PHYS 460 - LECTURE 17

WE HAVE NOW SPENT SEVERAL LECTURES EXPLORING THE SMALL GAP INSULATORS REFERRED TO AS SEMICONDUCTORS, AND DEMONSTRATED HOW WE UNDERSTAND CHARGE CARRIERS IN THESE SYSTEMS, AND CONTROL CHARGE TYPE AND DENSITY THROUGH DOPING.

TODAY, I AM GOING TO GIVE YOU AN INKLING AS TO WHY. APPLICATIONS OF SEMICONDUCTORS ARE NUMEROUS AND ~~ARE~~ CAN BE ARBITRARILY COMPLICATED, SO I CANNOT GO INTO GREAT DETAIL, BUT WE WILL BE ABLE TO SEE THE USEFULNESS BY CONSIDERING VERY SIMPLE EXAMPLES. IN PARTICULAR, IT MAY HAVE OCCURED TO YOU THAT SEMICONDUCTORS IN ISOLATION ARE NOT PARTICULARLY INTERESTING - JUST INSULATORS AT LOW-T AND METAL-ISH AT HIGH-T. THINGS CHANGE FAST THOUGH IF WE BRING DIFFERENT SEMICONDUCTORS IN CONTACT OR LET MATERIAL PROPERTIES (OR DOPING LEVELS) VARY IN SPACE

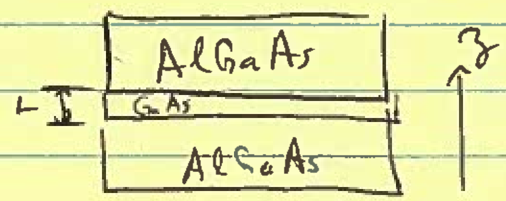
$\longrightarrow$ <u>INHOMOGENEOUS SEMICONDUCTORS</u>

TODAY WE WILL DESCRIBE TWO TYPES OF SEMICONDUCTOR "HETEROSTRUCTURES" (VARIATIONS BY CONSTRUCTION)

