EE40
Lecture 18
Josh Hug

8/06/2010

Logistics

- HW8 due today @5PM – short but tough
- Mini-midterm 3 next Wednesday
  - 80/160 points will be a take-home set of design problems which will utilize techniques we’ve covered in class
    - Posted online
  - Other 80/160 will be an in class midterm covering HW7 and HW8
- Final will include Friday and Monday lecture, Midterm won’t
  - Design problems will provide practice

Project 2

- Project 2 demos next Wednesday (after midterm), need two things to be "done":
  - **Check-off**: Verifying that your circuit works - can optionally be done before Wednesday if you're worried about circuit breaking before presentation
  - **Presentation**: Asking you questions about why your circuit works
  - **No lab report**
- Presentation will be Wednesday in lab
  - 1:15 PM until we're done (~3:00 PM?)
  - Cooper, Onur, and I will walk around asking questions
  - Bring your circuit even if function is checked-off

Project 2

- Booster lab actually due next week
  - For Booster lab, ignore circuit simulation, though it may be instructive to try the Falstad simulator
- Project 2 demos next Wednesday (after midterm)

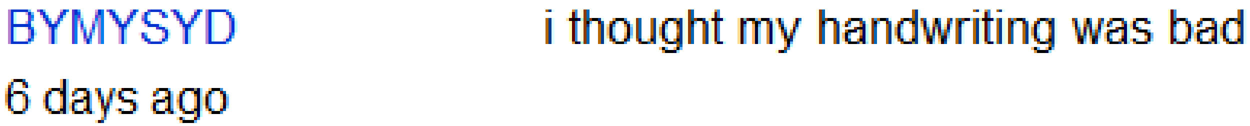
EE40 this Summer

- We’ve covered a terrifyingly large number of things for only 7 weeks
- By this time last semester, they had just finished RC and RL circuits and hadn’t started phasors yet, we’ve done all that and:
  - Phasors
  - Transfer Functions and Filtering
  - Real and Reactive Power
  - Bode Plots
  - Qualitatively: Integrated Circuits Manufacturing
  - Defining Digital Systems
  - MOSFET structure and 3 models of the MOSFET
  - Discussed analysis and design of transistor circuits
    - Function
    - Delay
    - Power Dissipation
  - Diode circuit analysis
- You’ll pardon me if we have a little fun…

Rewatching Lectures

- As you remember in lecture this week, I realized I like saying “kind of” and “sort of” a lot
  - I rewatched some of my lectures, and it is worse than I had feared
  - Annihilates any residual professorial gravitas remaining to a short grad student with long hair
- As expected, youtube comments are less than friendly
- Let’s set the record straight, iClicker style

BYMYSYD – we’ll start easy



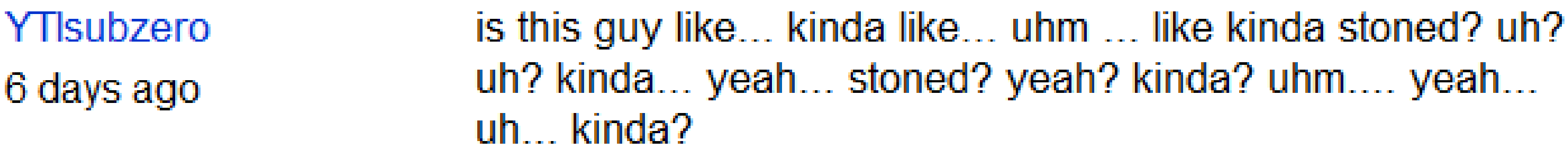
BYMYSYD

6 days ago

i thought my handwriting was bad

- How terrible is my handwriting?
  - A. Often illegible
  - B. Readable, but painful to behold
  - C. It’s fine
  - D. It’s great, also I am a liar
  - 4

YTISubZero



YTIsubzero
6 days ago

is this guy like... kinda like... uhm ... like kinda stoned? uh? uh? kinda... yeah... stoned? yeah? kinda? uhm.... yeah... uh... kinda?

- Do I seem to be high in class?
  - A. Never
  - B. Sometimes
  - C. I am basically watching Cheech and Chong give a lecture on electrical engineering [if you are too young, substitute “Harold and Kumar”]

Yokombo – Lecture on RC and RL circuits

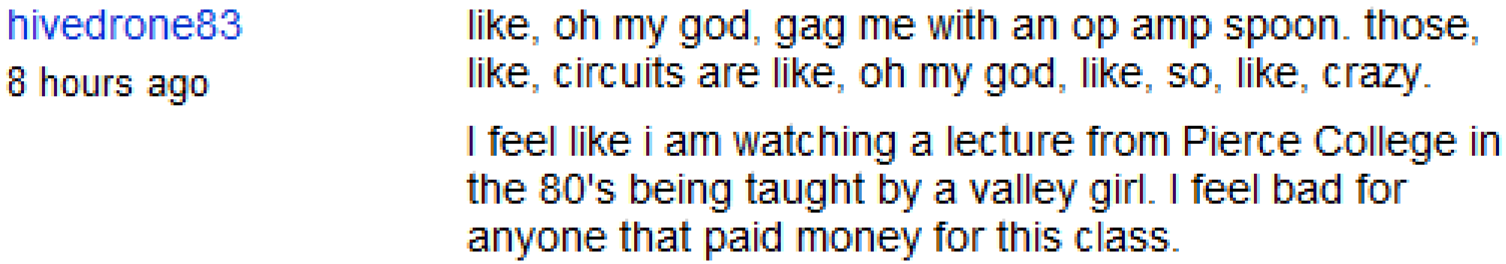
yokombo
1 day ago

Freak!

- How freakish am I?
  - A. Seem pretty normal
  - B. Normal, except the weird walk
  - C. Eccentric, in a safely professorish way
  - D. I have on occasion been afraid to come to class

Subscriptions (329)

hivedrone83



hivedrone83

8 hours ago

like, oh my god, gag me with an op amp spoon. those, like, circuits are like, oh my god, like, so, like, crazy.

I feel like i am watching a lecture from Pierce College in the 80's being taught by a valley girl. I feel bad for anyone that paid money for this class.

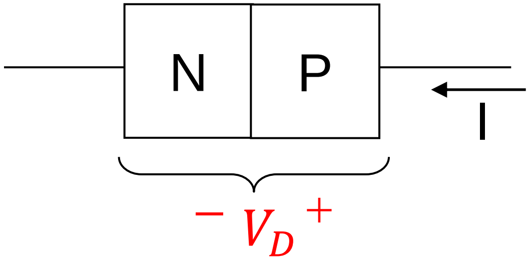
- This one was pretty funny.

Today

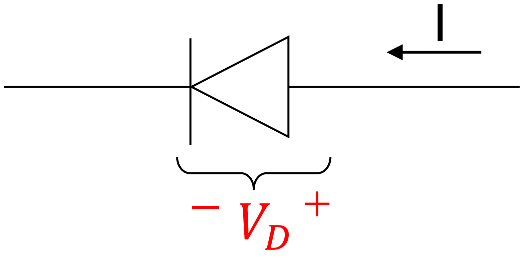
- Intro to semiconductor physics
- Diodes and PN-Junctions

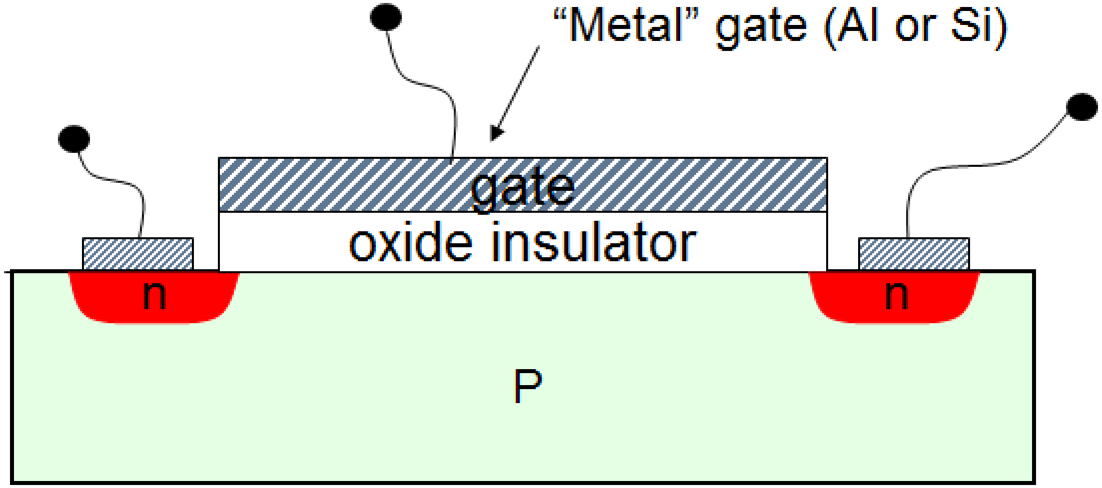
Semiconductor Devices

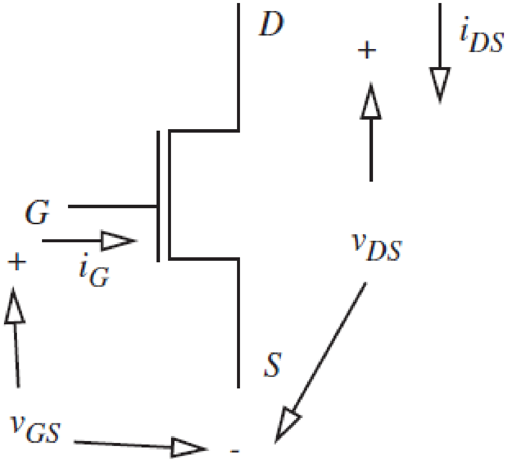
Physical Device



Symbol



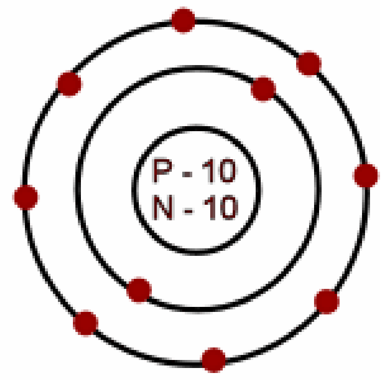




- What are “P” and “N”?
  - Magic?
  - Alchemy?

Atomic Structure

- Electrons are organized into DISCRETE orbitals, basically a nested set of shells
- If you rememe**e**ber high school chemistry:
  - Neon's electronic subshells: $1s^2 2s^2 2p^6$

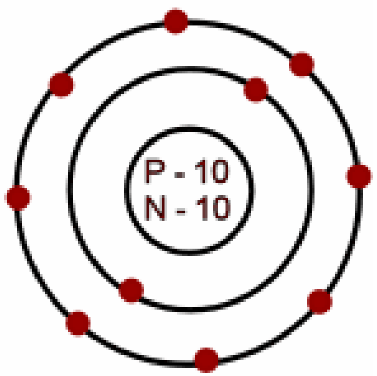


- The existence of these shells plays a key role in conductivity. It is hard to give an electron to someone with no room to hold it.

http://www.iq.poquoson.org/6sci/atoms/neonA.gif

Valence Shells

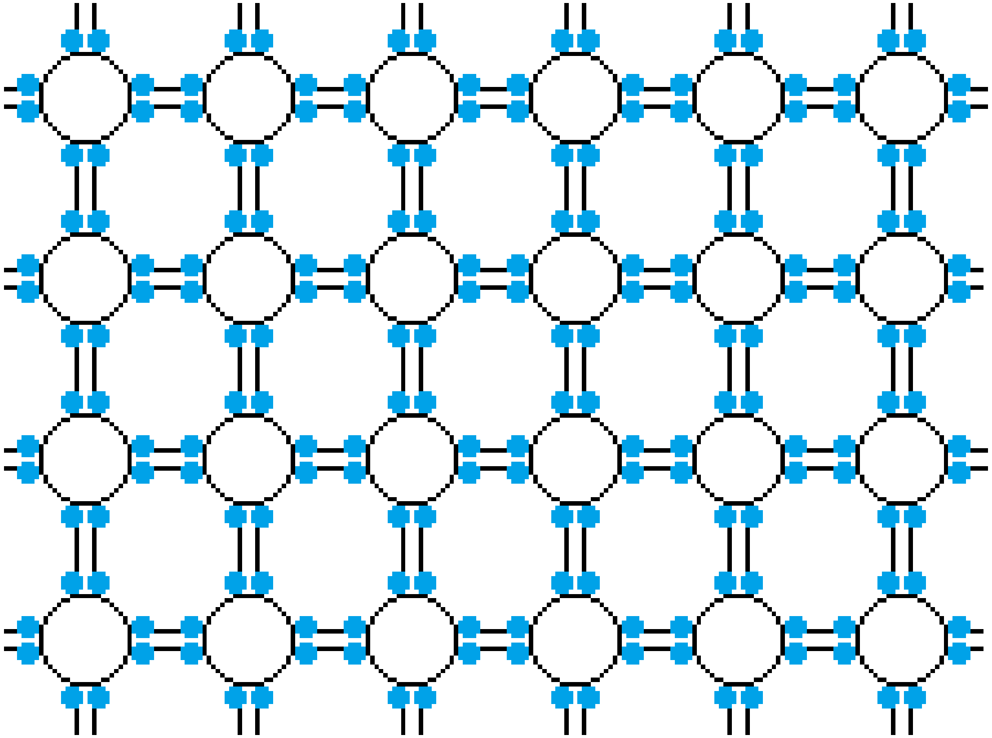
- Differently put: When you apply an electric field, the electrons want to speed up
- They’re close to nuclei, so they have to follow the rules: Only discrete energy levels (even when transiting across the material)



- Can’t go up to the next level, because the electric field can’t get them that high

Classification of Materials: Insulators

- Solids in which all electrons are tightly bound to atoms are **insulators**.
  - e.g. **Neon**: applying an electric field will tend to do little, because it is hard for an electron to move in to your neighbors valence shell.



