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!***

Contact Resistance

Metal-semiconductor Contacts

Specific Contact Resistance

Transfer Length

Contact String

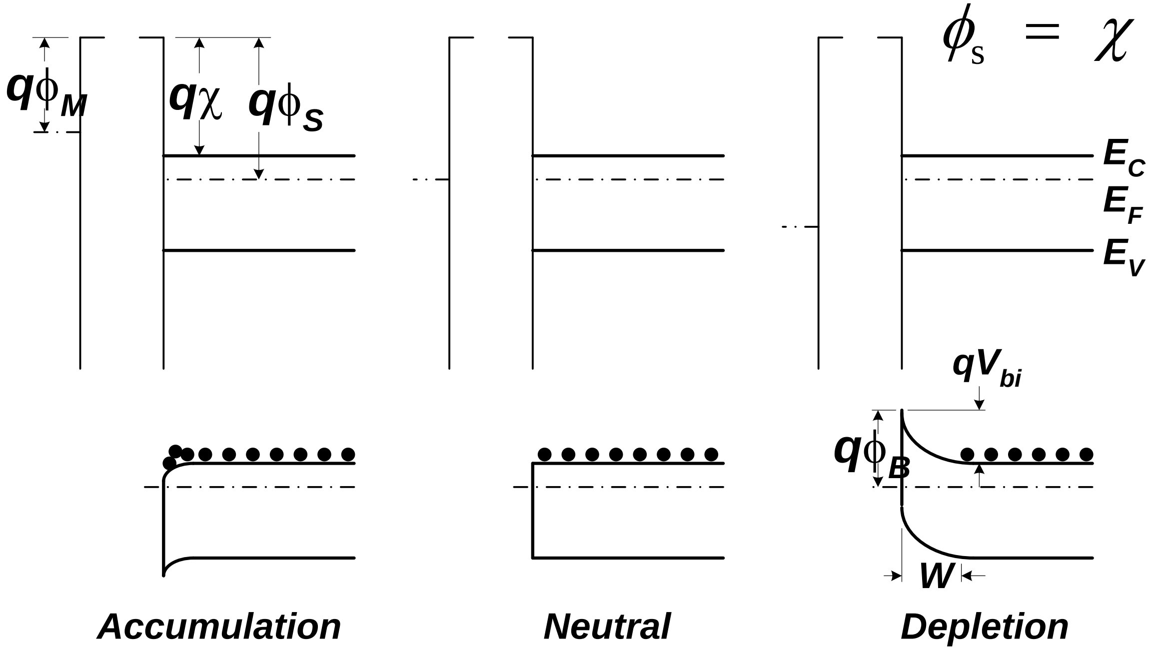
Transfer Length Method

Four-terminal Method

Metal – Semiconductor Contacts

- Every semiconductor device has contacts
- Contact resistance is a parasitic resistance
- Contacts are almost always metal-semiconductor contacts

$$\phi_S = \chi + (E_C - E_F)_{FB}$$



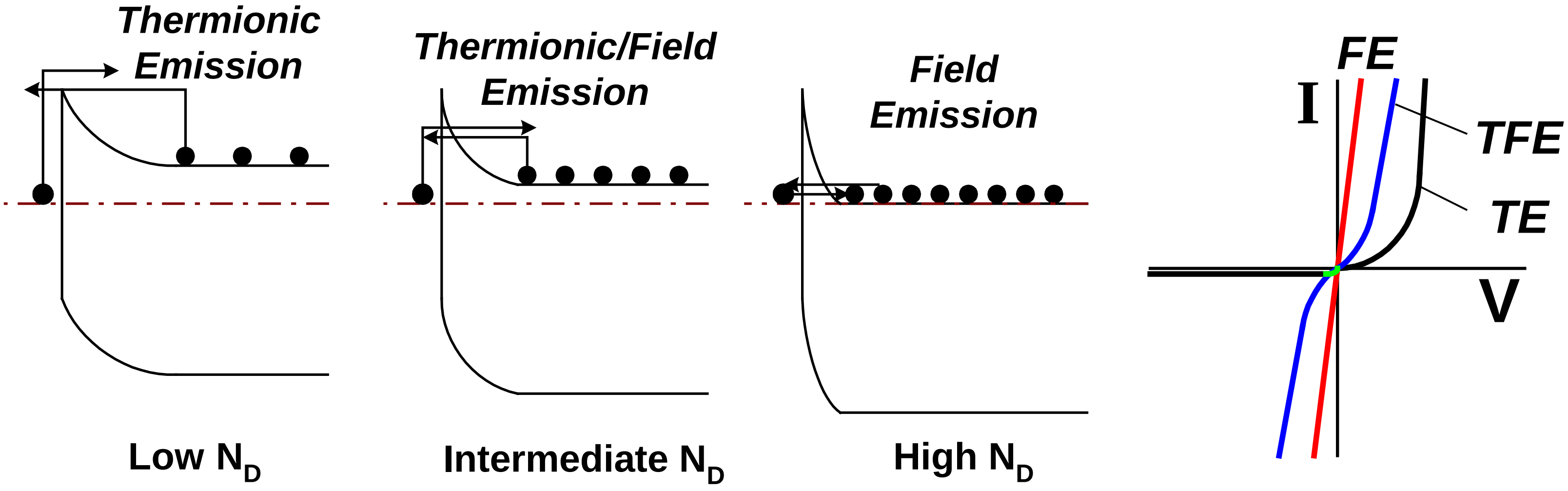
$$\boxed{\phi_B = \phi_M - \chi}$$

Metal – Semiconductor Contacts

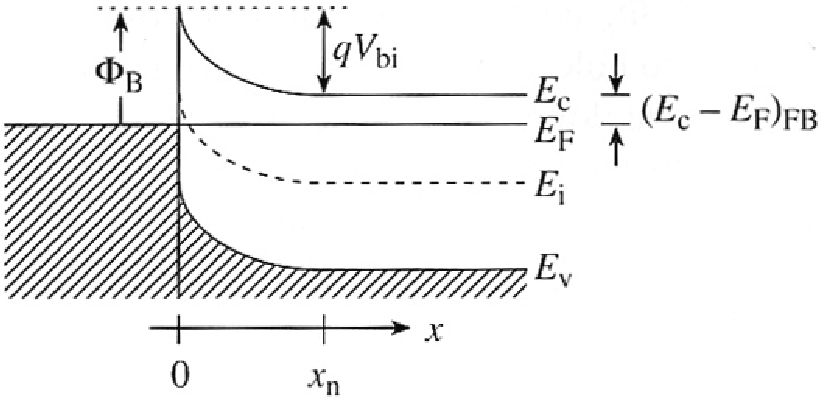
- Energetic barriers are most often described by the "Electron Affinity Model" (EAM).
- EAM is a purely theoretical model and ***REAL CONTACTS RARELY FOLLW THIS MODEL***.
- Nevertheless, EAM explains several aspects (depletion widths, capacitance, general IV shape, etc…) of ohmic and Schottky barrier diodes sufficiently that it is widely used.
- Reasons for the barrier height not agreeing with theory:
  - Image force lowering (lower than expected barrier)
  - Fermi-level pinning
  - Interface state filling (i.e. partially pinned or voltage dependent interface state occupation).
  - Lack of complete model understanding. Can you improve on the existing model?

