Course 19

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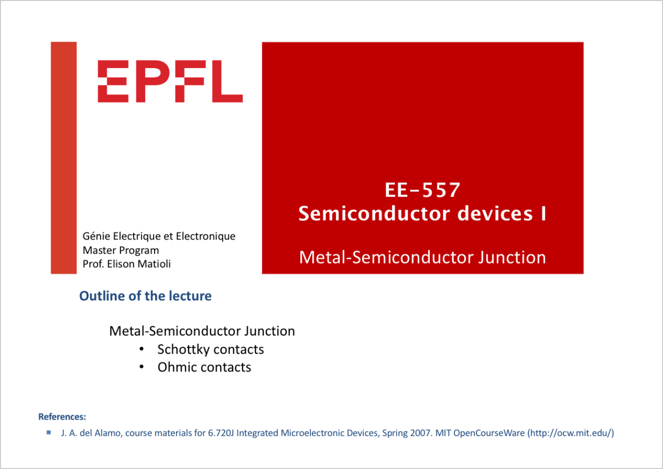


EE-557
Semiconductor devices I

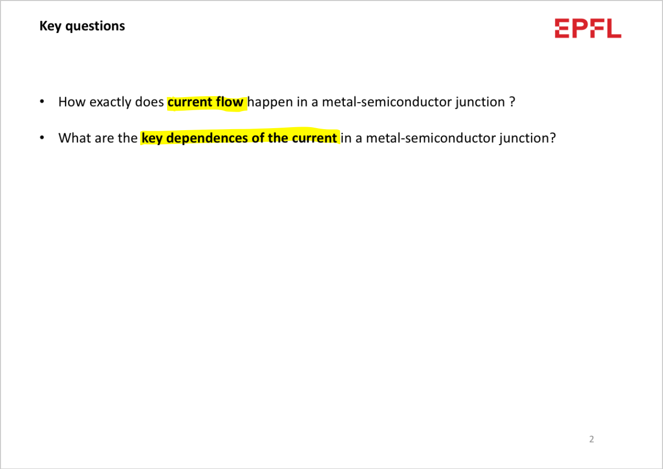
Metal-Semiconductor Junction

Génie Electrique et Electronique
Master Program
Prof. Elison Matioli

Outline of the lecture

Metal-Semiconductor Junction
- Schottky contacts
- Ohmic contacts

References:
- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)



Key questions

- How exactly does **current flow** happen in a metal-semiconductor junction ?
- What are the **key dependences of the current** in a metal-semiconductor junction?

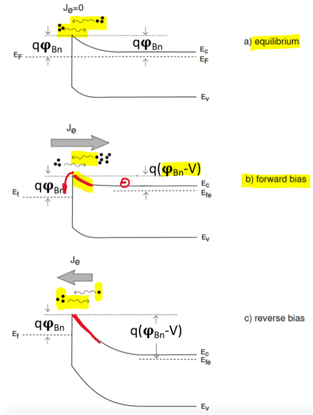
Metal-semiconductor junction outside TE

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

Metal-semiconductor junction outside TE

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,

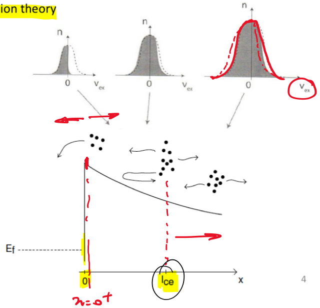
- electrons do not suffer any collisions,
- only those with enough E_K get over the barrier.
- actually, only half of those with enough E_K do!
- This is bottleneck: thermionic emission theory

In steady state:

Focus on bottleneck at x =0:

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

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

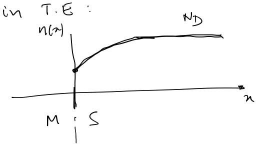


thermionic emission theory :

$$J_t = J_e(0^+) = J_{e,SM}(0^+) - J_{e,MS}(0^+)$$

$$J_{e,sm}(0^+) \simeq -q\cdot \boxed{n(0^+)}\cdot \underline{v_e(0^+)}$$

in T.E :



$$n_0(x) = N_D\cdot\exp\left(\frac{q\cdot\phi(x)}{KT}\right)$$

$$n_0(x=0) = N_D\cdot\exp\left(-\frac{q\,\phi_{bi}}{KT}\right)$$

when we apply V :

$$n_0(0^+) = N_D\cdot\exp\left(-\frac{q(\phi_{bi}-V)}{KT}\right)$$

this cannot be applied !

$$n(0^+) = \frac{n(lce)}{2}\cdot\exp\left[\frac{q(\phi(0^+)-\phi(lce))}{KT}\right] \quad [1]$$

$$n(lce) = N_D\cdot\exp\left(\frac{q\,\phi(lce)}{KT}\right) \quad [2]$$

$$\phi(0^+) = -(\phi_{bi}-V) \quad [3]$$

Using [1] :

[2] [3]

$$n(0^+) = \frac{N_D}{2}\cdot\exp\left(\cancel{\frac{q\cdot\phi(lce)}{KT}}\right)\cdot\exp\left(-\frac{q(\phi_{bi}-V)}{KT}\right)\cdot\exp\left(\cancel{-\frac{q\,\phi(lce)}{KT}}\right)$$

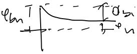
$$n(0^+) = \frac{N_D}{2}\exp\left(-\frac{q\cdot\phi_{bi}-V}{KT}\right) \underset{[4]}{\overset{\uparrow}{=}} \boxed{\frac{N_C}{2}\exp\left(-\frac{q(\varphi_{bn}-V)}{KT}\right)}$$

[4]

$$\phi_{bn} = \phi_{bi} + \varphi_n$$

$$\varphi_n = E_c - E_f$$

$$N_D = N_C\exp\left(-\frac{\varphi_n}{KT}\right)$$



Metal-semiconductor junction outside TE

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

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

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

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

n(0) is exactly half of what one would obtain if its was a bulk semiconductor in TE

All electrons at x = 0 are injected into metal

Note ∝ $e^{qV/kT}$ dependence of n(0)

Metal-semiconductor junction outside TE

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 that electrons are 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

$$v_{th} = \sqrt{\frac{8kT}{\pi . m^*_{ce}}}$$

$$J_{e,SM} = -q . n(0^+) . v_e$$

$$= +q . \frac{N_c}{2} \exp\left(-\frac{q(\varphi_{Bn} - V)}{kT}\right) . \sqrt{\frac{2kT}{\pi . m^*_{ce}}} =$$

$$= \underbrace{q . N_c . \sqrt{\frac{kT}{2\pi m^*_{ce}}}}_{A^* . T^2} . \exp\left(\frac{-q\varphi_n}{kT}\right) . \exp\left(\frac{qV}{kT}\right)$$

$$J_t = J_{e,SM}(0^+) - J_{e,MS}(0^+)$$

$$V = 0 \qquad J_t = 0 \Rightarrow J_{e,SM}(0^+) = J_{e,MS}(0^+)$$

Metal-semiconductor junction outside TE

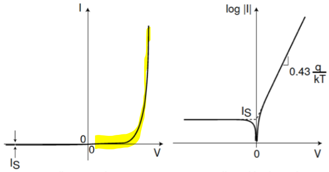
Still must **subtract electron injection from metal to semiconductor in TE**, so that when V → 0, J → 0:

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

Valid in forward and reverse bias.

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

I_S: Saturation current



linear scale

semilogarithmic scale

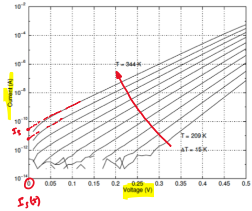
Metal-semiconductor junction outside TE

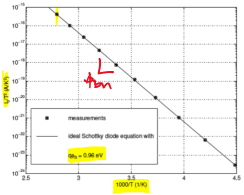
$$J = A^*T^2 \exp\frac{-q\varphi_{Bn}}{kT}(\exp\frac{qV}{kT} - 1)$$

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

$$- \frac{I_s}{T^2} = A_j A \exp\left(\frac{-q\phi_{Bn}}{kT}\right)$$

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





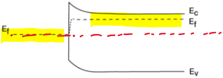
Metal-semiconductor junction outside TE

Thermionic emission theory valid if: thermionic current << drift current for $l_{ce} \le x \le x_d$.