Electrons in Conductors and Insulators

- Solids with “free electrons” – that is electrons not directly involved in the inter-atomic bonding- are the familiar **metals** (Cu, Al, Fe, Au, etc)
  - Often 1 free electron per atom

- Solids with no free electrons are the familiar **insulators** (glass, quartz crystals, ceramics, etc.)

Resistance of a Metal vs. Temperature

- How does the resistance of a metal vary with temperature?
  - A. Resistance **increases** as temperature goes up
  - B. Resistance **decreases** as temperature goes up

Why?

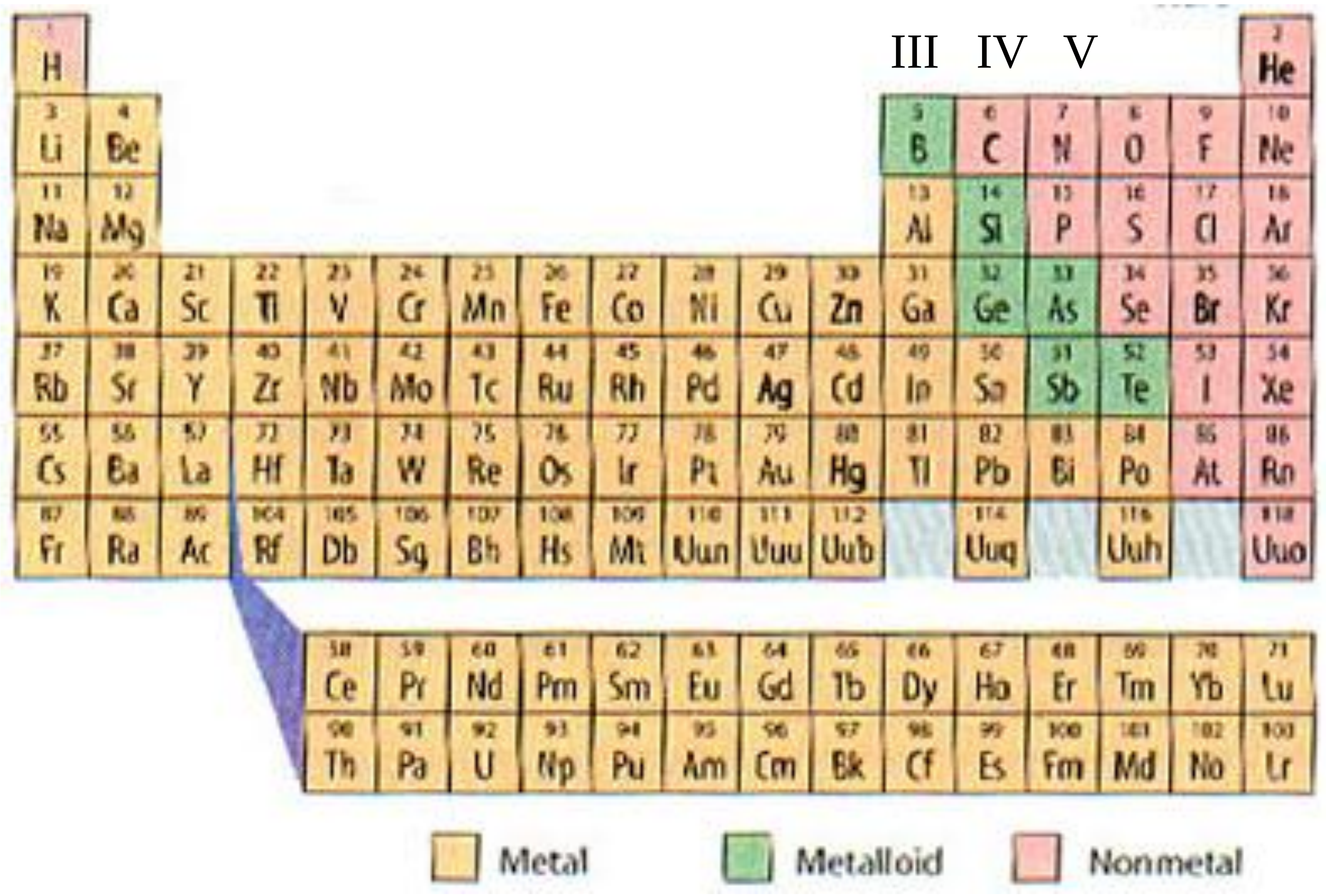
- In a hot metal everything is moving around a lot more
- Electrons trying to get from point a to point b are constantly running into this big disorderly surface fluctuating around them
- A very cold metal, by contrast, sits relatively still, so electrons can zoom along the lattice unhindered

Electrons in Semiconductors

- Silicon is an insulator, but at higher temperatures some of the bonding electrons can get free and make it a little conducting – hence the term "**semiconductor**"

- Pure silicon is a poor conductor (and a poor insulator). It has 4 valence electrons, all of which are needed to bond with nearest neighbors. No free electrons.

The Periodic Table

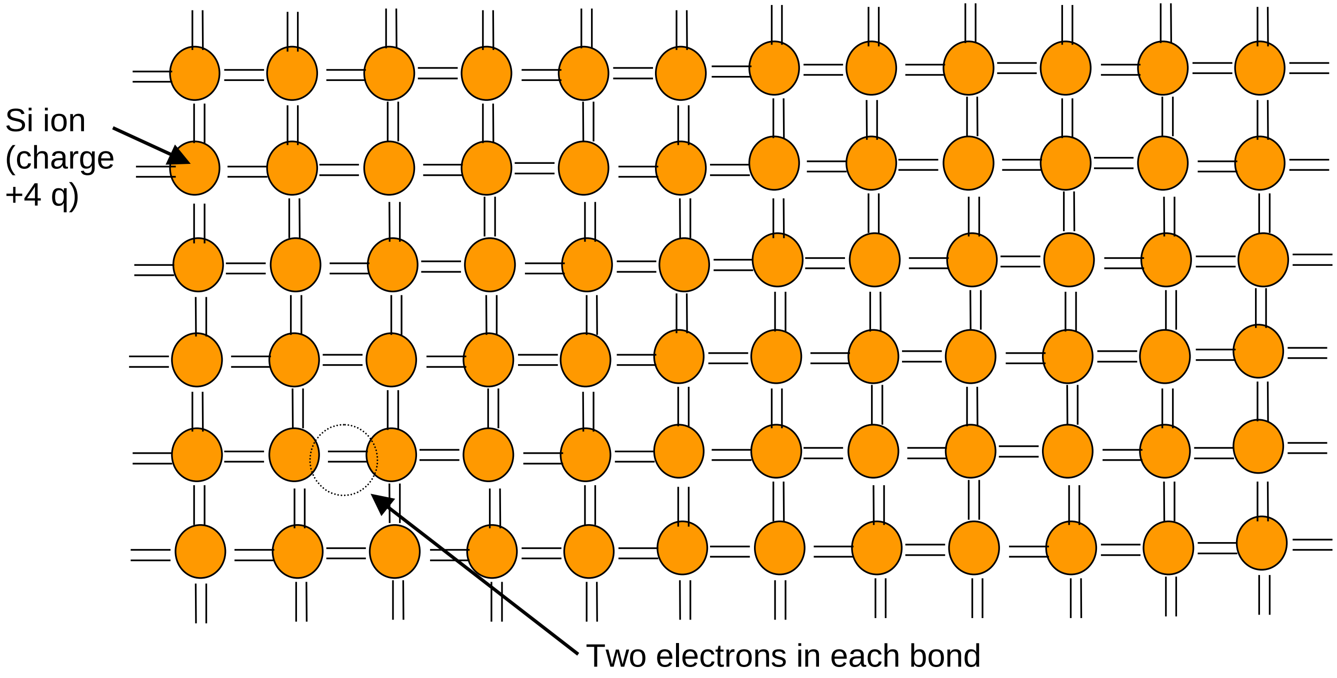


												III	IV	V			
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub		114 Uuq		116 Uuh		118 Uuo
				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

🟨 Metal 🟩 Metalloid 🟥 Nonmetal

Electronic Bonds in Silicon

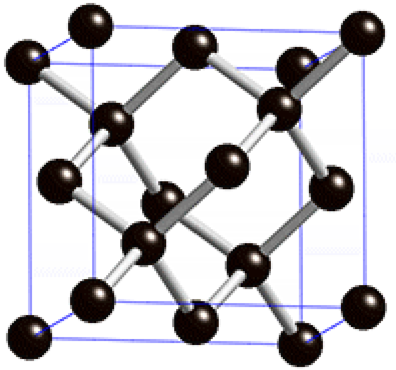
2-D picture of perfect crystal of pure silicon; double line is a Si-Si bond with each line representing an electron

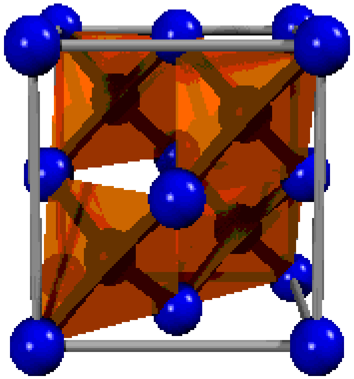


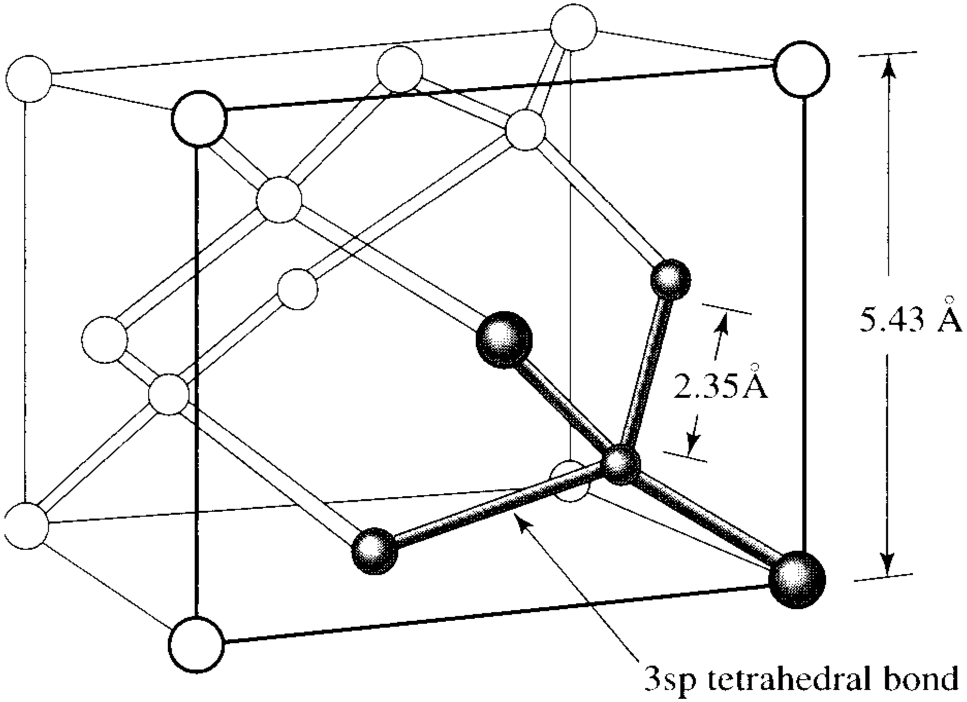
Essentially no free electrons, and no conduction → insulator

Actual structure is 3-dimensional tetrahedral- just like carbon bonding in organic and inorganic materials.