Carrier Motion

- In an ohmic contact, electrons must flow from metal to semiconductor or from semiconductor to metal



- Current is controlled by *barrier width* rather than *barrier height*



Energy band diagrams for ideal MS contacts

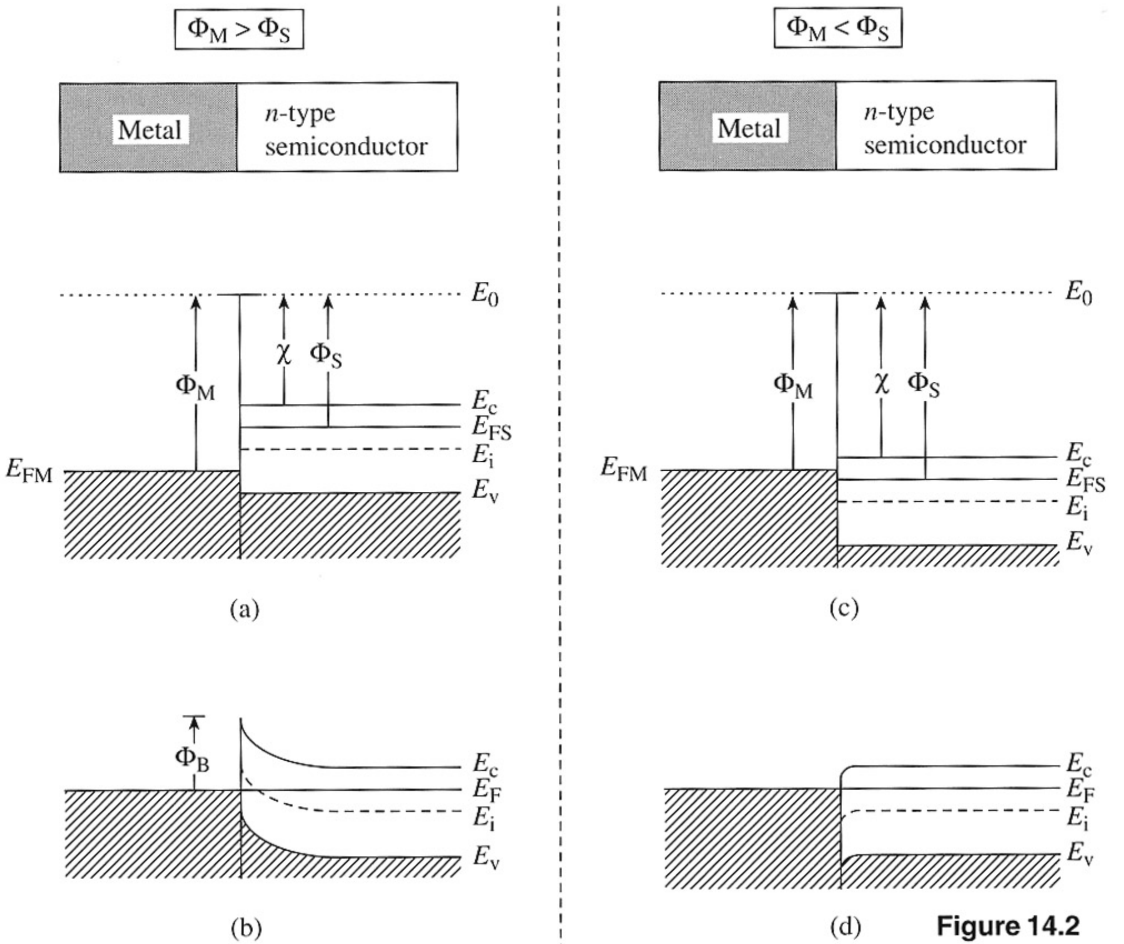


Figure 14.2

An instant after contact formation

Under equilibrium conditions

Schottky

$\Phi_M > \Phi_S$

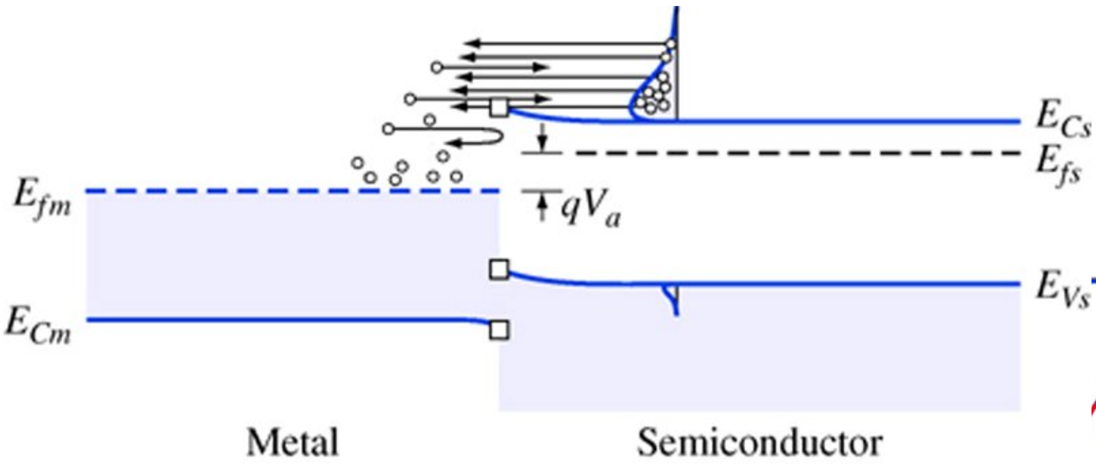
Ohmic

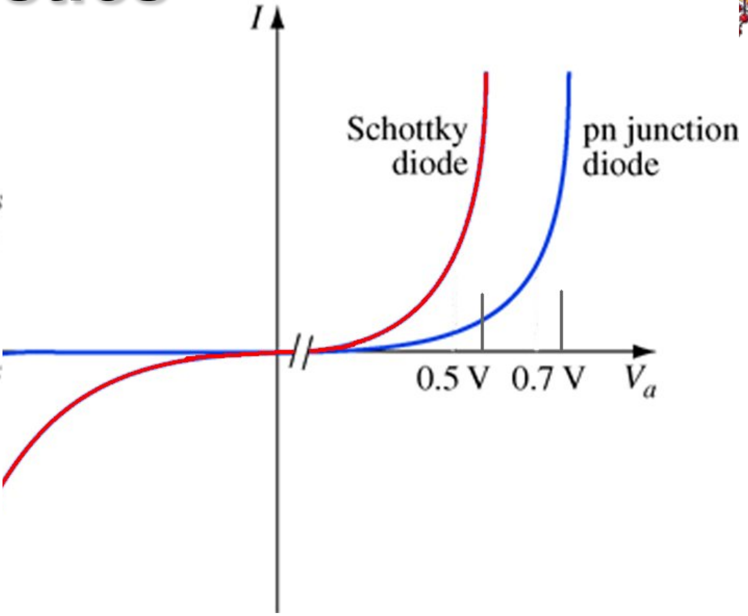
$\Phi_M < \Phi_S$

MS (n-type) contact with $\Phi_M > \Phi_S$

- After the contact formation, electrons will begin to flow from the semiconductor to the metal.
- The removal of electrons from the n-type material leaves behind uncompensated N_d^+ donors, creating a surface depletion layer, and hence a built-in electric field (similar to p^+-n junction).
- Under equilibrium, the Fermi-level will be constant and no energy transfer (current) flows
- A barrier Φ_B forms blocking electron flow from M to S.
- Based on the Electron Affinity Model (EAM), the simplest of models used to describe MS junctions, $\Phi_B = \Phi_M - \chi$ ... ideal MS (n-type) contact. Φ_B is called the "barrier height".
- Electrons in a semiconductor will encounter an energy barrier equal to $\Phi_M - \Phi_S$ while flowing from S to M.

