ECE 303 Lecture 22  
Not So Plain Diodes - Part II: Photodetectors & Metal Semiconductor Diodes

Last Time:
- Reviewed fundamentals of light and its interaction with semiconductors
- Discussed collection of light energy via semiconductor photovoltaic devices (a.k.a. "solar cells")

Now, light sensing diodes of a different type: PHOTODETECTORS

Killer Application: The detector at the end of a fiber-optic telecommunication link

Basic light to electrical power conversion process is the same as in a solar cell:
- Light provides energy necessary to break bond and promote electron from valence to conduction band
- Electric field in diode P-N junction separates electron and hole, setting up net current flow

But in photodetectors, priorities are very different: They CAN be very expensive

Only need to detect a single wavelength / energy of light
Want to be FAST as possible (so can detect more bits per second)

With consequences: Efficiency comes more easily because DO have to deal with only single color of light
Am willing to invest power in to get the signal out
These all drive me towards the use of a diode under REVERSE bias: Use of reverse bias does good things:

1) Depletion layer is MUCH wider

~ ALL the light can be absorbed in depletion layer

Electric field then properly separates n + p

=> Detection Efficiency

=> Speed (\(\xi\) field sweeps charge out quickly)

2) No light => ~ no signal

In reverse bias, diode passes little current (\(J_{\text{sat}}\))

Only get signal (draw power) when illuminated
Current drawn when no light ($J_{sat}$)? Phototdetector workers refer to this as the "dark current"

$$J_{reverse} = q \left( \frac{D_p \cdot p_n}{L_p} + \frac{D_n \cdot n_p}{L_n} \right)$$

Want this to be as small as possible

So, want minority carrier concentrations to be small:

$$\text{minority} = \frac{n_i^2}{\text{majority}}$$

But if increase majority doping, depletion layers shrink and may collect fewer $n + p$ in junction

Alternative:

$$n_i^2 = \frac{-E_g}{k \cdot T}$$

So higher bandgap materials => lower "dark current"

Could also make L's larger:

$$L = \sqrt{D \cdot \tau_{\text{minority}}}$$

So this again => High lifetime material (high purity materials)

However, when light is turned off, I want signal to stop quickly => Low lifetime materials

So lifetime (purity) is a compromise choice between low dark noise OR high speed
Avalanche Photodiodes (APD's): Reverse bias can also give you internal amplification of light detected!

Right out of last lecture: Light creates a few carriers which acquire enough E to make more...

Light creates 1st n + p pair  =>  p from 1st pair gains E, collides creating new n + p

Finally, only need to detect specific light wavelength so:

1) Choose semiconductor with DIRECT bandgap ~ light energy
2) MAKE semiconductor with correct bandgap (more on this in lectures 23 & 24)
3) Make sandwich of semiconductors so absorb at correct wavelength
Remember quantum wells?

\[ E_n \propto \frac{n^2}{L^2} \]

Narrow well:
Levels squeezed up
Only one left in well

Make narrow well by sandwiching thin layer of small bandgap material between large bandgap material:

Layer #1
Layer #2
Layer #3
Put together:

\[ E_{g1} \]
\[ E_{g2} (< E_{g1}) \]
\[ E_{g1} \]

Absorbs ONLY at that exact energy!
To tune (or make detectors for other light energy / $\lambda$) simply change THICKNESS of center layer:

Change in well width => Change in quantum well levels => Change in absorption energy

"Quantum Well Photodetector"

Type of detector typically used on fiber-optic links to select out a particular signal

Well layer thickness must be controlled to accuracy of atoms => "MBE" technique shown on my homepage

Linked from my homepage - Quantum Well Avalanche Photodetector (QW-APD) I made using MBE:
Above we are already mixing layers of different semiconductors

   What do we get if we add a layer of METAL?

In fact this configuration occurs in virtually ALL semiconductor devices:

   - Wires connecting IC's with power supplies and other IC's
   - Metalization paths inside an integrated circuit

To this point we have assumed that electrons & holes will flow smoothly between metal & semiconductor:

   No resistance, no energy steps... "Ain't necessarily so!"

Have to go back to bands

   Remember: Semiconductor = Insulator driven by heat or doping to become mild conductor
$T = 0 \text{ K, Undoped}$

\begin{align*}
&\quad \quad \text{Conduction Band} \\
&\quad \quad \text{Valence Band} \\
\end{align*}

$T > 0 \text{ K, Doped N-type}$

\begin{align*}
&\quad \quad \text{Conduction Band} \\
&\quad \quad \text{Valence Band} \\
\end{align*}

