Lecture 18 - Metal-Semiconductor Junction *(cont.)*

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Contents:

1. Metal-semiconductor junction outside equilibrium *(cont.)*

Reading assignment:

del Alamo, Ch. 7, §7.2.3

Key questions

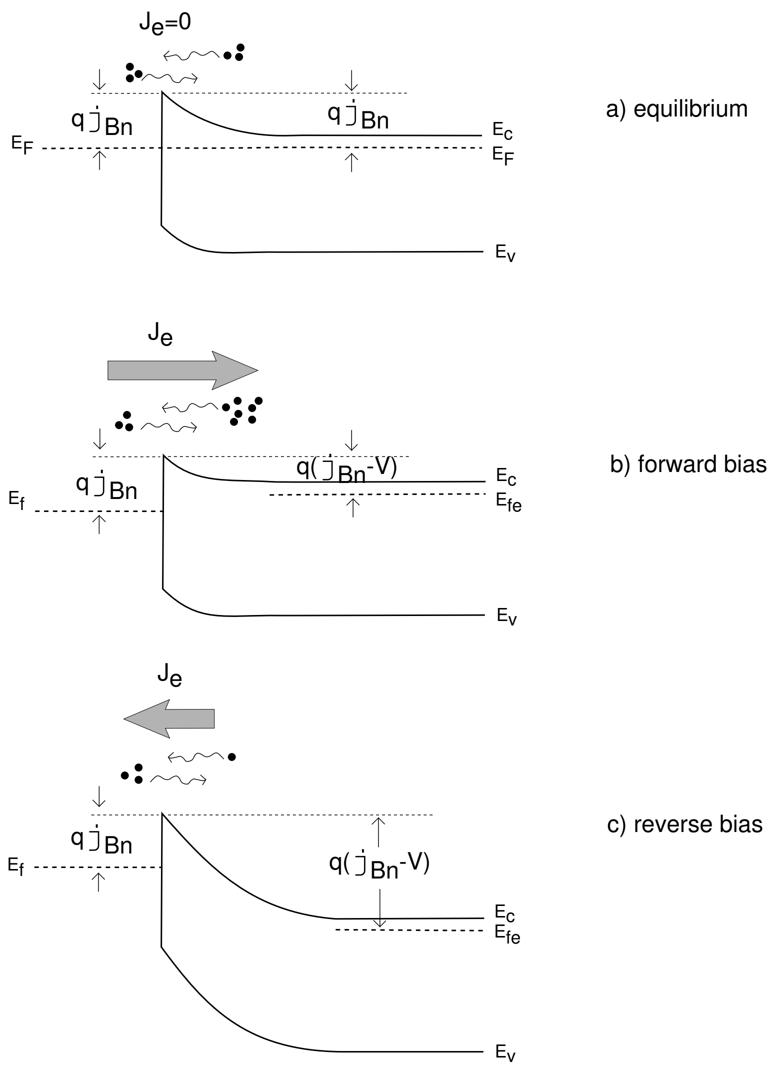
- In a metal-semiconductor junction under bias, is there current flow? If so, how exactly does it happen?
- What are the key dependences of the current in a metal-semiconductor junction?

1. Metal-semiconductor junction outside TE *(cont.)*

□ I-V Characteristics

Few minority carriers anywhere → *majority carrier device*

Bottleneck: transport through SCR



- in forward bias, $J \propto e^{qV/kT}$
- in reverse bias, J *saturates with* V

Balance between electron drift and diffusion in SCR:

- TE: perfectly balanced
- forward bias: $\mathcal{E} \downarrow \Rightarrow$ diffusion > drift
- reverse bias: $\mathcal{E} \uparrow \Rightarrow$ diffusion < drift

Net current due to imbalance of drift and diffusion $\Rightarrow$

□ Drift-diffusion model

Start with electron current equation:

$$J_e = q\mu_e n\mathcal{E} + qD_e\frac{dn}{dx} = qD_e(-\frac{qn}{kT}\frac{d\phi}{dx} + \frac{dn}{dx})$$