Crystal Structure of Silicon







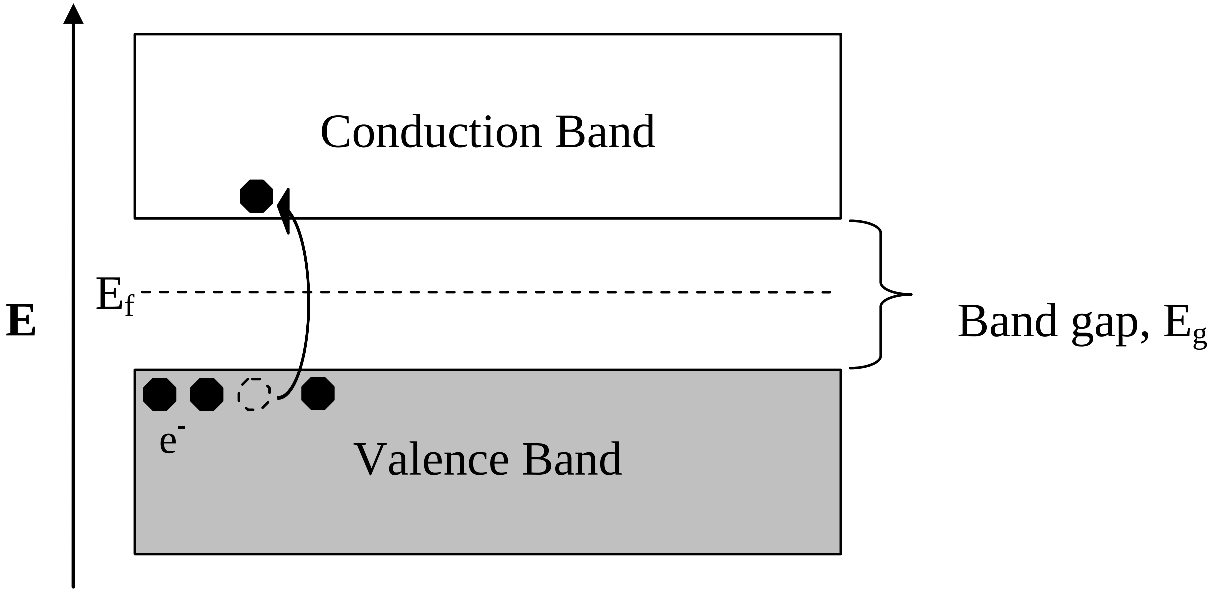
How dense?

$$\approx 5 \times 10^{22}/cm^3$$

Animated Movies from wikipedia

Bandgap

- Electrons are mobile in the "**conduction band**", but in the **"valence band"**, they are locked in (because valence band is full)
- The excited electrons move from the valence band into the conduction band
  - When there is an extremely strong electric field
  - Or when the crystal is illuminated with photons whose energy is larger than the bandgap energy
  - Or when the crystal is sufficiently heated

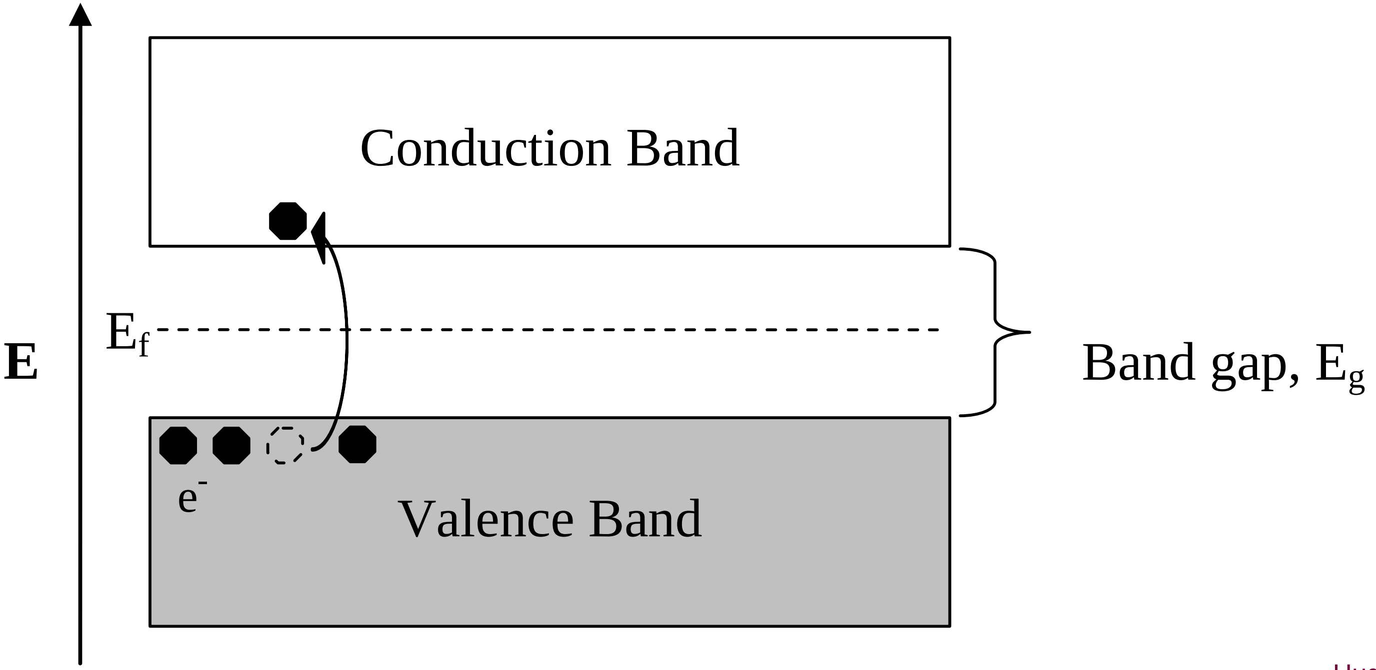


Semiconductors

- Resistance DECREASES with temperature
  - Yes, everything is jostling around more!
    - More electrons can be shaken free to move around
    - While traveling, these electrons endure scattering as they repeatedly run into the jostling landscape. Heat exacerbates this
  - You can't win if you don't play
    - More players
    - Worse odds
    - Still get more absolute number of successes

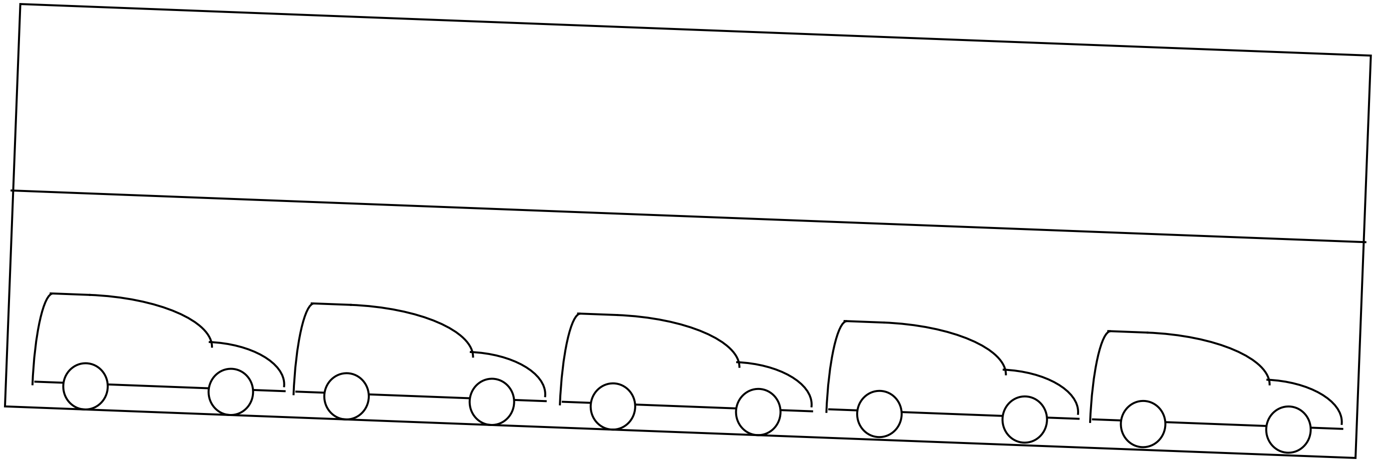
Bandgap

- If an electron is excited into the conduction band, it can move
- Interestingly, the “hole” left behind at the bottom can also move.
  - No actual hole particle, but the ensemble of electrons can move as a whole [no pun intended]



Shockley’s Parking Garage Analogy for Conduction in Si

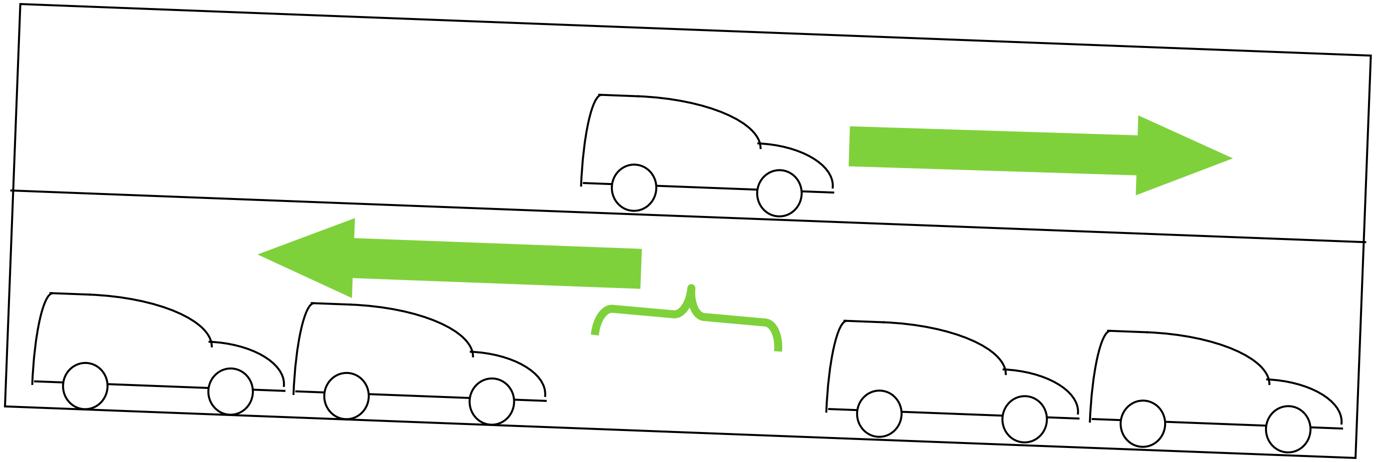
Two-story parking garage on a hill:



If the lower floor is full and top one is empty, no traffic is possible. Analog of an insulator or a non-excited semiconductor. All electrons are locked up.

