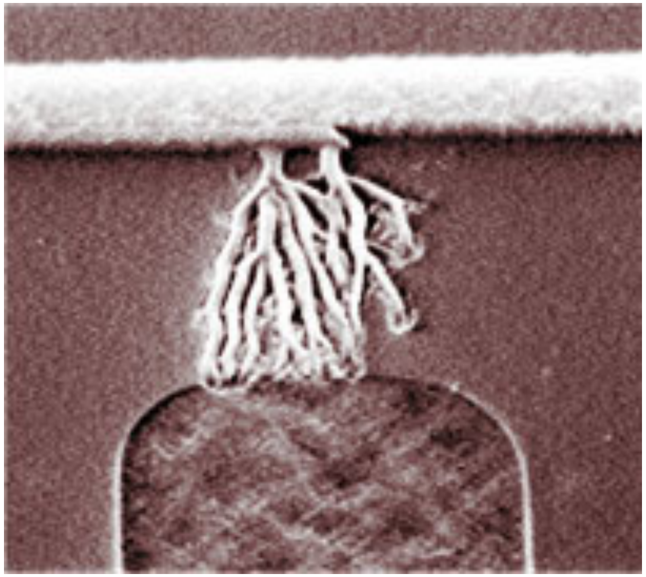
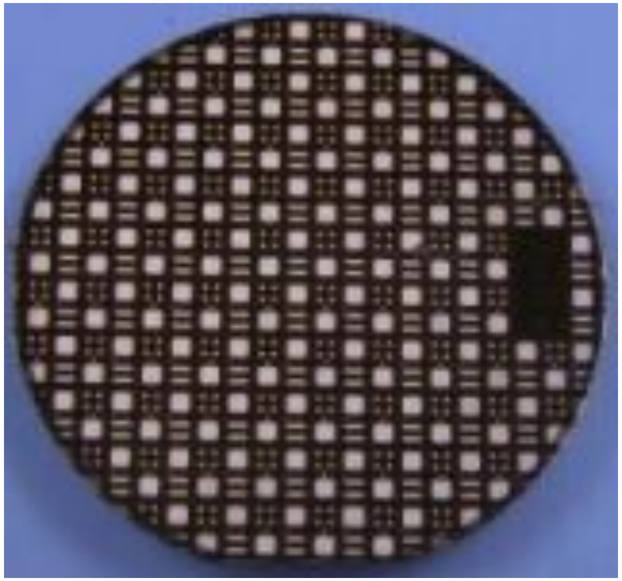
5.7 Metal-Semicon. Junctions / 5.5 Capacitance

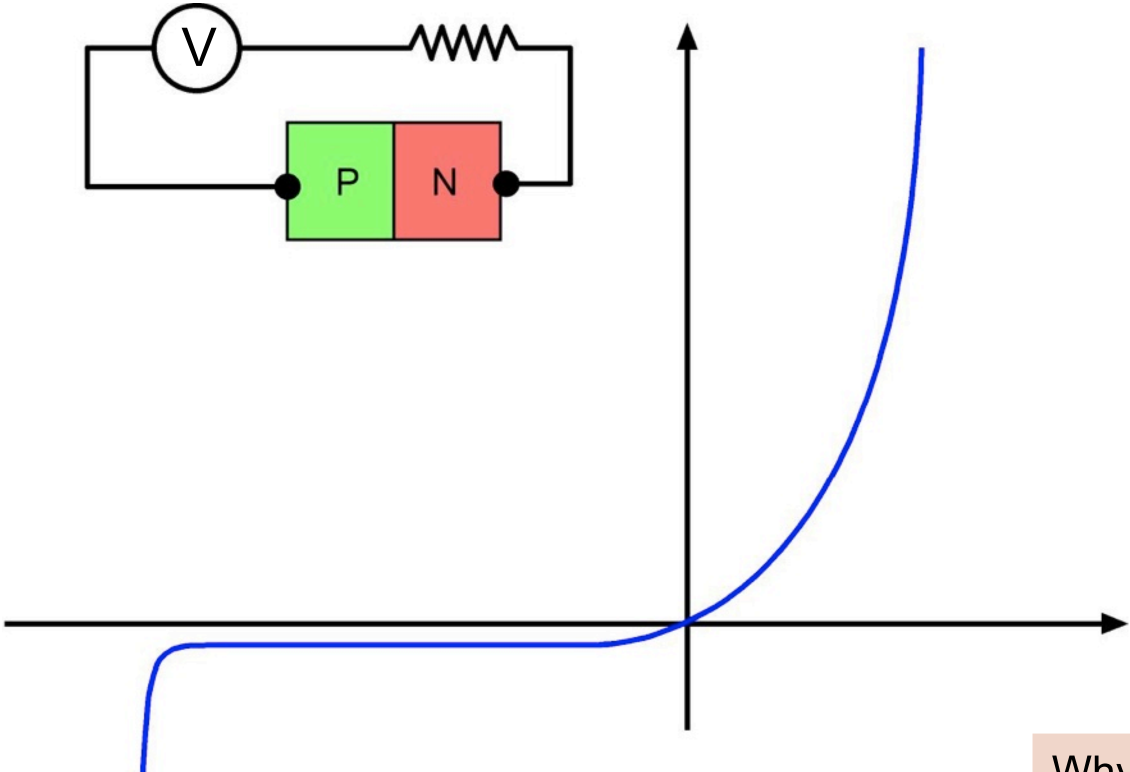
Two pictures today, what they have to do with voltage is opposite for each picture.





1600 V SiC Schottky rectifying diodes!

Switching Gears Now…



- So, up to this point we have ignored the metal contacts onto the semiconductor…

- When we join two different semiconductor materials some interesting things happened, right?

- Well metals are also quite different than semiconductors, so we need to investigate this more carefully… it can create a diode!

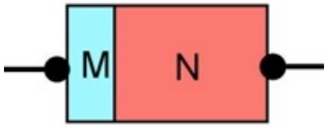
In 1938, Schottky effect, the current emitted into the vacuum depends on the metal work function, and by the presence of electric field.

Why make this type of diode?

Simple! Easy to do with exotic and wide-bandgap s/c such as SiC / GaN etc .. Difficult to do p-type doping for GaN & SiC! So make a diode w/ metal contact!

Why else do we care? Sometimes we DON'T WANT a diode contact!

- Schottky Barriers (Diodes)… metal/semiconductor



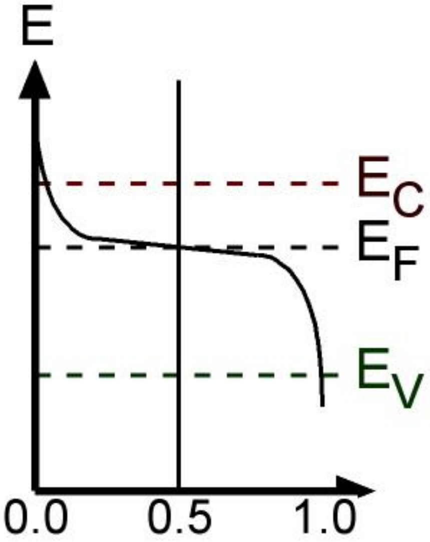
- Metal Work Function ($q\phi_m$) is the minimum energy (usually measured in electron volts) needed to remove an electron from the Fermi level in a metal to a point at infinite distance away outside the surface (vacuum level)… Al (4.3 eV), Au(4.8 eV).

- Semiconductor Work Function ($q\phi_s$) … vacuum level to Fermi level in a semiconductor.

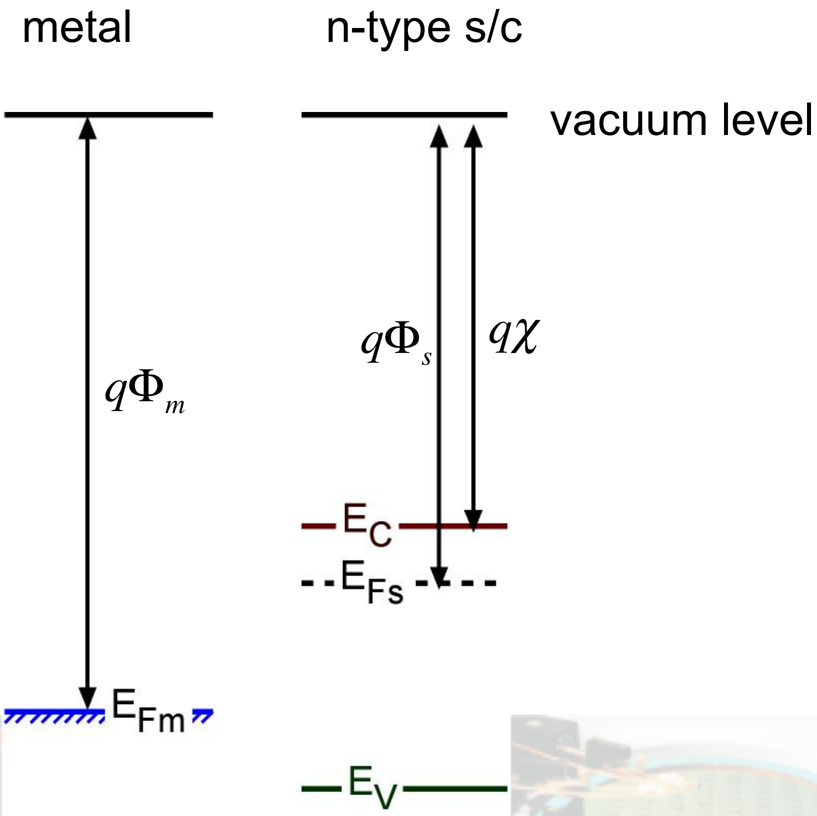
- Electron Affinity ($q\chi$) … vacuum level to conduction band in a semiconductor.

- Fermi level at zero K in semiconductor is the midpoint between empty and filled electron states for Fermions (electrons).

For a metal, Fermi level is similar but there is no band-gap!

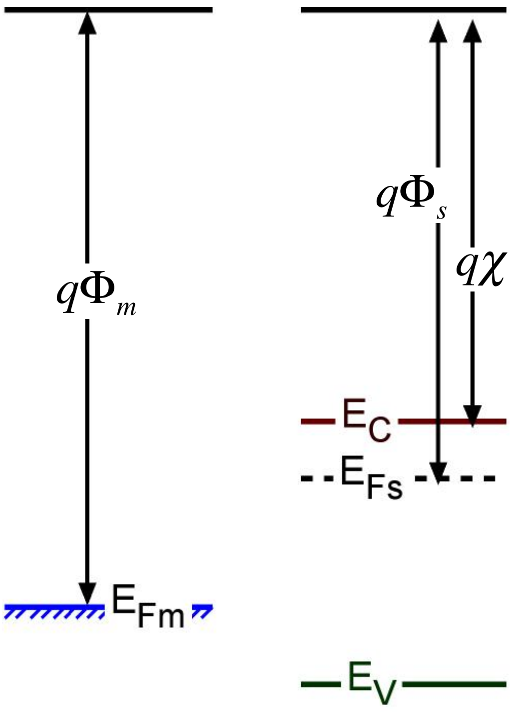


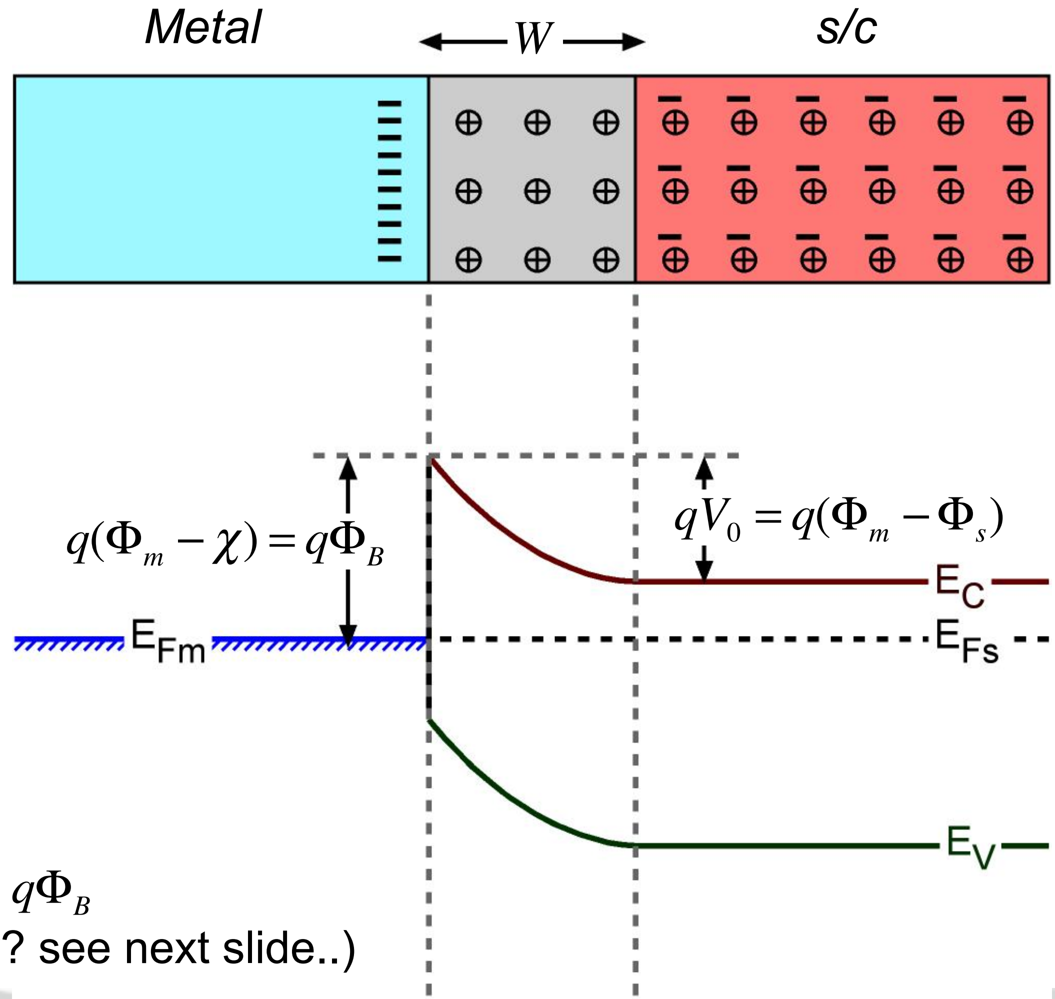
- Metal and n-type semiconductor…
- Note for metal, all electrons are basically at E_f (No bands…)
- To form a Schottky Barrier (diode) with n-type s/c: $\Phi_m > \Phi_s$
- What is the 1st thing that must happen in the diagram below?
- Metal is like n++++++++…., so what side will have all the depletion and band-bending?



Metal/Semicon. Junctions

- Remember, metal has a such a high density of electrons that it acts like n++ (so no band bending).