I-V Characteristics



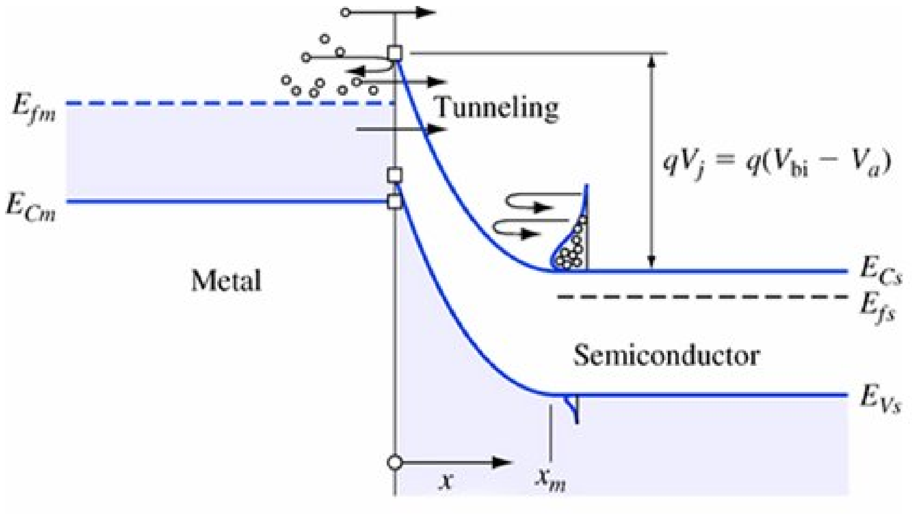


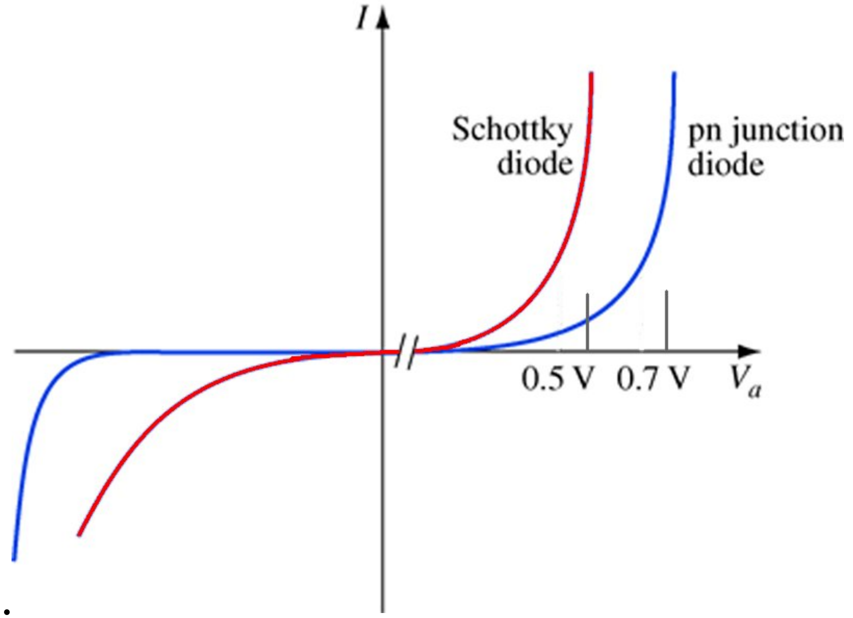
Since MS Schottky diode is a majority carrier device (i.e only majority carriers are injected from semiconductor to the metal) and thus has no minority carrier storage, the frequency response of the device is much higher than that of equivalent p^+ n diode.

The “turn on voltage” of a Schottky diode is typically smaller than a comparable p-n junction since the barrier to forward current flow (Φ_m-Φ_s) is typically small. This “turn on” voltage can be as small as 0.3 Volts in some Si Schottky diodes.

This makes a Schottky diode the best choice for power switch protection in inductive load applications (motors, solenoids, coils, etc…) and in high frequency rectification but not a good choice when low leakage or high breakdown voltage is required.

I-V Characteristics





Leakage in a Schottky diode is dominated by:

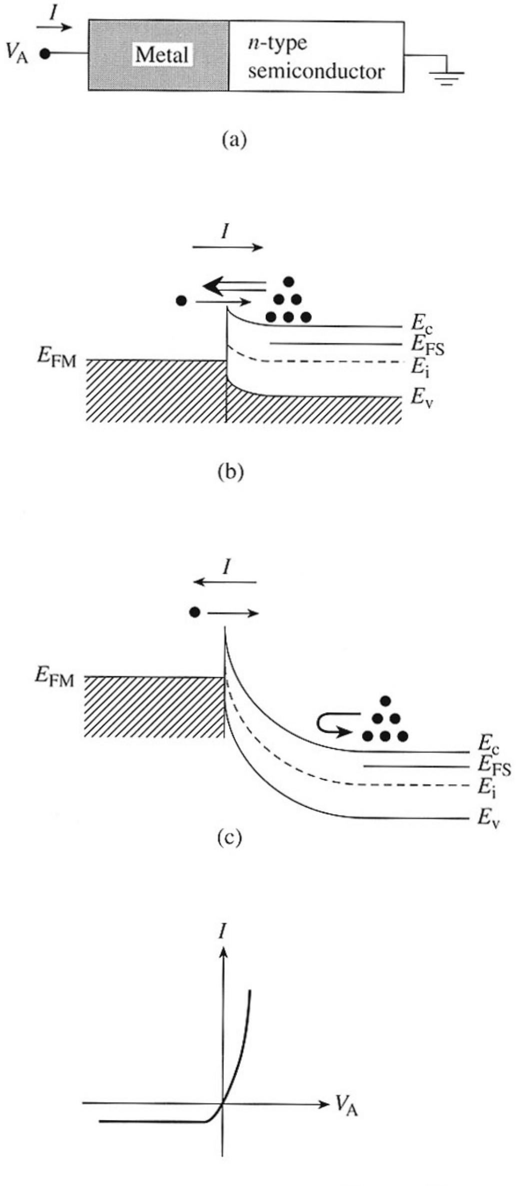
1) “Thermionic Emission” (metal electrons emitted over the barrier – not likely)
2) “Thermionic Field Emission” (metal electrons of higher energy tunneling through the barrier – more likely)
3) “Direct tunneling” (metal electrons tunneling through the barrier – most likely in higher doped semiconductors or very high electric fields).

