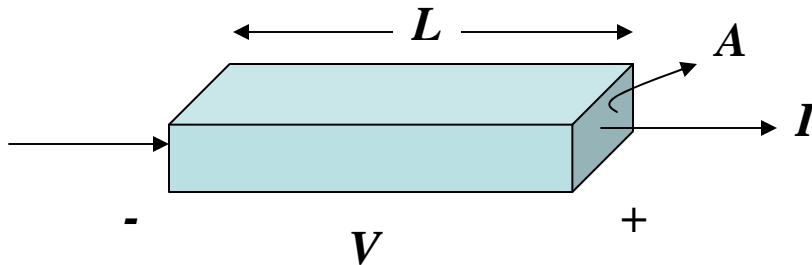


# Electrical, Magnetic and Mechanical Measurements

# Resistance Measurements

- Remember  $V = IR$
- $R$  (resistance) is dependent on the geometry and composition of the thin film.
- For a simple shaped object;



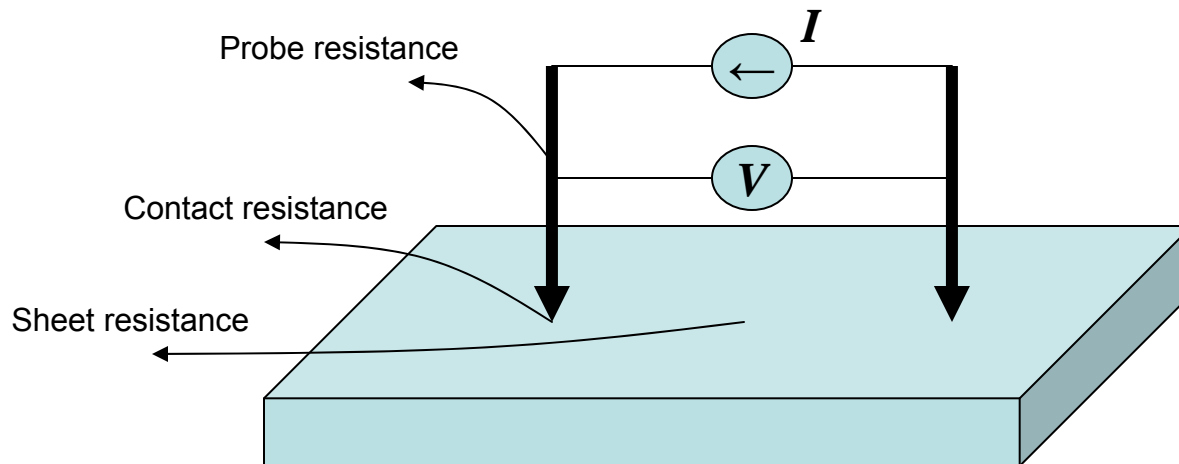
$$R \equiv \frac{V}{I}$$

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

- The resistivity,  $\rho$ , is a constant of the material (with some dependence on temperature, pressure, etc.) and can be used to gather information on the impurity levels, etc.
- Alternatively, if the material resistivity is known, then the overall resistance can be used to calculate thickness.

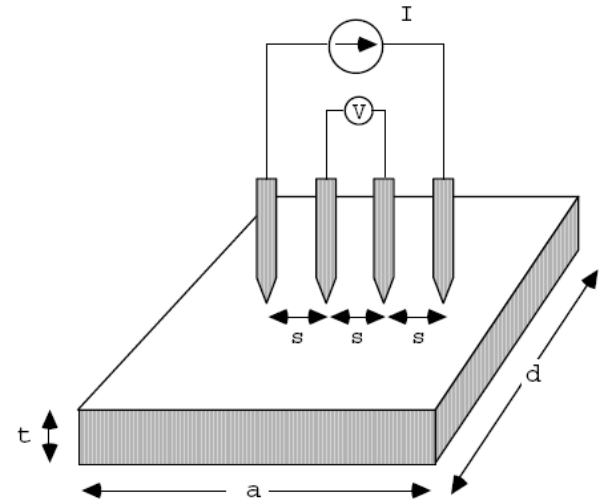
# Problems With a Simple Measurement

- Normally, one would apply a current and measure the potential difference between the two ends of the film to calculate the resistance.
- However, such a measurement actually includes several extraneous effects.
- In the setup below, the probe resistance has to be low for current to flow, but this in turn distorts the voltage reading.