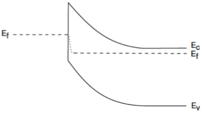
Bethe condition: $l_{ce}|\mathcal{E}_{max}| > 1.5\frac{kT}{q}$ (Potential drop in the first mean free path > 1.5x thermal potential)

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

Schottky diode

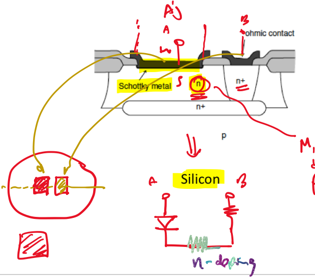
Key uniqueness: fast switching from ON to OFF and back, since it is a majority carrier device

Widely used:

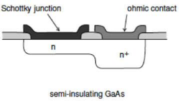
- in analog circuits: in track and hold circuits in A/D converters, pin drivers of IC test equipment
- In communications and radar applications: as detectors and mixers, also as varactors

$I = J \cdot A_j$

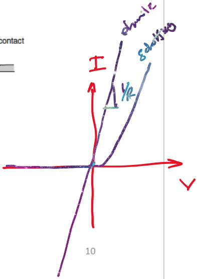
Typical implementations:



Silicon



GaAs

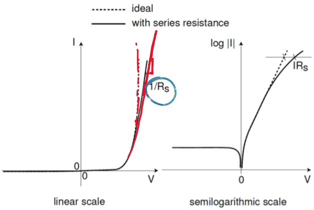


Schottky diode

Parasitics

Series resistance due to QNR ohmic drop
Voltage across junction is reduced and I-V characteristics modified:

$$I = I_S[\exp\frac{q(V - IR_s)}{kT} - 1]$$



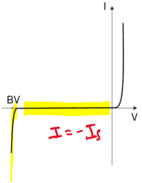
R_s bad because:
For given forward current, V increased and harder to control
it degrades dynamic response of diode

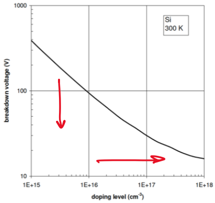
Schottky diode

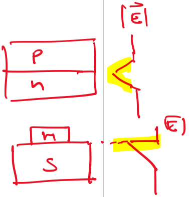
Breakdown

In reverse bias, as |V| ↑ → $|E_{max}|$ ↑

At a high-enough voltage, avalanche breakdown takes place → breakdown voltage







For moderate doping levels, BV function of N_D alone (independent of φBn):

For similar doping levels, BV is typically smaller than in Schottky diodes: high electric field occurs at the sharp interface of the metal and semiconductor (in pn junctions high fields are inside semiconductors)

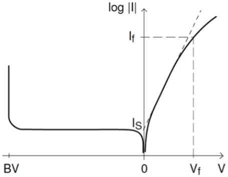
Schottky diode

Design issues:

Metal selection: $\varphi_{Bn} \uparrow \;\rightarrow\; V_f$ (for fixed I_f) $\uparrow$

$\rightarrow\; I_S \downarrow$

$\rightarrow$ more T sensitivity



Doping level selection:

$N_D \uparrow \;\rightarrow\; R_s \downarrow$

$\rightarrow\; C \uparrow$

$\rightarrow\; BV \downarrow$

Vertical extension of QNR: minimum value of t required to deliver BV (beyond that, R_s ↑)

Diode area:

$I = J \cdot \text{Ⓐ}$

$C = \varepsilon \text{Ⓐ} / t$

$A_j \uparrow \;\rightarrow\; C \uparrow$

$\rightarrow\; I_S \uparrow$

$\rightarrow\; R_s \downarrow$

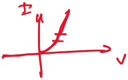
$\rightarrow\; V_f$ (for fixed I_f) $\downarrow$