Multiply by $\exp(-\frac{q\phi}{kT})$:

$$\begin{aligned} J_e\exp(-\frac{q\phi}{kT}) &= qD_e[-\frac{qn}{kT}\frac{d\phi}{dx}\exp(-\frac{q\phi}{kT}) + \frac{dn}{dx}\exp(-\frac{q\phi}{kT})] \\ &= qD_e\frac{d}{dx}[n\exp(-\frac{q\phi}{kT})] \end{aligned}$$

Integrate along the depletion region:

- left-hand side: $J_e \simeq J$ (negligible hole contribution), and J independent of x:

$$\int_0^{x_d} J_e \exp(-\frac{q\phi}{kT})dx = J\int_0^{x_d} \exp(-\frac{q\phi}{kT})dx$$

- right-hand side

$$\int_0^{x_d} qD_e \frac{d}{dx}[n\exp(-\frac{q\phi}{kT})]dx = qD_e n\exp(-\frac{q\phi}{kT})|_0^{x_d}$$

For left-hand side, use $\phi(x)$ obtained earlier:

$$\phi(x) = -(\phi_{bi} - V)(\frac{x^2}{x_d^2} - \frac{2x}{x_d} + 1) \qquad \text{for } 0 \leq x \leq x_d$$

For right-hand side, use boundary conditions:

- At $x = 0$:

$$\phi(0) = -(\phi_{bi} - V)$$

$$n(0) = N_D \exp\frac{-q(\phi_{bi}-V)}{kT} = N_c \exp\frac{-q\varphi_{Bn}}{kT}\exp\frac{qV}{kT}$$

- At $x = x_d$:

$$\phi(x_d) = 0$$

$$n(x_d) = N_D$$

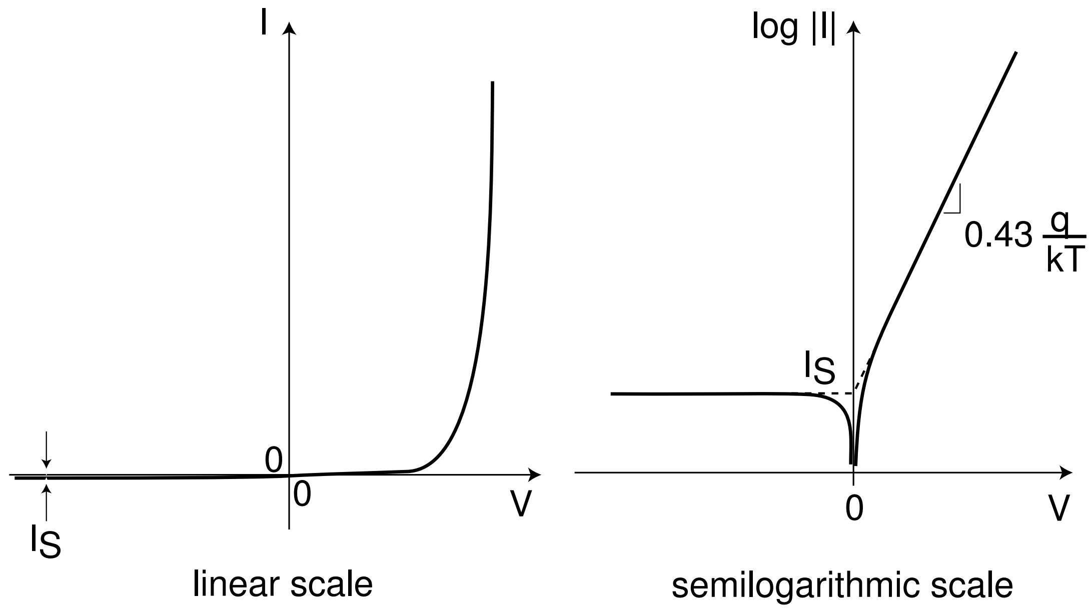
Do integral, substitute boundary conditions and get:

$$J = \frac{q^2 D_e N_c}{kT} \sqrt{\frac{2q(\phi_{bi} - V)N_D}{\epsilon}} \exp\frac{-q\varphi_{Bn}}{kT}(\exp\frac{qV}{kT} - 1)$$