1. QUANTUM WELLS AND 2DEGs
2. p-n JUNCTIONS $\rightarrow$ DIODES, SOLAR CELLS AND TRANSISTORS

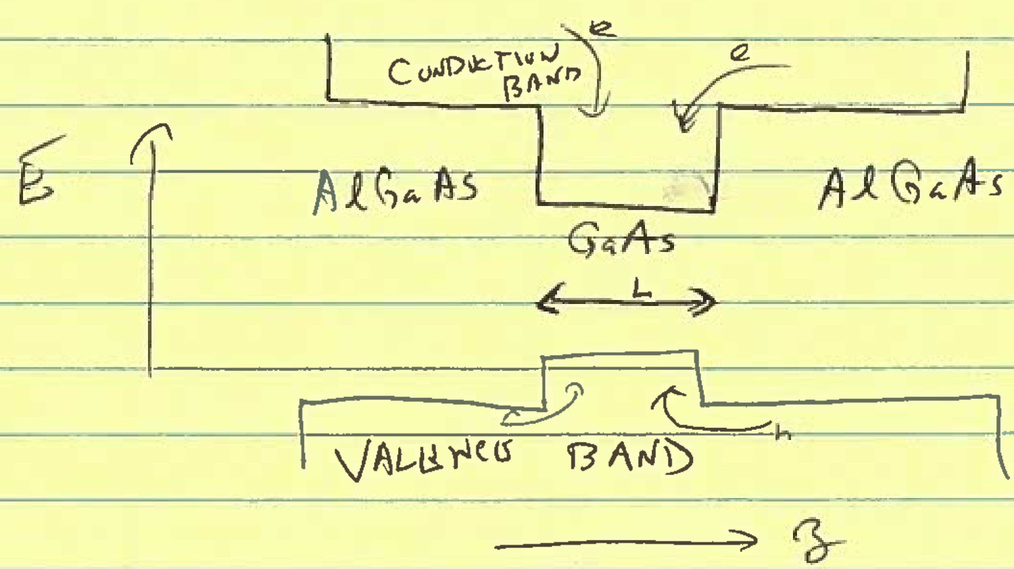
QUANTUM WELLS

A QUANTUM WELL IS A SIMPLE IDEA WITH USEFUL CONSEQUENCES. RECALL THAT ONE CAN CONTROL SEMICONDUCTING BAND GAPS THROUGH ALLOYING, FOR EXAMPLE IN THE MATERIAL $Al_x Ga_{1-x} As$ (AlGaAs FOR SHORT) THE GAP RANGES FROM 1.4eV WHEN $x=0$ TO 2.7eV WHEN $x=1$. SIGNIFICANTLY, THE LATTICE STRUCTURE DOES NOT CHANGE FOR A WIDE RANGE OF x. THIS ALLOWS FOR THE GROWTH OF THIN FILMS WITH NEAR PERFECT INTERFACES. CONSIDER THE STRUCTURE

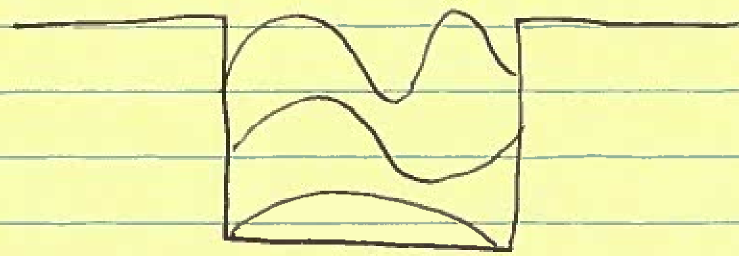


WHERE L IS SMALL (JUST A FEW LAYERS)

THEN, IF YOU LOOK AT THE ENERGY LEVEL DIAGRAMS AS A FUNCTION OF z, YOU SEE SOMETHING LIKE



DRAWN THIS WAY, YOU CAN SEE THAT THE CONDUCTION ELECTRONS CAN LOWER THEIR ENERGY BY CONFINING THEMSELVES TO THE GaAs LAYER AND FURTHER THE WHOLE SYSTEM LOOKS LIKE A TEXTBOOK POTENTIAL WELL PROBLEM

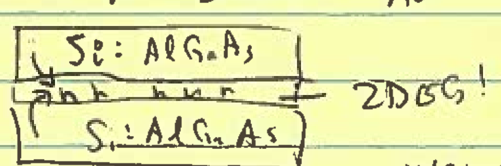


→ "QUANTUM WELL"

WELLS, AND CLOSE RELATIVES "QUANTUM DOTS" ARE OFTEN USED FOR FUNDAMENTAL STUDIES OF QUANTUM MECHANICS.

PERHAPS MORE USEFUL TO NOTE IS THAT THE ELECTRONS ARE NOT CONFINED IN THE x- AND y- DIRECTIONS! SO IF YOU CREATE A BUNCH OF CARRIERS BY DOPING THE AlGaAs, THE GaAs LAYER WILL "STEAL" THEM AND WILL GAIN A CERTAIN DENSITY OF CARRIERS WITHOUT ADDITION OF IMPURITIES ("MODULATION DOPING"). THUS, ONE CAN CREATE INCREDIBLY CLEAN TWO-DIMENSIONAL ELECTRON GASES (2DEGs) WITH MEAN FREE PATHS AS LARGE AS SEVERAL MICRONS