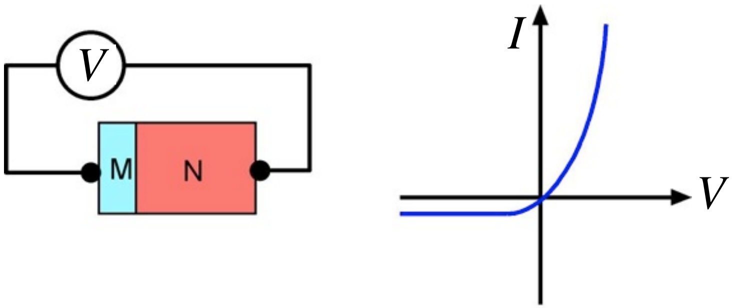


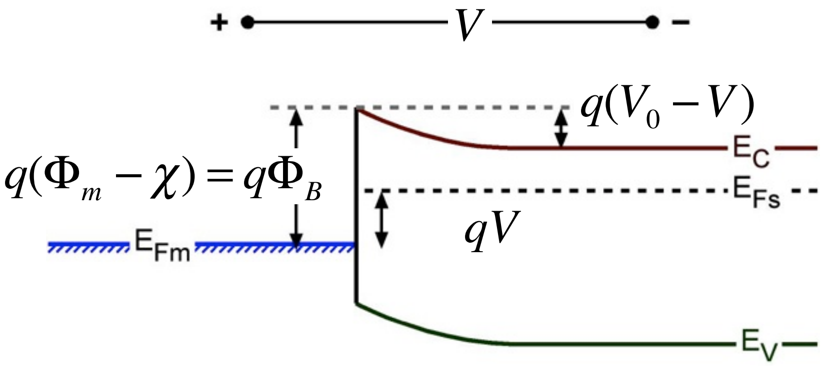


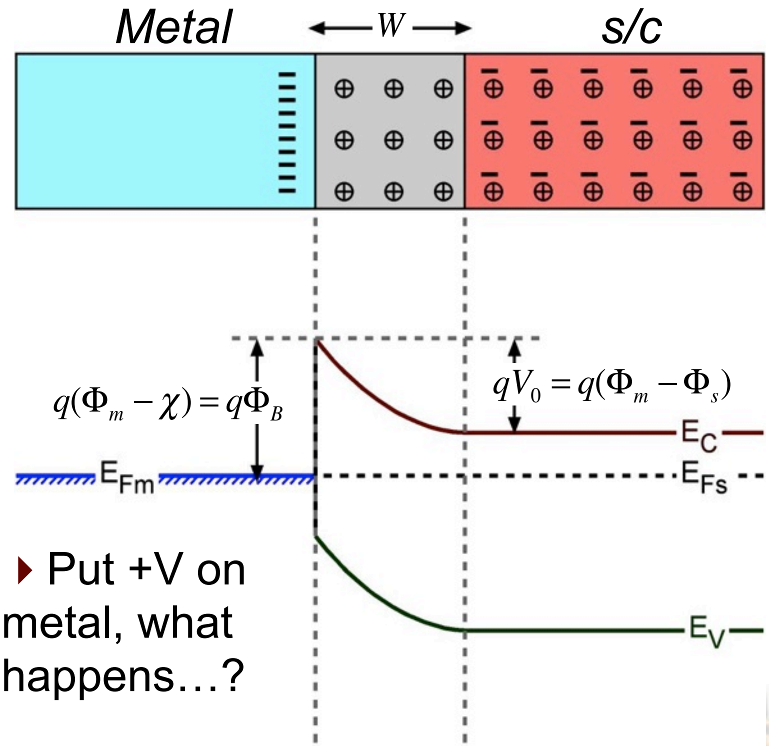
- Contact potential: qV_0
- Barrier height potential to e inject: $q\Phi_B$
- RECTIFICATION (based on e only? see next slide..)

…note semiconductor side looks just like 1/2 of a PN junction

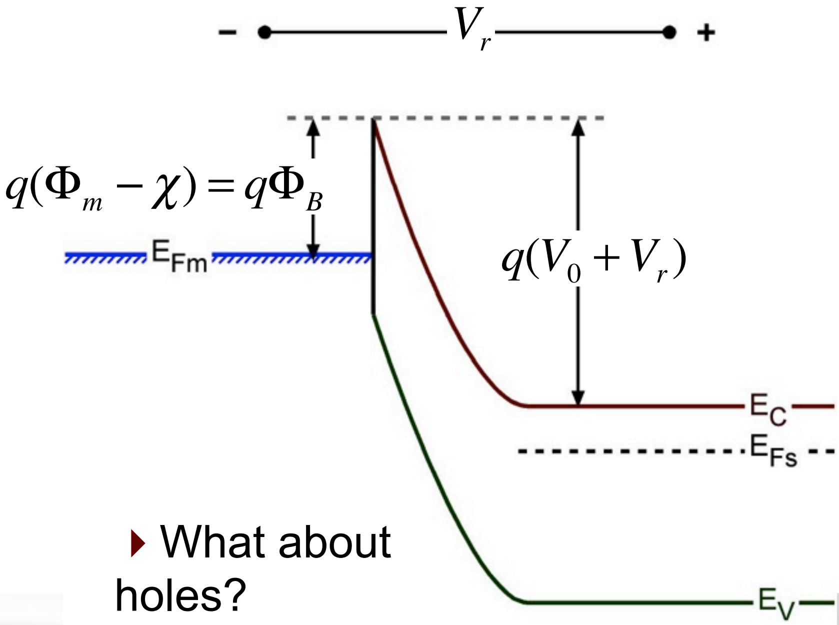
- N-type Schottky Diode with $\Phi_m > \Phi_s$





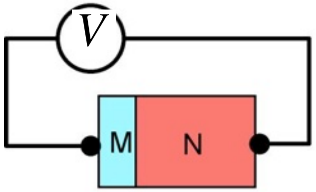


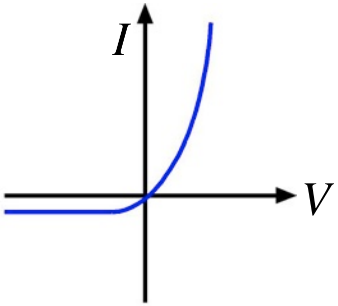
- Put +V on metal, what happens…?



- What about holes?

- Summary for
  N-type Schottky Diode with $\Phi_m > \Phi_s$

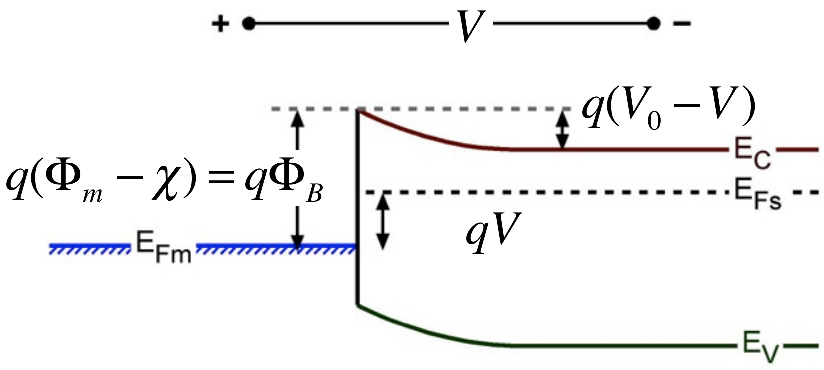


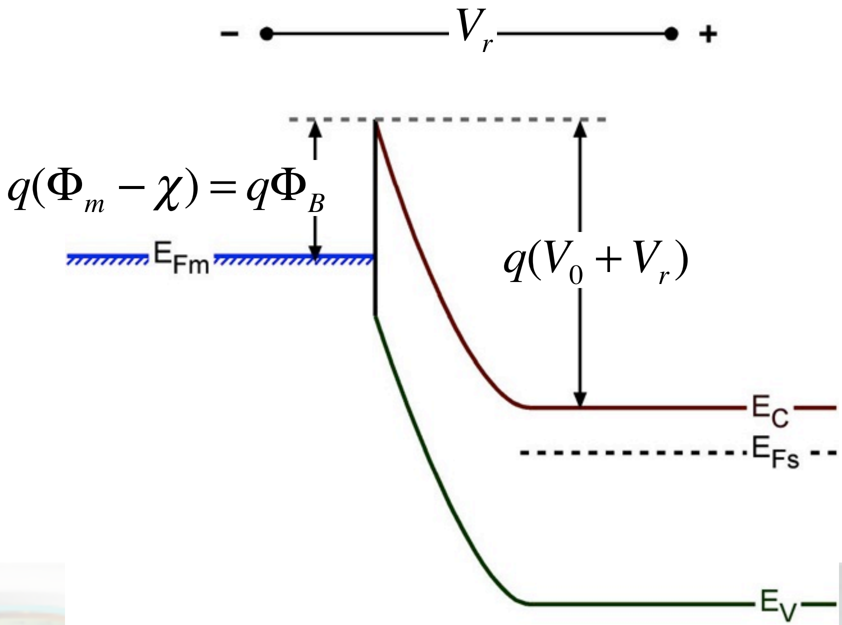


- Forward bias
  e diffusion into metal… and h drift current (but is way smaller)

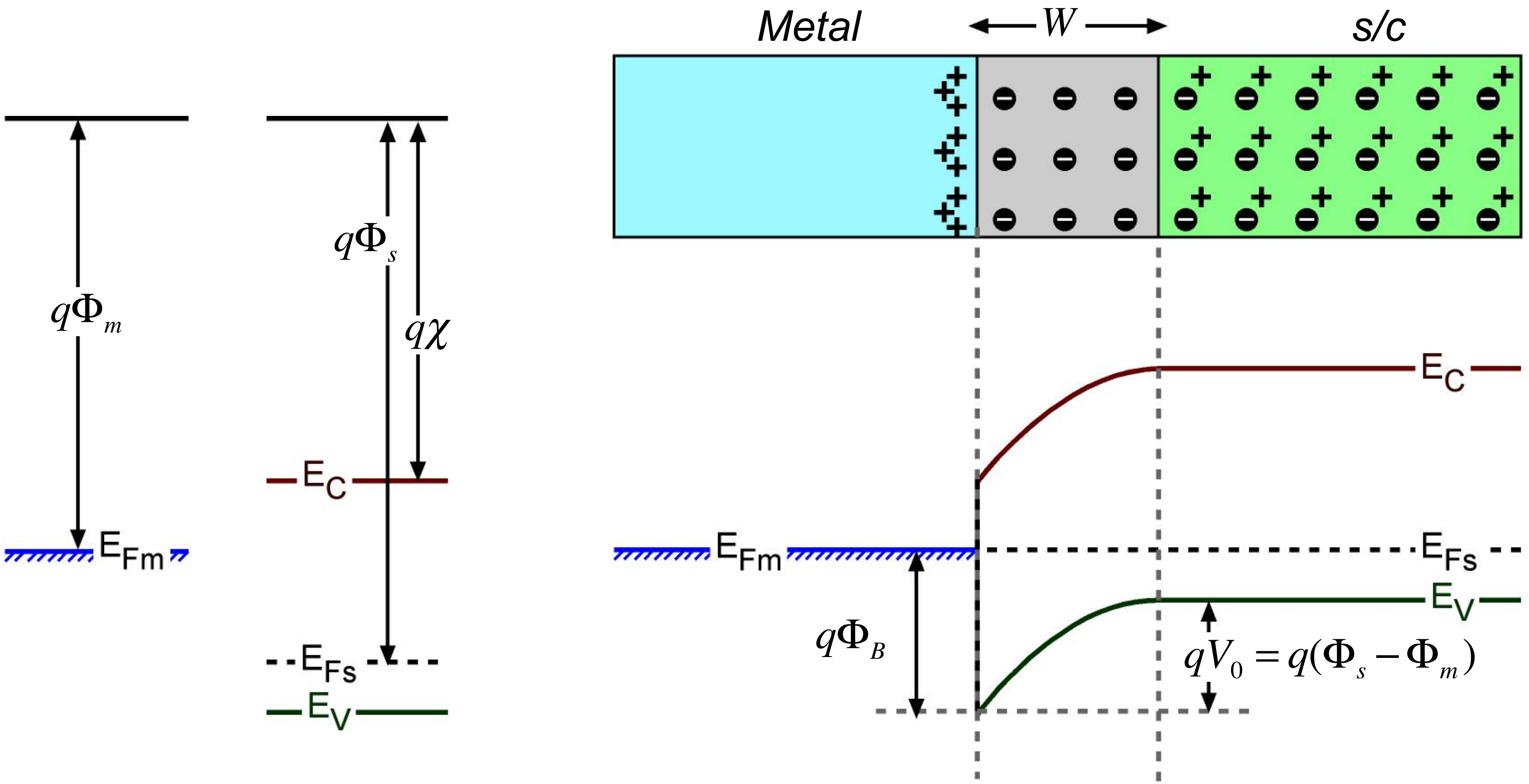
- Reverse bias
  drift current and,
  chance of e surmounting barrier height given by a Boltzman factor:

$$I_0 \propto e^{-q\Phi_B/kT}$$



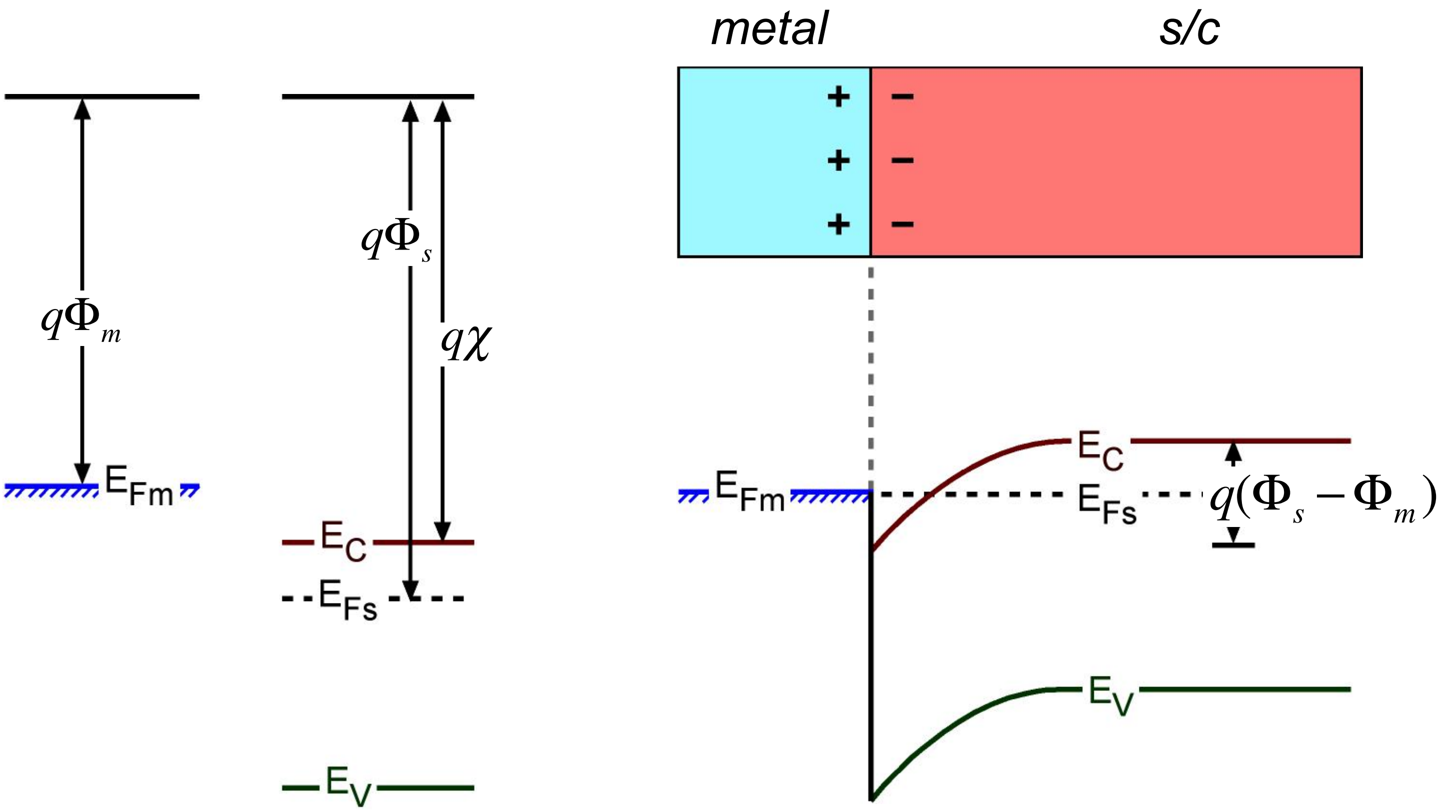


- Also valid for p-type semiconductors ($\Phi_m < \Phi_s$,block hole injection).