Shockley's Parking Garage Analogy for Conduction in Si

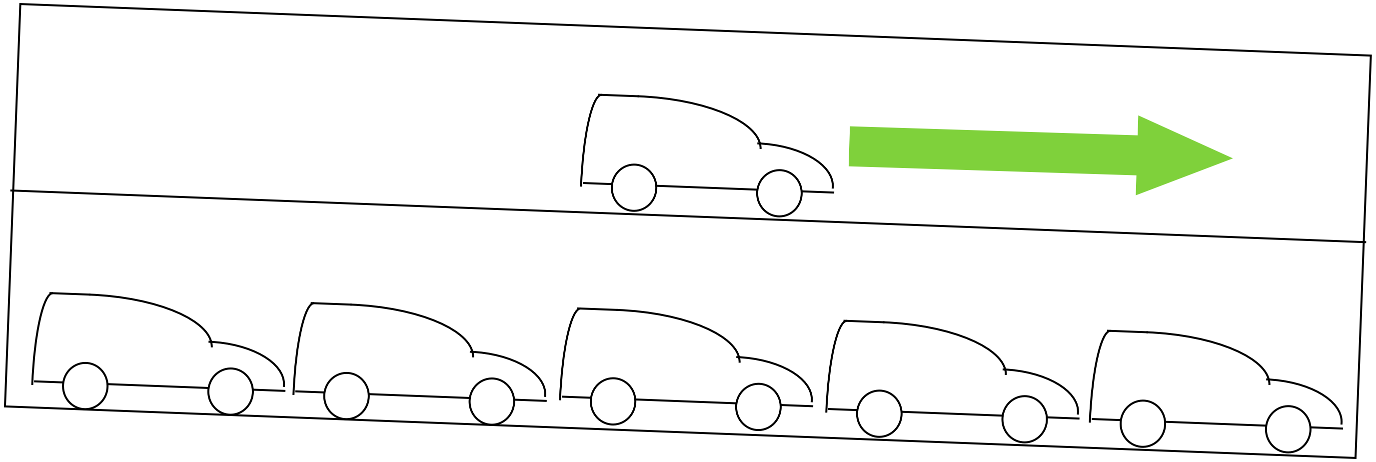
Two-story parking garage on a hill:



If one car is moved upstairs, it can move AND THE HOLE ON THE LOWER FLOOR CAN MOVE. Conduction is possible. Analog to warmed-up semiconductor. Some electrons get free (and leave "holes" behind).

Shockley's Parking Garage Analogy for Conduction in Si

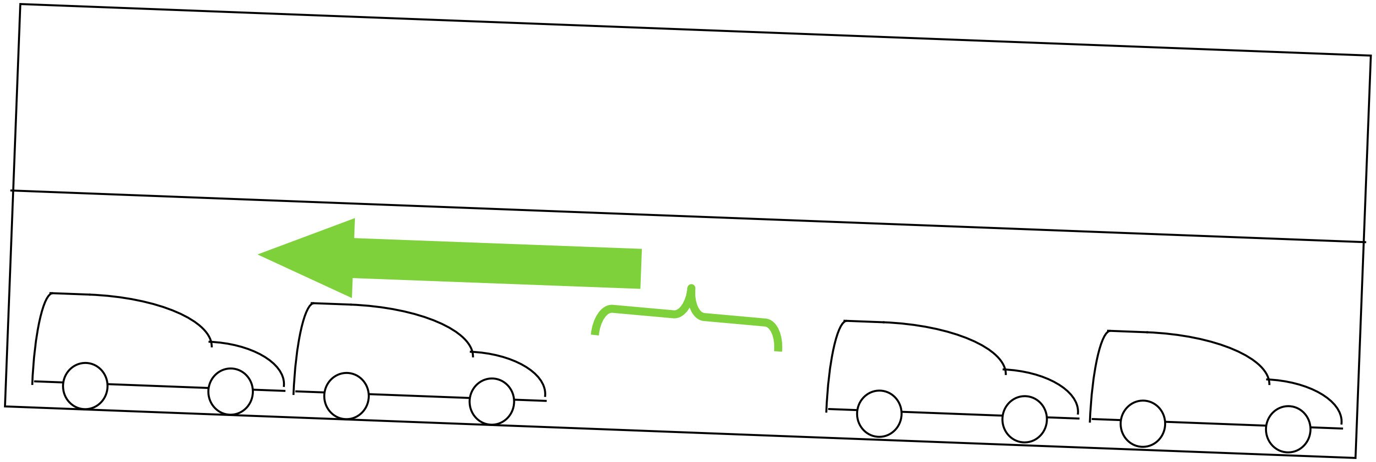
Two-story parking garage on a hill:



If an extra car is "donated" to the upper floor, it can move. Conduction is possible. *Analog to **N-type semiconductor.*** (An electron donor is added to the crystal, creating free electrons).

Shockley's Parking Garage Analogy for Conduction in Si

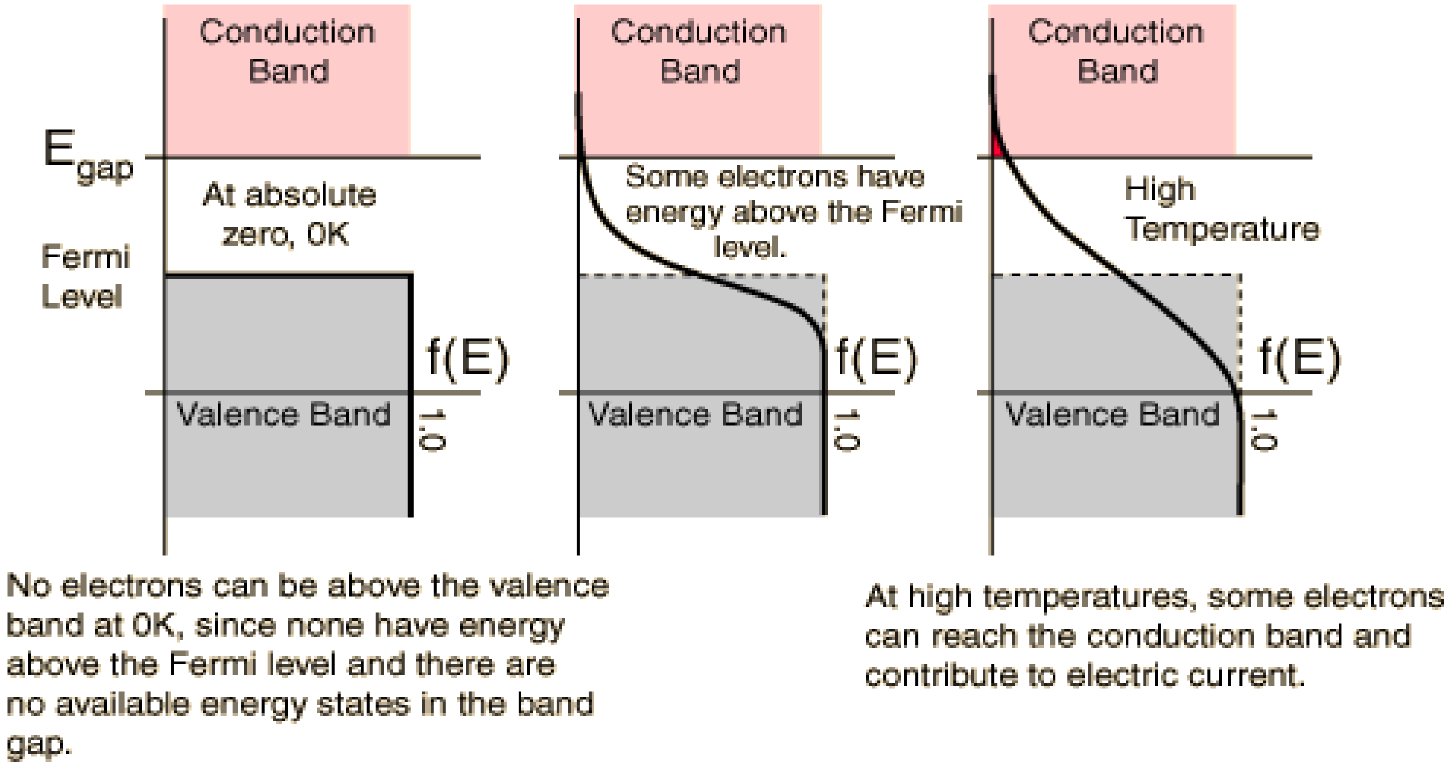
Two-story parking garage on a hill:



If a car is removed from the lower floor, it leaves a HOLE which can move. Conduction is possible. *Analog to* ***P-type semiconductor****.* (Acceptors are added to the crystal, “consuming” bonding electrons,creating free holes).

Fermi-Dirac Distribution

- Fermi-Dirac function provides the probability that an energy level is occupied by a fermion which is under thermal equilibrium. Electrons as well as holes are Fermions and hence obey Fermi-Dirac statistics.

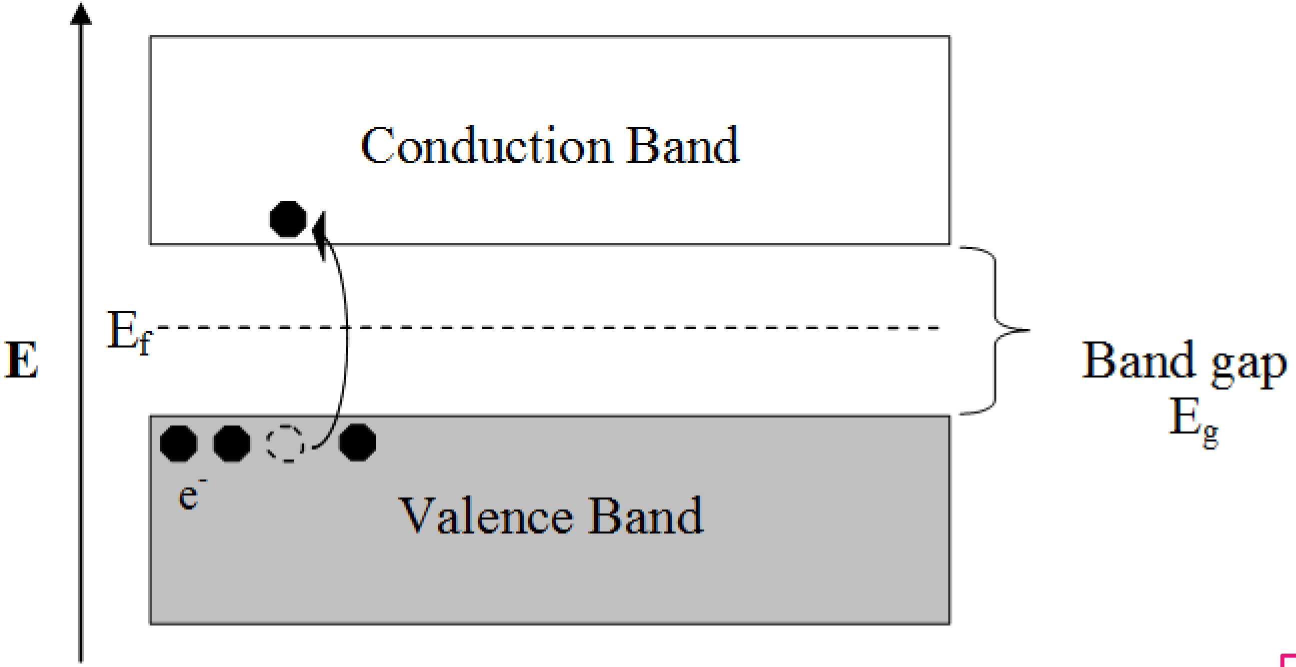


No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

At high temperatures, some electrons can reach the conduction band and contribute to electric current.

Fig. 5. Fermi function plots at absolute zero, mid-range, and high temperature.

Fermi-Dirac Distribution of Electrons and Holes



n = # electrons
p = # holes
n_i = intrinsic carrier concentration

N_C =# states in conduction band
N_V =# states in valence band
E_g =Energy gap between bands
k =Boltzman constant
T =Temperature

$$n = p$$
$$n \times p = n_i^2$$

$$n_i = \sqrt{N_c N_v e^{-\frac{E_g}{kT}}}$$

@ Room temperature: $n_i \approx 10^{10}/cm^3$

10 billion electrons seems like a lot to me

- iClicker Question: If silicon has approximately $10^{10}/cm^3$ free electrons, is that a lot compared to the number of free electrons in a cm^3 of iron?
  - A. No, a cm^3 of iron has at least 10^{20} times as many electrons
  - B. No, a cm^3 of iron has at least 10^{10} times as many electrons
  - C. They have about the same number
  - D. Silicon has at least 10^{10} as many electrons per cm^3

Density of Silicon $\approx 5 \times 10^{22}/cm^3$

How to get conduction in Si?