Enlarging the right diagram, focusing on the top of the valence band / bottom of the conduction band

\begin{align*}
\text{"Vacuum Level"} &= \text{free electron} \\
q \chi &\quad q \Phi_s \\
E_F &\quad E_C \\
E_C &\quad E_V
\end{align*}
Vacuum Level / Energy = Energy of an electron that has been freed from attractive potentials of the crystal and is now at rest in free space

\[ \phi_s = \text{"Semiconductor Work Function"} = \text{Energy / charge needed to free electron at } E_F \text{ from semiconductor} \]

\[ \approx \text{"Ionization Energy" of an atom / q} \]

\[ \phi_s \text{ units} = \text{Energy / Charge} = \text{Volts} \]

**PROBLEM:** \( \phi_s \) depends on \( E_F \), which depends on the doping of the semiconductor

So we define another parameter that will not change with doping:

\[ \chi = \text{"Semiconductor Electron Affinity"} = \text{Energy / charge released as electron falls into semiconductor} \]
Now let's move to the metal's band diagram

IMPORTANT: In a metal, all valence electrons are very weakly bound to the atoms

All atoms contribute free electrons! Not just donors or occasional hot atom!

As if ALL metal atoms ~ donors!

\[ M \leftrightarrow M^+ + n^- \quad \text{Ionization "Reaction"} \]

But the number of metal atoms / volume ~ \(10^{23} / \text{cm}^3\) >> Semiconductor dopant concentrations

\[ M^+ \text{ and } n^- \sim 10^{23} / \text{cm}^3 \quad \text{Like an extremely N-type semiconductor!} \]
Imagine a metal approaching an N-semiconductor:

Now bring them into contact:

Semiconductor loses electrons => Depletion layer and band bending:
Depletion layer in semiconductor:  Uncovered $N_d^+ \Rightarrow Q^+$

HOLD IT!  Where is the balancing depletion region in the metal ($Q^-$) ?

In the metal:  Equilibrium $n^-$ concentration is $\sim 10^{23} / \text{cm}^3 = \text{HUGE}$

There will be equal total charge / contact area on the metal side

But because the concentration of charge is so much larger, width of $Q^-$ layer is minuscule!

Corresponds to $\delta$ layer where small percentage of metal electrons flow toward interface

So narrow it does not even show up on diagram!

(Remember "one-sided" P-N junction band diagrams?)
But curves on left (metal) side are really MUCH higher.

What about the current flow versus an applied voltage side to side?
Barrier to electron flow from metal => N-semiconductor:

\[ \Delta_{\text{metal\_to\_semi}} = q \cdot \phi_{BN} = q \cdot (\phi_m - \chi) \]

Barrier to electron flow N-semiconductor => metal, at zero applied voltage is again called the "built-in voltage"

\[ \Delta_{\text{semi\_to\_metal}} = q \cdot V_{bi} \]

\( V_{bi} \) is how far the semiconductor \( E_F \) dropped to match up with the metal's \( E_F \) = the initial mismatch

\[ V_{bi} = q \cdot (\phi_m - \phi_s) \]

because the \( \phi \)'s were how far \( E_F \)'s were below vacuum level

Or if define \( \phi_N \) as how far the semiconductor's \( E_F \) is below the conduction band:

\[ \phi_s = \chi + \phi_N = \chi - (E_c - E_F) \]

Then:

\[ V_{bi} = q \cdot (\phi_m - \phi_s) = q \cdot [\phi_m - (\chi + \phi_N)] = q \cdot (\phi_m - \chi) - q \cdot \phi_N \]

\[ V_{bi} = q \cdot (\phi_{BN} - \phi_N) \]

converting to new symbols
And then letting this come to equilibrium by letting electrons flow to left:

\[ q \cdot \phi_{BN} = q \cdot (\phi_m - \chi) \]

\[ V_{bi} = q \cdot (\phi_m - \phi_s) \]

**NOTE:** What real *learning* value do these new symbols \( \phi_N \) and \( \phi_{BN} \) have?

Negative learning value (often confuse students) - are just ways of restating things

We teach them because they ARE the shorthand symbols pros working with metal-semi junctions use

First of a number of quirky things that came about due to fragmented development of this field!
What about the electric field in the unbiased metal-semiconductor junction?

Here charge density $= q N_d^+ \sim q N_d$

Gauss's Law: $\nabla \cdot \xi = \frac{\rho}{\varepsilon} = \frac{q \cdot N_d}{\varepsilon}$

Integrating from $x_n$ to $x$: $\xi(x) = \frac{-q \cdot N_d \cdot (x_n - x)}{\varepsilon}$

$\alpha$ slope of bands

(Will use this later)

Now let's apply a reverse bias to the metal-semiconductor junction ("reverse" = making barriers higher)

Nothing's going to get across!
Compared to **forward bias** ("forward" = making barriers smaller)

- Barrier unchanged!
- No electrons => semiconductor
- Electrons => metal
- Reduced barrier: $V_{bi} - V_{applied}$

