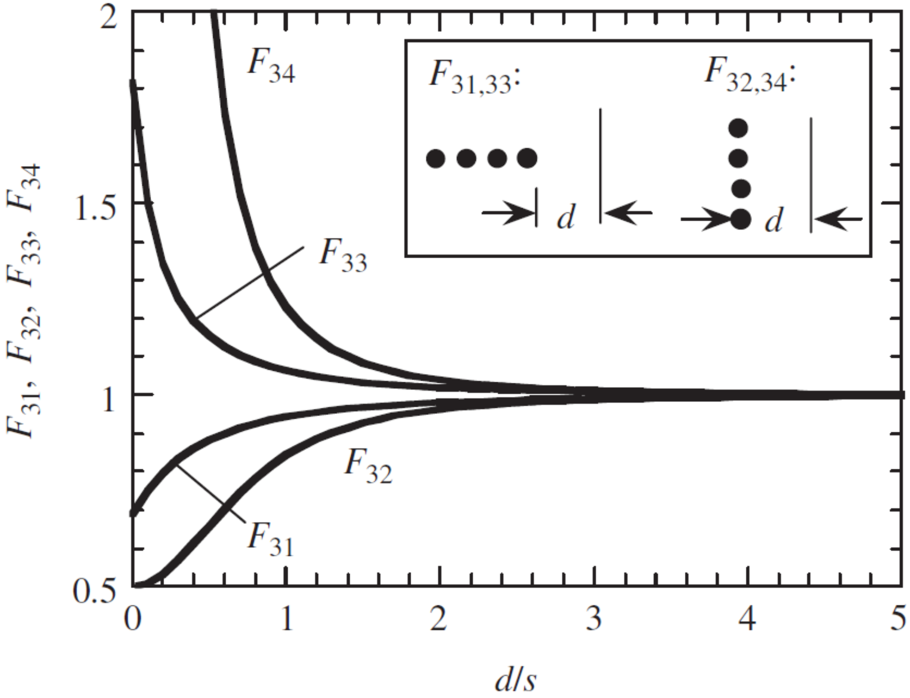


Fig. Boundary proximity correction factors versus normalized distance d (s = probe spacing) from the boundary. F_{31} and F_{32} are for non-conducting boundaries, F_{33} and F_{34} are for conducting boundaries.

2. Dual configuration/configuration switched method

- Two measurements
  - Current through ports 1,4 and voltage sensed between 2,3.
  - Current through 1,3 and voltage between 2,4.
- Advantages
  - No longer need for high symmetry condition.
  - Lateral dimensions not needed.
  - Measurements self-correct for probe spacings.

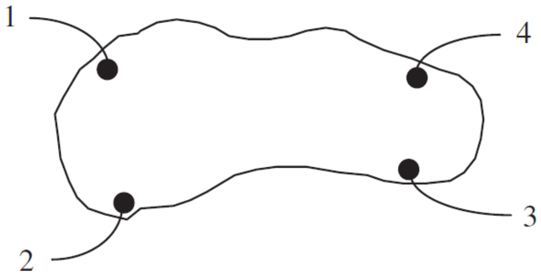
2. Resistivity of arbitrary shaped samples

- Based on conformal mapping developed by van der Pauw.
- Resistivity can be measured even the current pattern is unknown.
- Prerequisites:
  - Contacts lie at the circumference of the sample.
  - Contacts are sufficiently small.
  - Samples are uniformly thick.
  - Surface of the sample are singly connected.

2. Resistivity of arbitrary shaped samples

- For a arbitrary shaped sample

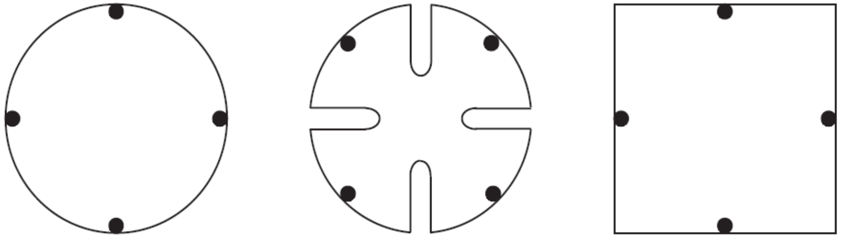
$$\rho = \frac{\pi t}{\ln(2)} \frac{R_{12,34} + R_{23,41}}{2} F$$