We must either:

1) Chemically modify the Si to produce free carriers (permanent) or

2) Transiently "induce" them by electric fields, photons, or temperature (temporary)

For the first approach, controlled impurities, "dopants", are added to Si:

Add group V elements (5 bonding electrons vs four for Si), such as phosphorus or arsenic

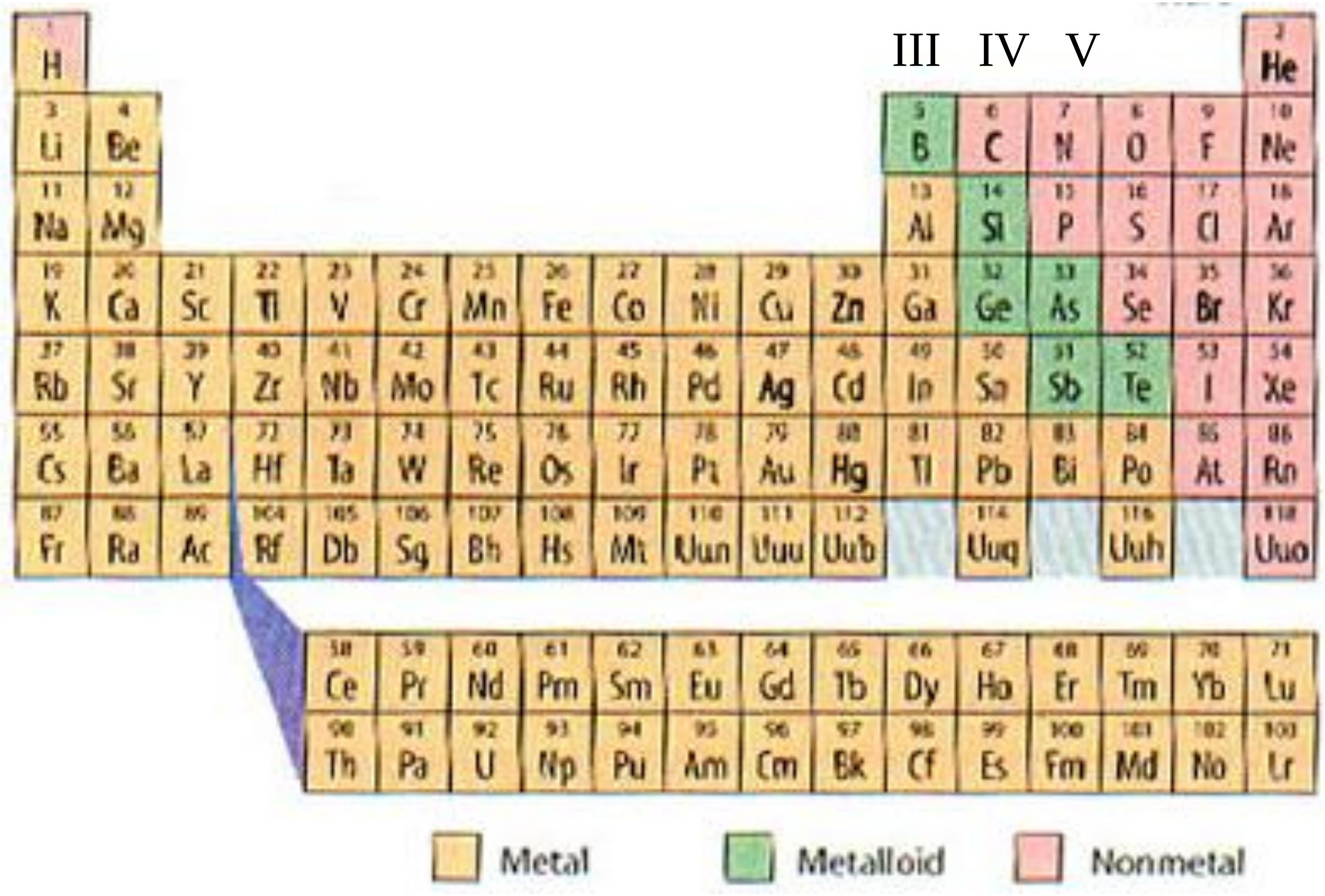
(Extra electrons produce "free electrons" for conduction.)

or

Add group III elements (3 bonding electrons), such as boron

Deficiency of electrons results in "free holes"

The Periodic Table



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37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub		114 Uuq		116 Uuh		118 Uuo
				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

🟨 Metal

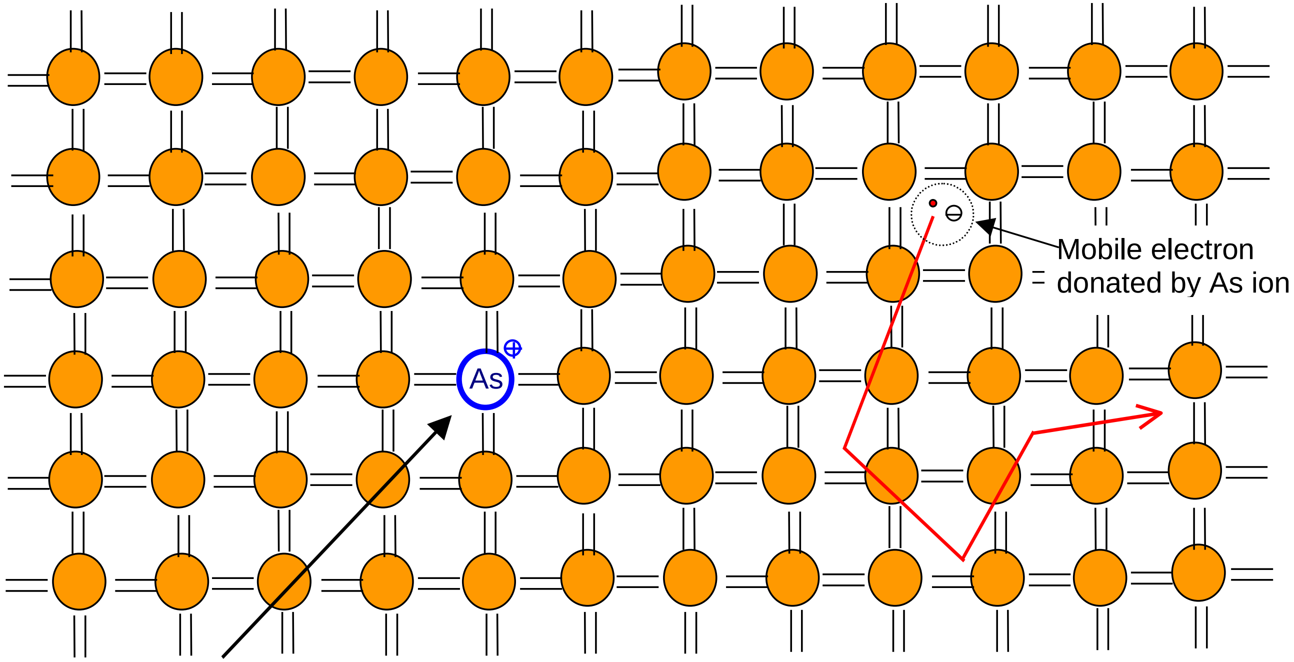
🟩 Metalloid

🟥 Nonmetal

Doping Silicon with Donors (n-type)

Donors donate mobile electrons (and thus "n-type" silicon)

Example: add arsenic (As) to the silicon crystal:



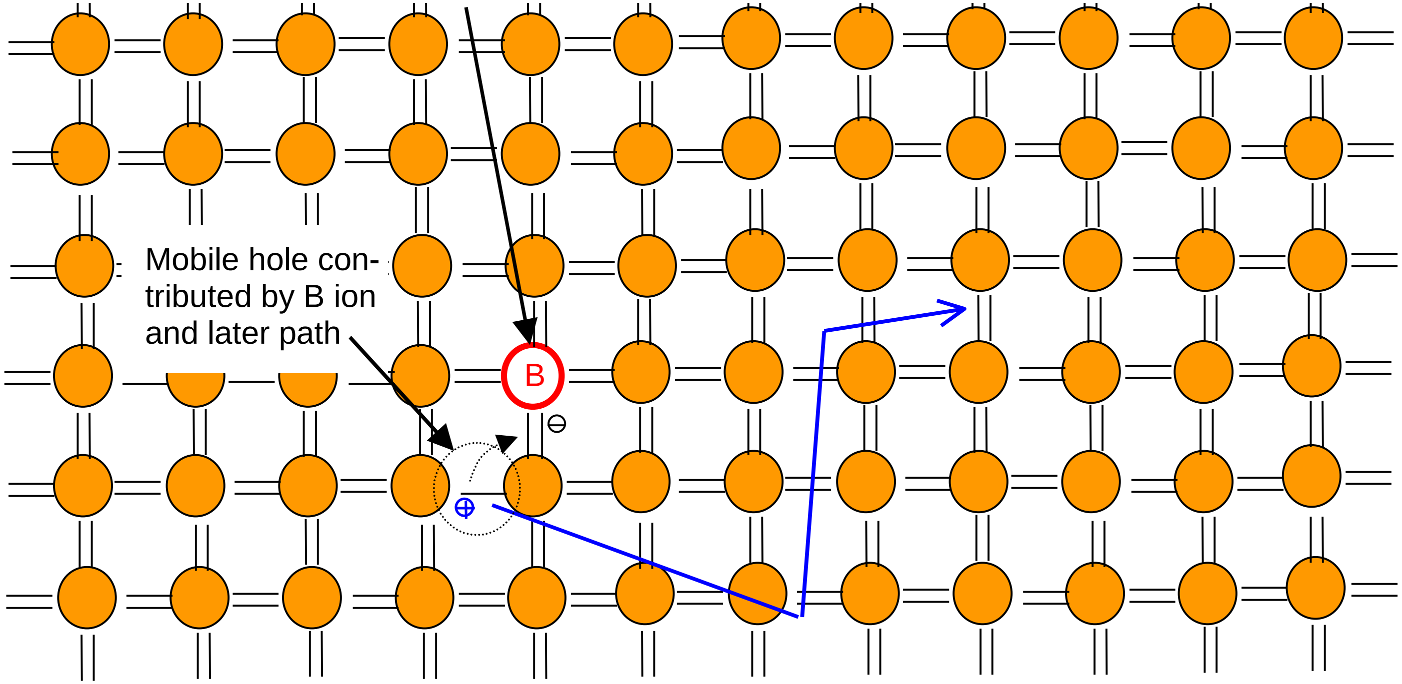
Mobile electron donated by As ion

Immobile (stuck) positively charged arsenic ion after 5th electron left

The extra electron with As, "breaks free" and becomes a free electron for conduction

Doping with Acceptors (p-type)

Group III element (boron, typically) is added to the crystal



Immobile (stuck) negative boron ion after accepting electron from neighboring bond

Mobile hole contributed by B ion and later path

The “hole” which is a missing bonding electron, breaks free from the B acceptor and becomes a roaming positive charge, free to carry current in the semiconductor.   It is positively charged.

Doping

- Typical doping densities: 10^{16}~10^{19} cm^{-3}
- Atomic density for Si: 5 x 10^{22} atoms/cm^{3}
- Dopant concentration of 10^{18} cm^{-3} is 1 in 50,000
- Doping is like
  - Two people in all of Berkeley wearing a green hat

Electron and Hole Densities in Doped Si

- Instrinsic (undoped) Si

$$\boxed{\begin{gathered} n = p = n_i \\ np = n_i^{\,2} \end{gathered}}$$

- N-doped Si
  - Assume each dopant atom contributes one electron

$$n = N_d$$
$$p = n_i^2 / N_d$$

- p-doped Si
  - Assume each dopant atom contributes one hole

$$p = N_a$$
$$n = n_i^2 / N_a$$

Doping Example

- Undoped silicon has an intrinsic carrier concentration of roughly 10^{10} electrons/cm^3, and 10^{10} holes$/cm^3$
- If we add phosphorus (group V atom with an extra electron) we get n-type silicon
- If we add 10^{15} atoms of phosphorus per cm^3, our new electron concentration is roughly 10^{15} electrons per cm^3
- n_i^2 remains constant (trust me)
- New hole concentration:
  - $p = \frac{10^{20}/cm^6}{10^{15}/cm^3} = 10^5/cm^3$

$$n = N_d$$

$$n_i = np = 10^{10}/cm^3$$

$$p = n_i^2/N_d$$

- Will new material be more or less conductive?

Summary of n- and p-type silicon

Pure silicon is an insulator. At high temperatures it conducts weakly.

If we add an impurity with extra electrons (e.g. arsenic, phosphorus) these extra electrons are set free and we have a pretty good conductor (n-type silicon).

If we add an impurity with a deficit of electrons (e.g. boron) then bonding electrons are missing (holes), and the resulting holes can move around … again a pretty good conductor (p-type silicon)

Now what is really interesting is when we join n-type and p-type silicon, that is make a pn junction. It has interesting electrical properties.