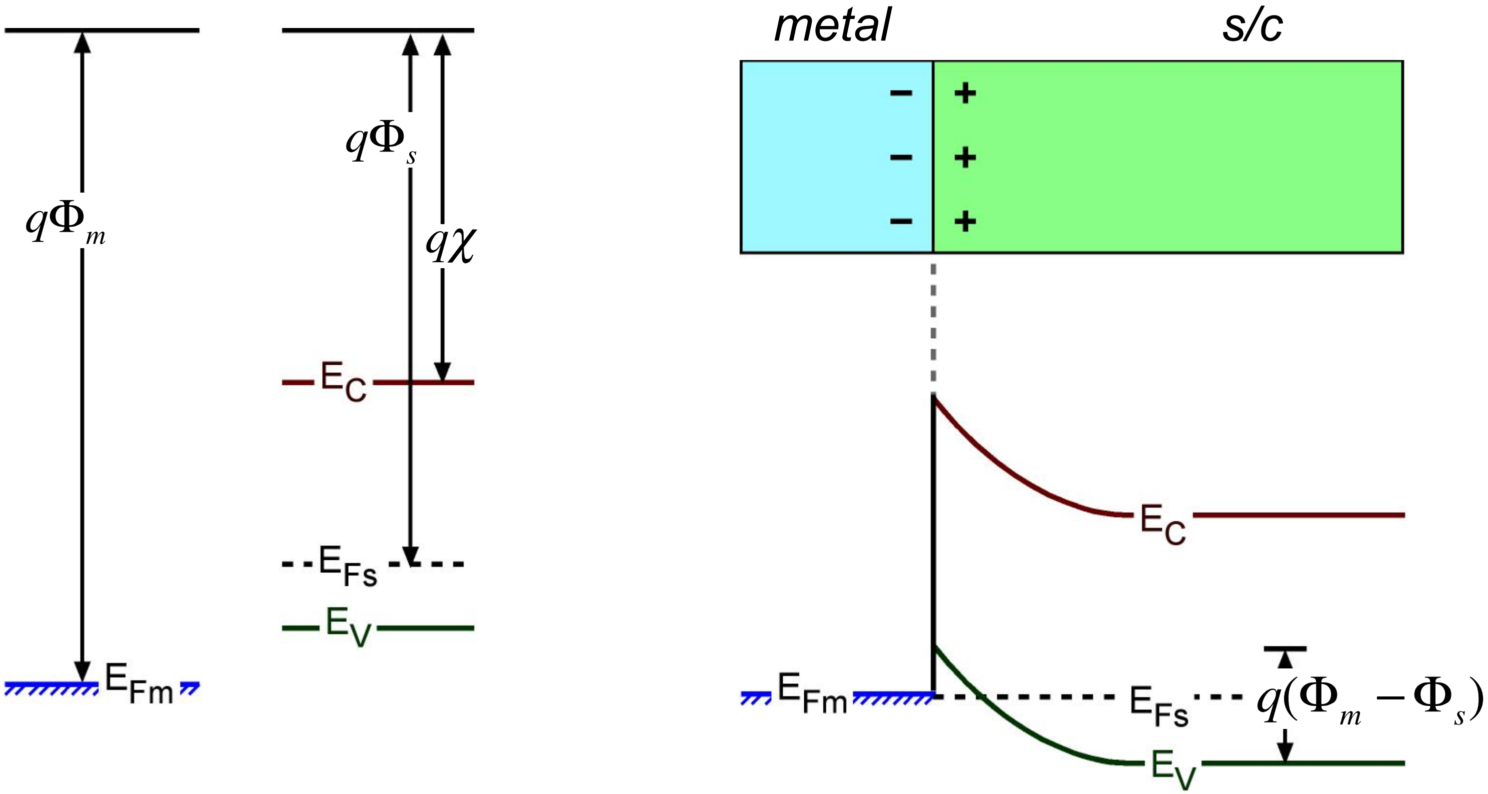
- Barrier height potential to h inject: $q\Phi_B$
- Contact potential: qV_0
- RECTIFICATION (based on h only)

- What if n-type and $\Phi_s > \Phi_m$

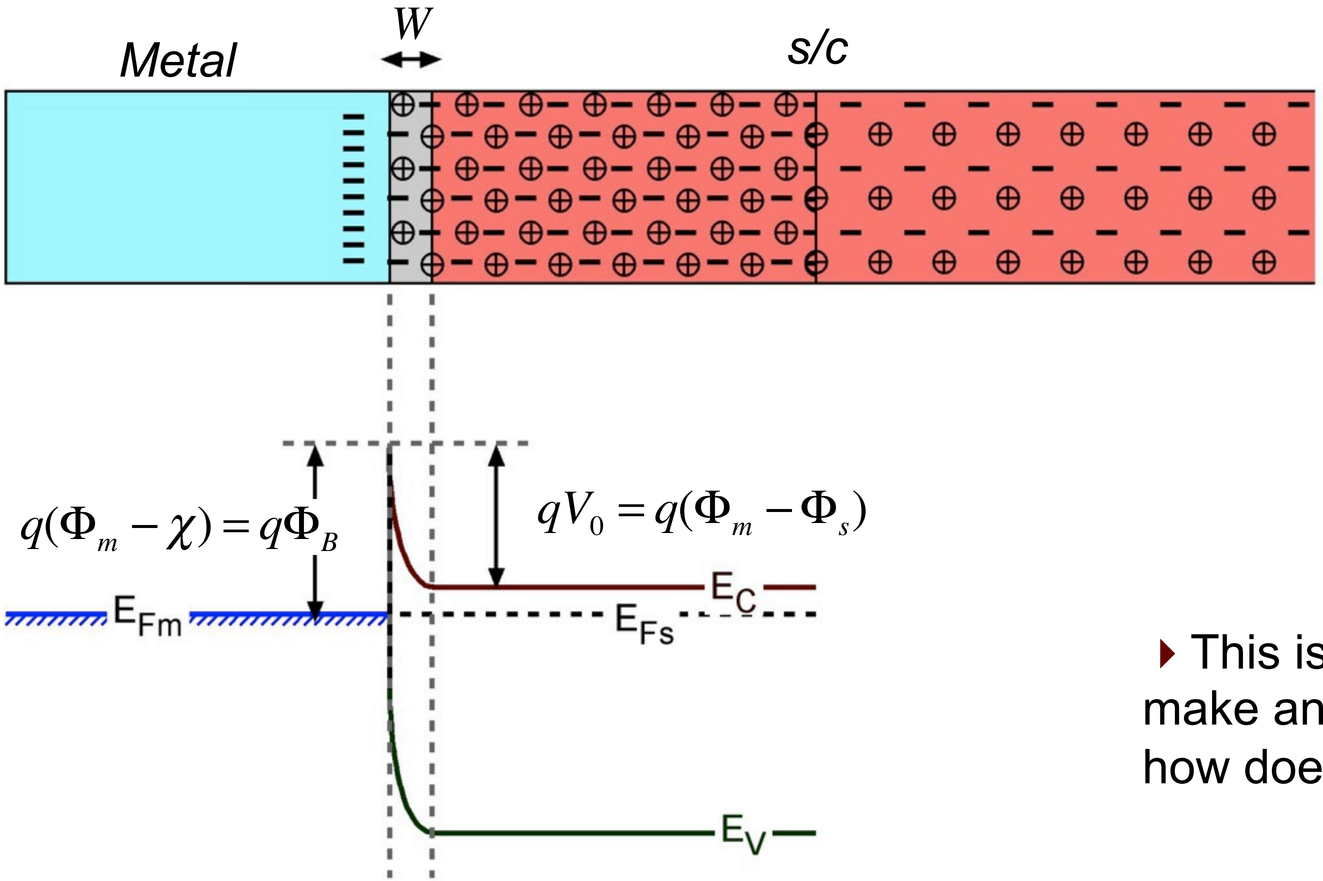


- Typically heavily dope s/c near contact to eliminate accumulation…
- *What will IV plot look like (assuming some series resistance)?*

- What if p-type and $\Phi_m > \Phi_s$



- Ohmic contacts are essential! In ALL our previous junctions we assumed we could easily connect electrodes to our diodes!



- This is another way to make an ohmic contact, how does it work?

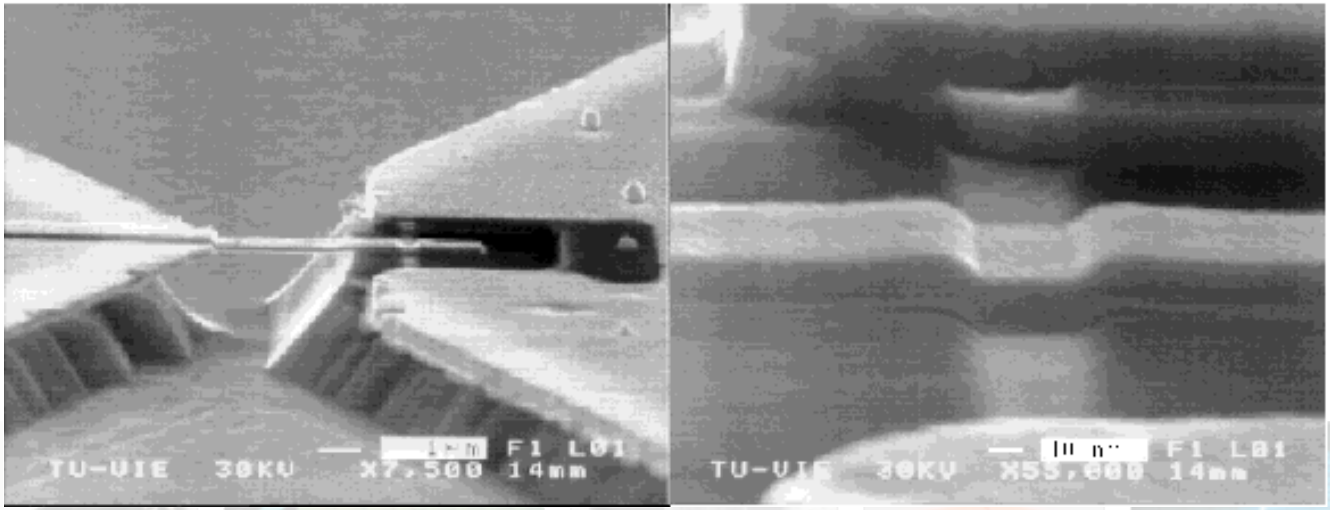
Advanced Stuff…

- Some example material systems and their barrier heights…

	Ag	Al	Au	Cr	Ni	Pt	W
Φ_M (in vacuum)	4.3	4.25	4.8	4.5	4.5	5.3	4.6
n-Ge	0.54	0.48	0.59		0.49		0.48
p-Ge	0.5		0.3				
n-Si	0.78	0.72	0.8	0.61	0.61	0.9	0.67
p-Si	0.54	0.58	0.34	0.5	0.51		0.45
n-GaAs	0.88	0.8	0.9			0.84	0.8
p-GaAs	0.63		0.42				

http://ece-www.colorado.edu/~bart/

- THz Schottky Diodes… (why the strange and complex design?)

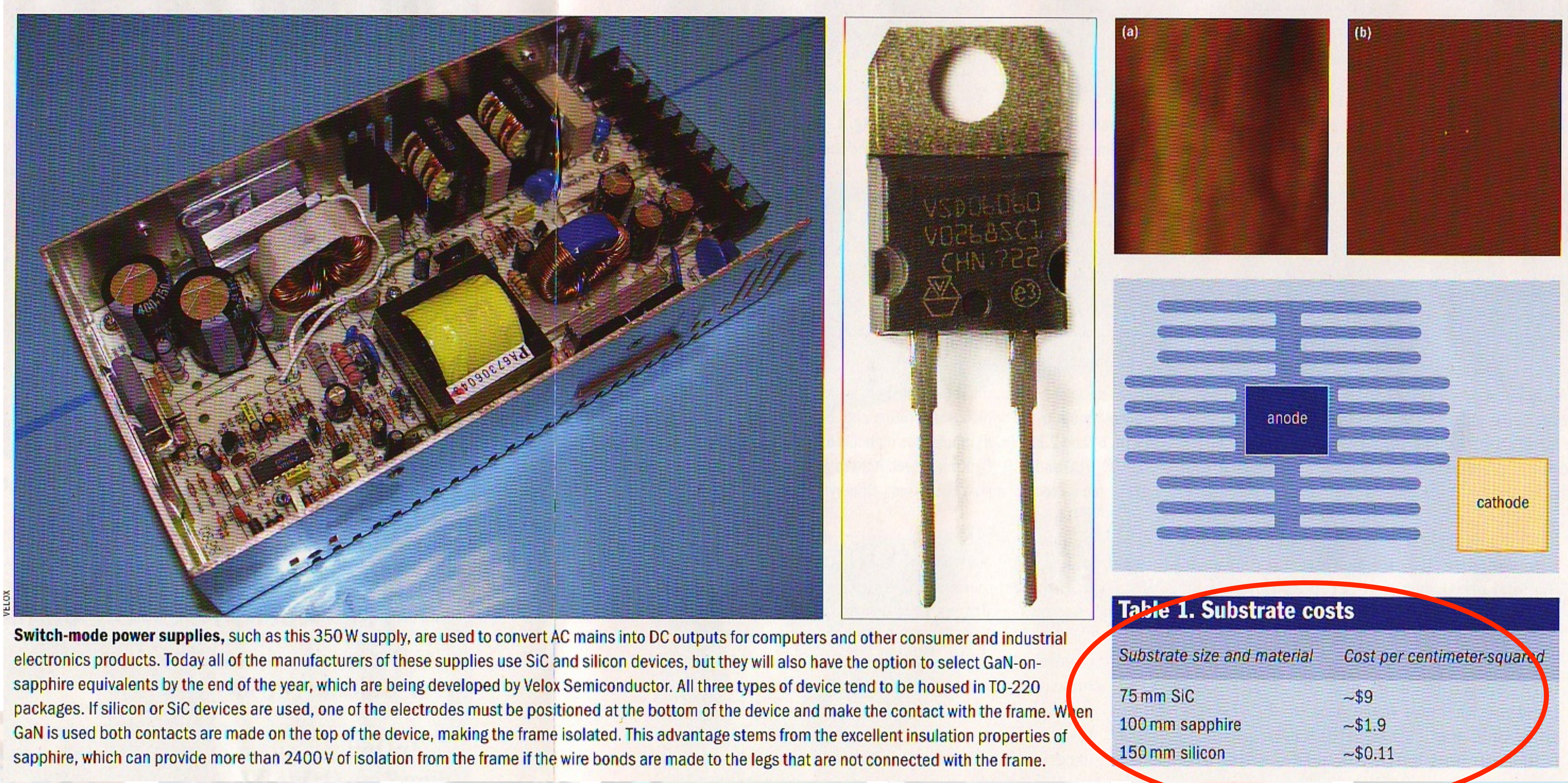


Submicron Schottky diodes for THz applications, E.Zotl, M.Hauser Institut für Festkörperelektronik

Advanced Stuff…

- More on GaN developments… (see top image of electrodes, why the geometries?)