Total current, multiply J by area A_j:

$$I = I_S(\exp\frac{qV}{kT} - 1)$$

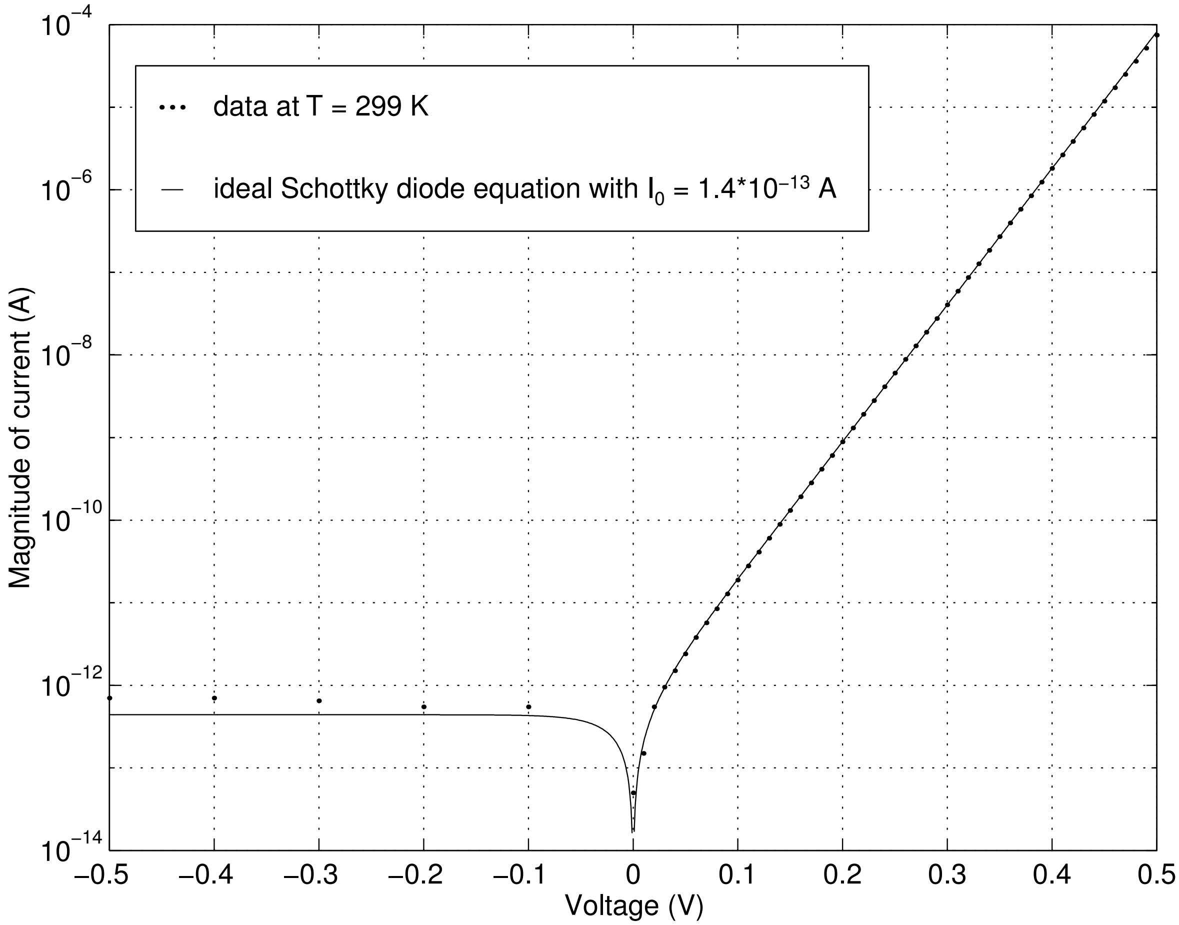
$I_S \equiv saturation\ current\ (A)$



Key dependencies of drift-diffusion model:

- $I \propto \exp \frac{qV}{kT} - 1$
- $I_S \propto \exp \frac{-q\varphi_{Bn}}{kT}$
- I_S weakly dependent on V

Experiments (Schottky diode from Analog Devices):



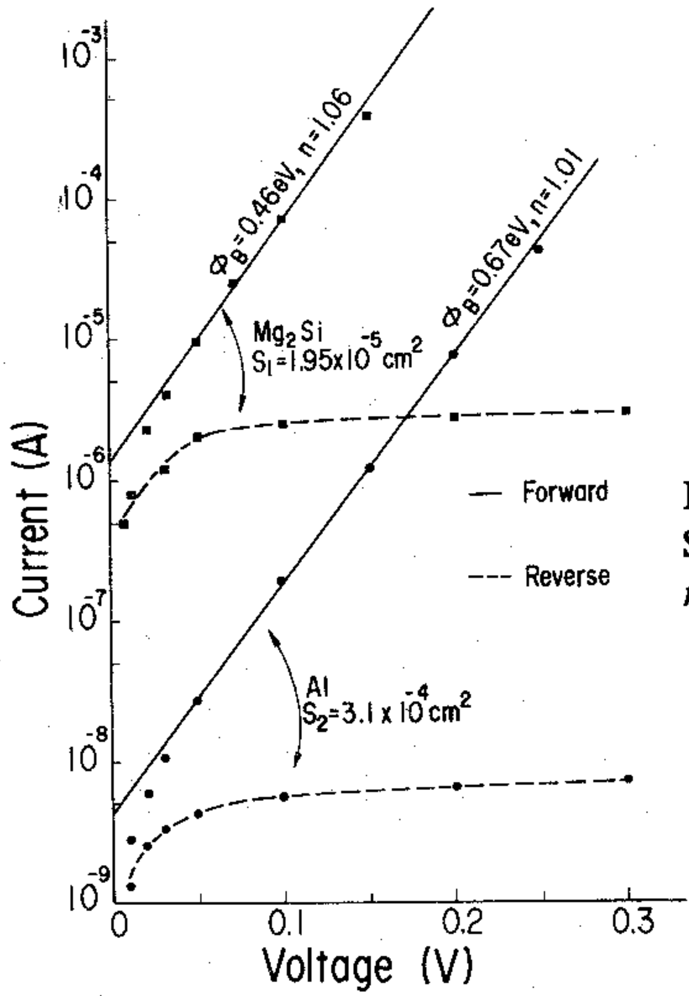


FIG. 5. ***V-I*** **characteristics of Schottky-barrier diodes,** $\mathbf{Mg_2Si}$**-*n*Si and Al-*n*Si.**

Courtesy of the American Institute of Physics. Used with permission. Figure 5 on page 1598 in Akiya, Masahiro, and Hiroaki Nakamura. "Low Ohmic Contact to Silicon with a Magnesium/Aluminum Layered Metallization." *Journal of Applied Physics* 59, no. 5 (1986): 1596-1598.

Temperature dependence of I_S:

$$I_S \propto T^{1/2} \exp \frac{-q\varphi_{Bn}}{kT}$$

<u>not</u> seen in practice!

What one finds experimentally is:

$$I_S \propto T^2 \exp \frac{-q\varphi_{Bn}}{kT}$$

Made implicit assumption: *quasi-equilibrium* across SCR $\Rightarrow$ drift/diffusion balance only slightly broken.