NB - NEED LOW-T FOR CONFINEMENT

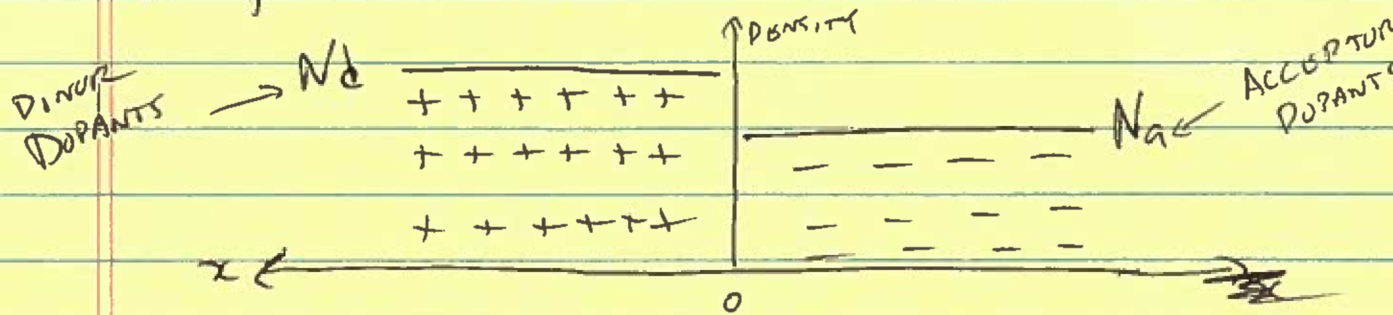


2DEGs ARE CENTRAL TO MANY GROUNDBREAKING DISCOVERIES, INCLUDING INTEGER AND FRACTIONAL QUANTUM HALL EFFECT

p-n JUNCTIONS

JUNCTIONS PLAY A CENTRAL ROLE IN MOST OF THE APPLICATIONS OF SEMICONDUCTORS. AGAIN, SIMPLE IDEA WITH HUGE CONSEQUENCES.

IMAGINE YOU HAVE AN n-TYPE SEMICONDUCTOR AND YOU BRING IT INTO ~~A~~ CONTACT WITH A p-TYPE SEMICONDUCTOR



DONORS ADD POSITIVE LATTICE CHARGES THAT ARE NEUTRALIZED BY NEGATIVE ELECTRON CARRIERS. LIKEWISE ACCEPTORS ADD NEGATIVE LATTICE CHARGES COMPENSATED BY EXCESS IN HOLE DENSITY.

IN PARTICULAR, CONSIDER THE CASE WHEN

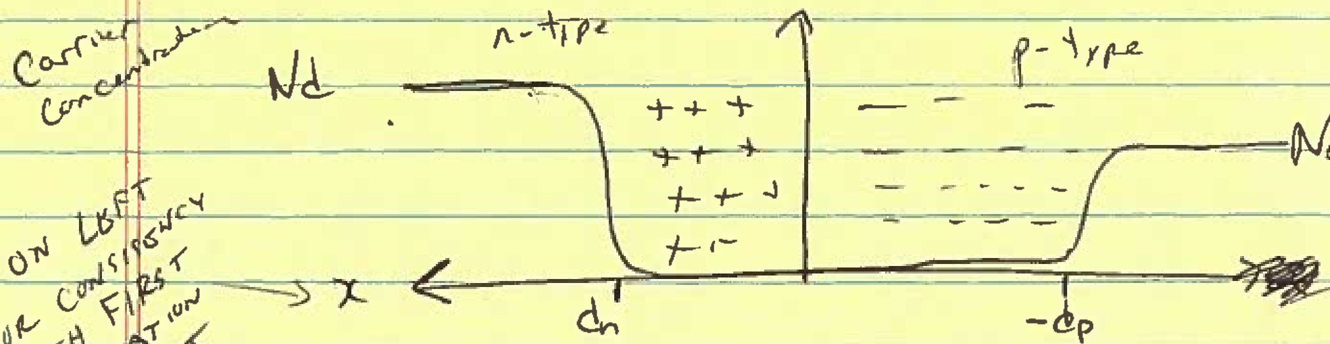
$$N_d(x) = \begin{cases} N_d & x > 0 \\ 0 & x < 0 \end{cases}$$

