Lecture 15 - Metal-Semiconductor Junction *(cont.)*

October 7, 2002

Contents:

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

Reading assignment:

del Alamo, Ch. 6, §6.2.3

Seminar:

October 1: *High Performance CMOS Design at IBM* by J. Welser, IBM; Rm. 34-101, 4 PM.

Announcement:

Quiz 1: October 10, Rm. 50-340 (Walker), 7:30-9:30 PM; lectures #1-13 (up to metal-semiconductor junction, no space-charge-region transport). Open book. *Calculator required.*

Key questions

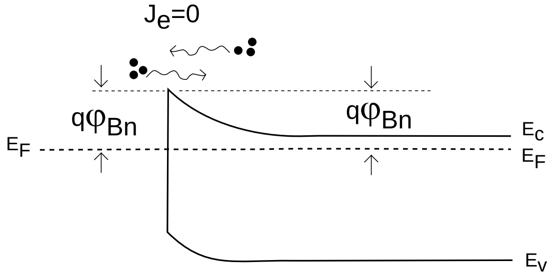
- In a metal-semiconductor junction under bias, is there current flow? If so, how exactly does it happen?
- What are the key dependences of the current in a metal-semiconductor junction?
- How appropriate is the use of the Boltzmann relation across SCR out of equilibrium?

1. M-S junction outside equilibrium *(cont.)*

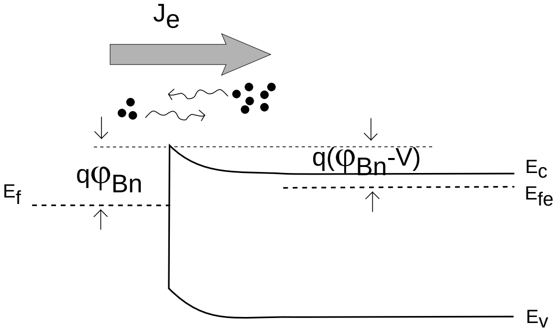
□ I-V Characteristics

Few minority carriers anywhere → *majority carrier device*

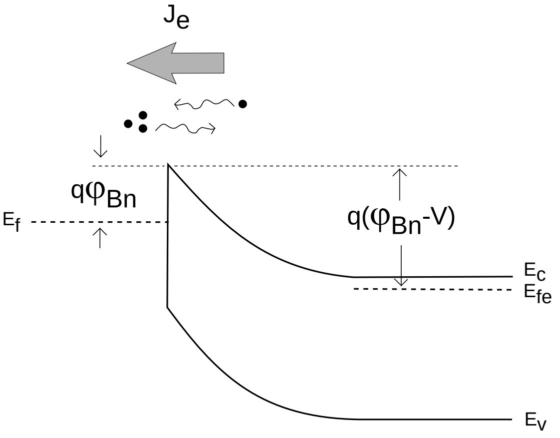
Bottleneck: transport through SCR



a) equilibrium



b) forward bias



c) reverse bias

- 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 ⇒

□ 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: $J_e \simeq J_t$ (negligible hole contribution), and J_t independent of x (steady state):

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

and use $\phi(x)$ obtained earlier:

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

- Right-hand side

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

Need $n(0),\ \phi(0),\ n(x_d),\ \phi(x_d)$.

- $x = x_d$ is edge of depletion region with quasi-neutral bulk:

$$\phi(x_d) = 0$$

$$n(x_d) = N_D$$

- $x = 0$ is metal-semiconductor interface:

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

$$n(0) = ?$$

What if I use Boltzmann relation across SCR?

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

This would give:

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

Under what conditions could I do this?

Let's see where it leads first...