Quasi-equilibrium assumption good if:

$$|J| \ll |J_e(drift)|, \ |J_e(diff)|$$

Test at $x = 0$:

$$\frac{|J|}{|J_e(drift)|} \simeq 1 \ !$$

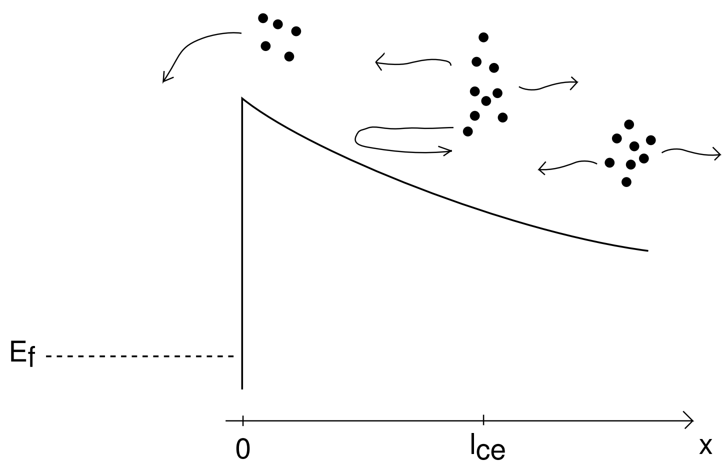
Assumption fails at $x = 0$. Need to look at situation closely around $x = 0$.

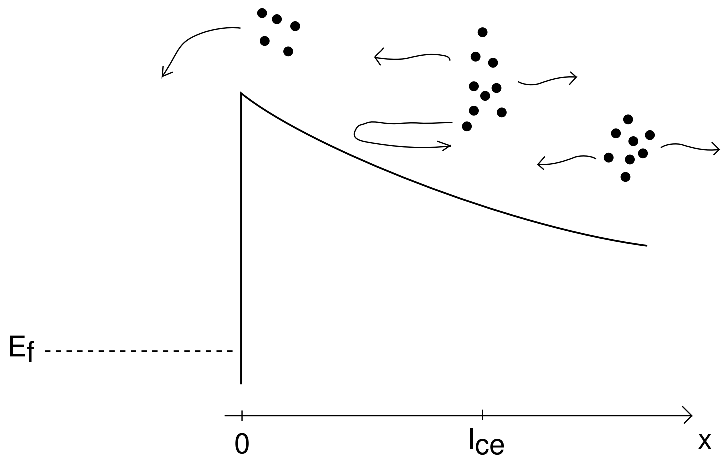
□ Thermionic-emission theory

Closer than a mean free path from the interface, arguments of drift and diffusion do not work!

In the last mean free path,

- electrons do not suffer any collisions,
- only those with enough E_K get over the barrier
- actually, only half of those with enough E_K do
- this is bottleneck: *thermionic emission theory*





In steady state:

$$J_t \simeq J_e = -qn(x)v_e(x)$$

Focus on bottleneck at $x = 0$:

$$J = -qn(0)v_e(0)$$

□ First compute $n(0)$:

$n(0)$ is only a fraction of the carriers present at $n(l_{ce})$:

$$n(0) = \frac{n(l_{ce})}{2} \exp \frac{q[\phi(0) - \phi(l_{ce})]}{kT}$$

If rest of SCR is in *quasi-equilibrium*:

$$n(l_{ce}) \simeq N_D \exp \frac{q\phi(l_{ce})}{kT}$$

Also:

$$\phi(0) = -(\phi_{bi} - V)$$

Then:

$$n(0) = \frac{N_D}{2} \exp \frac{-q(\phi_{bi} - V)}{kT} = \frac{N_c}{2} \exp \frac{-q(\varphi_{Bn} - V)}{kT}$$

- $n(0)$ is exactly half of what one would obtain if it was in TE with bulk.
- All electrons at $x = 0$ are injected into metal.
- Note $\propto e^{qV/kT}$ dependence on $n(0)$.