$$N_a(x) = \begin{cases} 0 & x > 0 \\ N_a & x < 0 \end{cases}$$

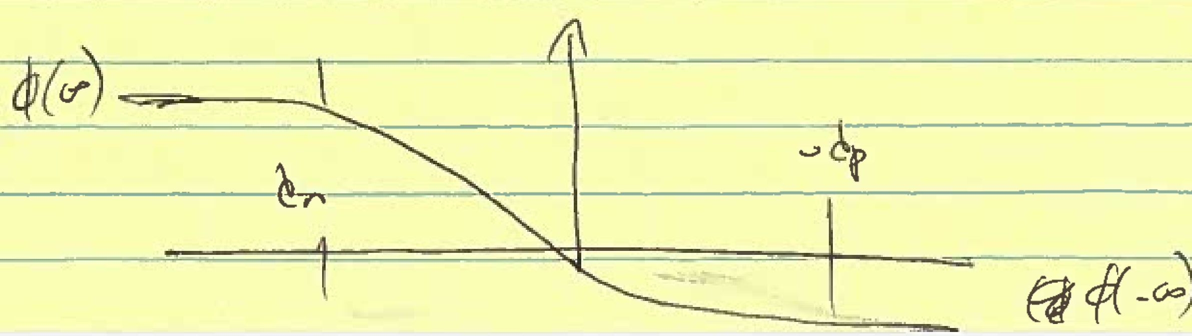
WHAT HAPPENS? WELL, ELECTRONS AND HOLES ARE NEVER STATIONARY. SOME ELECTRONS FROM THE LEFT WILL FALL INTO HOLE LEVELS ON THE RIGHT AND "RECOMBINE" AND HOLES DO THE SAME FROM RIGHT TO LEFT

THIS HAPPENS RANDOMLY AT FIRST, AND CREATES A LAYER AT THE INTERFACE WHICH IS DEPLETED OF CHARGE CARRIERS
→ "DEPLETION LAYER" (NO ELECTRONS OR HOLES)

WHAT HAPPENS THEN? WELL, WITHOUT CHARGE CARRIERS, THERE ~~IS~~ IS NOTHING TO COMPENSATE THE LATTICE CHARGES, LEADING TO A NET POSITIVE CHARGE ON THE n-type SIDE AND NET NEGATIVE ON P-TYPE SIDE



THIS CHARGE IMBALANCE CREATES A NET ELECTRIC FIELD, IN EFFECT BECOMING A PARALLEL PLATE CAPACITOR. THE FIELD GROWS AS THE DEPLETION LAYER GROWS, UNTIL THERE IS A PERFECT BALANCE (POTENTIAL COST PERFECTLY COUNTERS TENDENCY FOR ELECTRONS/HOLES TO SWITCH SIDES)



WE CAN ESTIMATE THE SIZE OF THE DEPLETION LAYER AND VOLTAGE ACROSS JUNCTION.

RECALL

$\phi(x) =$ INDUCED ELECTRIC POTENTIAL

$$n(x) = N(T)\, e^{-\frac{(\varepsilon_c - e\phi(x) - \mu)}{k_B T}}$$

AND

$$p(x) = P(T)\, e^{-\frac{(\mu - \varepsilon_v + e\phi(x))}{k_B T}}$$

WHERE I HAVE MODIFIED THE EXPONENT TO ACKNOWLEDGE THE ENERGY ASSOCIATED WITH THE INDUCED ELECTRIC FIELD

NOW LET'S ASSUME OUR SEMICONDUCTORS ARE IN THE EXTRINSIC LIMIT BUT AT HIGH ENOUGH TEMPS THAT ALL DONOR/ACCEPTOR LEVELS ARE IONIZED

$$\Rightarrow \quad N_d = n(x \to \infty) = N(T)\, e^{-\frac{(\varepsilon_c - e\phi(\infty) - \mu)}{k_B T}}$$

$$= N_d\, e^{-\frac{e(\phi(\infty) - \phi(x))}{k_B T}}$$

$$N_a = p(x \to -\infty) = P(T)\, e^{-\frac{(\mu - \varepsilon_v + \phi(-\infty))}{k_B T}}$$

SO IF WE ARE IN EQUILIBRIUM, $\mu = $ CONST EVERYWHERE (OR ELSE PARTICLES WILL HAVE NET AVERAGE MOTION)

$$\frac{N_d}{N} \times \frac{N_a}{P} = \exp\left[-\frac{(\varepsilon_c - \varepsilon_v - e\phi(\infty) + e\phi(-\infty))}{k_B T}\right]$$

$$\Rightarrow \quad \boxed{e\Delta\phi = e(\phi(\infty) - \phi(-\infty)) = \Delta + k_B T \ln\left(\frac{N_d N_a}{N(T) P(T)}\right)}$$