- For a symmetrical sample $R_{12,34}=R_{23,41}$ and F=1

$$\rho \approx 4.532\, t R_{12,34}$$

$$R_{RH} = \frac{\rho}{t} \approx 4.532\, R_{12,34}$$



2. Resistivity of arbitrary shaped samples

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

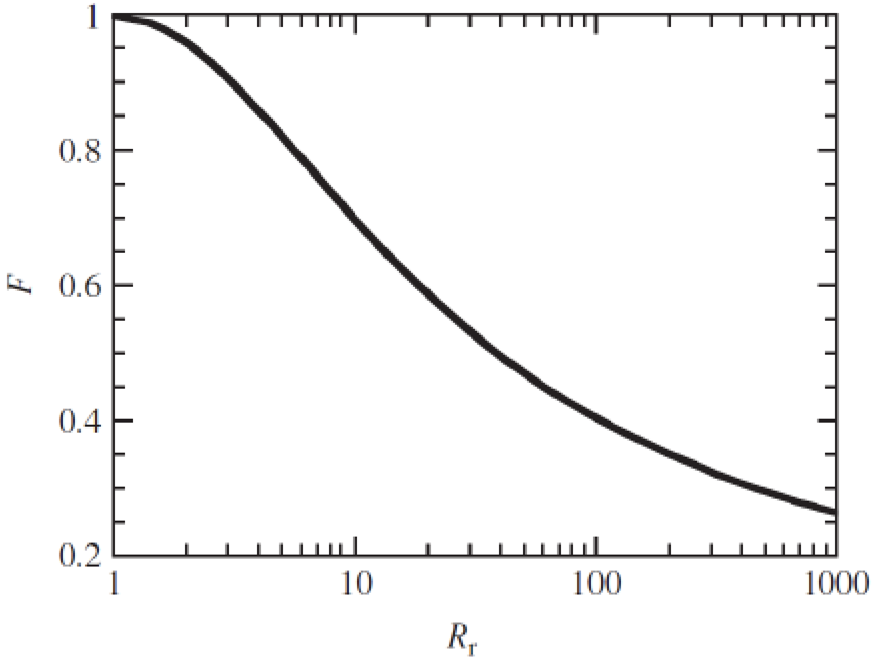


Fig. The van der Pauw correction factor F versus Rr

2. Resistivity of arbitrary shaped samples

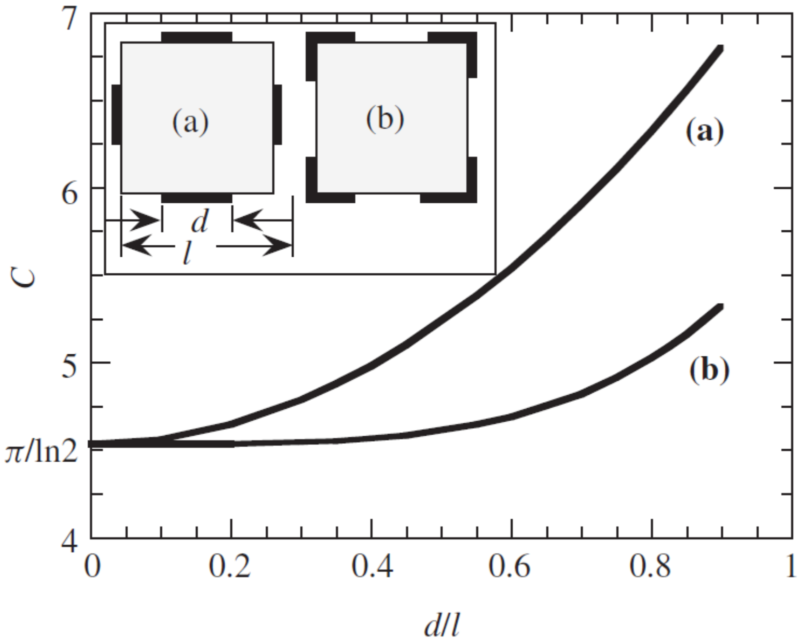


Fig. Correction factor C versus d/l for contacts at the center and at the corners of the square.

$$\rho = CtR_{12,34}$$

$$R_{sh} = CR_{12,34}$$

3.Measurement Errors and Precautions

- Sample Size
- Minority/Majority Carrier Injection
- Probe Spacing

$$F_S \approx 1 + 1.082(1 - s_2/s_m)$$

- Current
- Temperature
- Surface Preparation
- High Resistivity, High Sheet Resistance Materials

4. Wafer mapping

- Originally developed to characterize ion implantation uniformity.
- Parameter proportional to ion implant dose is measured across the sample, e.g., sheet resistance.
- Data converted into two or three dimensional countour maps.
- Most popular methods are four-point probe sheet resistance, modulated photoreflectance and optician densitometry.

4. Double implant

- A modified four probe method used for sheet resistance measurements.
- Two step method:
  - P-type (n-type) impurity implanted into n-type (p-type) substrate and wafer annealed. The sheet resistance is measured.
  - A second implantation is done, but without annealing. The sheet resistance is measured again, and compared to the first measurement.