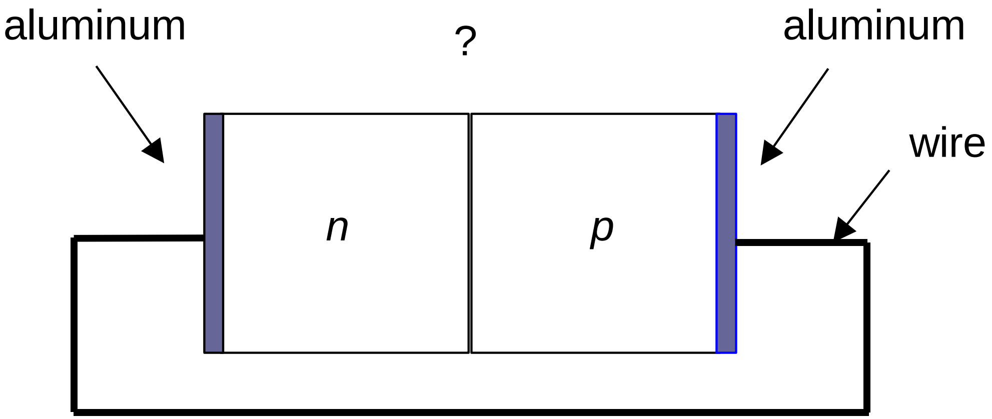
Junctions of n- and p-type Regions

p-n junctions form the essential basis of all semiconductor devices.

A silicon chip may have 10^8 to 10^9 p-n junctions today.

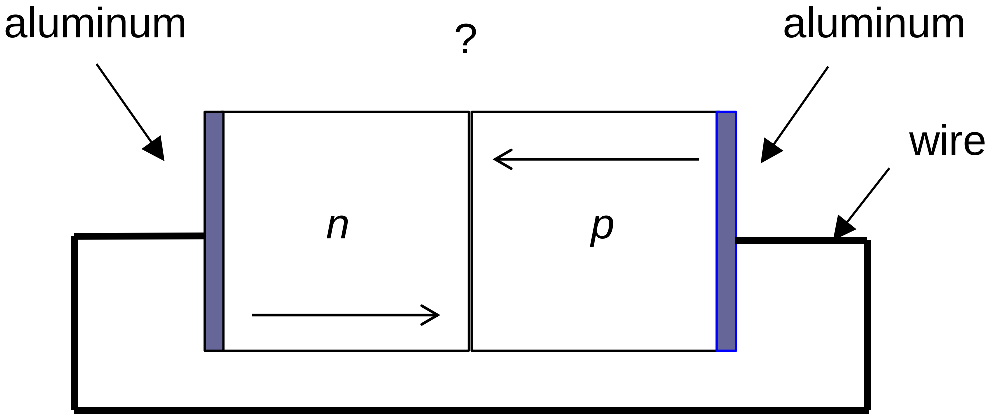
How do they behave?   What happens to the electrons and holes?
What is the electrical circuit model for such junctions?

***n* and *p* regions are brought into contact :**



Junctions of n- and p-type Regions

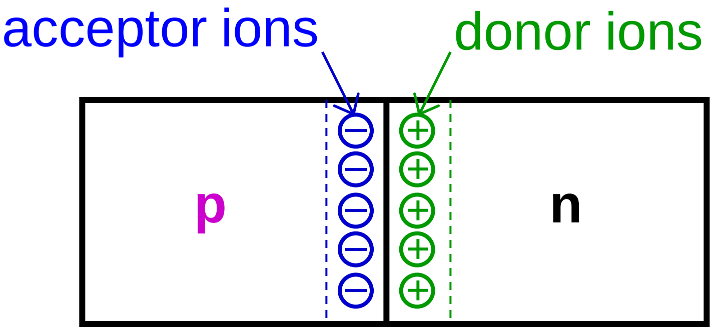
***n* and *p* regions are brought into contact :**



- Electron are running around randomly on the n side, and holes on the p side **[diffusion]**
- Before the regions are touching, they are in a homogeneous box just rearranging themselves meaninglessly
- Once regions touch, electrons and holes mix

Depletion Region *Approximation – Aha!*

- When the junction is first formed, mobile carriers ***diffuse*** across the junction (due to the concentration gradients)
  - Holes diffuse from the p side to the n side, leaving behind negatively charged immobile acceptor ions
  - Electrons diffuse from the n side to the p side, leaving behind positively charged immobile donor ions

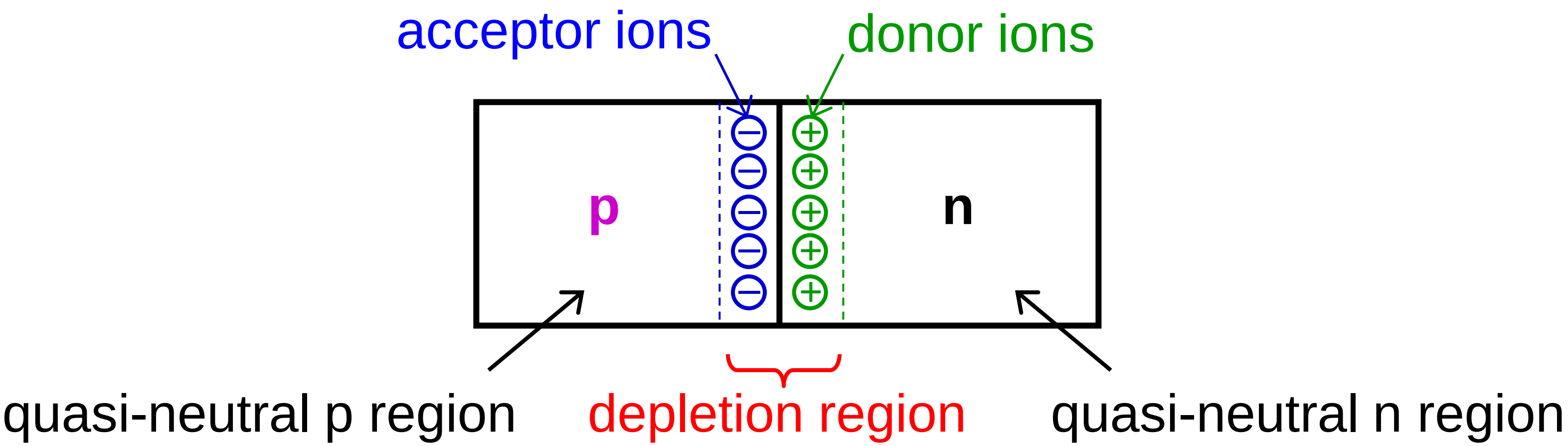


→A region depleted of mobile carriers is formed at the junction.

- The space charge due to immobile ions in the depletion region establishes an electric field that opposes carrier diffusion.

Charge Density Distribution

Charge is stored in the depletion region.



acceptor ions

donor ions

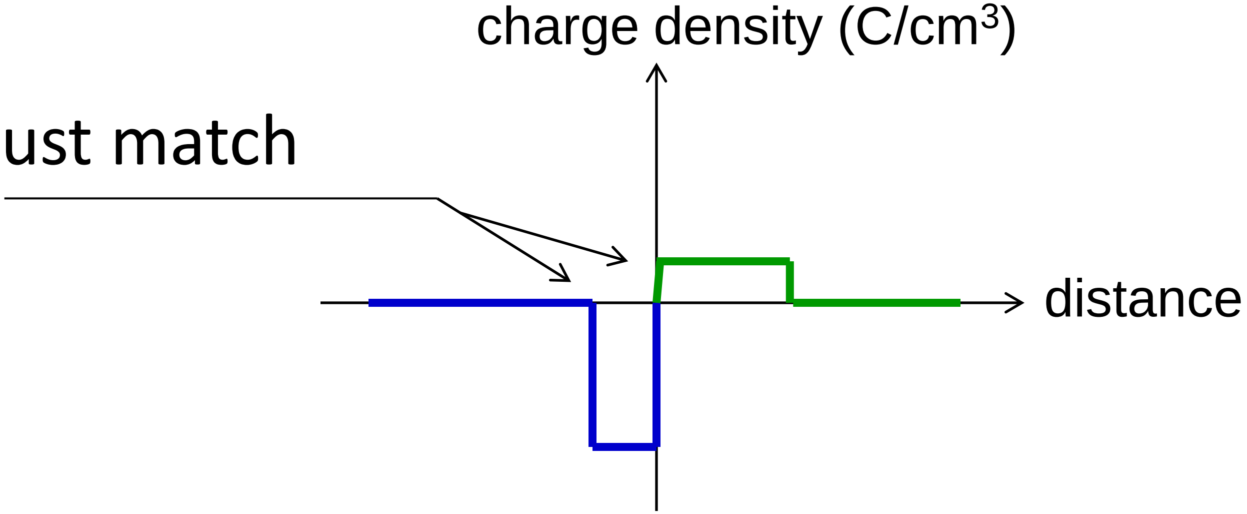
p

n

quasi-neutral p region

depletion region

quasi-neutral n region



charge density (C/cm^3)

distance

Area must match

Two Governing Laws

Gauss's Law describes the relationship of charge (density) and electric field: **Electric field is integral of charge density**

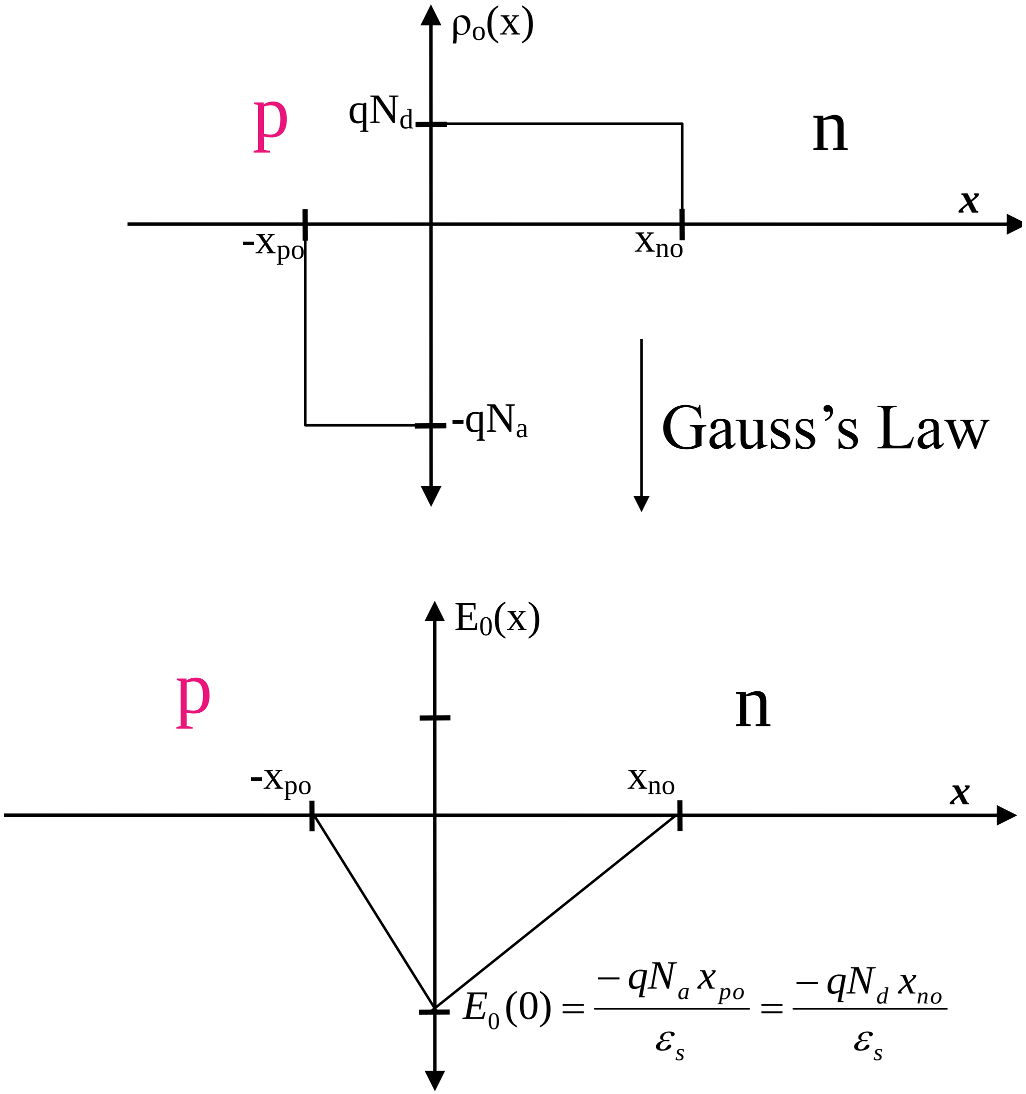
$$\boxed{\frac{dE}{dx}=\frac{\rho}{\varepsilon}}$$