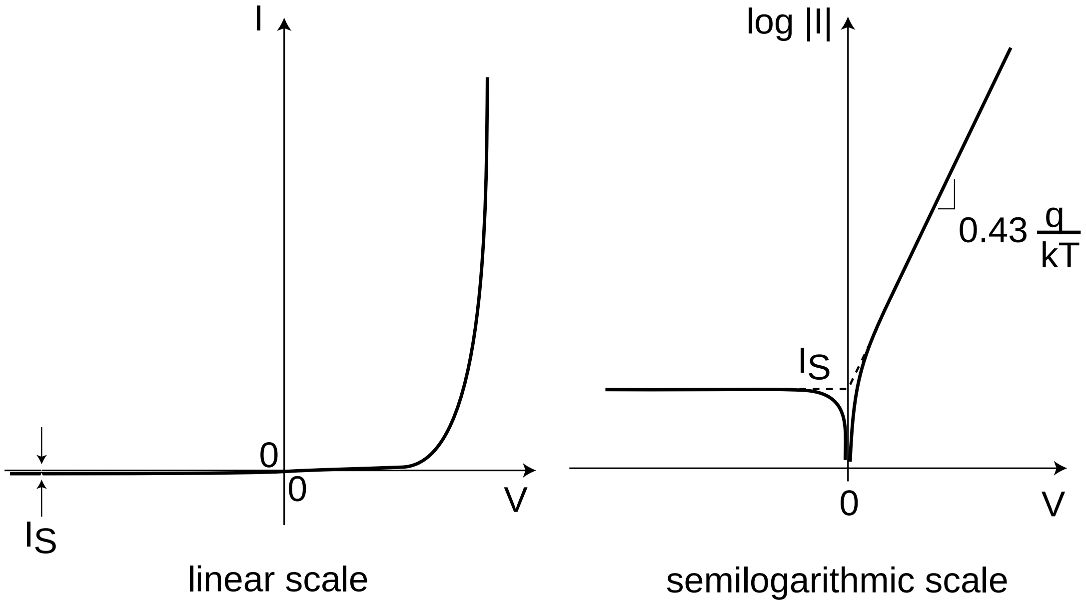
Do integral, substitute boundary conditions and get:

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

Total current, multiply J_t by area A_j:

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

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

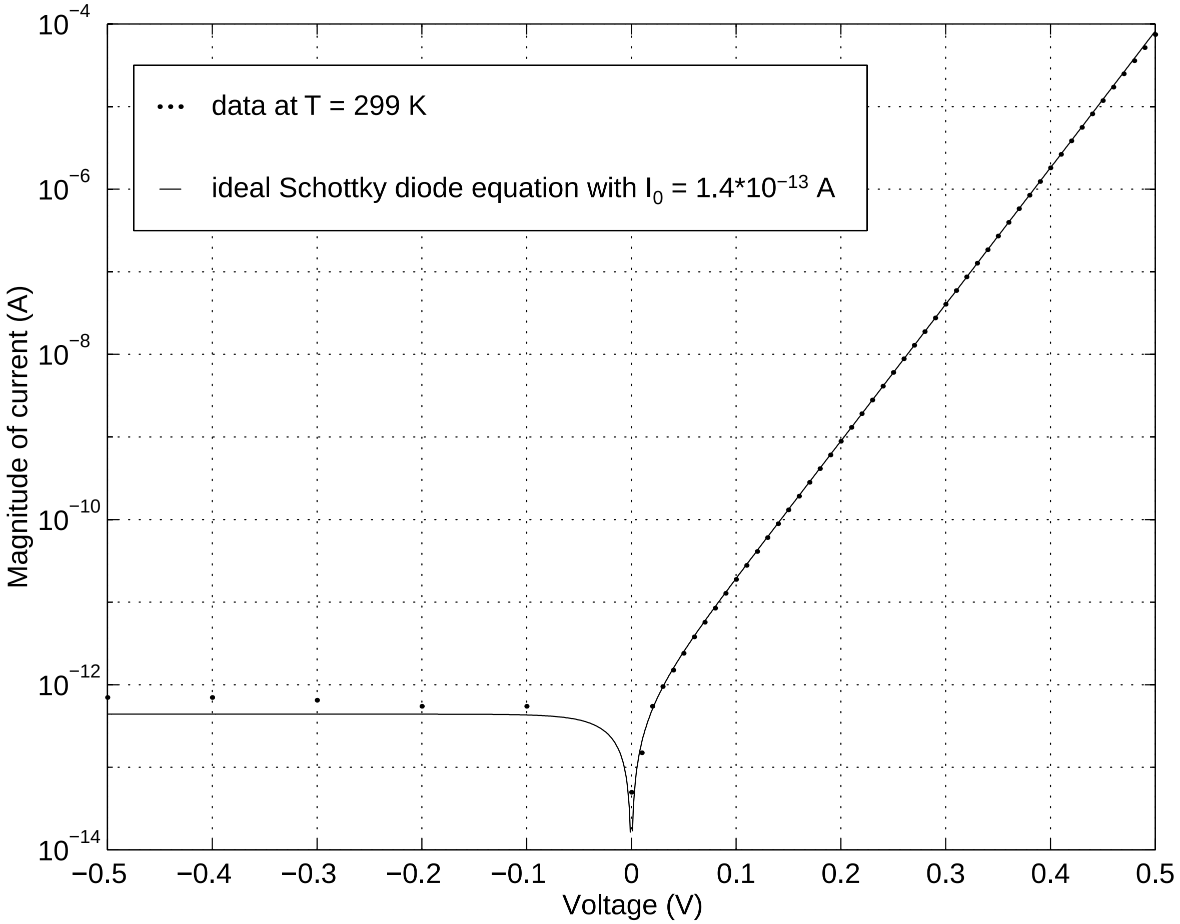


linear scale semilogarithmic scale

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 [PtSi/n-Si Schottky diode courtesy of B. Scharf (Analog Devices)]:



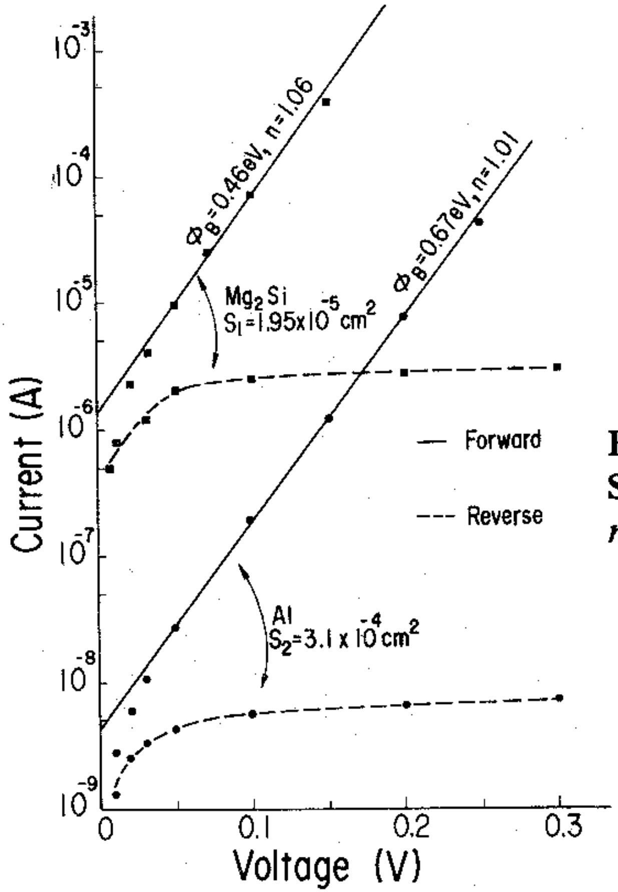


FIG. 5. *V-I* characteristics of Schottky-barrier diodes, Mg_2Si-*n*Si and Al-*n*Si.

Courtesy of the American Institute of Physics. Used with permission.
[from Akiya and Nakamura, JAP 59, 1596, 1986]

Another dependence in drift-diffusion model:

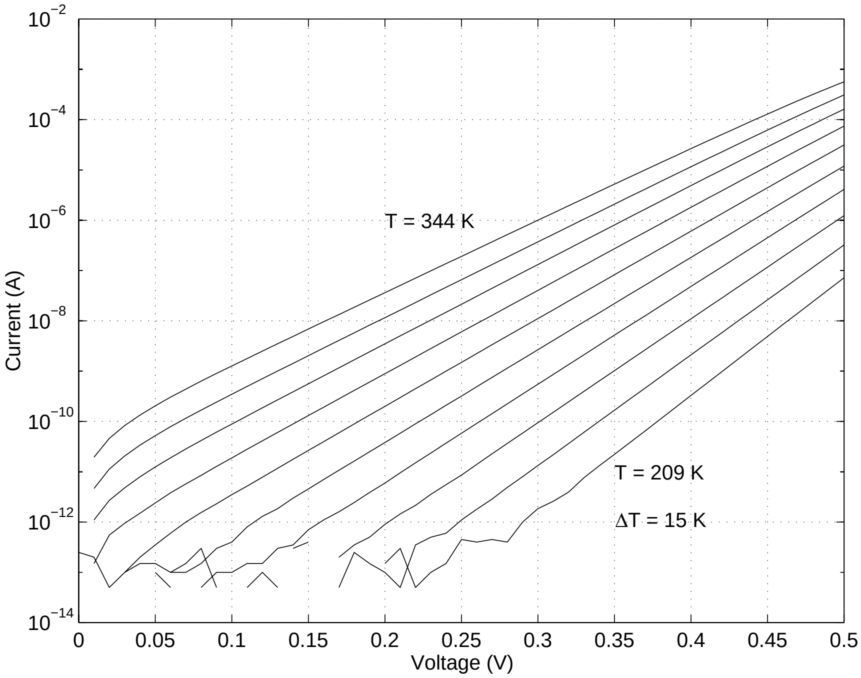
- Temperature dependence of I_S: $I_S \propto T^{-1/2} \exp \frac{-q\varphi_{Bn}}{kT}$

Not seen in practice!

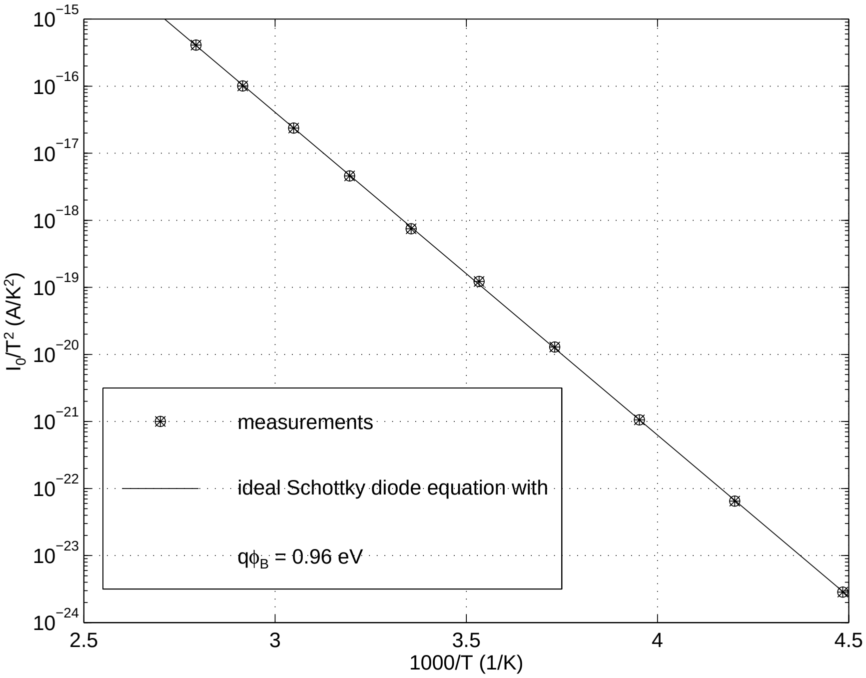
What one finds experimentally is:

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

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



10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
Current (A)
T = 344 K
T = 209 K
ΔT = 15 K
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Voltage (V)



10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
I_0/T^2 (A/K^2)
measurements
ideal Schottky diode equation with
$q\phi_B$ = 0.96 eV
2.5
3
3.5
4
4.5
1000/T (1/K)

☐ Source of problem with drift-diffusion model: Boltzmann relation is only valid in thermal equilibrium!

Boltzmann relation derived from:

$$J_e = J_e(drift) + J_e(diff) = 0$$

Out of TE, $J_e(drift) \neq -J_e(diff) \Rightarrow$ Boltzmann not applicable.