Since generation does not require the entire bandgap energy to be surmounted, the reverse leakage current for a Schottky diode is generally much larger than that for a p^+n diode. Likewise, breakdown (for the same reason) is generally at smaller voltages.

MS (n-type) contact with $\Phi_M > \Phi_S$

A forward bias will reduce the barrier height unbalancing the electron current flow, resulting in a huge forward current that increases exponentially with applied voltage

A reverse bias will increase the barrier height resulting in a small “reverse current” flow that will be dominated by tunneling currents for high doped semiconductors and/or thermally assisted field emission for moderate/low doped semiconductors.

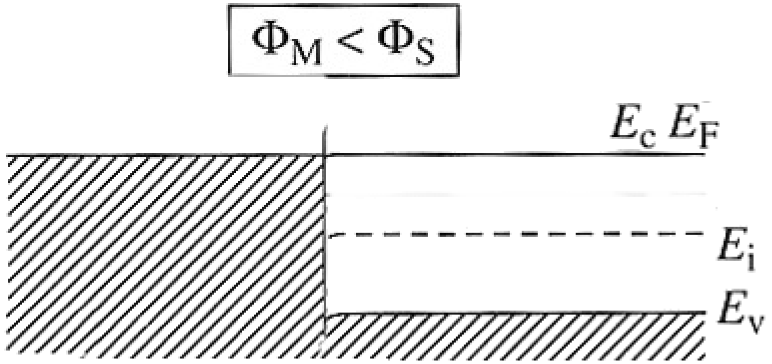


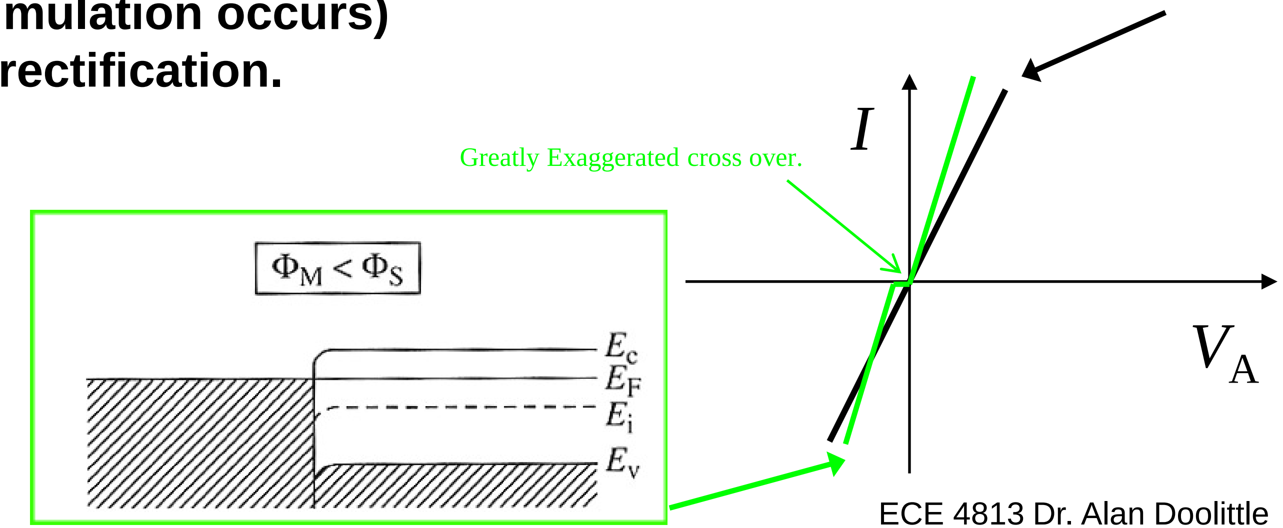
(d)

Figure 14.3

Ohmic Contacts: MS (n-type) contact with $\Phi_M < \Phi_S$

- There is no barrier for electron flow from the semiconductor to the metal. So, even a small $V_A > 0$ results in large current.
- The small barrier that exists for electron flow from metal to the semiconductor, but vanishes when $V_A < 0$ is applied to the metal. Large current flows when $V_A < 0$.
- The MS (n-type) contact when $\Phi_M < \Phi_S$ behaves like an ohmic contact.
- Lack of depletion (accumulation occurs) means (essentially) no rectification.



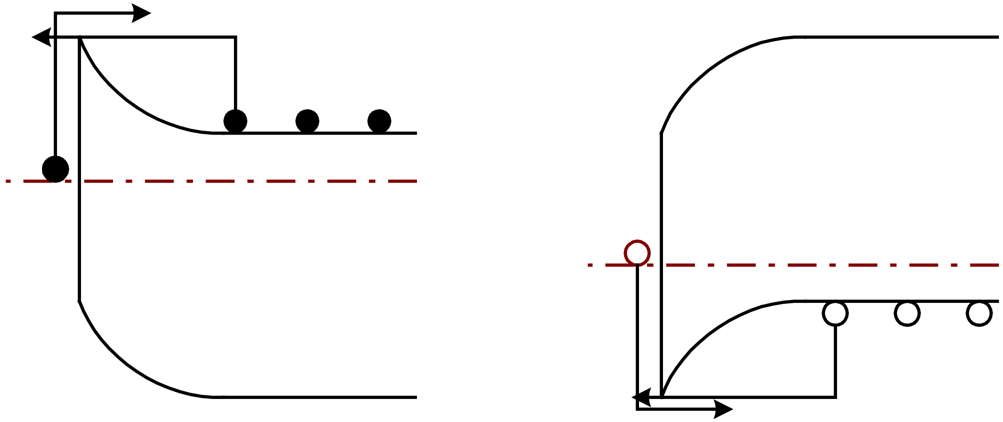


Generalization of Metal Semiconductor Contact Energy Relationships

	n-type	**p-type**
$\Phi_M > \Phi_S$	rectifying	ohmic
$\Phi_M < \Phi_S$	ohmic	rectifying