$$\boxed{E(x)-E(x_0)=\frac{1}{\varepsilon}\int_{x_0}^{x}\rho(x)dx}$$

Poisson's Equation describes the relationship between electric field distribution and electric potential: **Potential is integral of negative electric field.**

$$\boxed{\phi(x)-\phi(x_0)=\int_{x_0}^{x}-E(x)dx}$$

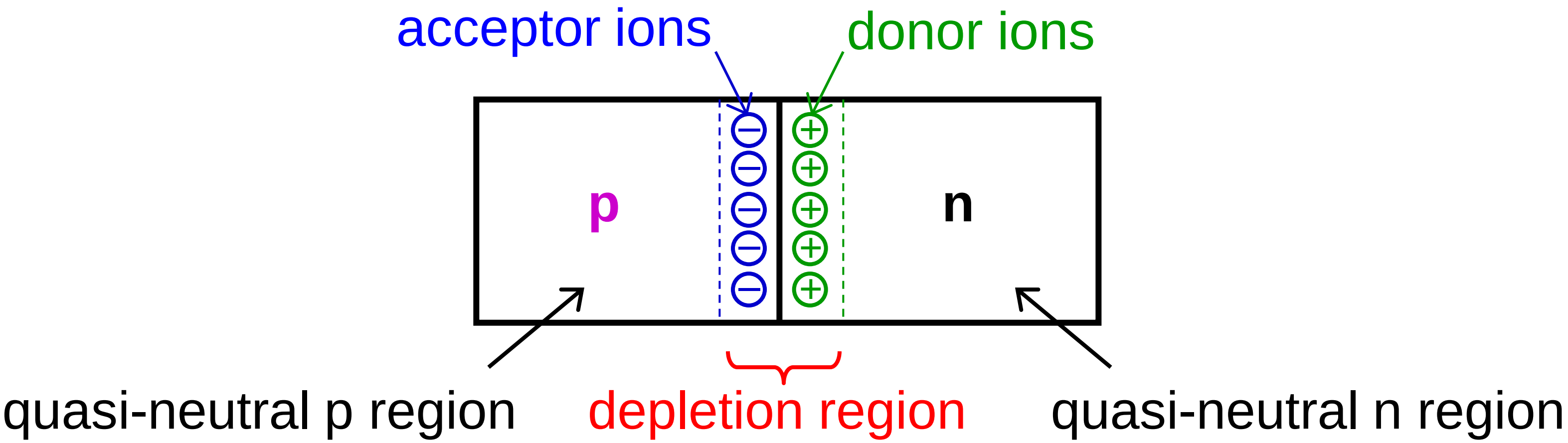
Electric Field from Electric Charge

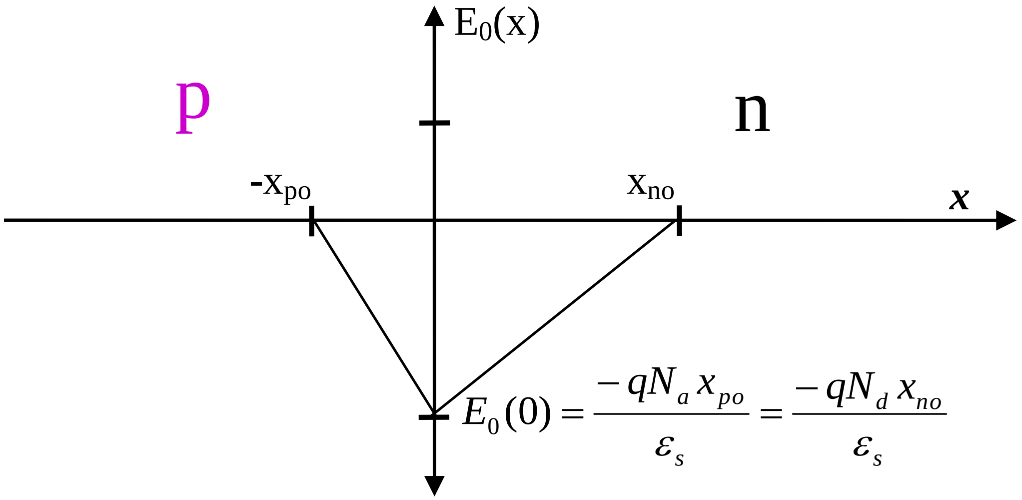


$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

Why do we care about electric field?

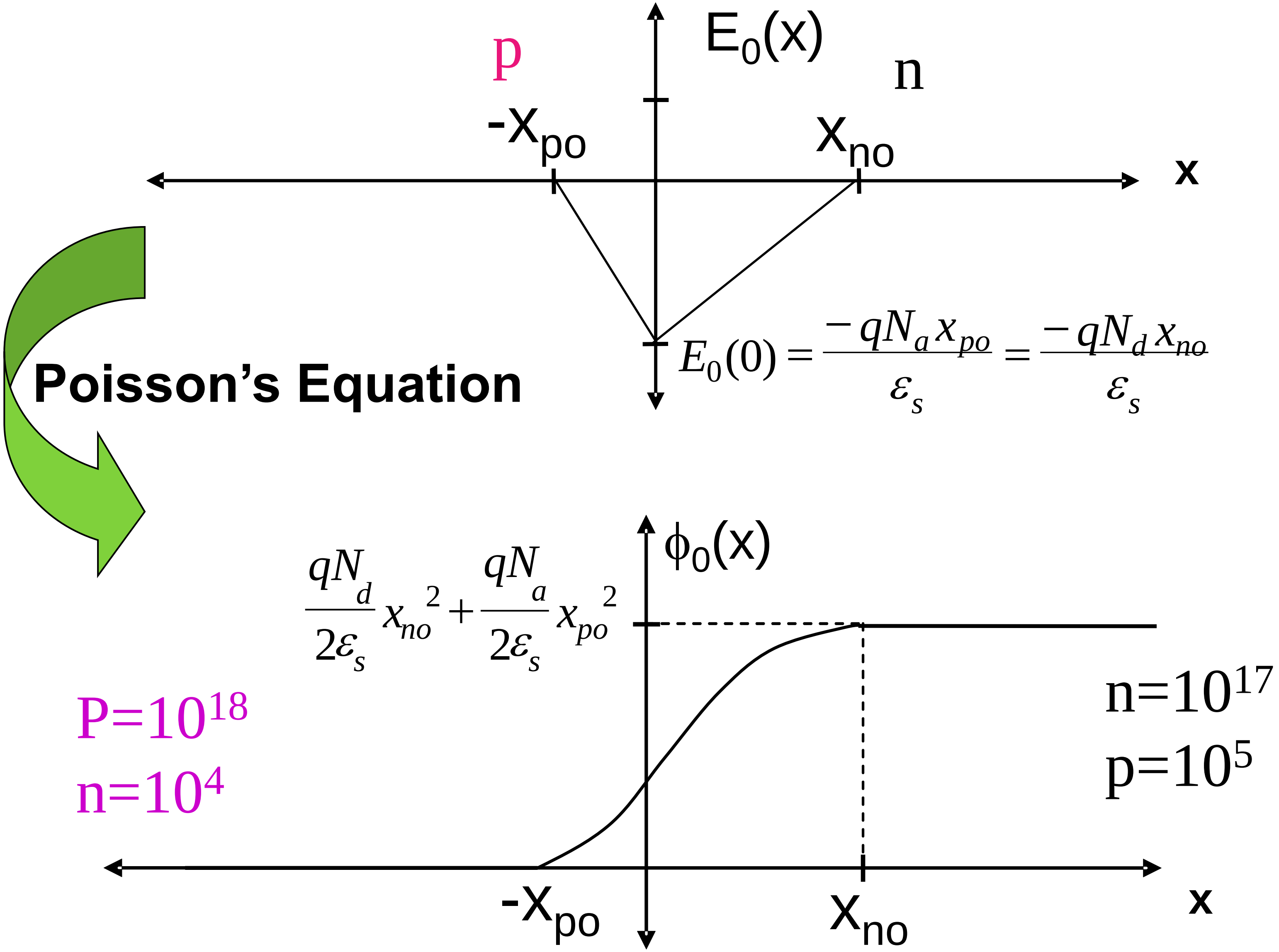
- Tells us how a free charge will behave





$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

Electric Potential from Electric Field



$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

Poisson's Equation

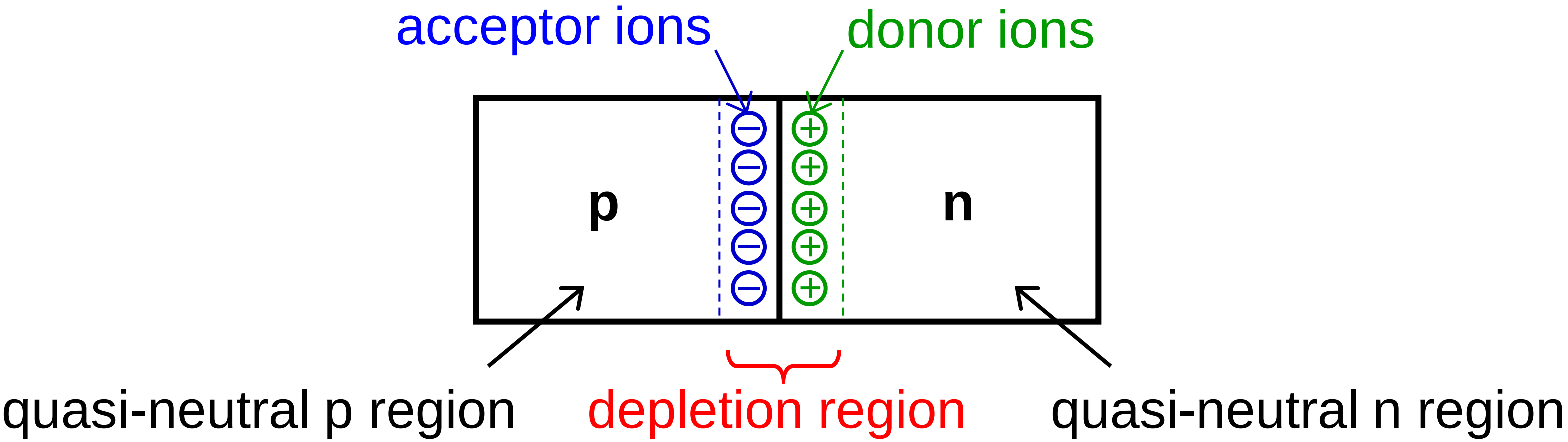
$$\frac{qN_d}{2\varepsilon_s} x_{no}^2 + \frac{qN_a}{2\varepsilon_s} x_{po}^2$$

$P = 10^{18}$
$n = 10^4$

$n = 10^{17}$
$p = 10^5$

Why do we care about potential?