But... if difference between $J_e(drift)$ and $-J_e(diff)$ is small, error in Boltzmann relation might be tolerable $\Rightarrow$ *Quasi-equilibrium.*

Quasi-equilibrium assumption good if:

$$|J_t| \simeq |J_e| \ll |J_e(drift)|,\ |J_e(diff)|$$

Test at $x = 0$:

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

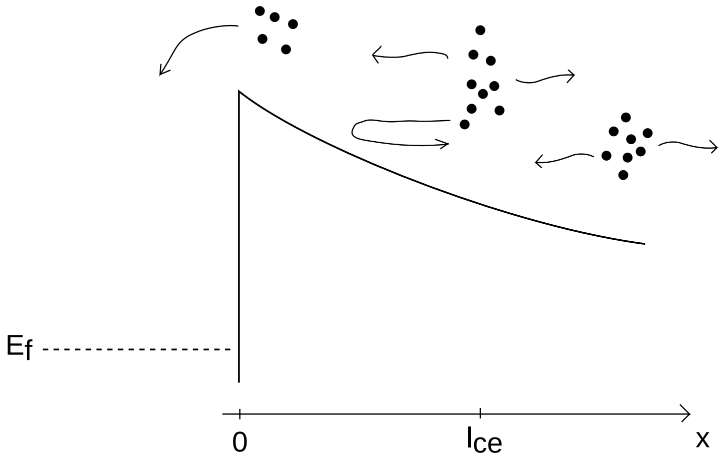
Assumption fails at $x = 0$. Need to look at situation closely around $x = 0$.

□ 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 (*ballistic transport*),
- 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*



Focus on bottleneck at $x = 0$:

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

Assume *quasi-equilibrium* up to the last mean-free path.

☐ Electron current:

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

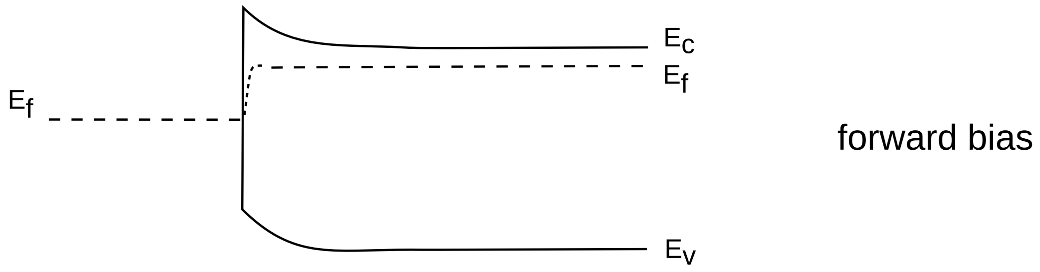
with:

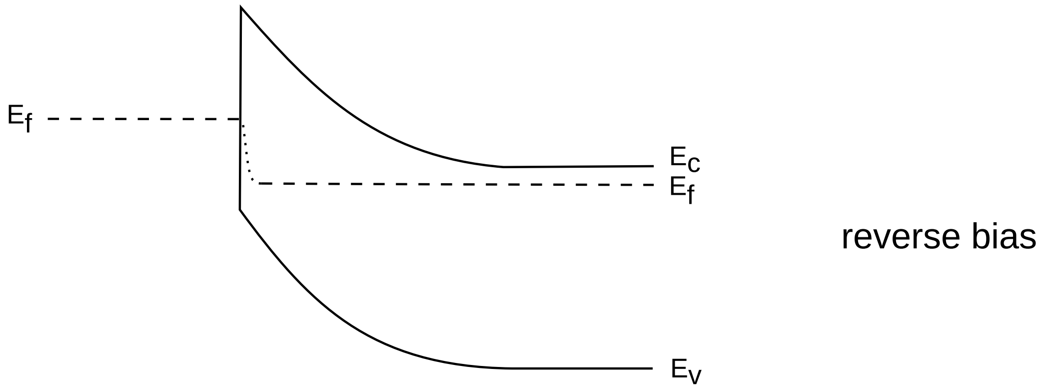
$$A^* = \frac{4\pi q k^2 m_o}{h^3} \sqrt{\frac{(\frac{m_{de}^*}{m_o})^3}{\frac{m_{ce}^*}{m_o}}}$$

$A^* \equiv$ Richardson's constant

☐ If thermionic emission theory applies:

- E_{fe} flat throughout SCR up to $x = l_{ce}$.
- From $x = 0$ to $x = l_{ce}$, E_{fe} has no physical meaning (electron distribution is not Maxwellian!)





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