Carrier Motion

- *n*-type and *p*-type substrates are analogs of one another



n - Substrate　　*p - Substrate*

Specific Contact Resistivity

- The specific contact resistivity, ρ_c, is an area-independent parameter

$$\rho_c = \left(\frac{dJ}{dV}\right)^{-1}_{V=0}$$

- Thermionic emission

$$J = A^* T^2 e^{-q\phi_B / kT}\left(e^{qV/kT} - 1\right)$$

$$\boxed{\rho_c = \frac{k}{qA^* T} e^{q\phi_B / kT} = \rho_1 e^{q\phi_B / kT}}$$

- For $\phi_B = 0.6$ V, $A^* = 110$ A/cm^{2}K^2, $T = 300$ K

$$\rho_c = 1600\ \Omega\text{-cm}^2 \Rightarrow R_c = 1.6\text{x}10^{11}\ \Omega\ !!$$

($A = 1\ \mu$mx1 μm)

Specific Contact Resistivity

- **Thermionic emission**

$$\boxed{\rho_c = \rho_1 e^{q\phi_B / kT}}$$

- **Thermionic-field emission**

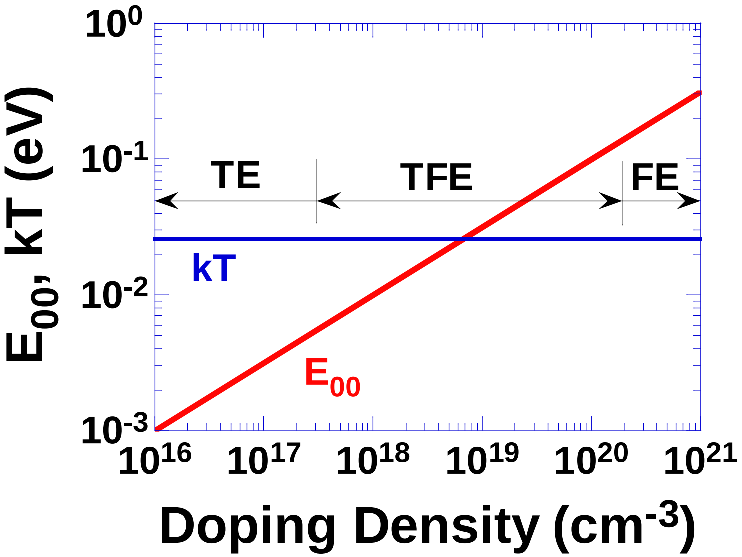
$$\boxed{\rho_c = \rho_1 C_1 e^{q\phi_B / E_o}}$$

- **Field emission**

$$\boxed{\rho_c = \rho_1 C_2 e^{q\phi_B / E_{oo}}}$$

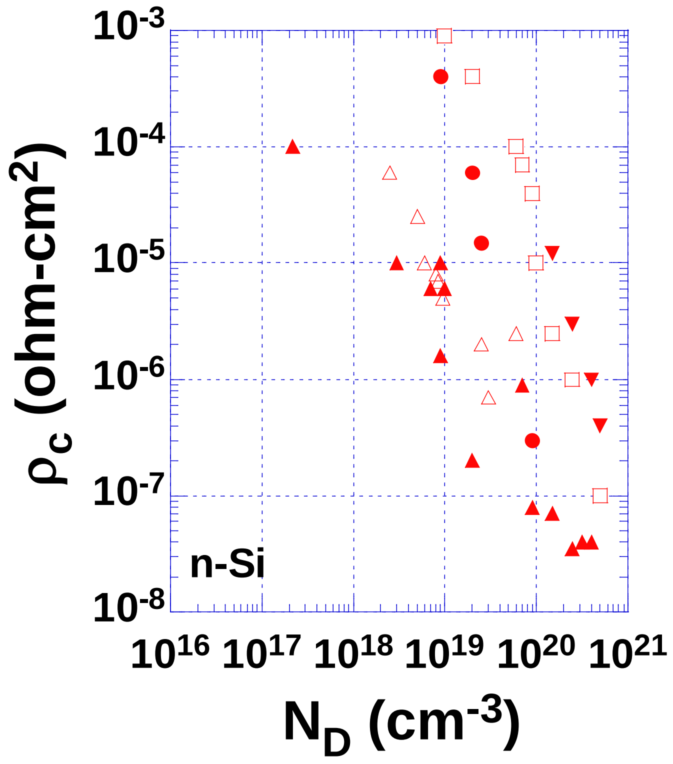
$$E_o = E_{oo} \coth E_{oo} / kT$$

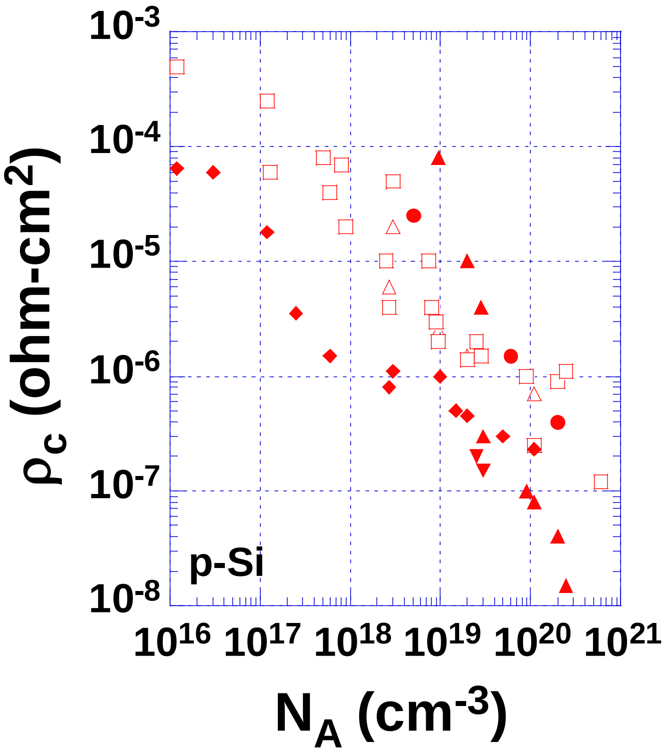
$$E_{oo} = \frac{qh}{4\pi}\sqrt{\frac{N_D}{K_s \varepsilon_o m^*_{tunn}}}$$



Specific Contact Resistivity

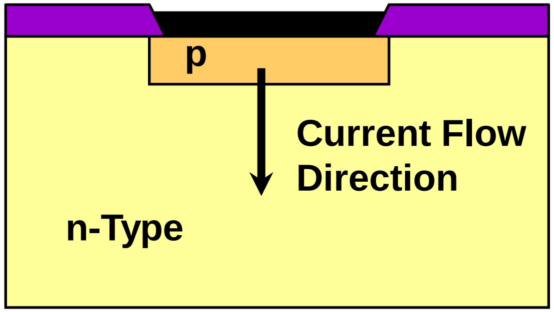
- ρ_c is very sensitive to doping density