E1>E2and ϕ1> ϕ2

4. Modulated Photoreflectance

Used to determine the implant dose of ion implanted wafers

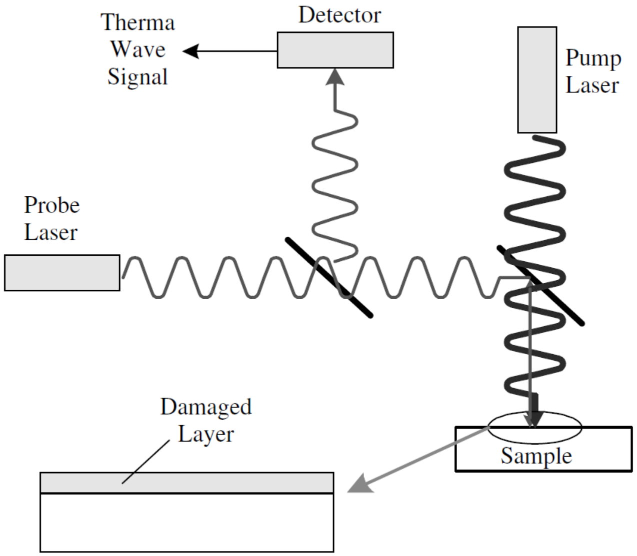


Fig. Schematic diagram of the modulated photoreflectance apparatus.

4. Carrier Illumination

- Determine junction depth
- Method similar to modulated photoreflectance.

$$\Delta n = \frac{q^2 \Delta N}{2 K_s \varepsilon_o m^* \omega^2}$$

- Sensitive to the active dopant density and the profile abruptness

4.Optical Densitometry

- Transparent substrate coated with a thin film consisting of a polymer carrier and an implant sensitive radiochromic dye.
- When this polymer-coated glass wafer is ion implanted, the film darkens.
- The amount of darkening depends on the implant energy, dose, and species.
- sensitive microdensitometer used.
- Used to measure doping density

5. Eddy current

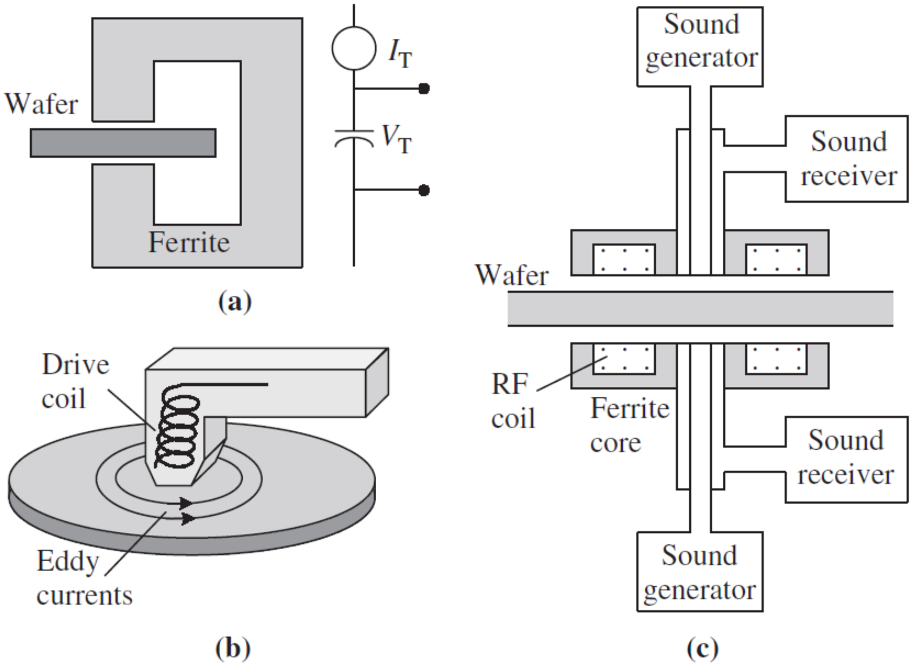


Fig. (a) Schematic eddy current experimental arrangement, (b) practical implementation after Johnson and (c) schematic showing the eddy current coils and the thickness sound generator.

$$I_T = \frac{KV_T}{n^2}\int_0^t \sigma(x)dx = \frac{KV_T}{n^2}\frac{1}{R_{sh}} \qquad t < \delta \qquad \left(\delta = \sqrt{\rho/\pi f \mu_0}\right)$$

5. Eddy current

- For resistivity the sample thickness must be known.
- Two methods are used: differential capacitance probe and ultrasound.