$e\Delta\phi$ IS ON ORDER OF Δ AND CHANGES WITH N_d, N_a

SO THIS TELLS YOU THE $x \to \pm\infty$ LIMITS. FINDING A FORMULA FOR $\phi(x)$ AND THE SIZE OF $d_{d,a}$ REQUIRES SOLVING MAXWELL'S EQUATION

$$-\nabla^2\phi(x) = -\frac{d^2\phi}{dx^2} = \frac{4\pi\rho(x)}{\epsilon}$$

WHERE $\rho(x)$ IS CHARGE DENSITY

SINCE IMPURITIES ARE FULLY IONIZED, WE KNOW

$$\rho(x) = e\left[N_d(x) - N_a(x) - n(x) + p(x)\right]$$

WE CAN SIMPLIFY BY FURTHER NOTING

$$n(x) = N_d\, e^{-e(\phi(\infty) - \phi(x))/k_BT}$$

AND $$p(x) = N_a\, e^{-e(\phi(x) - \phi(-\infty))/k_BT}$$

WHICH TELLS US THAT $n(x) \approx N_d$ AND $p(x) \approx N_a$ OUTSIDE DEPLETION ZONE. SINCE $\phi(x)$ CHANGES SO RAPIDLY (WE WILL SEE), $|\phi(x) - \phi(\pm\infty)|$ IS ALSO $\gg k_BT \Rightarrow n(x) \ll N_d$, $p(x) \ll N_a$

$\rho(x) = N_d(x) - N_a(x)$

$$\Rightarrow \quad \phi''(x) = \begin{cases} 0 & x > d_n \\ -\frac{4\pi e N_d}{\epsilon} & 0 < x < d_n \\ \frac{4\pi e N_a}{\epsilon} & -d_p < x < 0 \\ 0 & x < -d_p \end{cases}$$

INTEGRATE TWICE AND DEMAND CONTINUITY AT $x = d_n$ AND $x = -d_p$

$$\Rightarrow \quad \phi(x) = \begin{cases} \phi(\infty) & x > d_n \\ \phi(\infty) - \left(\frac{2\pi e N_d}{\epsilon}\right)(x - d_n)^2 & 0 < x < d_n \\ \phi(-\infty) + \left(\frac{2\pi e N_a}{\epsilon}\right)(x + d_p)^2 & -d_p < x < 0 \\ \phi(-\infty) & x < -d_p \end{cases}$$

CONTINUITY OF $\phi'(x)$ AT $x=0$ IMPLIES

$$-\frac{4\pi e N_d}{\epsilon}(\cancel{x}^{0} - d_n) = \frac{4\pi e N_a}{\epsilon}(\cancel{x}^{0} + d_p)$$

$$\boxed{N_d d_n = N_a d_p}$$

AND CONTINUITY OF $\phi(x)$ AT $x=0$ GIVES

$$\phi(\infty) - \left(\frac{2\pi e N_d}{\epsilon}\right) d_n^2 = \phi(-\infty) + \left(\frac{2\pi e N_a}{\epsilon}\right) d_p^2$$

$$\Delta\phi = \frac{2\pi e}{\epsilon}\left(N_d d_n^2 + N_a d_p^2\right)$$

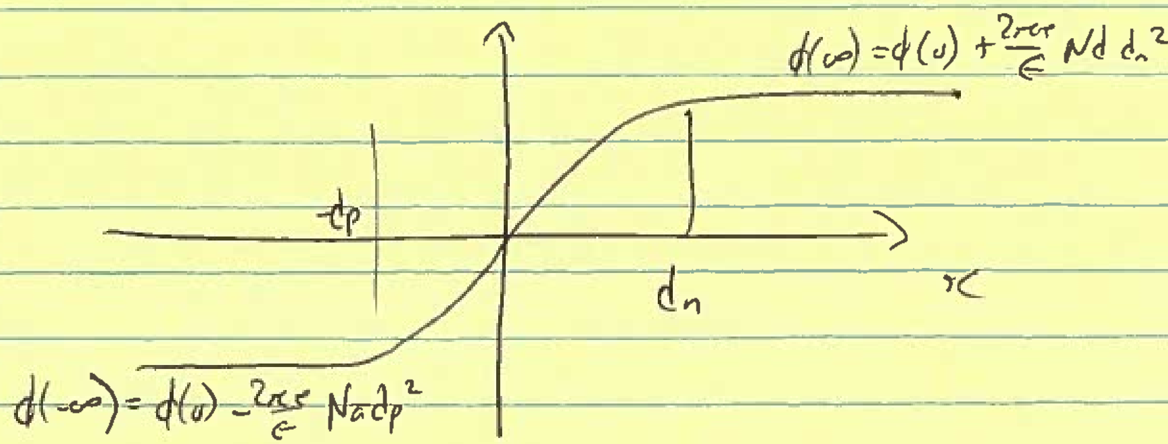
OR ~~SUBST~~ USING $d_p = d_n \times \frac{N_d}{N_a}$