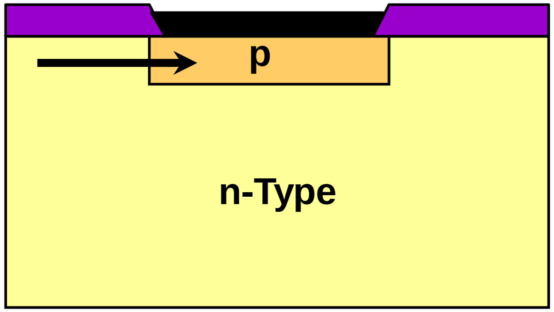




Contact Resistance

- **Contacts are characterized by:**
  - **Contact resistance, R_c (Ω)**
  - **Specific contact resistivity, ρ_c (Ω -cm^2)**





$$R_c = \frac{\rho_c}{A_c} = \frac{\rho_c}{LW}$$

$$R_c = \frac{\rho_c}{A_{eff}} = \frac{\rho_c}{L_T W}$$

Not derived in notes. See text page 141-142 for discussion

A_c = actual contact area

A_{eff} = effective contact area

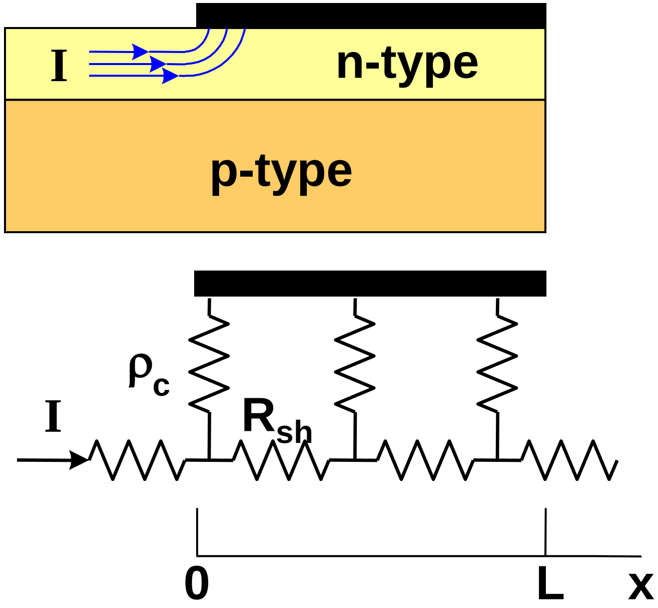
A_{eff} can be *less* than A_c

$$L_T = \sqrt{\rho_c / R_{sh}}$$

$L_T \equiv$ Transfer Length is the distance over which "most" (1/e) the current transfers to (from) the metal into (out of) the semiconductor.

Contact - Current Crowding

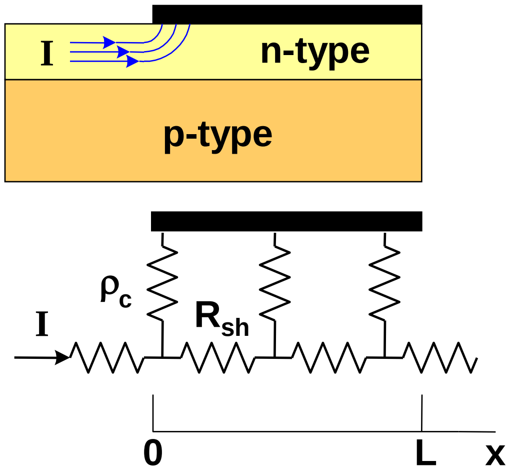
- Current flowing into/out of a contact can crowd into a portion of the contact
- Current has the choice to flow through ρ_c or R_{sh}



$$V(x) = \frac{I\sqrt{R_{sh}\rho_c}\,\cosh\left(L-x\right)/L_T}{Z\sinh L/L_T};\; L_T = \sqrt{\frac{\rho_c}{R_{sh}}}$$

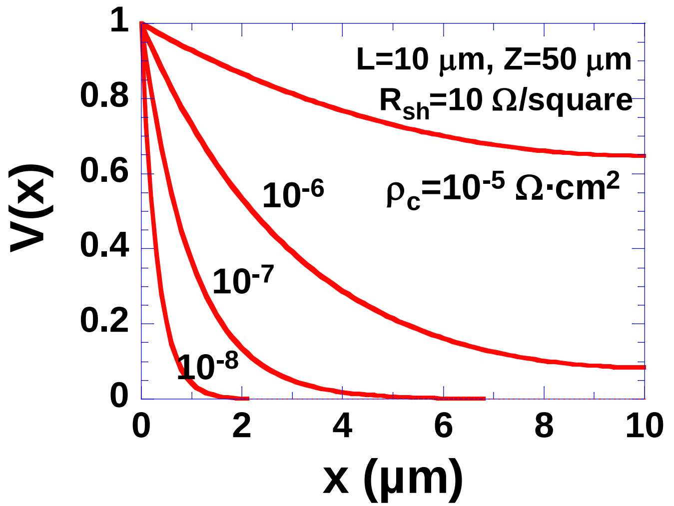
Contact - Current Crowding

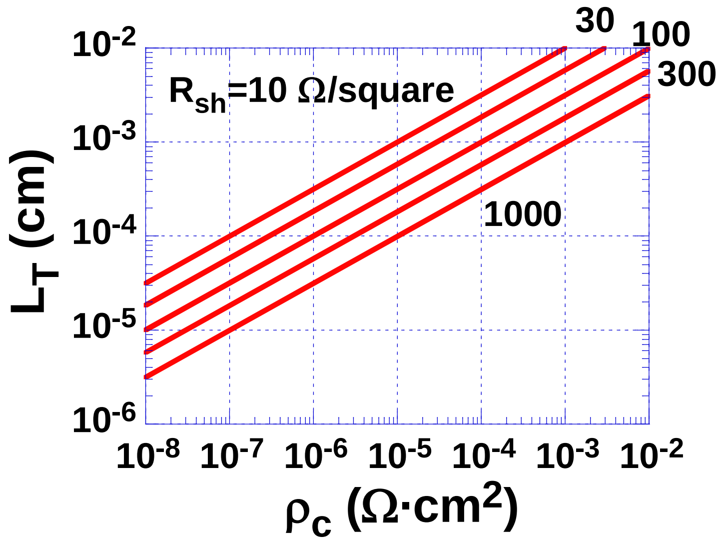
- L_T: transfer length



$$V(x) = \frac{I\sqrt{R_{sh}\rho_c}\,\cosh\left((L-x)/L_T\right)}{Z\sinh L/L_T}$$