“GaN Schottky barrier diodes threaten to overturn SiC” *Murphy et al., Cmp. Semicond. Vol. 14, No. 3, Pg. 18,, April 2008.,*



Switch-mode power supplies, such as this 350 W supply, are used to convert AC mains into DC outputs for computers and other consumer and industrial electronics products. Today all of the manufacturers of these supplies use SiC and silicon devices, but they will also have the option to select GaN-on-sapphire equivalents by the end of the year, which are being developed by Velox Semiconductor. All three types of device tend to be housed in TO-220 packages. If silicon or SiC devices are used, one of the electrodes must be positioned at the bottom of the device and make the contact with the frame. When GaN is used both contacts are made on the top of the device, making the frame isolated. This advantage stems from the excellent insulation properties of sapphire, which can provide more than 2400 V of isolation from the frame if the wire bonds are made to the legs that are not connected with the frame.

Table 1. Substrate costs

Substrate size and material	*Cost per centimeter-squared*
75 mm SiC	~$9
100 mm sapphire	~$1.9
150 mm silicon	~$0.11

Advanced Stuff…

- Heterojunctions…

joining two different semiconductors!

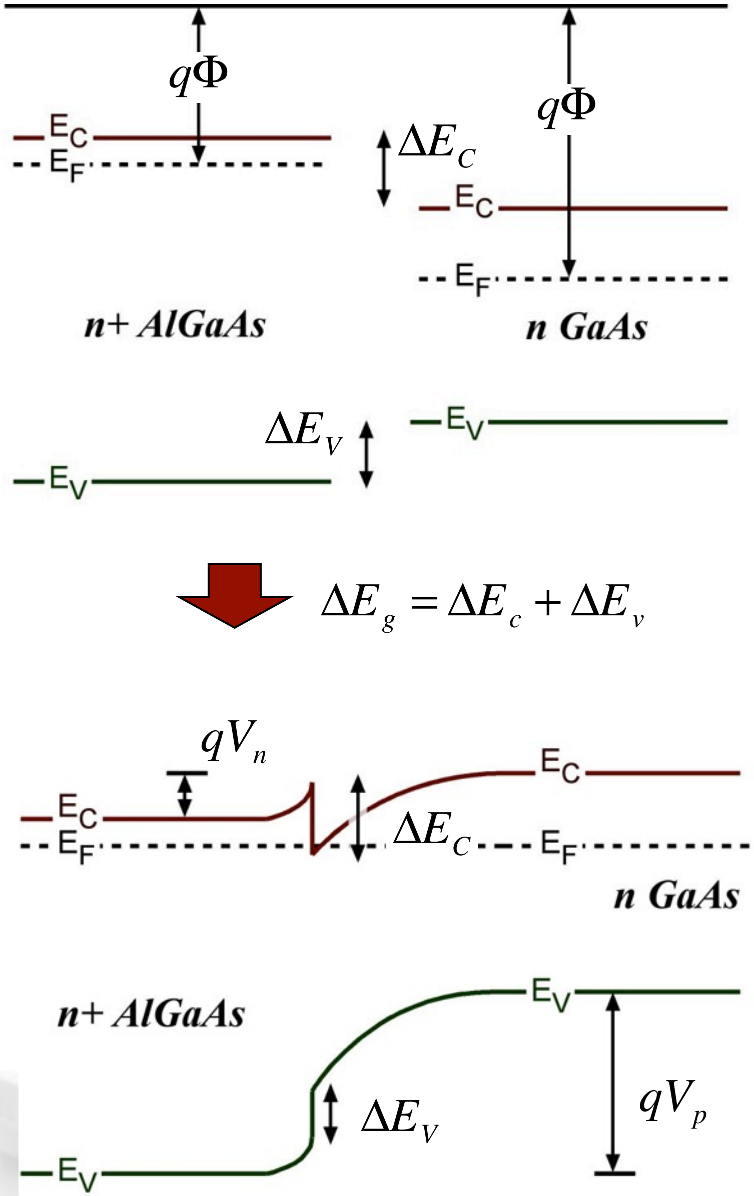
More relevant to CH6 (HEMT) and CH8 (LEDs, Lasers), but introduce here as is good review for metal-semiconductor junctions too (same approach):

(1) Align Fermi levels (always!)

(2) Maintain ΔE_C and ΔE_V at the semiconductor junction

(3) Connect E_c/E_v keeping E_g constant as bend bands,

(4) Consider doping effects to distribute the amount of band-bending due to $\Delta\Phi$



$$\Delta E_g = \Delta E_c + \Delta E_v$$

Review!

- What are the two general types of metal semiconductor contacts (that we care about)?

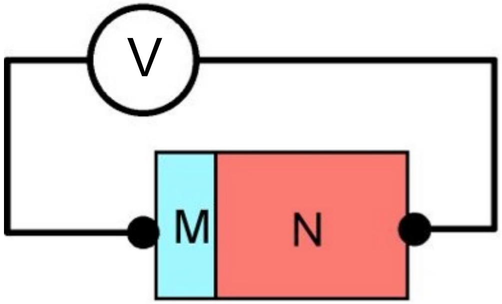
- When making a contact to device like a diode or MOSFET or BJT, what type of metal/semicon. contact do you want?

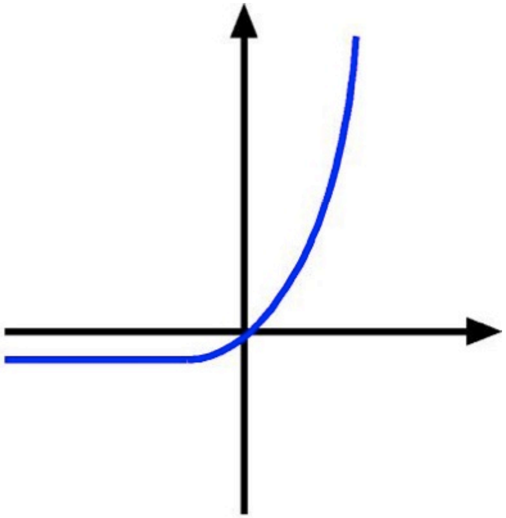
- When making high voltage rectifiers, why are metal/semicon. diodes preferred?

- If you are stuck with Si and have to make a bunch of different types of metal/semicon. for many different purposes, what is the one parameter for the metal that you will need to know?

- For a Shottky diode what type of currents cause current flow in forward bias? In reverse bias?

- Operate different or basically the same as PN junctions?





5.5b - Capacitance

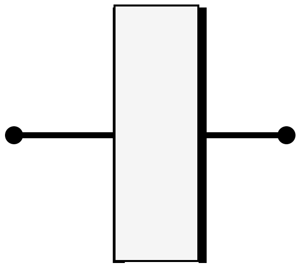
- 1st Topic, 5.5b Diode Capacitance…

(1) Why might we care?

(2) Even if not a diode, if I have any blackbox device that gives me a dQ for a dV… does it have capacitance?

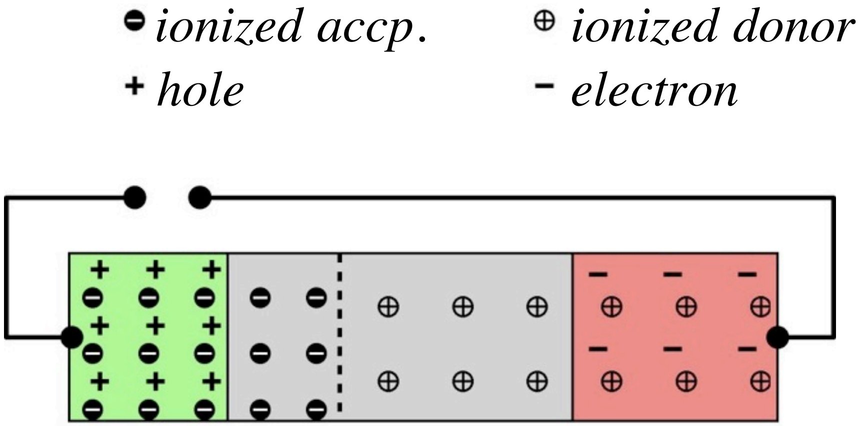
$$C = \frac{Q}{V} = \boxed{\left|\frac{dQ}{dV}\right|} = \boxed{\frac{\varepsilon_0 \varepsilon_r A}{d}}$$

C_S C_J



- C_{diode}=C_S+C_J
- C_s = storage cap. (talk more later)
- C_J = depletion ('junction') cap. (talk now)

- *where is the 'dielectric'*
- *how change w/ V?*



- Lets derive depletion cap., remember these…?

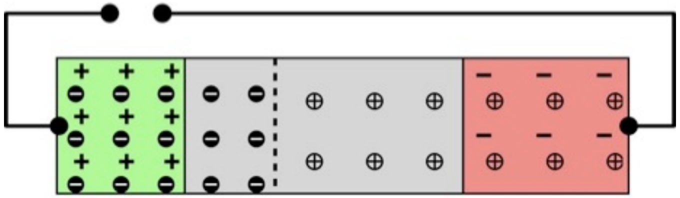
$$|Q| = qAx_{n0}N_d = qAx_{p0}N_a$$

$$x_{n0} = \frac{N_a}{N_a + N_d}W \quad x_{p0} = \frac{N_d}{N_a + N_d}W$$

$$W = \left[\frac{2\varepsilon(V_0)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

Depletion Capacitance

- Under steady state bias for V_{app} + or -



$$W = \left[\frac{2\varepsilon\left(V_0 - V_{app}\right)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

- We can also show for *either* side:

$$x_{n0} = \frac{N_a}{N_a + N_d} W \qquad x_{p0} = \frac{N_d}{N_a + N_d} W$$

$$|Q| = qAx_{n0}N_d = qAx_{p0}N_a$$

$$|Q| = qA\frac{N_a N_d}{N_a + N_d} W \Rightarrow |Q| = A\left[2q\varepsilon(V_o - V_{app})\frac{N_a N_d}{N_a + N_d}\right]^{1/2}$$

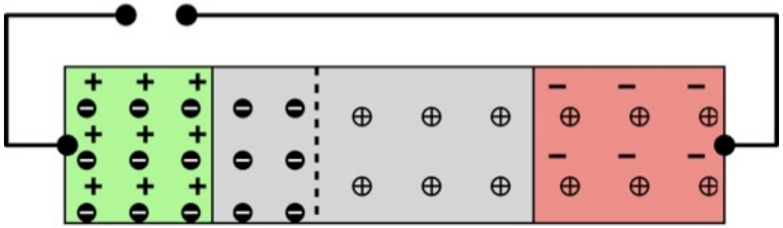
$$(1/x)^{1/2} = (x)^{-1/2}$$

$$(x)\times(x)^{-1/2} = (x)^{1/2}$$

Depletion Capacitance

- Recall C=Q/V or C=|dQ/dV|, we can use the latter

because we know C_J changes with voltage



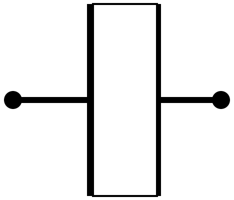
$$|Q| = A\left[2q\varepsilon(V_o - V_{app})\frac{N_aN_d}{N_a+N_d}\right]^{1/2}$$

$$C_J = \left|\frac{dQ}{dV}\right| = A\left[2q\varepsilon\frac{N_aN_d}{N_a+N_d}\right]^{1/2}\frac{(V_o - V_{app})^{-1/2}}{2}$$

$$C_J = \frac{A}{2}\left[2q\varepsilon\frac{1}{(V_o - V_{app})}\frac{N_aN_d}{N_a+N_d}\right]^{1/2}$$

$$C_J = \varepsilon A\left[\frac{q}{2\varepsilon(V_o - V_{app})}\frac{N_aN_d}{N_a+N_d}\right]^{1/2}$$

$$W = \left[\frac{2\varepsilon\left(V_0 - V_{app}\right)}{q}\left(\frac{N_a+N_d}{N_aN_d}\right)\right]^{1/2}$$



$$C_J = \frac{\varepsilon A}{W} = \frac{\varepsilon_0\varepsilon_{Si}A}{W}$$

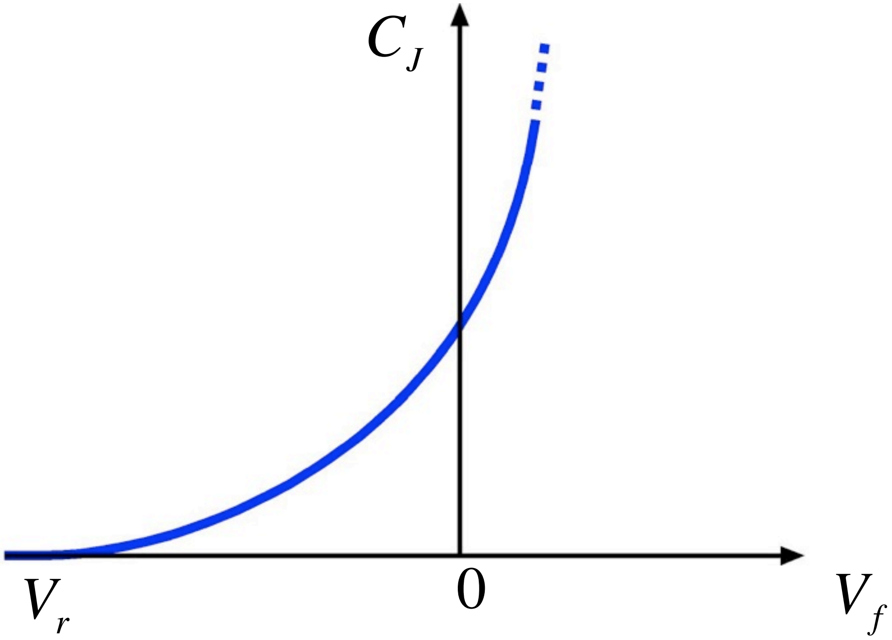
Just like parallel plate cap!

$$C = \frac{\varepsilon_0\varepsilon_r A}{d}$$

- Want an example W?