$$\Delta\phi = \frac{2\pi e}{\epsilon}\left(N_d d_n^2 + \frac{N_d^2}{N_a} d_n^2\right)$$

$$\Delta\phi = \frac{2\pi e}{\epsilon}\frac{N_d}{N_a}(N_a + N_d) d_n^2$$

$$\boxed{\begin{aligned} d_n &= \left(\frac{\epsilon \Delta\phi \left(\frac{N_d}{N_a}\right)}{2\pi e\, (N_a + N_d)} \right)^{1/2} \\ \text{SIMILARLY} \quad d_p &= \left(\frac{\epsilon \Delta\phi \left(\frac{N_a}{N_d}\right)}{2\pi e\, (N_a + N_d)} \right)^{1/2} \end{aligned}}$$

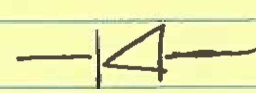
PLUGGING IN REALISTIC VALUES $e\Delta\phi \sim 1\,eV$, $N_a, N_d \sim 10^{14} - 10^{18}/cm^3 \rightarrow \sim 10^2 - 10^4\,\text{Å} < 1\,\mu m$



APPLICATION ①

RECTIFICATION : THE DIODE

MANY OF YOU MAY KNOW THE p-n JUNCTION BY ANOTHER NAME: THE DIODE. IT IS USUALLY GIVEN THE SYMBOL



IN WIRING DIAGRAMS AND IS KNOWN AS A WAY OF CONTROLLING THE DIRECTION OF CURRENTS

HOW DOES THIS WORK?

CONSIDER JUST HOLES FOR NOW. THERE ARE TWO MAIN SOURCES OF HOLE CURRENT

(1) A HOLE MAY BE "GENERATED" ON THE n-doped SIDE BY FLUCTUATIONS AND THEN BE SWEPT ACROSS THE DEPLETION REGION. THIS IS THE "GENERATED CURRENT"

$$J_h^{gen}(V)$$

(2) A HOLE FROM THE p-doped side MAY HAVE ENOUGH THERMAL ENERGY TO OVERCOME THE FIELD IN THE DEPLETION REGION TO "RECOMBINE" WITH AN ELECTRON ON THE OTHER SIDE

→ "RECOMBINATION CURRENT" $J_h^{rec}(V)$

WHEN $V=0$, THERE IS NO FLOW. SO

$$J_h^{gen}(0) + J_h^{rec}(0) = 0$$

SIMILAR ARGUMENTS FOR ELECTRONS GIVES

$$J_e^{gen}(0) + J_e^{rec}(0) = 0$$

NOW LET $V \neq 0$. THE p-n JUNCTION LOOKS LIKE TWO METALS SEPARATED BY A THIN INSULATING DEPLETION LAYER

$\longrightarrow$ MOST VOLTAGE DROP ACROSS DEPLETION LAYER!

SO IF $(\Delta\phi)_0 = \Delta + k_BT \ln\left[\frac{N_d N_a}{N_c P_v}\right]$ IS THE POTENTIAL DIFFERENCE IN ~~#~~ $V=0$ (EQUILIBRIUM), WE CAN DEFINE

$$\Delta\phi = (\Delta\phi)_0 - V$$

~~THIS VOLTAGE DOES NOT AFFECT~~

THIS IS THE POTENTIAL DIFFERENCE RECOMBINATION HOLES MUST OVERCOME TO MAKE IT TO THE n-doped SIDE

$$\Rightarrow \quad J_h^{rec} \propto e^{-e((\Delta\phi)_0 - V)/k_BT}$$

BUT WE KNOW $J_h^{rec}\big|_{V=0} = J_h^{gen}\big|_{V=0} = \text{const}$ SINCE J_h^{gen} IS LARGELY V INDEPENDENT