□ Then compute $v_e(0)$:

Over the last mean free path, carriers basically travel at v_{th}

But, velocity pointing at different angles. After taking care of statistics:

$$v_e(0) = -\frac{v_{th}}{2} = -\sqrt{\frac{2kT}{\pi m_{ce}^*}}$$

(minus sign indicates carriers traveling against x)

□ Finally, electron current:

$$J = A^* T^2 \exp\frac{-q\varphi_{Bn}}{kT} \exp\frac{qV}{kT}$$

with:

$$A^* = \frac{4\pi q k^2 m_o}{h^3}\sqrt{\frac{(\frac{m_{de}^*}{m_o})^3}{\frac{m_{ce}^*}{m_o}}}$$

$A^* \equiv$ Richardson's constant

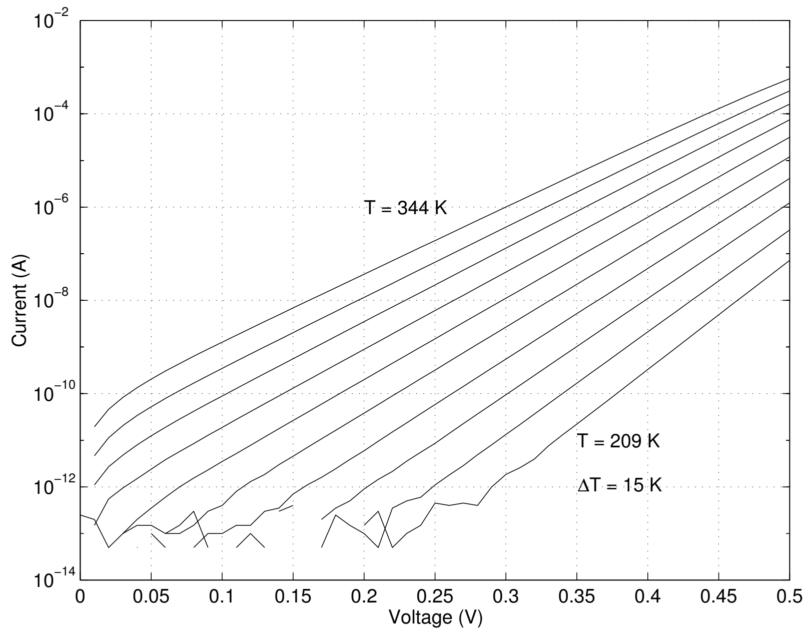
Still must subtract electron injection from metal to semiconductor in TE, so that when $V \to 0,\ J \to 0$:

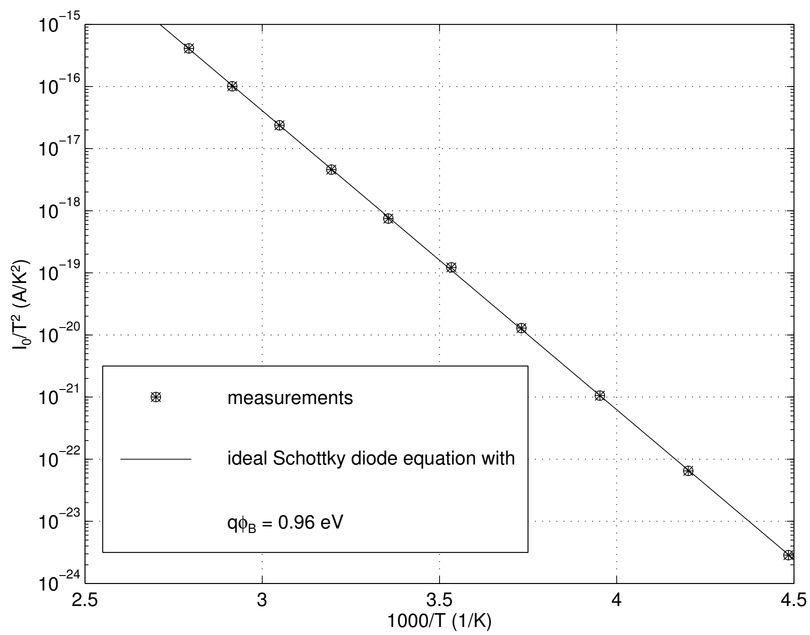
$$J = A^* T^2 \exp \frac{-q\varphi_{Bn}}{kT} (\exp \frac{qV}{kT} - 1)$$