Ex 5-2, for Na=10^{18}, and Nd=$5\text{x}10^{15}$, ***W= 0.5 µm.***

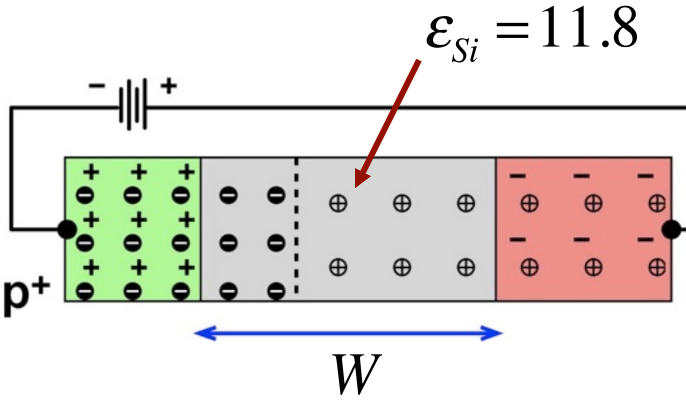
Depletion Capacitance



Hey! We can use C_J to measure Nd for a p+n or metal-n diode!

Some diodes are designed for strong capacitance changes: ‘Varactor’ diodes!

Tunable impedance!
Z=R+1/wC
R= resistance
1/wC=reactance



- Example for p^+n

$$N_a >> N_d$$

$$W \sim x_{n0}$$

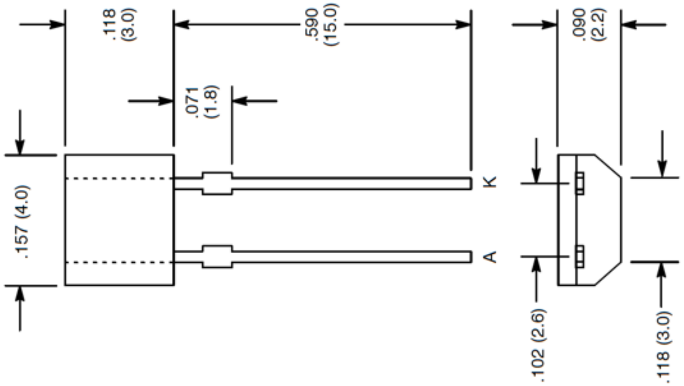
$$\Rightarrow \quad C_J = \varepsilon A\left[\frac{q}{2\varepsilon(V_o - V_{app})}\,\frac{N_aN_d}{N_a + N_d}\right]^{1/2}$$

$$\Rightarrow \quad C_J \approx \varepsilon A\left[\frac{q}{2\varepsilon(V_o - V_{app})}N_d\right]^{1/2}$$

- If V_{app} gets close to V_0, W gets very small and C becomes large!

Varactor Diode

ELECTRONICS, INC.
44 FARRAND STREET
BLOOMFIELD, NJ 07003
(973) 748–5089
http://www.nteinc.com



Electrical Characteristics: (T_A = +25°C unless otherwise specified)

Parameter	Symbol	Test Conditions	Min	Typ	Max	Unit
Breakdown Voltage	$V_{(BR)R}$	$I_R = 10\mu A$	16	–	–	V
Reverse Current	I_R	$V_R = 9V$	–	–	100	nA
Interterminal Capacitance	$C_{1.2V}$	$V_R = 1.2V$, f = 1MHz	420.0	–	459.1	pF
	$C_{3.5V}$	$V_R = 3.5V$, f = 1MHz	144.2	–	192.1	pF
	$C_{6.0V}$	$V_R = 6.0V$, f = 1MHz	45.71	–	60.91	pF
	$C_{8.0V}$	$V_R = 8.0V$, f = 1MHz	20.30	–	23.54	pF
Figure of Merit	Q	$V_R = 1V$, f = 1MHz	200	–	–	
Capacitance Ratio	C_R	$C_{1.2V}/C_{8.0V}$, f = 1MHz	15.5	–	–	
matching Tolerance	ΔC_m	$(C_{max} - C_{min})/C_{min}$	–	–	0.03	

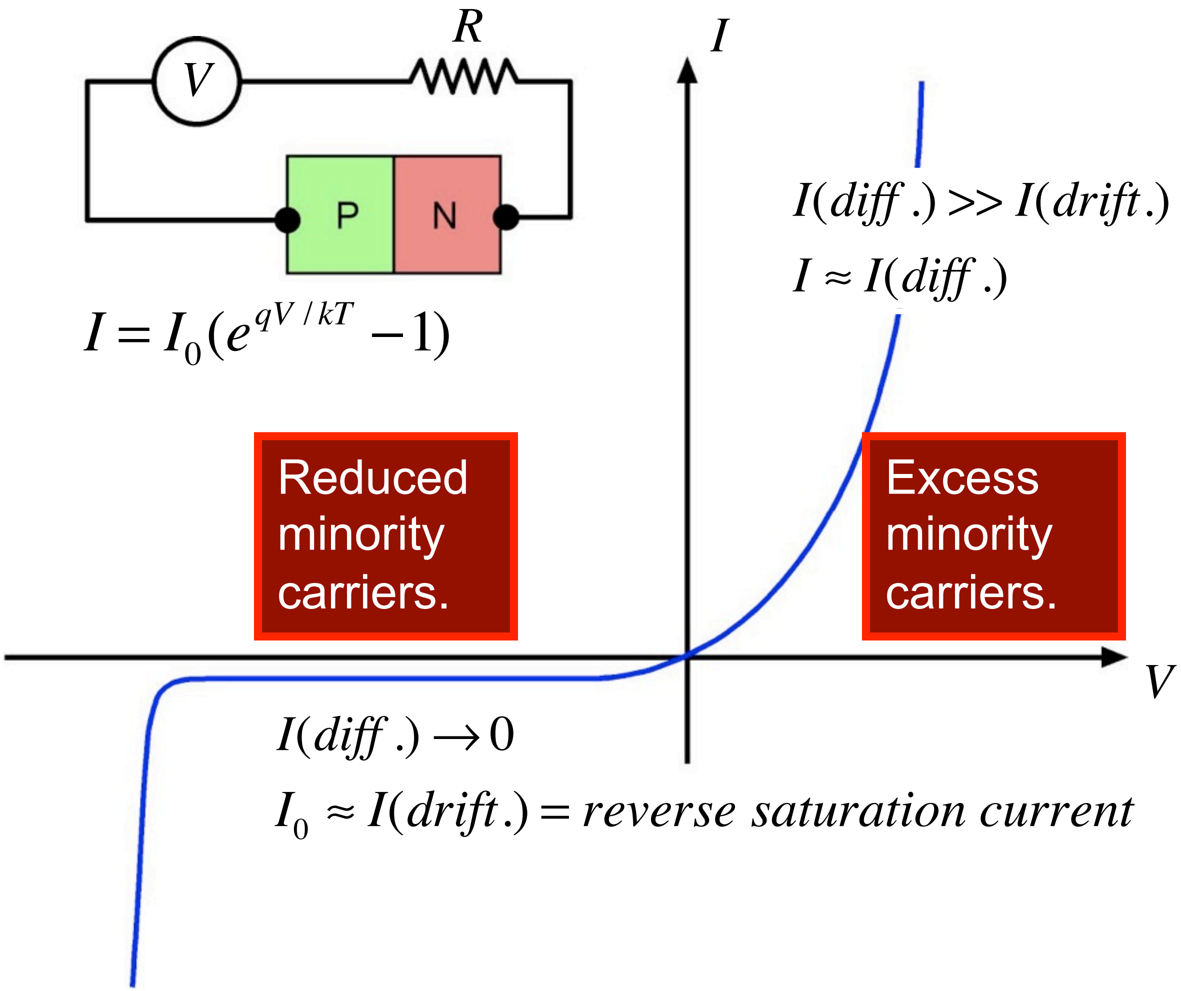
Storage Capacitance (C_S)

$$C = \frac{Q}{V} = \underbrace{\boxed{\left|\frac{dQ}{dV}\right|}}_{C_S} = \underbrace{\boxed{\frac{\varepsilon_0\varepsilon_r A}{d}}}_{C_J}$$

- $C_{diode}=C_S+C_J$
- C_J = depletion (or junction) cap.
- C_s = storage (or diffusion) cap. (talk more now)

Any guesses to start?
- what is C_S in rev. bias?
- what is C_S in for. bias?
- how change in for. bias?

- Lets look at dQ/dV in detail first…



$$I = I_0(e^{qV/kT} - 1)$$

$$I(diff.) >> I(drift.)$$
$$I \approx I(diff.)$$

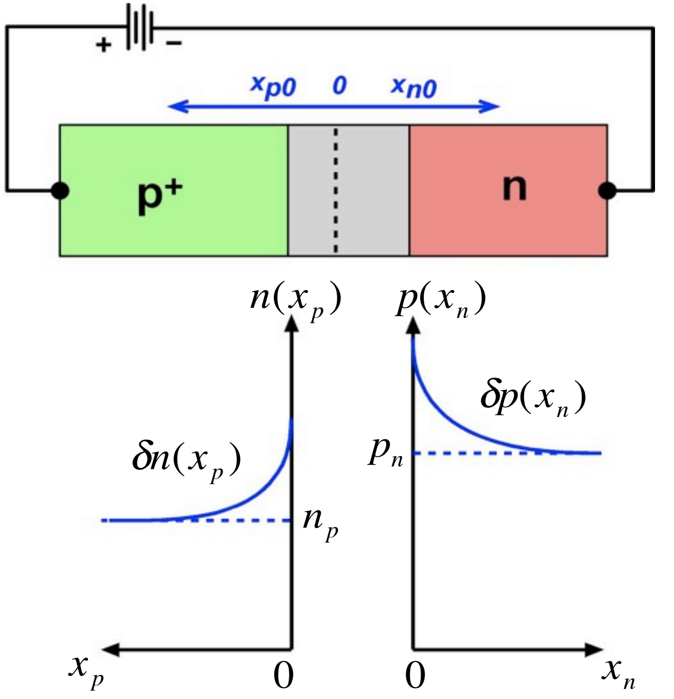
Reduced minority carriers.

Excess minority carriers.

$$I(diff.) \rightarrow 0$$
$$I_0 \approx I(drift.) = reverse\ saturation\ current$$

Storage Capacitance (C_S)

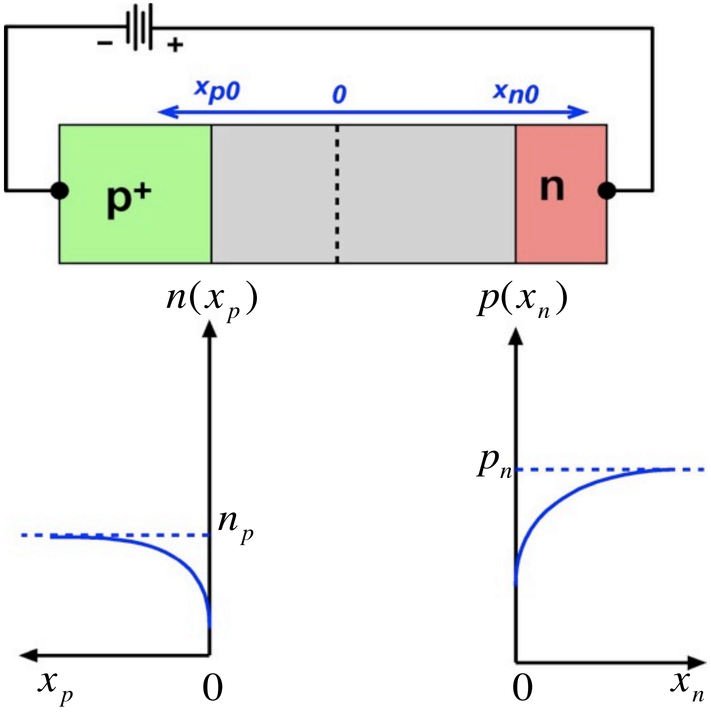
Excess minority carriers.



$$\delta n(x_p) = \Delta n_p e^{-x_p/L_n}$$

$$\delta n(x_p) = n_p(e^{qV/kT} - 1)\, e^{-x_p/L_n}$$

Reduced minority carriers.



$$\delta n(x_p) = \Delta n_p e^{-x_p/L_n}$$

$$\Delta n_p = n_p(e^{qV/kT} - 1) \cong -n_p$$

$$C = \frac{Q}{V} = \boxed{\left|\frac{dQ}{dV}\right|} = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

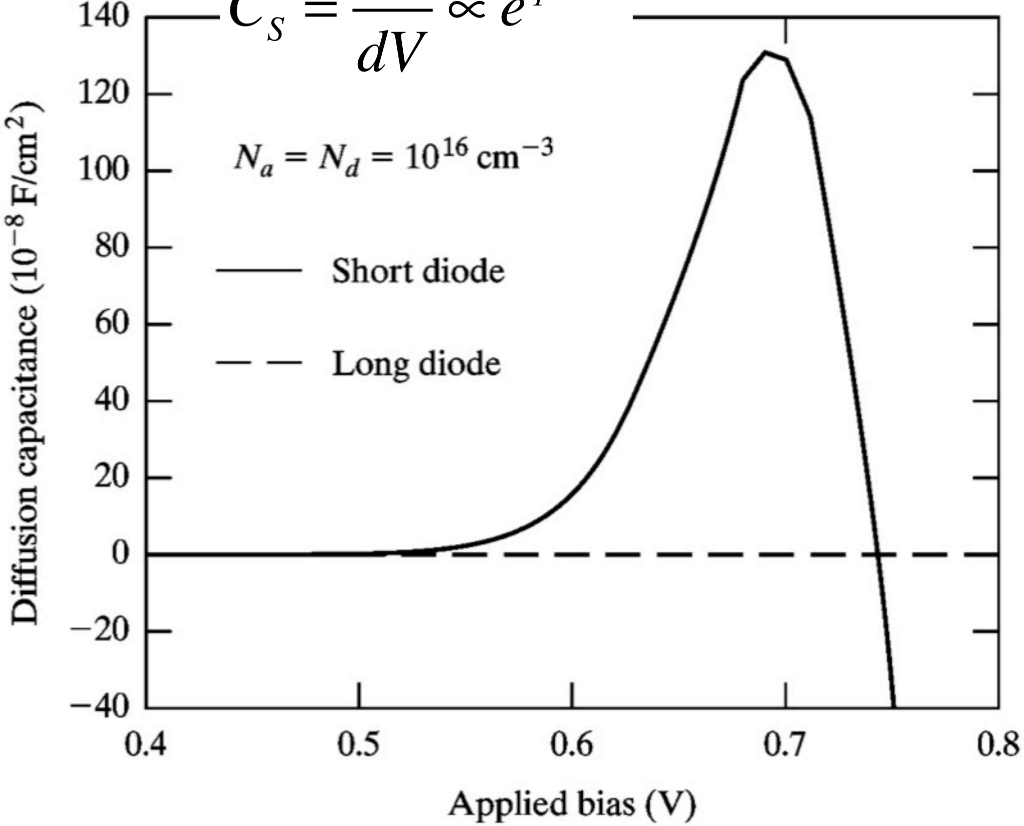
- This is called *storage capacitance (C_s)*
- *Does it change in reverse bias?*
- *Does it change in forward bias?*

