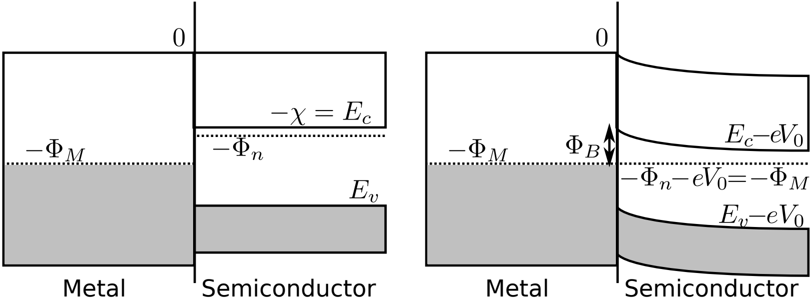
MTLE-6120: Advanced Electronic Properties of Materials

Metal-semiconductor junctions: Schottky diodes and Ohmic contacts

Reading:

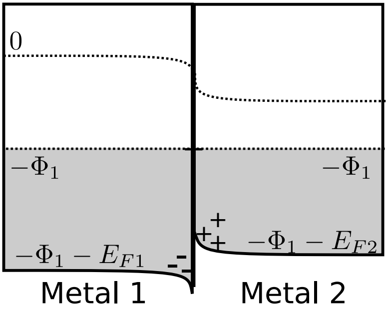
- Kasap 5.9 - 5.10

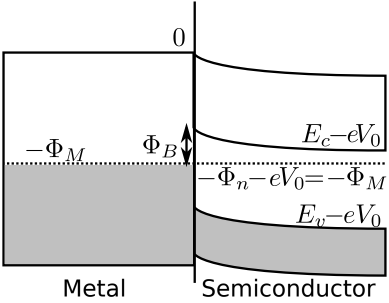
Metal-semiconductor contact potential



- Fermi levels relative to vacuum (Φ) not in same position
- Distinction for semiconductor: $\Phi \neq$ work function
- Consider case when metal level below n-type semiconductor
- Fermi levels line up for equilibrium
- Electron transfer to metal in current example
- Schottky barrier height $\Phi_B = \Phi_M - \chi$
- Contact potential: $V_0 = \Phi_M - \Phi_n$

Depletion region





- Region of semiconductor near interface where charge transfer occurs
- Number of charge carriers reduce, hence depletion region
- In metal-metal case, bands on both sides respond
- In metal-semiconductor case, only semiconductor responds: why?

Debye screening

- Poisson equation for variation of electrostatic potential:

$$\nabla^2\phi(\vec{r}) = -\frac{\rho(\vec{r})}{\epsilon_0}$$

- Charge density $\rho\vec{r}$ includes external and bound charge
- Previously considered bound charge due to $\vec{P}$ response to $\vec{E} = \nabla\phi$
- What if material responds directly to potential as $\rho = \rho(\phi)$?
- Specifically consider small change from neutral potential ϕ_0,

$$\rho(\vec{r}) \approx \rho'(\phi_0)\,(\phi(\vec{r}) - \phi_0)$$

- Poisson equation becomes (using ϵ to account for dipolar reponse):

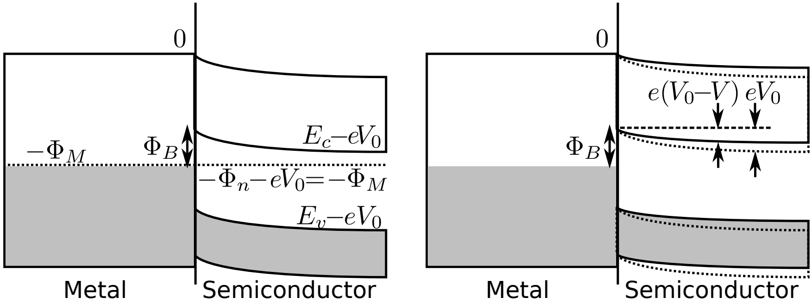
$$\nabla^2(\phi - \phi_0) + \frac{\rho'(\phi_0)}{\epsilon}(\phi - \phi_0) = 0$$

with 1D solutions of the form $\phi(x) = \phi_0 + e^{\pm x/\lambda_D}$
where $\lambda_D = \sqrt{\epsilon/\rho'(\phi_0)}$ is the Debye screening length