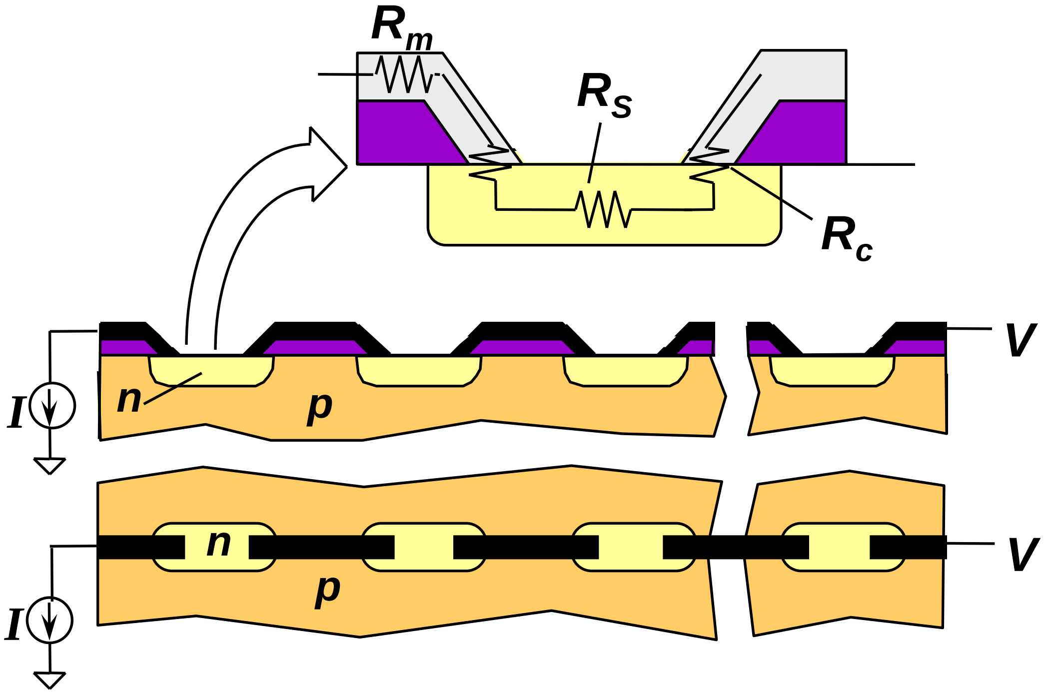
$$L_T = \sqrt{\frac{\rho_c}{R_{sh}}}$$





Contact String (Chain)

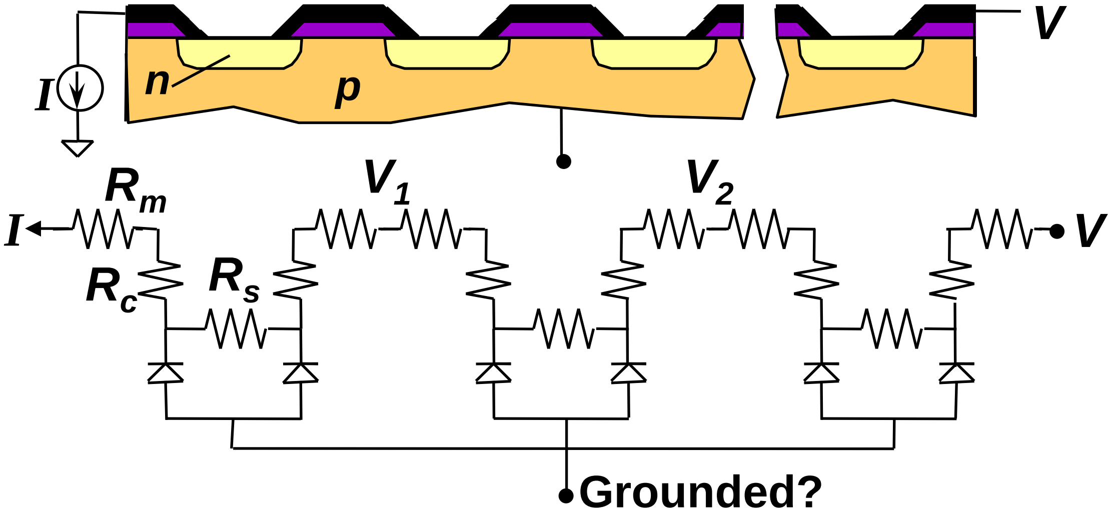
- 2*N* series-connected contacts are measured (*N* ≈ 100-1000 or more)
- Does not allow separation of R_m, R_s, and R_c
- Suitable for process control, but not for detailed contact characterization
- Must know R_s from independent measure of sheet resistance in order to extract R_C



$$R = N(R_m + R_s + 2R_c) \approx N(R_s + 2R_c)$$

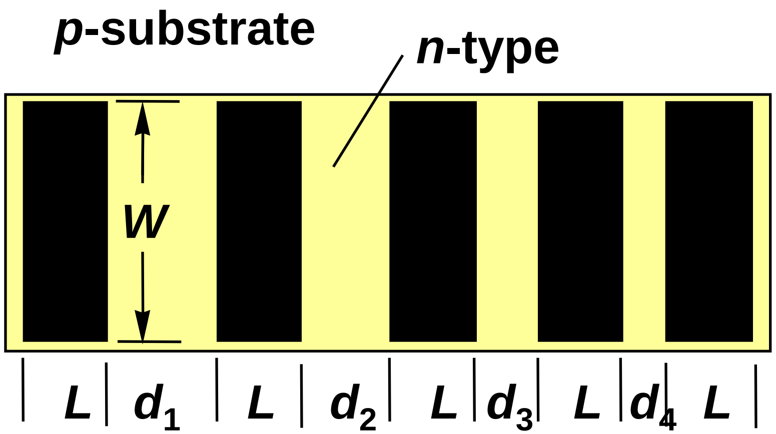
Contact String (Chain)

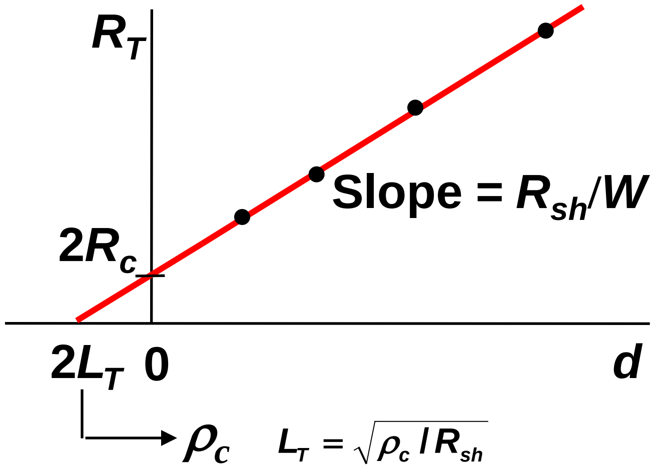
- Contact string consists of *pn* junctions
- The junctions are *reverse* biased
- When the junction voltage exceeds V_{BD}, it breaks down
- Can have the case where poor contacts, *i.e.*, high R_c, cannot be detected because junctions break down
- Measurement depends on substrate grounded or not