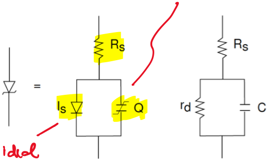
$\rightarrow$ more expensive

Schottky diode

Equivalent circuit models

$C = C_j$





a) general

b) small-signal

$$r_d \simeq \frac{kT}{qI}$$

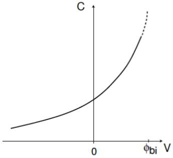
General model:

"Ideal diode" in parallel with capacitor and in series with resistor. Ideal diode is element with exponential I-V characteristics and no capacitances

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

Schottky diode

Capacitance in Schottky diodes is much smaller than in pn junctions:



Cj

$$C(V) = \frac{\epsilon}{x_d(V)}$$

$$C(V) = \sqrt{\frac{\epsilon q N_D}{2(\phi_{bi} - V)}} = \frac{C(V=0)}{\sqrt{1 - \frac{V}{\phi_{bi}}}}$$

$\boxed{1/C^2 \times V}$ → slope : N_D

cross 0 x-axis : ϕ_{bi}

Schottky diode

Equivalent circuit models (real example)

Schn
Ni

Ω
Ti/Al/Ni/Au

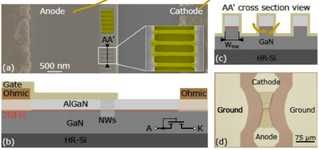
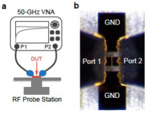
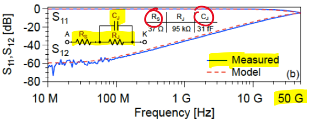


Fig. 1. (a) SEM image of a 30 nm-wide NW-FER. The inset shows the NW array before gate metal deposition. (b) Lateral and (c) cross-section (along AA') schematics of the device. (d) Optical image of a NW-FER showing the ground-signal-ground (GSG) pads for RF measurements.





G. Santoruvo, M. Samizadeh Nikoo, and E. Matioli, **Broadband Zero-Bias RF Field-Effect Rectifiers Based on AlGaN/GaN Nanowires**, IEEE Microwave and Wireless Components Letters ol. 30, no. 1, pp. 66-69Nov. 2019

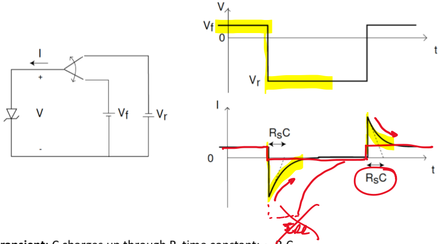
Dynamics

R_s, C_j

$R_s . C_j$: time constant

Uniqueness of Schottky diodes: they switch fast!

Large-signal example:

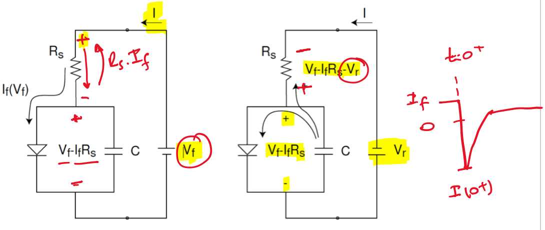


switch-off transient: C charges up through R_s time constant: ~ R_sC

switch-on transient: C discharges through R_s time constant: ~ R_sC

Dynamics

Switch-off transient:



t=0⁻

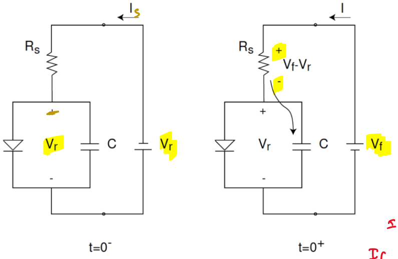
t=0⁺

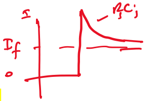
$$I(0^-) = I_f(V_f)$$

$$I(0^+) = -(\frac{V_f - V_r}{R_s} - I_f)$$

Dynamics

Switch-on transient:





$$I(0^-) = -I_s$$

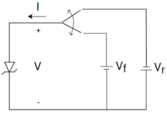
$$I(0^+) = \frac{V_f - V_r}{R_s}$$

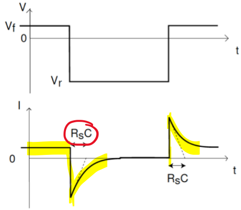
note: in this notation, V_r is negative

Dynamics

Uniqueness of Schottky diodes: they switch fast!

Large-signal example:





switch-off transient: C charges up through R_s time constant: ~ R_sC

switch-on transient: C discharges through R_s time constant: ~ R_sC

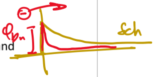
For fast switching ⇒ minimize R_s and C

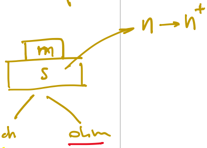
Ohmic contact

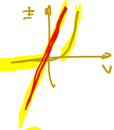
Ohmic contacts: means of electrical communication with outside world.

- Key requirement: very small resistance to carrier flow back and forth between metal and semiconductor.
- Can support substantial currents in both forward and reverse biases.
- Achieved by highly doping the semiconductor at the metal interface
- Ohmic contact = MS junction with large J_S
- V small → linearize I-V characteristics:

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







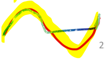


Figure of merit for ohmic contacts:

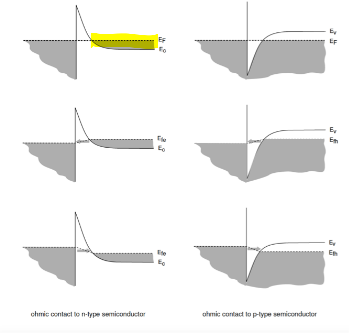
$\rho_c \equiv$ ohmic contact resistivity ($\Omega \cdot cm^2$)

Good values: $\rho_c \leq 10^{-7}\ \Omega \cdot cm^2$

Ohmic contact

How does one make a good ohmic contact?

- Classically, use metal that yields **small $q\varphi_{Bn}$**
- **Increase N_D** until carrier tunneling is possible



ohmic contact to n-type semiconductor

ohmic contact to p-type semiconductor

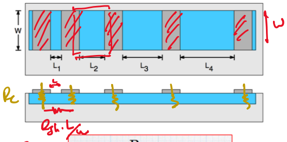
Ohmic contact resistance:

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

$$A_c \uparrow \Rightarrow \ R_c \downarrow$$

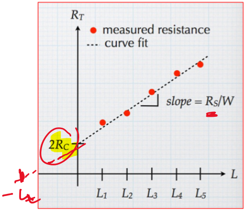
Lateral ohmic contact

Transmission line measurement (TLM)

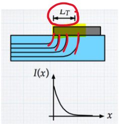


$R = 2R_c + \frac{\rho_{sh} \cdot L}{W}$

$$R_T = \frac{R_S}{W}(L + 2L_T)$$



At the edge of the contact, the current flowing in (or out) is significant. Moving away from that edge, the current drops off until, at the far edge, there is no current: current crowding



L_T is the transfer length

$$L_T = \sqrt{\frac{\rho_C}{R_S}}$$

The effective area of the contact can be treated as $L_T W$:

$$R_C = \frac{\rho_C}{L_T W} = \frac{R_S L_T}{W}$$

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 ⇒ rectifying behavior:

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

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 $q\varphi_{Bn}$.

Ideal BV of Schottky diode entirely set by doping level.

No minority carrier storage in Schottky diode ⇒ fast switching.

Dominant time constant of Schottky diode: R_sC.

Good ohmic contacts fabricated by increasing doping level ⇒ carrier tunneling.

ρ^c, specific contact resistance (in $\Omega \cdot cm^2$), in Si at 300K: $\rho_c < 10^{-7}\,\Omega \cdot cm^2$