$$t = s - (d_1 + d_2) = s - \varepsilon_o A(C_1^{-1} + C_2^{-1})$$

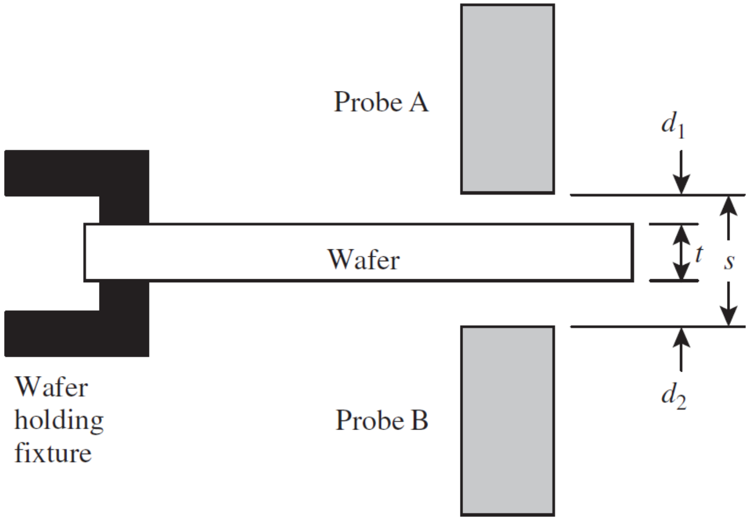


Fig. Capacitive wafer thickness and flatness measurement system.

6. Differential Hall Effect

Resistivity profile of a non-uniformly doped sample by measuring the resistivity, removing a thin layer of the sample, measuring the resistivity, removing, measuring, etc

$$R_{sh} = \frac{1}{q \int_x^t [n(x)\mu_n(x) + p(x)\mu_p(x)]\, dx}$$

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

6. Spreading Resistance Profiling

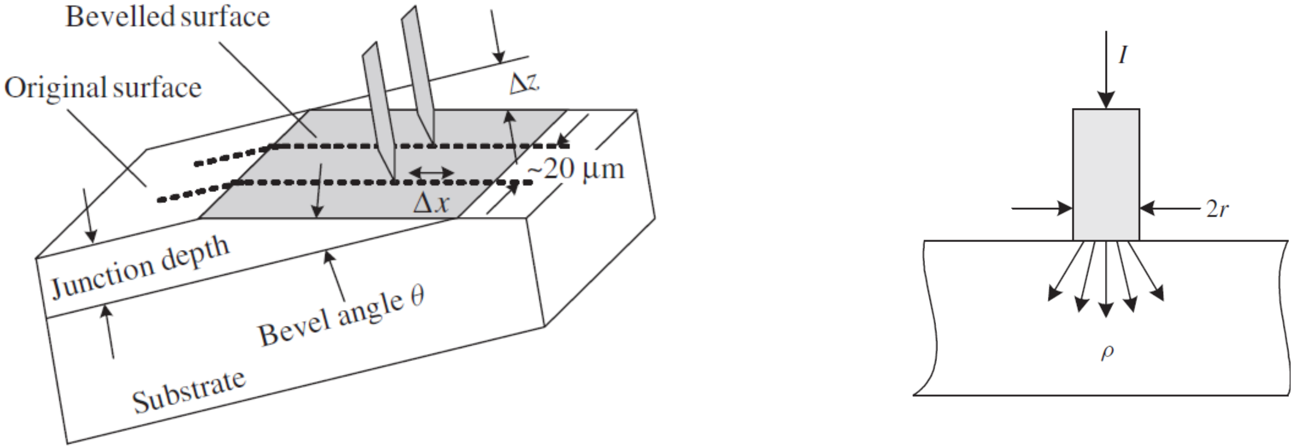


Fig. Spreading resistance bevel block and the beveled sample with probes and the probe path shown by the dashed line.

Spreading resistance for a semi-infinite sample: $$R_{sp} = \frac{\rho}{4r} \text{ ohms}$$

Spreading resistance for a hemispherical sample: $$R_{sp} = \frac{\rho}{2\pi r}$$

spreading resistance with four-point probe measurements:

$$R_{meas} = R_{cont} + R_{spread} = R_{cont} + \frac{\rho}{2r} C$$

7. Conclusions

- **Four-point probe**:
- Pros:
  - Well established use
  - Absolute measurement, no need for calibrated standards
  - In wafer mapping a powerful tool for process-monitoring
- Cons:
  - Causes surface damage and leaves metal deposits on the sample
- **Eddy current**:
- Pros:
  - Non-contact
  - Availability of commercial equipment
- Cons:
  - inability to determine sheet resistance of thin diffused or ion-implanted layers

7. Conclusions

- **Modulated Photoreflectance:**
- Pros:
  - Non-contact, non-destructive.
  - Commercially available.
  - Rapid measurements.
  - Data presented very informatively using contour plots.
  - Possible to measure through an oxide layer.
- Cons:
  - Measurement only qualitative thus requiring calibrated standards.
  - Profiling not possible.
  - Only average values obtained.
  - Laser drift and post-implant damage relaxation