Transfer Length Method (TLM)

- **Consists of identical contacts with varying spacings *d***





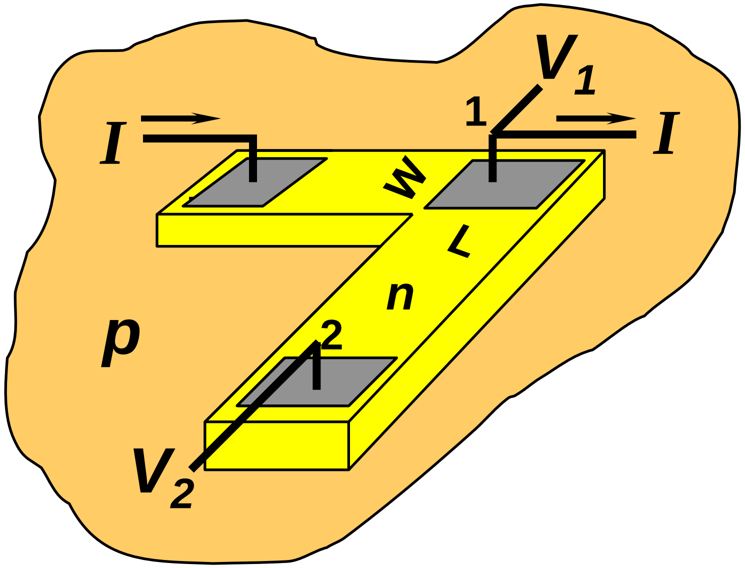
$L_T = \sqrt{\rho_c / R_{sh}}$

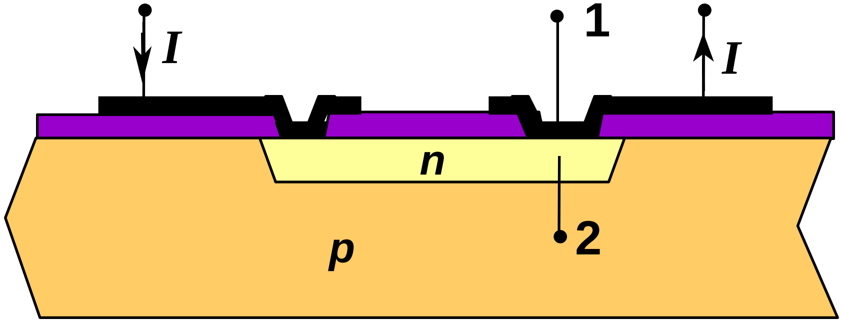
$$R_T = 2R_c + R_s \approx \frac{2\rho_c}{L_T W} + \frac{R_{sh} d}{W}$$

$$\boxed{R_T \approx \frac{2R_{sh}(L_T)^2}{L_T W} + \frac{R_{sh} d}{W} = \frac{R_{sh}(d + 2L_T)}{W}}$$

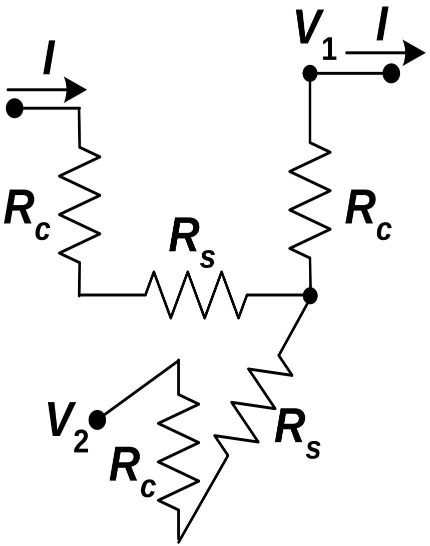
Four Terminal (Kelvin) Method

- Determines the contact resistance independent of the sheet resistance



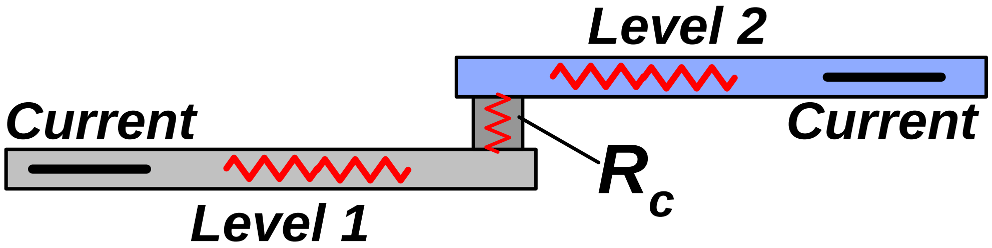


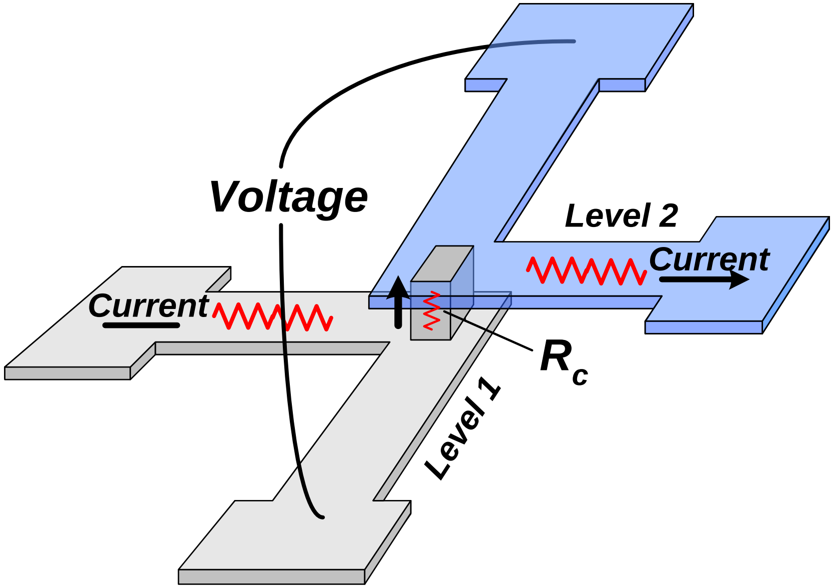
$$R_c = \frac{V_{12}}{I}; \rho_c \approx R_c WL$$



Heed warnings on accuracy (too complex to discuss in class) summarized in our text on pages 150-156.

Via Contact Resistance





Review Questions

- What is the most important parameter to give low contact resistance?
- What are the three metal-semiconductor conduction mechanisms?
- What is Fermi level pinning?
- Does the contact chain give detailed contact characterization? Why or why not?
- What is the transfer length method?
- Why is the Kelvin contact test structure best for contact resistance measurements?