$$\Rightarrow \quad J_h^{rec} = J_h^{gen}\, e^{\frac{eV}{k_BT}}$$

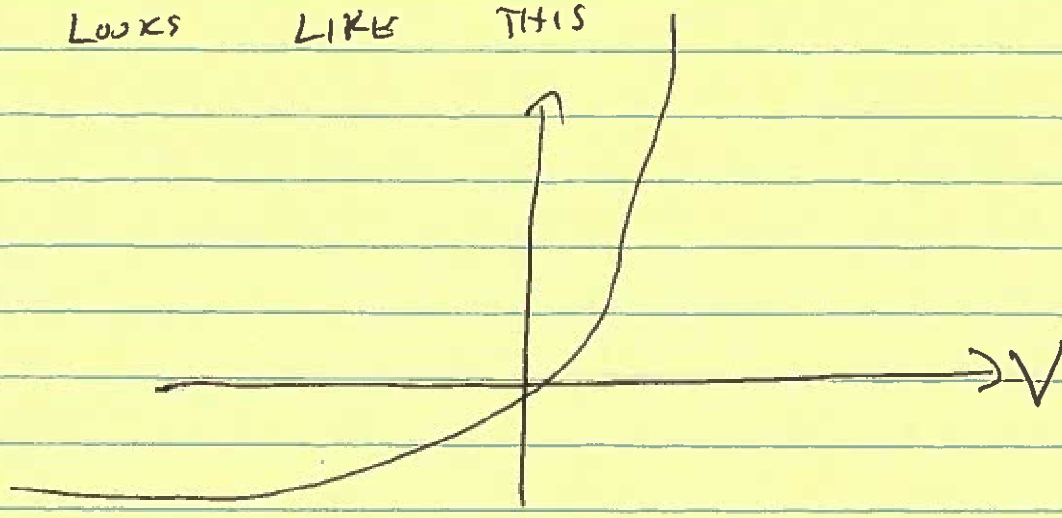
$$\Rightarrow \quad J_h = J_h^{rec} - J_h^{gen} = J_h^{gen}\left(e^{\frac{eV}{k_BT}} - 1\right)$$

APPLYING THE SAME ANALYSIS TO ELECTRONS, WE CONCLUDE CURRENT $I(V)$ IS

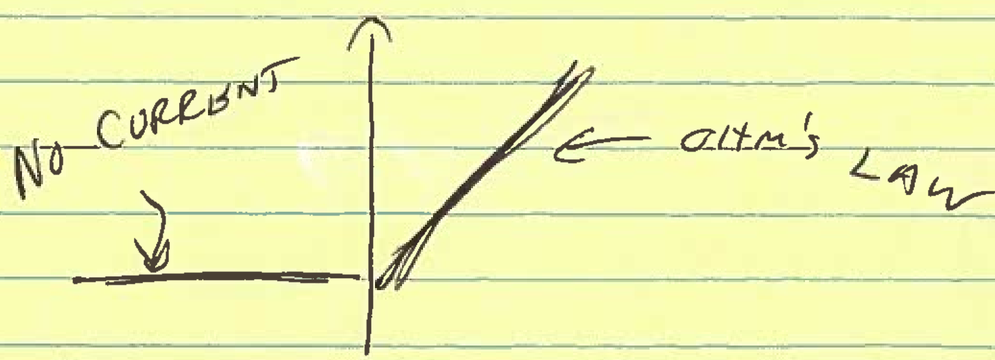
$$\boxed{\begin{aligned} I &= e\left(I_h^{gen} + I_e^{gen}\right)\left(e^{eV/k_BT} - 1\right) \\ &= I_s\left(e^{eV/k_BT} - 1\right) \end{aligned}}$$

SATURATION CURRENT

THIS IS KNOWN AS THE "DIODE EQUATION" AND LOOKS LIKE THIS



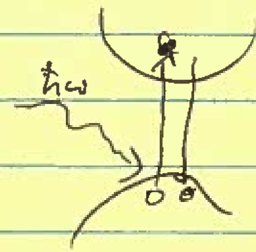
OR CHARACTERIZED LIKE THIS



<u>APPLICATIONS</u>: RADIO POWER CONVERSION, DETECTORS, LOGIC, WAVEFORM, MODULATION, CURRENT CONTROL...