# Four Point Probe

- By separating the current application and voltage readout the effect of the probe resistance is minimized.
- The 4-point probe has 4 Tungsten probes in a line. The outer pair is for current application and the inner pair is for voltage readout.
- One would still need to do some “modeling” to extract useful information such as the resistivity or thickness.

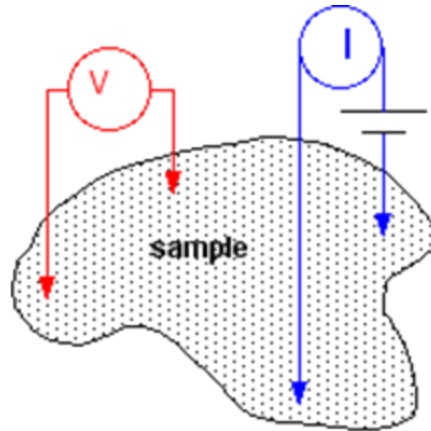


# Some Limiting Cases

- For a bulk, thick layer ( $t > s$ ):  $\rho = 2\pi s \frac{V}{I}$
- For a thin layer ( $t \ll s$ ):  $\rho = kt \frac{V}{I}$ 
  - $\rho$ : resistivity
  - $k$ : geometric factor ( = 4.53 for a semi-infinite sheet)
  - More realistically edge effects require the use of a table of factors:
$$\rho = (CF_d)(CF_t)t \frac{V}{I}$$

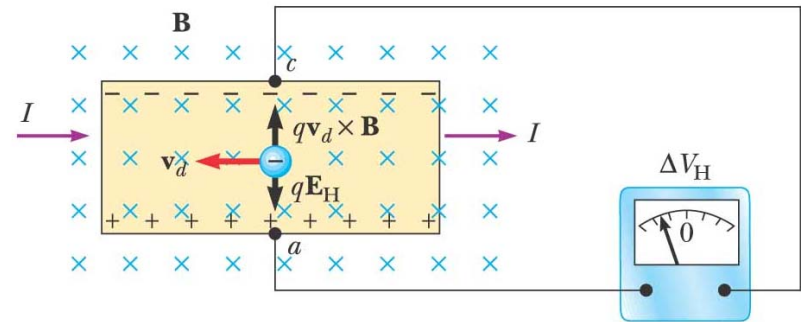
# Van Der Pauw Method

- It is an alternative to the inline 4-point probe.
- The voltage and current probes can be placed arbitrarily.
- It requires two measurements (with the contact points alternated) and more post-measurement analysis.



# Hall Effect

- A current is applied to the sample under a magnetic field.
- The electrons in motion are deflected by the magnetic field and start accumulating at one side of the film and therefore set up an electric field and a voltage difference.
- Information about the number of carriers, the type of carriers (electrons-holes) can be obtained.



$$V_H = -\frac{IB}{dne} = R_H \frac{IB}{d} \quad \text{Hall voltage for a metal}$$

# Magnetic Measurements

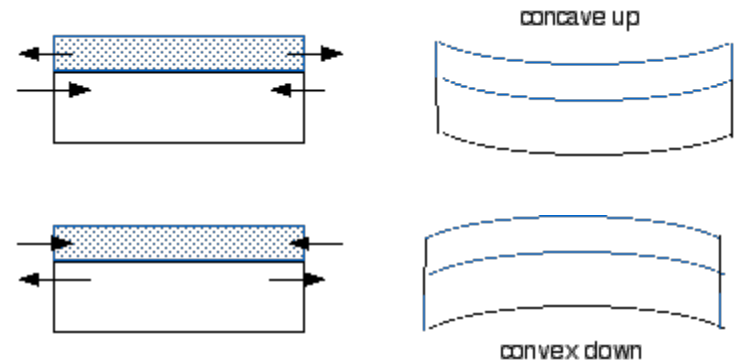
- Direct magnetic measurements using magnetometers
  - Magnetization, de-magnetization
  - SQUID magnetometers
- Magneto-optic Kerr effect
  - An applied magnetic field can cause the polarization of light passing through the film to change.
  - Can be used with ellipsometry.