Valid in forward and reverse bias.

$$I_S = A_j A^* T^2 \exp \frac{-q\varphi_{Bn}}{kT}$$

I_S/T^2 is thermally activated with $E_a = q\varphi_{Bn}$





□ Thermionic emission theory valid if:

$$\text{thermionic current} \ll \text{drift current}$$

for $l_{ce} \leq x \leq x_d$.

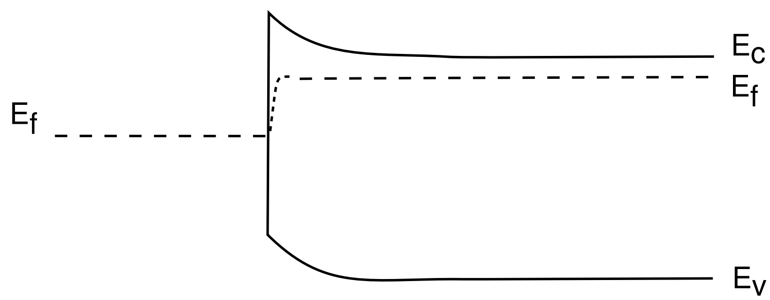
Bethe condition:

$$l_{ce}|\mathcal{E}_{max}| > 1.5\frac{kT}{q}$$

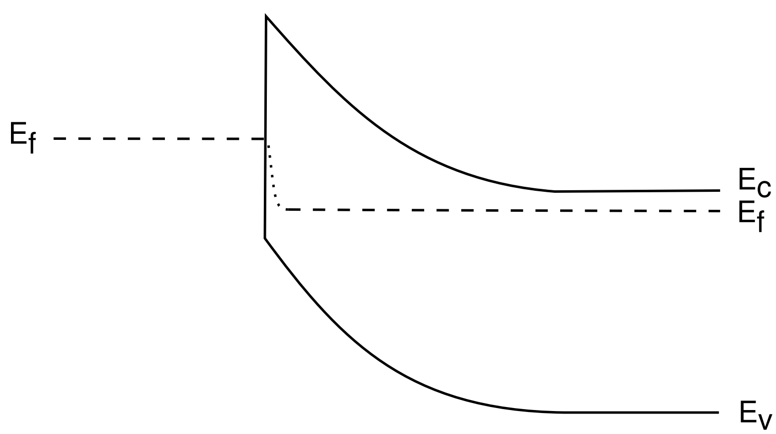
Easily satisfied in Si at around room temperature (mean free paths are rather long).

□ If thermionic emission theory applies:

- E_{fe} flat throughout SCR up to $x = l_{ce}$.
- Beyond $x = l_{ce}$, E_{fe} has no physical meaning (electron distribution is not Maxwellian!)



forward bias



reverse bias

Key conclusions

- Minority carriers play no role in I-V characteristics of MS junction.
- Energy barrier preventing carrier flow from S to M modulated by V, barrier to carrier flow from M to S unchanged by $V \Rightarrow$ rectifying behavior:

$$I = I_S(\exp\frac{qV}{kT} - 1)$$

- *Drift-diffusion theory* of current: small perturbation of balance of drift and diffusion inside SCR.
- *Drift-diffusion theory* of current exhibits several dependences observed in devices, but fails temperature dependence.
- *Thermionic emission theory* of current: bottleneck is flow of carriers over energy barrier at M-S interface. Transport at this bottleneck is of a *ballistic nature*.
- I_S/T^2 is thermally activated; activation energy is $q\varphi_{Bn}$.

Self study

- Thermionic emission theory