**Consequences:**
1. Electrons do NOT flow out of metal
2. Electrons DO flow out of semiconductor

Once these electrons enter metal, they quickly lose energy (fall down big step)

They can't then diffuse back into the semiconductor - **Diodes turn off very quickly!**

= **Fundamentally different than semi-semi P-N junction we explored earlier!**

This metal-semiconductor junction **DOES** act as a diode: **"Schottky Barrier Diode"**

But the equation for this diode's current will be very different from that of P-N junction
Our new Metal / Semiconductor "Schottky" Diode vs. Our old Semiconductor / Semiconductor P-N Diode

First difference (pointed out above) is that in Schottky diode (left) there is no hole flow (blue)

More subtle difference comes for carriers that CAN cross the diode junction:

In the P-N diode (above right), the carriers that crossed CAN COME BACK

Two way motion across P-N junction implied a certain equilibrium across the junction

We applied this in our heavy use of Fermi functions to derive the P-N junction I vs. V equation
Calculating P-N diode current (lecture 18) we went through steps of:

1) Found how many carriers have energy to cross
2) Asserted that those electrons WOULD easily cross, balancing number at that energy on both sides
3) From then-established population on other side, calculated their diffusion deeper into that side

But in our new Schottky diodes (above left), the electrons that cross the junction CANNOT COME BACK

Unlikely

Once they have crossed the junction electrons loose excess energy VERY quickly

Once lost, VERY unlikely can gather energy to cross back

So calculation of Schottky diode (given in book's chapter 9 ) instead involves:

1) Find how many carriers had energy to cross *(same as above)*
2) From their excess energy (= kinetic energy) calculate their velocity in direction of junction *(different!)*
3) Multiply number x velocity at each possible E, integrate to get total current *(different!)*
I am going to spare you that full derivation Schottky (metal/semiconductor) diode current because:

Reason #1) The math gets exceedingly messy (especially that final energy integration)

Reason #2) Such Schottky diodes are only used in very rare / specialized applications

But you should at least know the result - For a Schottky (metal/semiconductor) diode:

\[
J(V_{\text{applied}}) = A \cdot T^2 \cdot e^{-\frac{q \cdot \phi_{BN}}{k \cdot T}} \left( e^{\frac{q \cdot V_{\text{applied}}}{k \cdot T}} - 1 \right)
\]

Where:

\[
\phi_{BN} = q \cdot (\phi_m - \chi)
\]

\[
A = \frac{4 \pi \cdot m_{\text{eff}} \cdot k^2}{h^3} = "\text{Richardson Constant"}
\]

With strange symbols coming from early energy band diagram for the metal/semiconductor junction:
Underlying diode current conduction process also known as THERMIONIC EMISSION

Note similarities and differences between Schottky diode and "classic" P-N diode equations:

**Schottky Barrier (metal/semiconductor) diodes:**

\[
J(V_{\text{applied}}) = A \cdot T^2 \cdot e^{-q \cdot \phi_{BN} / k \cdot T} \left( \frac{q \cdot V_{\text{applied}}}{k \cdot T} - 1 \right)
\]

\[
\phi_{BN} = q \cdot (\phi_m - \chi)
\]

\[
A = \frac{4 \pi \cdot m_{\text{eff}} \cdot k^2}{h^3}
\]

**P-N Junction (semiconductor/semiconductor) diodes:**

\[
J_{\text{PN diode with thick layers}} = J_{\text{sat}} \left( \frac{q \cdot V_{\text{applied}}}{k \cdot T} - 1 \right)
\]

\[
J_{\text{sat}} = \left( \frac{q \cdot D_p \cdot p_0}{L_p} + \frac{q \cdot D_n \cdot n_0}{L_n} \right)
\]

Same final voltage dependence term (Hence shapes of I vs. V are ~ same)

Entirely different prefactor / saturation current!!

**What is KILLER APPLICATION for such Schottky barrier diodes??**

**Ultrafast diodes:** Because previously "injected" current CAN'T come back

So when voltage reversed, current cuts off essentially immediately
Unlike P-N diode where, even after voltage reversed, must wait for some injected carriers to trickle back across

So from a high-speed / AC perspective, Schottky diodes are much more ideal in their behavior

Then why not use them wherever diodes are required?

Because metal/semiconductor diodes are very fragile / susceptible to damage:

Too much voltage or current => Heating => Mixing of metal and semiconductor

Metal-Semiconductor mixture has different (generally sharply worse) barrier

=> Short-circuits and/or sharply degraded diode behavior

 Couldn't P-N diodes suffer similar damage?

Metals and semiconductors can mix at just 200-400C

But semiconductor/semiconductor P-N diodes will not significantly rearrange their dopants until nearly 1000C

So application of Schottky / Metal-Semiconductor / Thermionic Diodes is very limited:

To things like ultra-high speed signal detection

*The specialization that launched UVA's semiconductor device lab!*