APPLICATION (2): SOLAR CELLS

WE KNOW THAT IN EQUILIBRIUM, PHOTONS CAN EXCITE ELECTRONS ACROSS THE GAP, WHICH THEN RECOMBINE, EMITTING A PHOTON OF THE SAME SIZE



IF A PHOTON IS INCIDENT ON THE DEPLETION LAYER HOWEVER, THE INTRINSIC $\Delta\phi$ SWEEPS THE HOLE AND ELECTRON IN OPPOSITE DIRECTIONS

$\longrightarrow$ NO RECOMBINATION

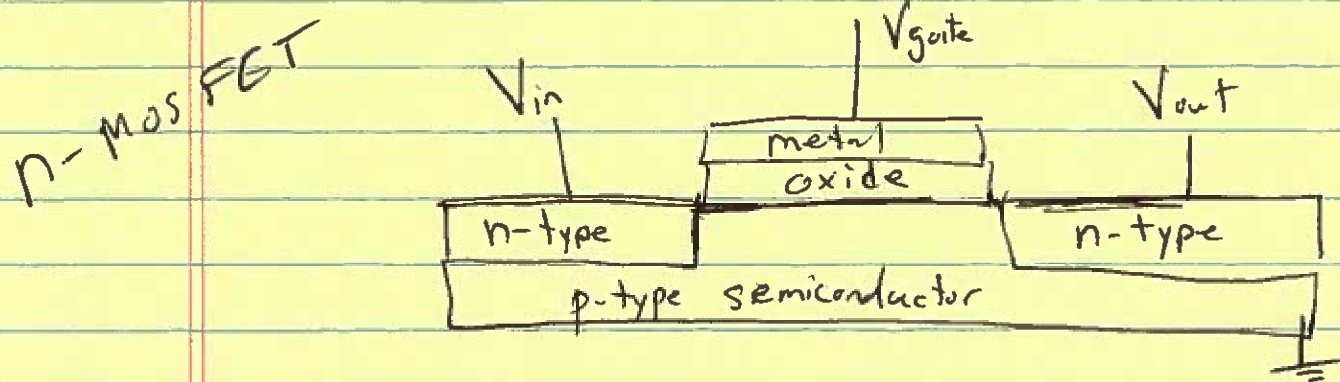
$\longrightarrow$ LIGHT INDUCED CURRENT

$\longrightarrow$ SOLAR CELL!

MODERN SOLAR CELLS USE MUCH THE SAME TECHNIQUE, BUT STRIVE TO MAXIMIZE THE RANGE OF USEFUL ω AND THE EFFICIENCY OF THE ENTIRE PROCESS.

TWO p-n JUNCTIONS — THE TRANSISTOR

A TRANSISTOR IS A DEVICE USED AS AN AMPLIFIER OR SWITCH, AND COMES IN MANY FORMS. THE MOST COMMON IS CALLED A MOSFET (METAL-OXIDE-SEMICONDUCTOR FIELD EFFECT TRANSISTOR. THE DESIGN LOOKS LIKE SO



HERE YOU ARE APPLYING A VOLTAGE ACROSS $\Delta V = V_{out} - V_{in}$, AND TRYING TO INDUCE A CURRENT. WHEN $V_{gate} = 0$, THERE IS A DEPLETION LAYER SEPARATING n & p SEMICONDUCTORS $\longrightarrow$ LOW CURRENT. HOWEVER, APPLYING A GATE VOLTAGE BUILDS UP CHARGE IN THE METAL, WHICH INDUCES A FIELD BELOW THE (INSULATING) OXIDE

$\longrightarrow$ ATTRACTS NEGATIVE CHARGE TO AREA BENEATH GATE. FOR $V > V_{threshold}$, ACTS AS A BRIDGE BETWEEN V_{in} & V_{out}

$\longrightarrow$ AMPLIFIER!