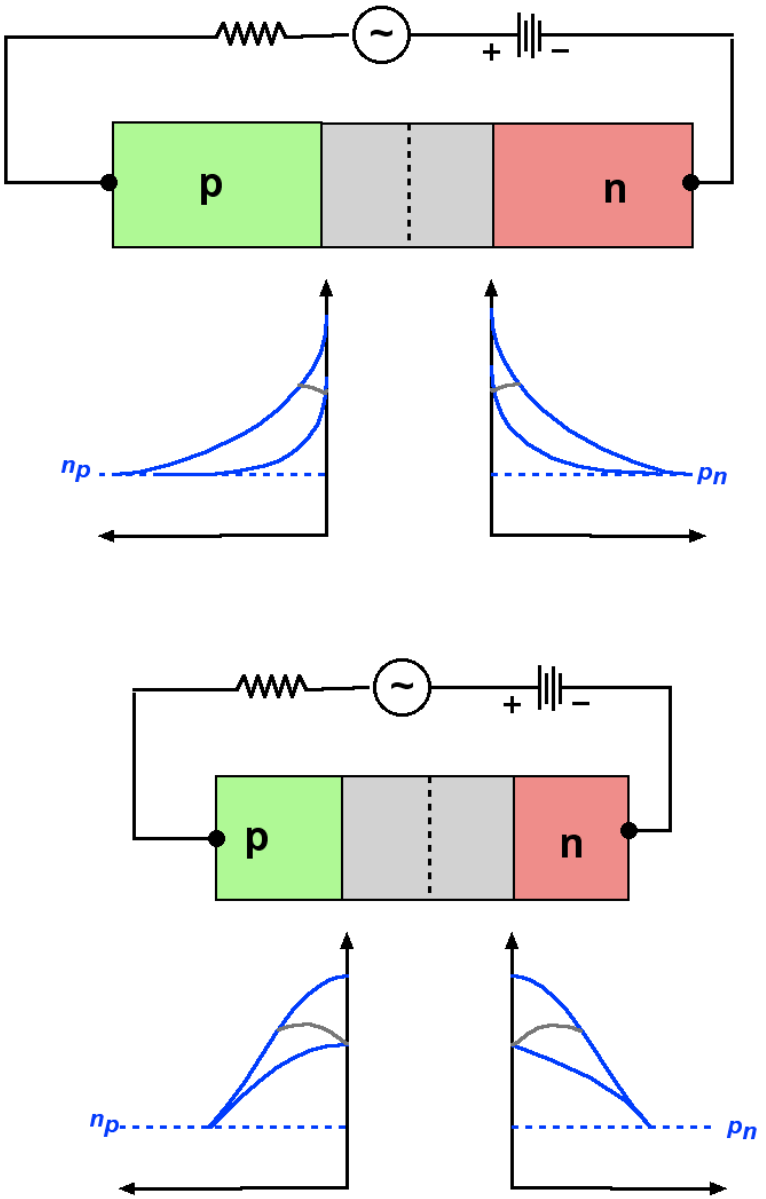
Storage Capacitance (C_S)

- However, calculating C_S is more complex (and beyond this undegrad class)… Depends on diode length! Most diodes are 'short' on at least one side and C_S will dominate in forward bias.

- Long diodes have no C_S. Lets leave it at that…

$$C_S = \frac{dQ}{dV} \propto e^{qV/kT}$$





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Thin Solid Films 498 (2006) 244 – 248

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Short-diode like diffusion capacitance of organic light emission devices

Mei-Na Tsai [a,b], T.C. Chang [a,e,*], Po-Tsun Liu [c], Chung-Wen Ko [d], Che-jen Chen [d], Kang-mien Lo [b]

As applied voltage was larger than the built-in voltage, the capacitance is augmented by diffusion capacitance with increasing the forward bias voltage. In contrast, the capacitance dropped quickly.

…. We infer that the phenomena were resulted from the extremely thin OLED structure, just like short p –n semiconductor diodes.

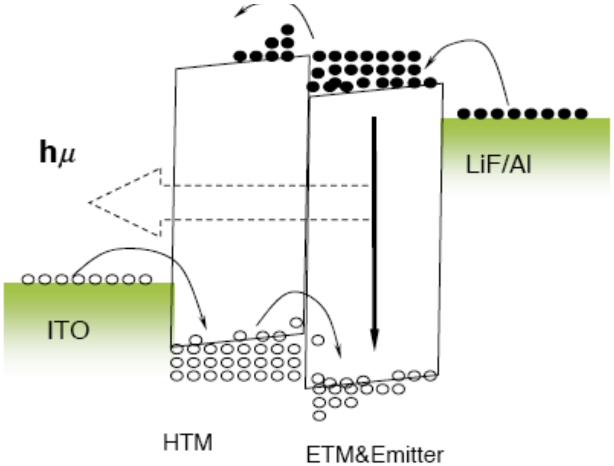
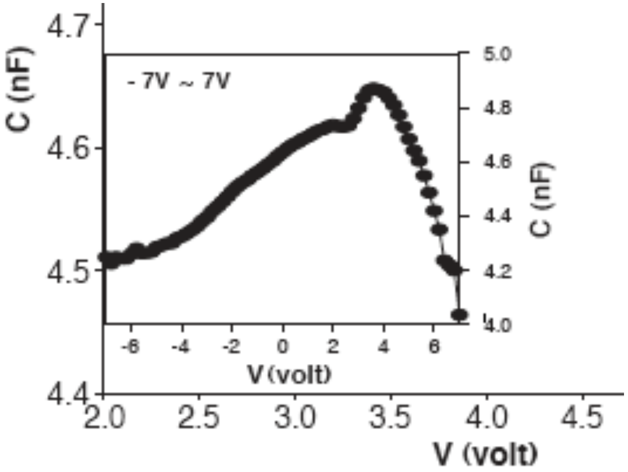
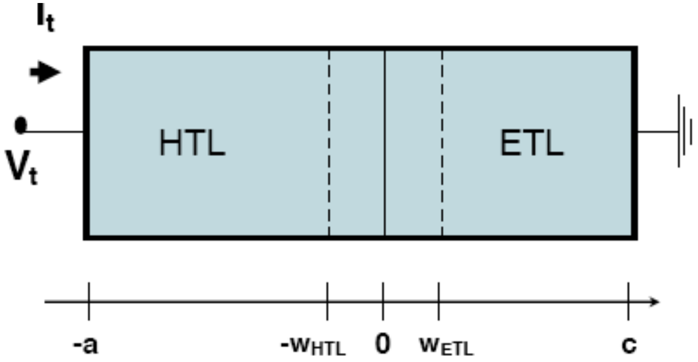


Fig. 4. Double-layer device, with holes injected from ITO, result in minority holes stored in EML layer, and minority electrons stored in HTL layer.



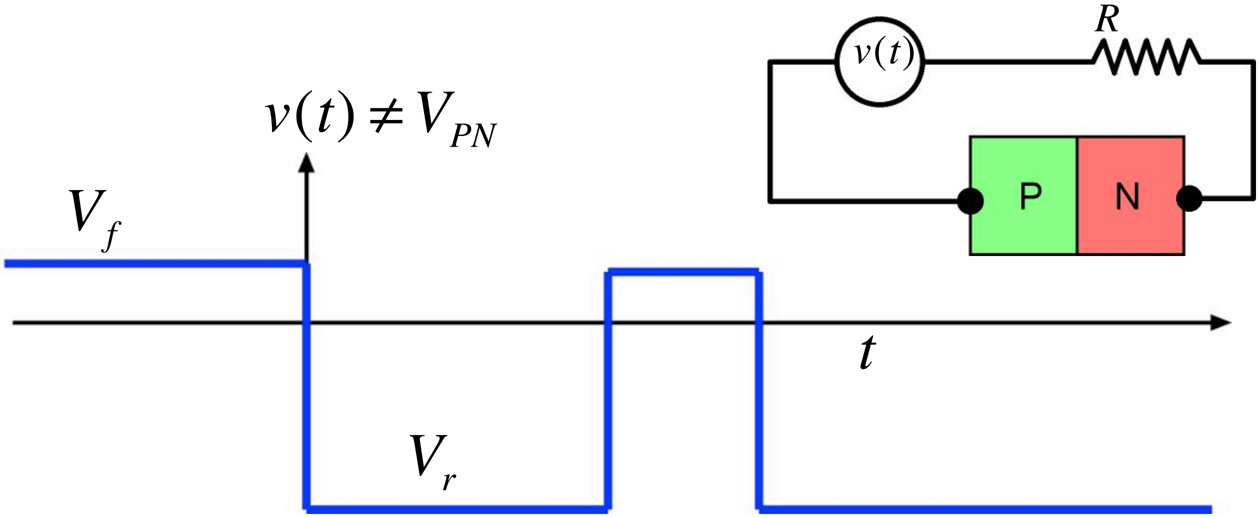


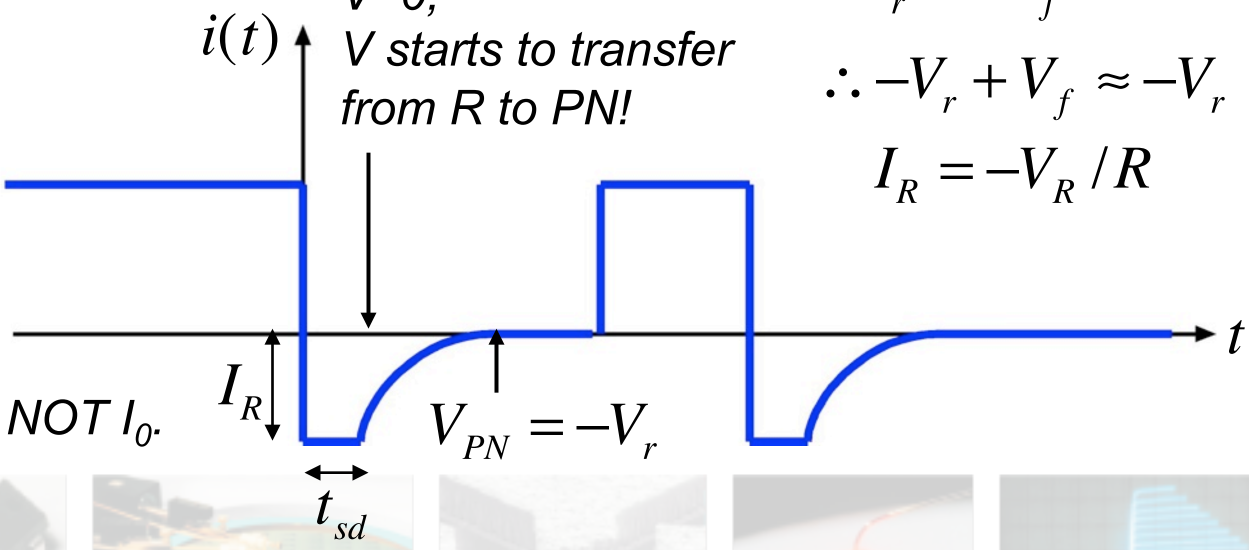
Last Topic! Forward to Reverse…

- That stored charge in forward bias, before you can get to reverse bias you need to bring in current to recombine with it! See the current spike effect at right!
- We won't explain in detail (see extra slides at end for details)…
- For p⁺n it can be shown:

$$t_{sd} \approx \tau_p \ln\left(1+\frac{I_f}{I_R}\right)$$

$$\approx 0.1\ to\ 10\ \mu s$$





V=0,
V starts to transfer from R to PN!

$$-V_r >> V_f$$

$$\therefore -V_r + V_f \approx -V_r$$

$$I_R = -V_R / R$$

I_R is NOT I_0.

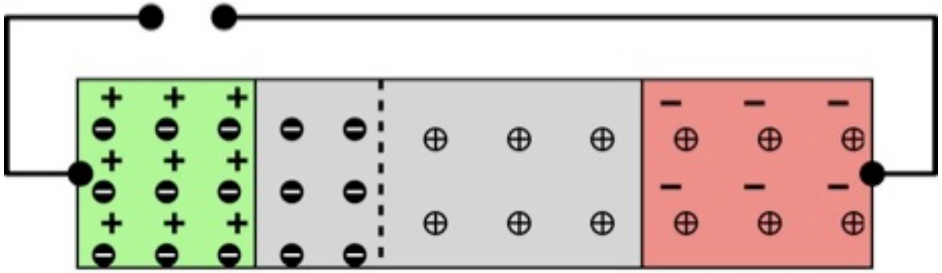
- I find some unmarked black box with two wires coming out of it, and when I place a DC voltage on it, it stores a charge… does it have a capacitance? How could we calculate it?

- I find a second unmarked black box with two wires coming out of it, and when I change voltage on it, I see a change in charge on it… does it have a capacitance? How could we calculate it?

- What dominates capacitance in a reverse biased diode?

- How does it change with increased reverse bias?

- What dominates capactiance for a forward biased diode?



$$C = \frac{Q}{V} = \left|\frac{dQ}{dV}\right| = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

Advanced Stuff…

- You now know enough to combine ANY two semiconductors, ANY metal / semiconductors, ANY doping levels, and draw an IV diagram with currents that are reverse saturated, tunnel currents, forward bias exponential, or ohmic!

- Interested in the latest semiconductor and device developments? Interested in empowering your career? Sign up for these free industry magazines and read them!

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- Efficiency droop analysed

Osram & Lumileds expand in Malaysia • Finisar to buy Ignis

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Last Topic! Forward to Reverse…

- Last topic: 5.5a Forward to Reverse Transient

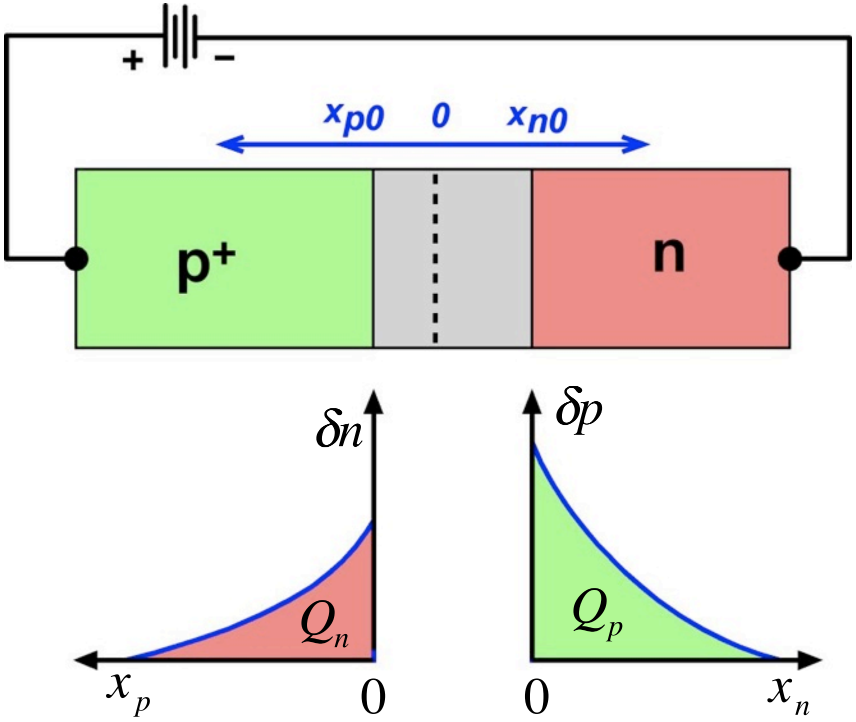
- In steady state forward bias we have excess minority carriers…

$$Q_p = q\,A\int_0^{\infty} \delta p(x_n)\,dx_n$$

$$Q_p = q\,A\,\Delta p_n\,L_p$$

- Forward biased, and we instantly turn off (V=0)… exponential decay in Q.