# Mechanical Measurements

- Internal - Residual Stress
- Indentation
- Friction and wear
- Adhesion

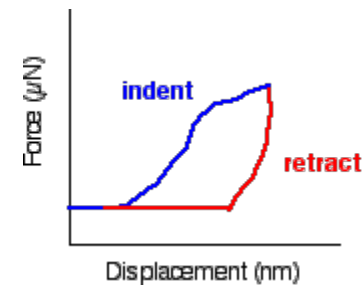
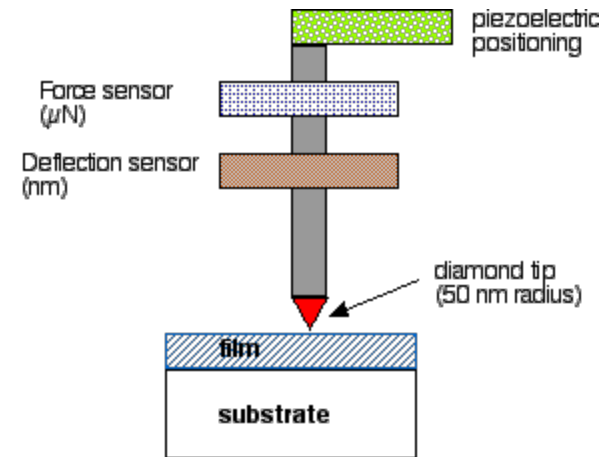
# Internal and Residual Stress

- Film is deposited on a flexible substrate
- Tensile stress (film wants to be smaller)
- Compressive stress (film wants to be larger)
- Measuring the curvature of the sample
  - Height measurements at edge and center using profilometer
  - Interferometry with a flat reference
  - Optical reflection



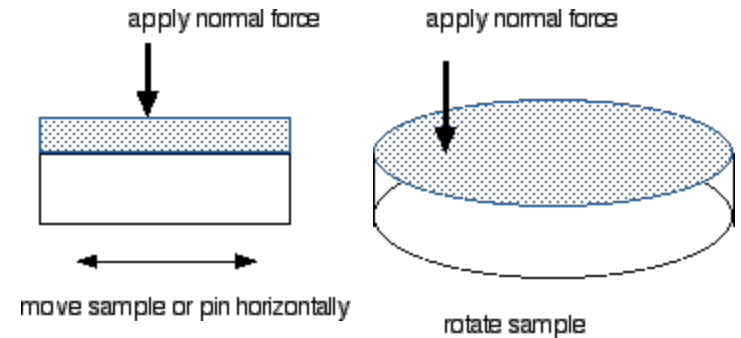
# Micro- and Nano- indentation

- Generate stress-strain curves
  - Apply a small force ( $0.3 \mu\text{N}$ )
  - measure a displacement on a tip ( $2 \text{ \AA}$ )
- Can determine hardness, elastic modulus, stress relaxation.

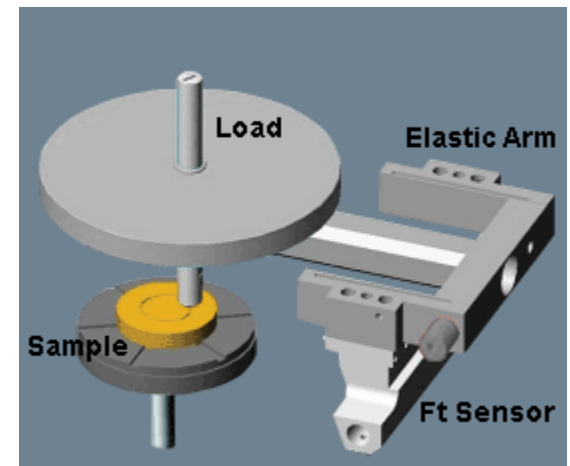


# Friction and Wear Testing

$$F_{fr} = \mu F_n$$



- Use strain gauges to measure the forces, calculate the friction coefficient.



# Adhesion Tests

- Adhesive tape test
  - simple, cheap, qualitative
- Scratch tests
  - drag stylus of known radius over film find minimum load on stylus needed to remove film completely