Debye screening length

- $\lambda_D = \sqrt{\epsilon/\rho'(\phi_0)}$: length scale over which potential restores to neutral
- Depletion region non-neutral $\rightarrow$ becomes neutral over λ_D length scale
- Therefore width of depletion region $\sim \lambda_D$
- In metals, $\rho'(\phi_0) = e^2 g(E_F)$
- Typical $\lambda_D \sim \sqrt{\frac{8.85\times10^{-12}\ \mathrm{F/m}}{(1.6\times10^{-19}\ \mathrm{C})^2\cdot10^{47}\ \mathrm{J^{-1}m^{-3}}}} \sim 0.6$ Å
- Metals restore potential within an atomic layer!
- In semiconductors, $\rho'(\phi_0) = e^2 n_{\mathrm{maj}}/(k_B T)$, where $n_{\mathrm{maj}} \approx N_{a/d} =$ majority carrier density (larger of n, p)
- For 10^{14}/cm^3 doped Si at room temperature, $\lambda_D \sim 400$ nm
- For 10^{18}/cm^3 doped Si at room temperature, $\lambda_D \sim 4$ nm
- In all cases, $\lambda_D \propto n^{-1/2}$, where $n =$ free carrier density
- λ_D in metals $\ll$ in semiconductors $\Rightarrow$ depletion region entirely in semiconductor!

Applied bias



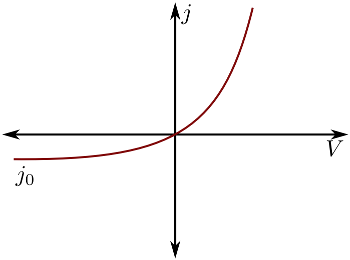
- Neutral case: band bending in semiconductor = contact potential V_0
- Apply potential bias: change band bending in semiconductor
- Forward bias $\equiv$ reduce band bending to $V_0 - V$
- Rate of electrons M $\to$ SC $\propto \exp \frac{-\phi_B}{k_B T}$
- Rate of electrons SC $\to$ M $\propto \exp \frac{-e(V_0 - V)}{k_B T}$

Schottky diode: $I - V$ characteristics

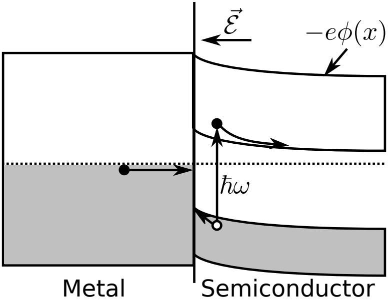
- Net current density $j = j_2 \exp\frac{-e(V_0-V)}{k_BT} - j_1 \exp\frac{-\phi_B}{k_BT}$
- At equilbrium $V = 0$, $j = 0 \Rightarrow j_2 \exp\frac{-eV_0}{k_BT} = j_1 \exp\frac{-\phi_B}{k_BT} = j_0$ (say)
- Therefore:

$$j = j_0 \left(\exp\frac{eV}{k_BT} - 1 \right)$$

- Exponentially increasing current in forward bias $(V > 0)$
- Current saturates to $-j_0$ in reverse bias
- j_0 is given by Richardson-Dushman equation, just different B_e!

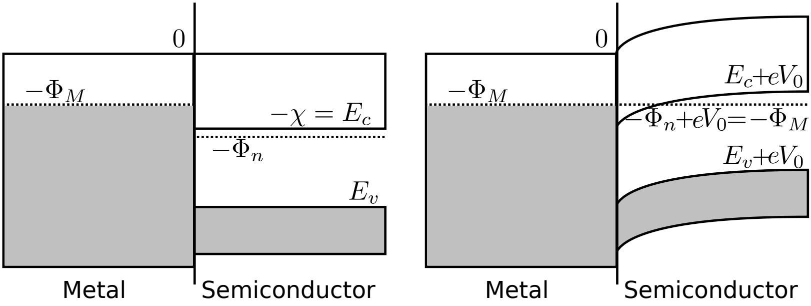


Schottky photovoltaic devices



- Contact potential $\Rightarrow$ built-in field at interface
- Photon absorption $\to$ e-h pair, separated by field
- In n-type junction, e relaxes to band edge and driven into bulk SC
- h recombines at interface (met by e current in metal)
- Below band-gap, interfacial generation also possible

Ohmic contact



- Similar geometry to Schottky diode, but different level alignment
- Consider metal Fermi level lines up inside conduction band (or analogously for p-type material, inside valence band)
- Bands bend in opposite direction to equalize Fermi levels
- No barrier Φ_B any more, electrons free to flow
- $j(V)$ dominated by linear resistance of bulk semiconductor
- I-V follows Ohm's law $\Rightarrow$ Ohmic contact

Peltier effect in Ohmic contacts

- Electrons flowing to the left pick up energy $E_c - E_F$
- Electrons flowing to the right lose energy $E_c - E_F$
- Energy drawn/dissipated from/as thermal energy at junction
- Combine p and n-type junctions to get cooling in same metal
- Reverse operation: thermoelectric generator (heat to electricity)