- ~µs to ~ns matters! (numerous delays in series in a GHz device).



$$\tau_n = \frac{1}{\alpha_r(n_p + p_p)} \approx \frac{1}{\alpha_r p_p}$$

$$\tau_p \approx \frac{1}{\alpha_r n_n}$$

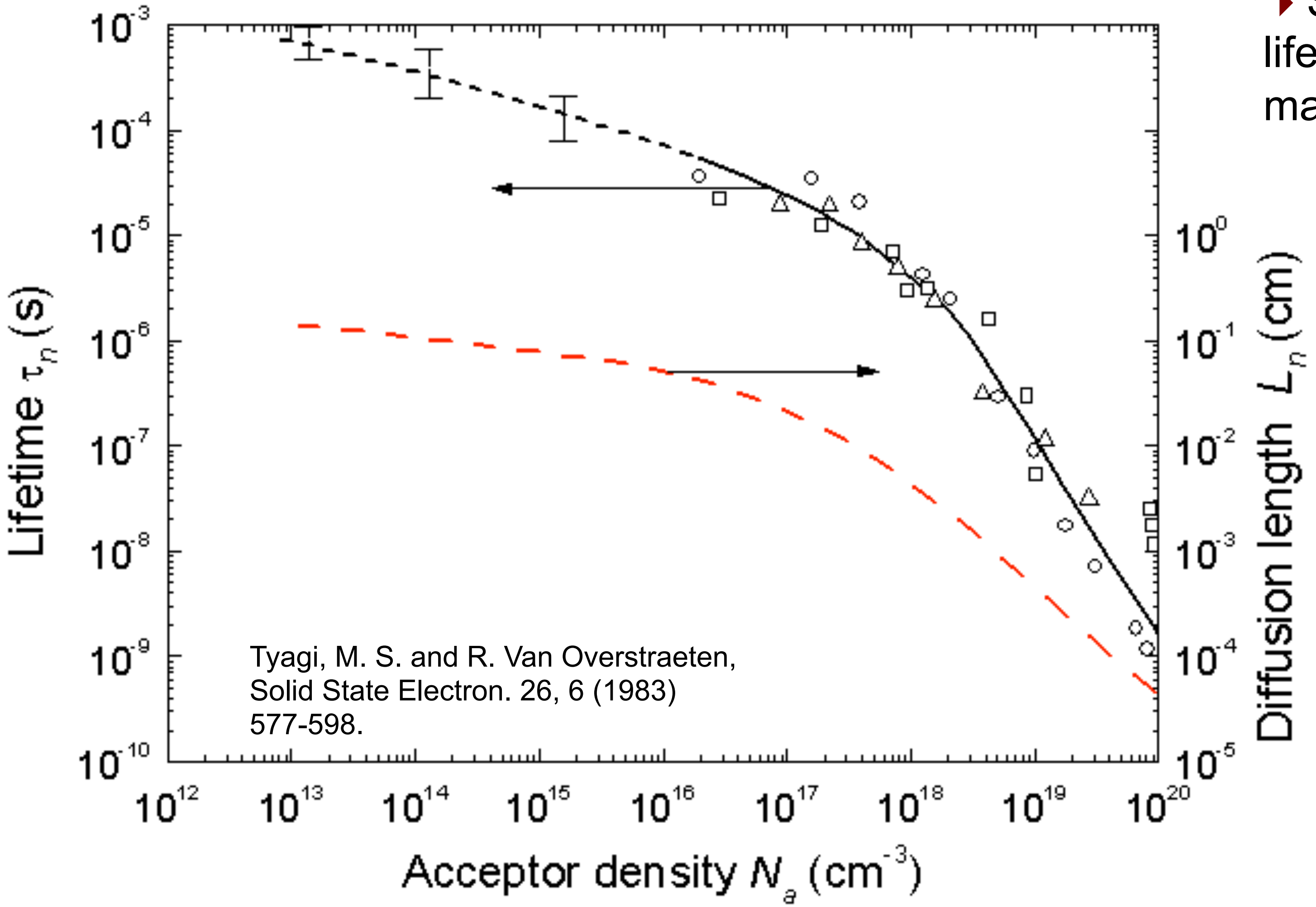
$$e^{-t/\tau_n}$$

$$e^{-t/\tau_P}$$

$$recombination\ rate\ \alpha_r (cm^{-3}s^{-1})$$

Last Topic! Forward to Reverse…

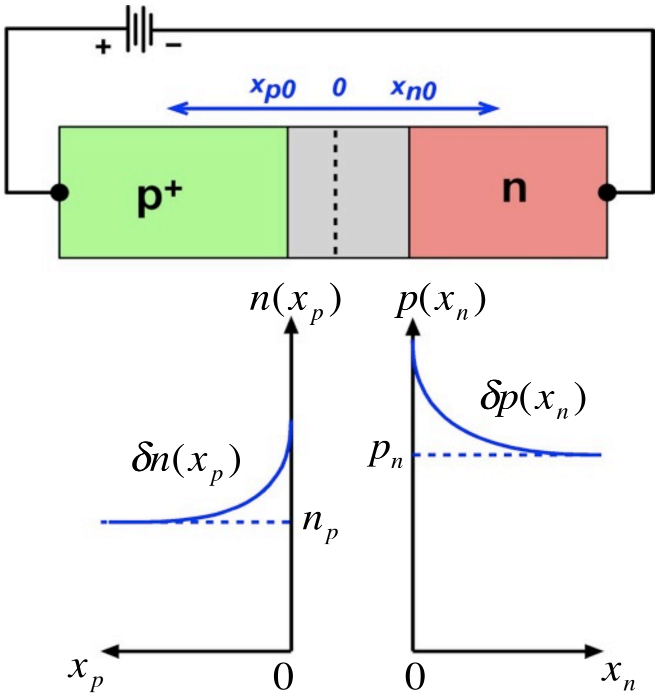
http://www.ioffe.rssi.ru/SVA/NSM/Semicond/Si/



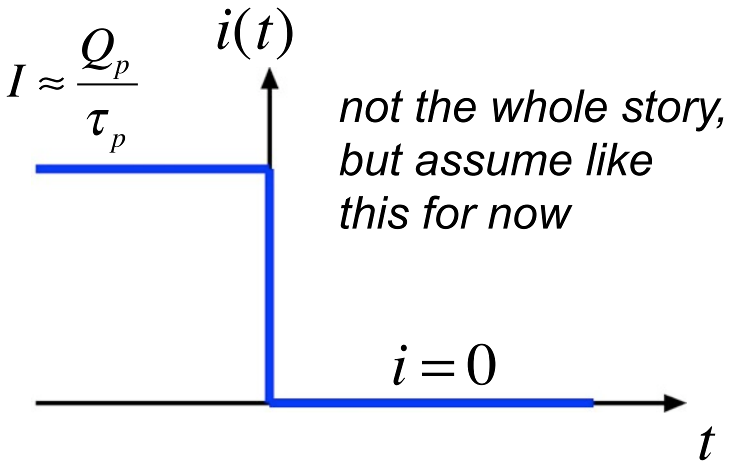
Tyagi, M. S. and R. Van Overstraeten, Solid State Electron. 26, 6 (1983) 577-598.

- Similar for hole lifetime in n-type material

Last Topic! Forward to Reverse…



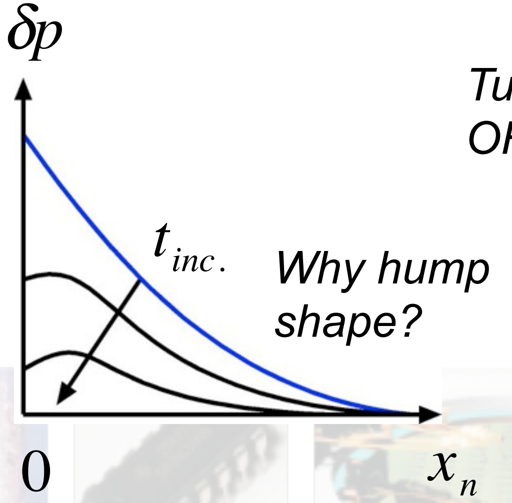
- p⁺n diode I domin. by hole diff. from p-side



not the whole story, but assume like this for now

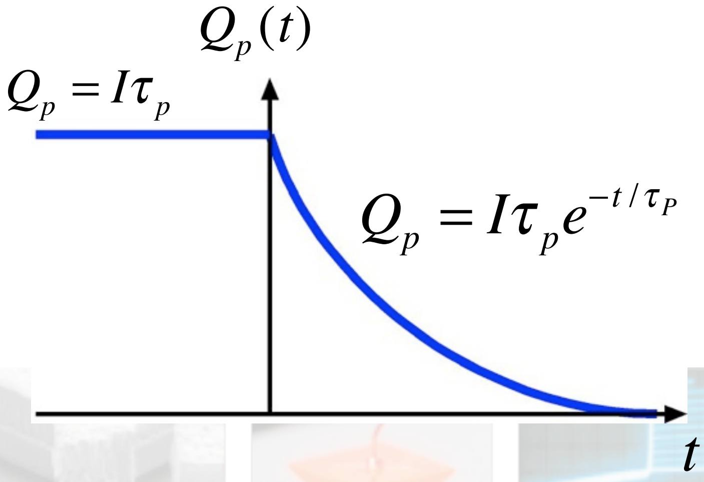
Most of the holes recombine, what does this require? I_n!

Turn OFF



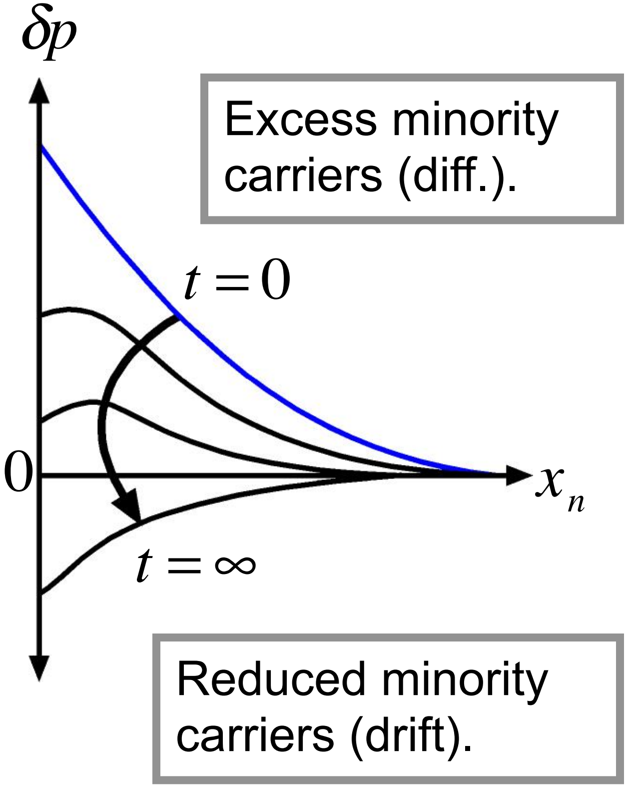
Why hump shape?

Turn OFF



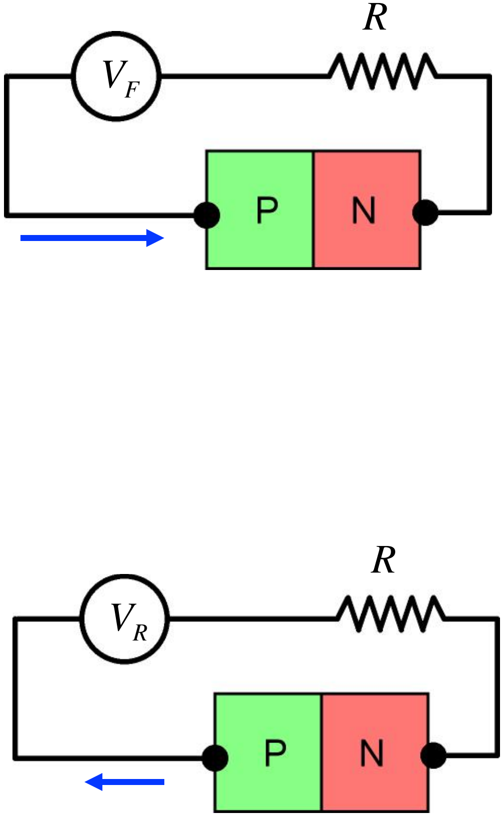
Last Topic! Forward to Reverse…

- Because of resistor R, ***current limited to V_R/R***
- In forward bias we built up a large excess of minority carriers
- Because of R, it will take a time t_{sd} (storage delay time) to reach thermal equilibrium values (Q_p=0 junction voltage =0)
- Only after this happens can the junction become reverse biased

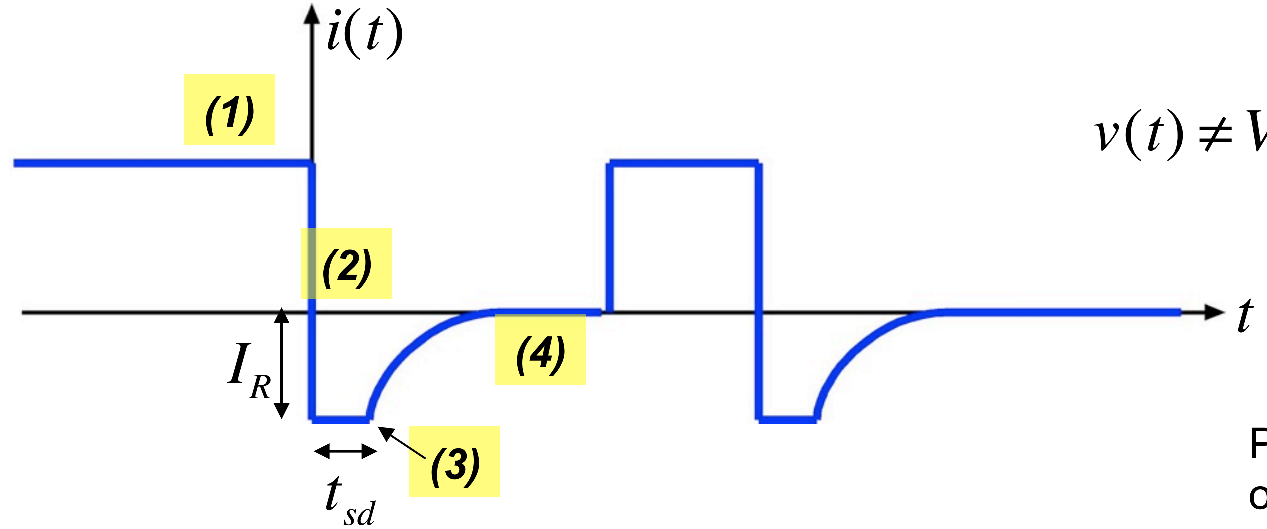


Excess minority carriers (diff.).

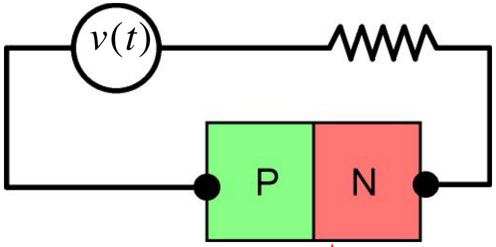
Reduced minority carriers (drift).



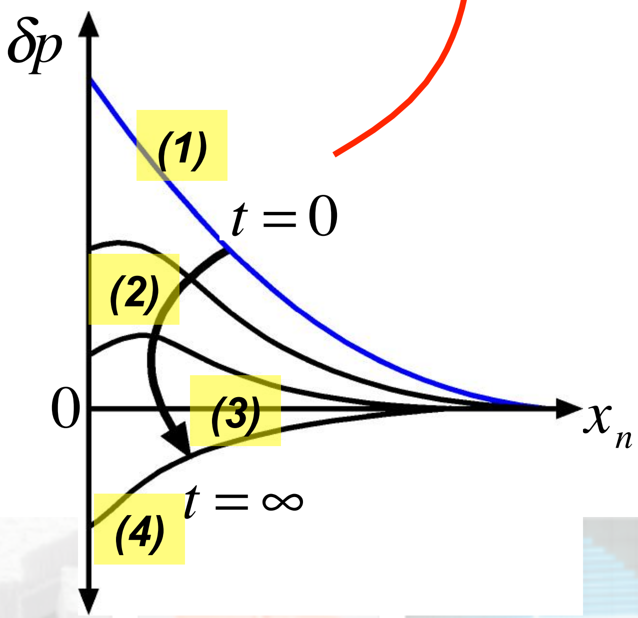
Last Topic! Forward to Reverse…



$$v(t) \neq V_{PN}$$



Plot of the excess of minority holes…



***(1)** We built up a excess of minority carriers in forward bias, once $V_f > V_o$ all additional voltage is across R (I=V/R)*

***(2)** We reverse bias v(t), but until the excess minority carrier population recombines the voltage across PN does not change much so all of v(t) appears across R, and I=v(t)/R.*

***(3)** The excess minority charge reaches zero, but we are still not reverse biased until drift current causes the minority carrier population to go to zero at the depletion edge*

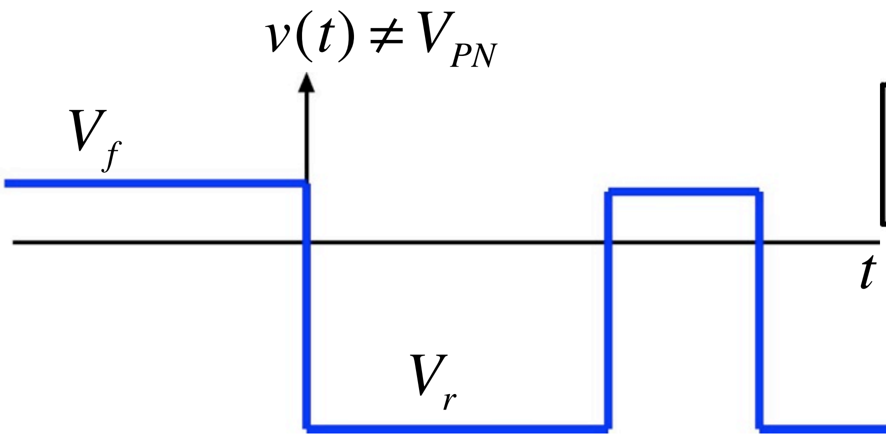
***(4)** We then finally get to reverse saturation current…*

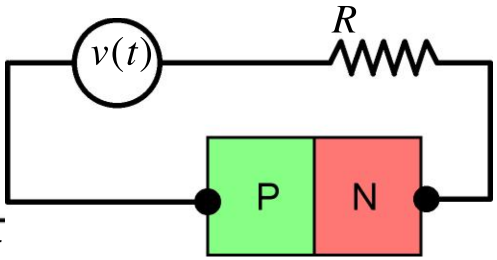
Last Topic! Forward to Reverse…

- For p$^+$n it can be shown:

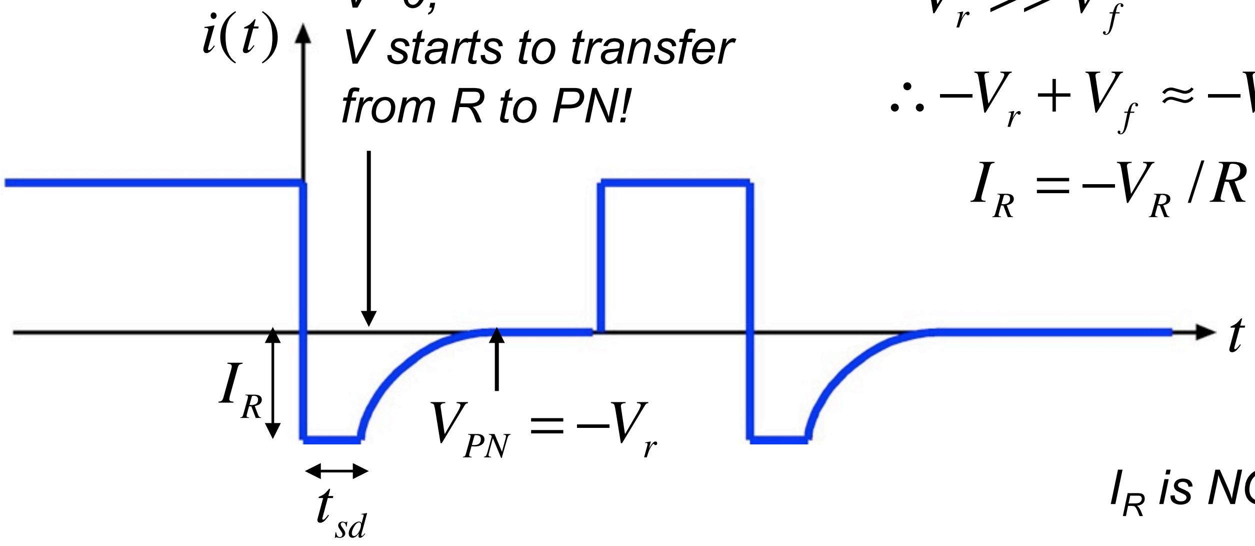
$$t_{sd} \approx \tau_p \ln\left(1+\frac{I_f}{I_R}\right)$$

$$\approx 0.1\ to\ 10\ \mu s$$





V=0,
V starts to transfer from R to PN!



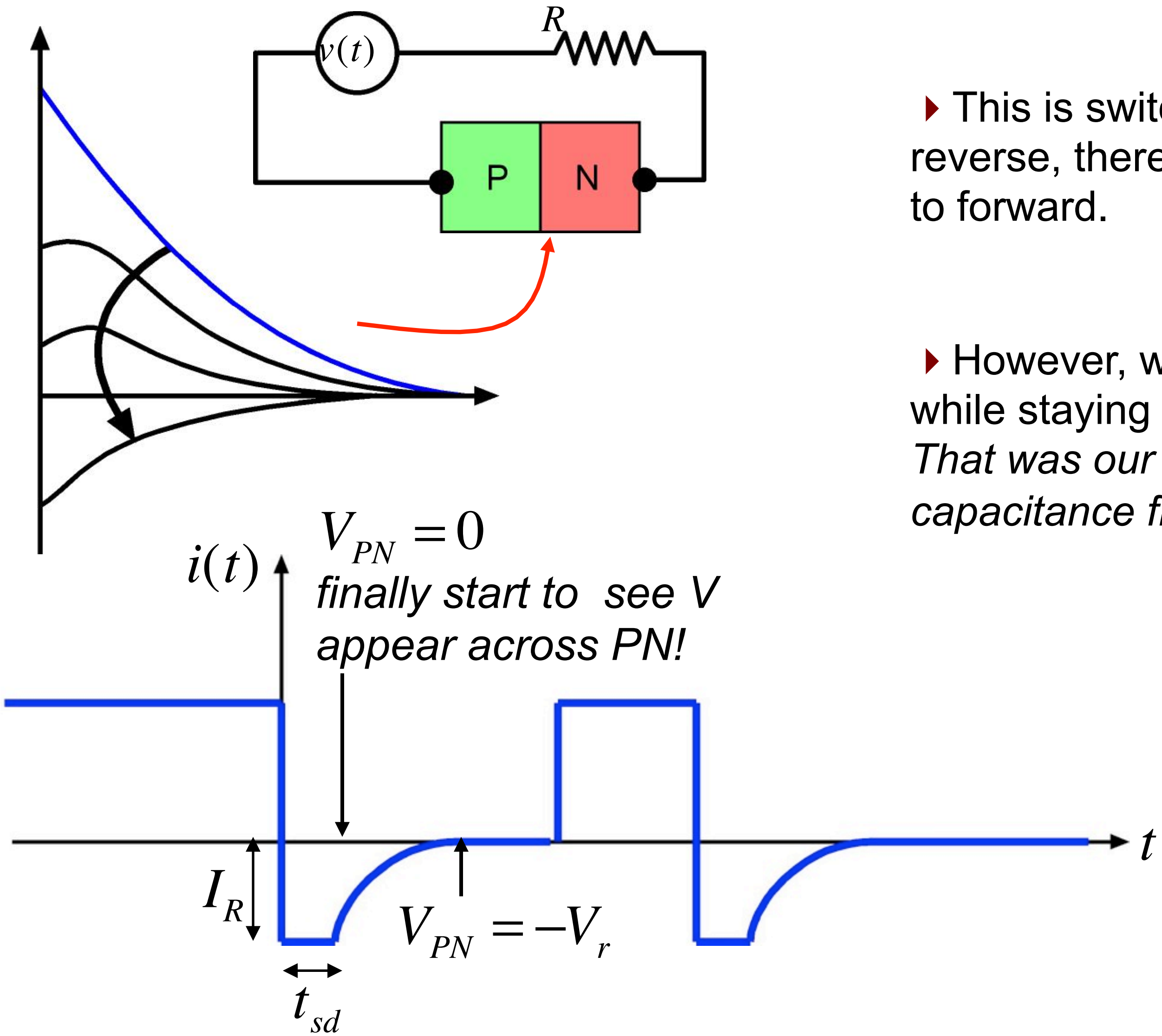
$$-V_r >> V_f$$

$$\therefore -V_r + V_f \approx -V_r$$

$$I_R = -V_R / R$$

I_R is NOT I_0.

Last Topic! Forward to Reverse…



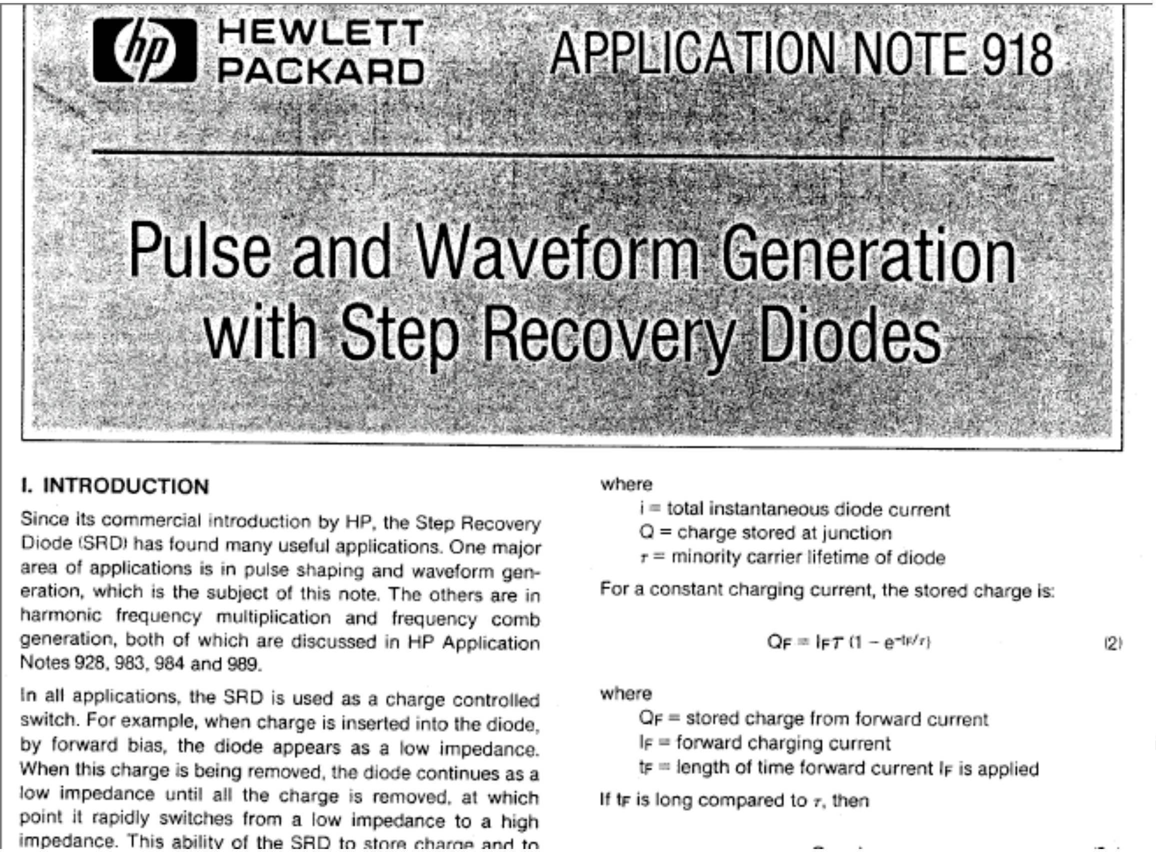
$V_{PN}=0$
finally start to see V appear across PN!

$V_{PN}=-V_r$

- This is switching from forward to reverse, there is no delay from reverse to forward.

- However, what about switching V while staying in forward or reverse? *That was our depletion and storage capacitance from Section 5-5b…*

Last Topic! Forward to Reverse…



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APPLICATION NOTE 918

Pulse and Waveform Generation with Step Recovery Diodes

I. INTRODUCTION

Since its commercial introduction by HP, the Step Recovery Diode (SRD) has found many useful applications. One major area of applications is in pulse shaping and waveform generation, which is the subject of this note. The others are in harmonic frequency multiplication and frequency comb generation, both of which are discussed in HP Application Notes 928, 983, 984 and 989.

In all applications, the SRD is used as a charge controlled switch. For example, when charge is inserted into the diode, by forward bias, the diode appears as a low impedance. When this charge is being removed, the diode continues as a low impedance until all the charge is removed, at which point it rapidly switches from a low impedance to a high impedance. This ability of the SRD to store charge and to

where

i = total instantaneous diode current
Q = charge stored at junction
τ = minority carrier lifetime of diode

For a constant charging current, the stored charge is:

$$Q_F = I_F \tau \left(1 - e^{-t_F/\tau}\right) \qquad (2)$$

where

Q_F = stored charge from forward current
I_F = forward charging current
t_F = length of time forward current I_F is applied

If t_F is long compared to τ, then

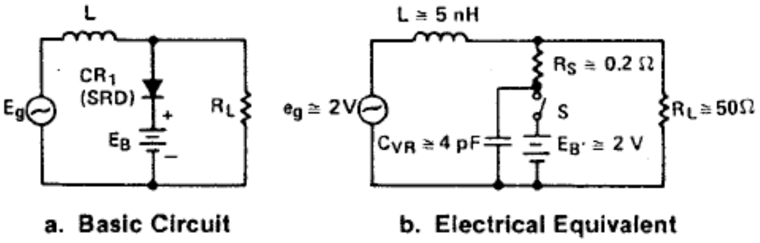

Figure 36. Impulse Generator Circuit