- Another view of free charge movement



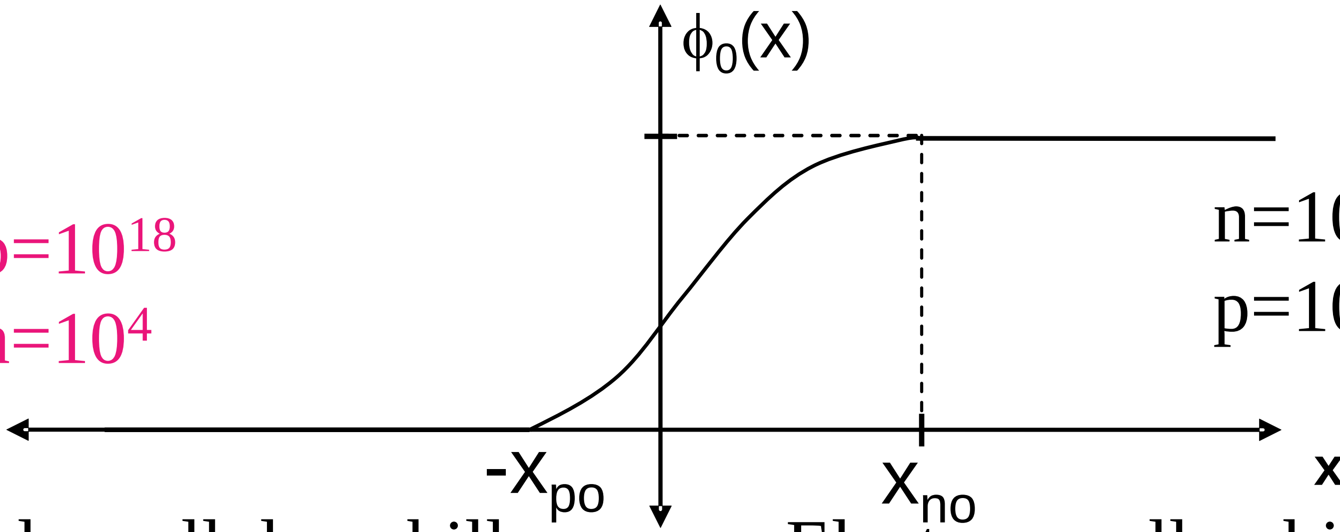
acceptor ions

donor ions

quasi-neutral p region

depletion region

quasi-neutral n region



$p=10^{18}$

$n=10^{4}$

$n=10^{17}$

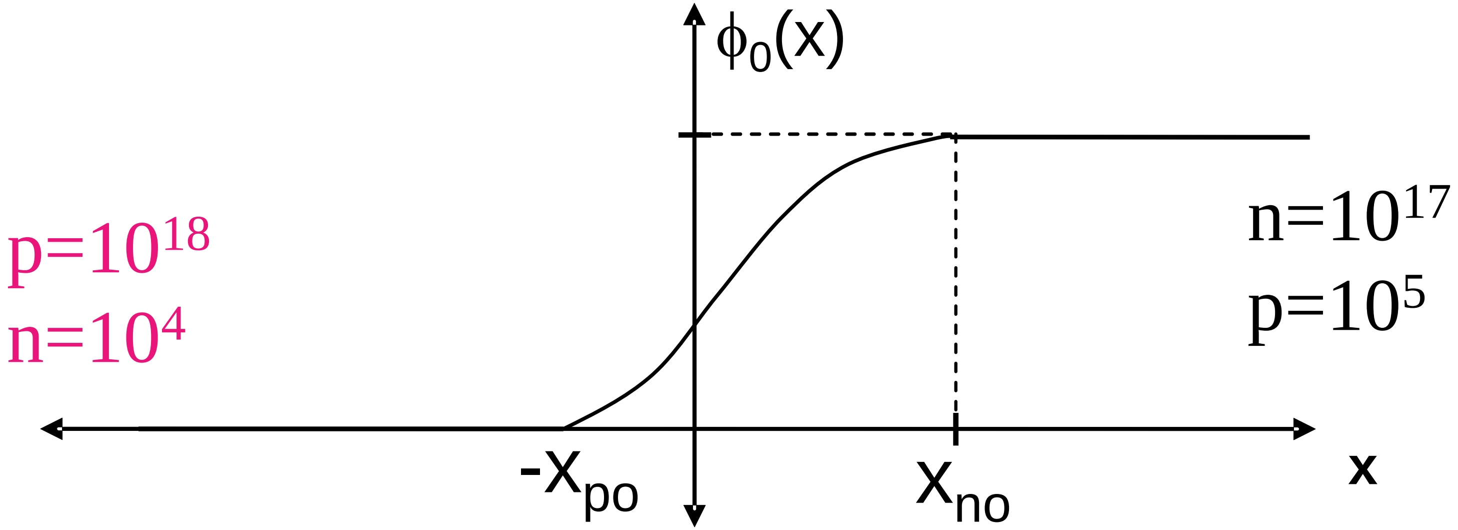
$p=10^{5}$

Holes roll downhill

Electrons roll uphill

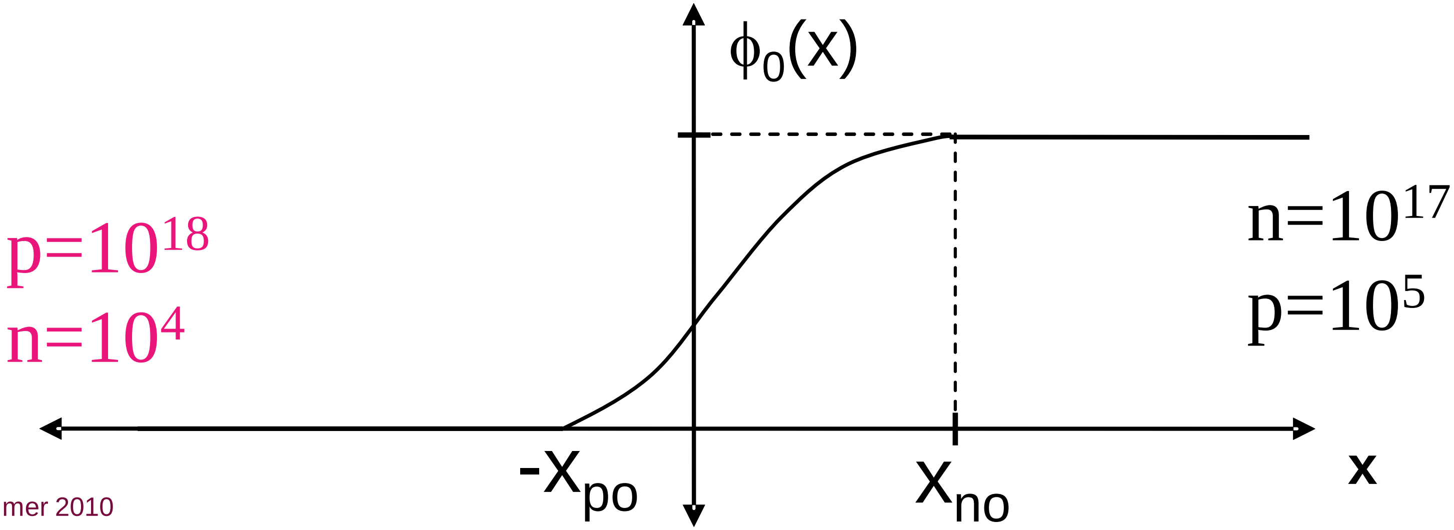
Diffusion vs. Drift

- Free holes on the p-side will randomly wander **(diffuse throughout)** the flat part of the plane
- On the p-side, holes are the **majority carrier**
- A very small number of them will get lucky and will roll up the hill
- This is the **“hole diffusion current”**

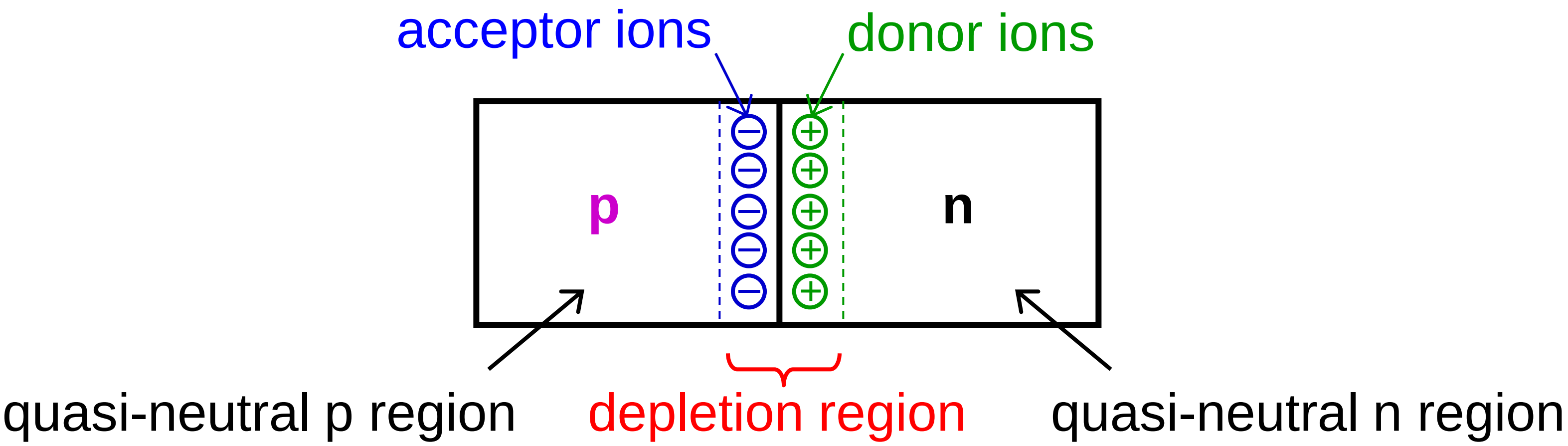


Diffusion vs. Drift

- Free holes on the n-side will randomly wander (diffuse throughout) the flat part of the plane
- On the n-side, holes are the **minority carrier**
  - If they happen to hit the sloping part of the hill, they will **DRIFT** down the hill because of the electric field
- This is the "**hole drift current**"

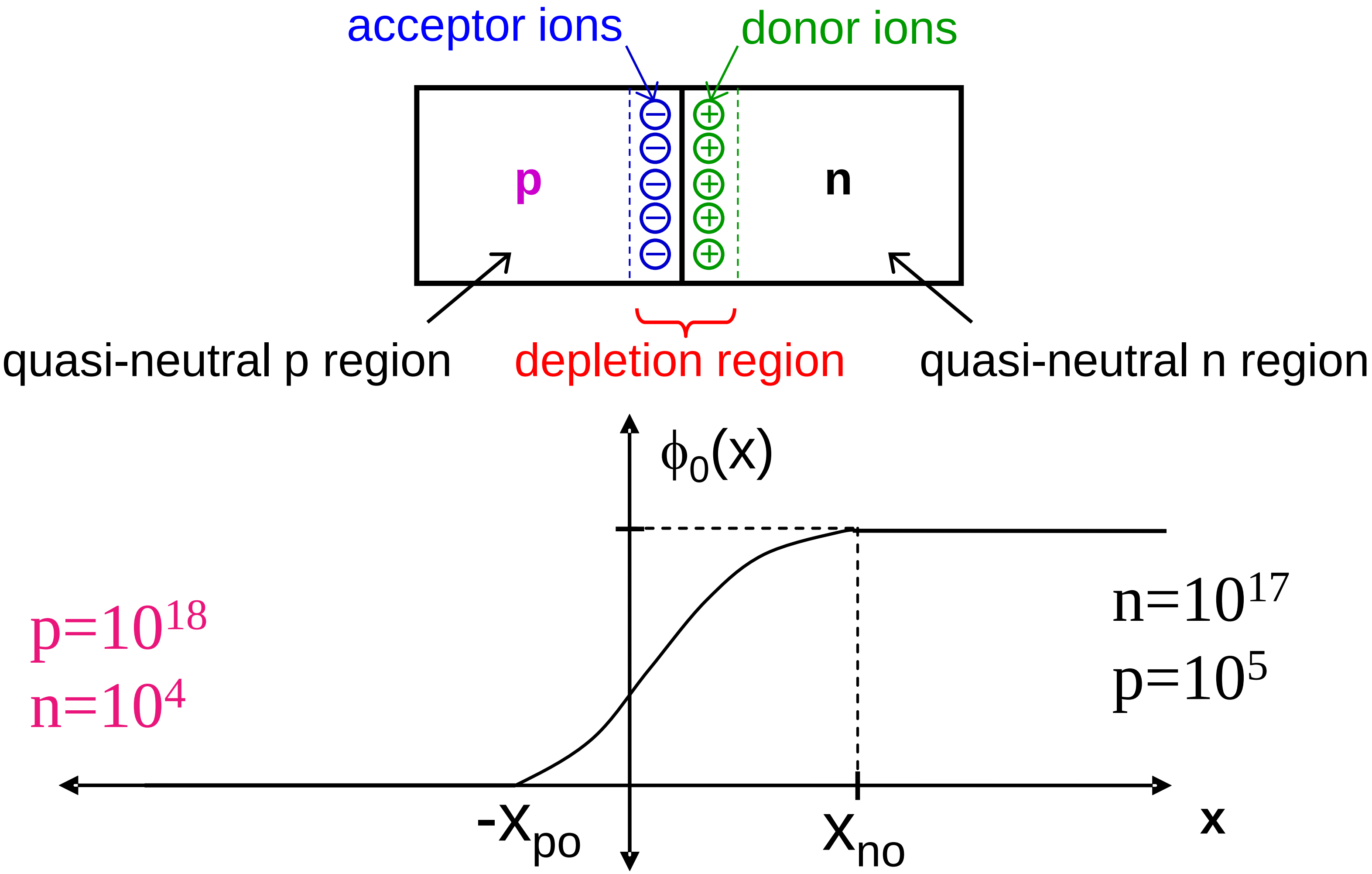


Diffusion vs. Drift



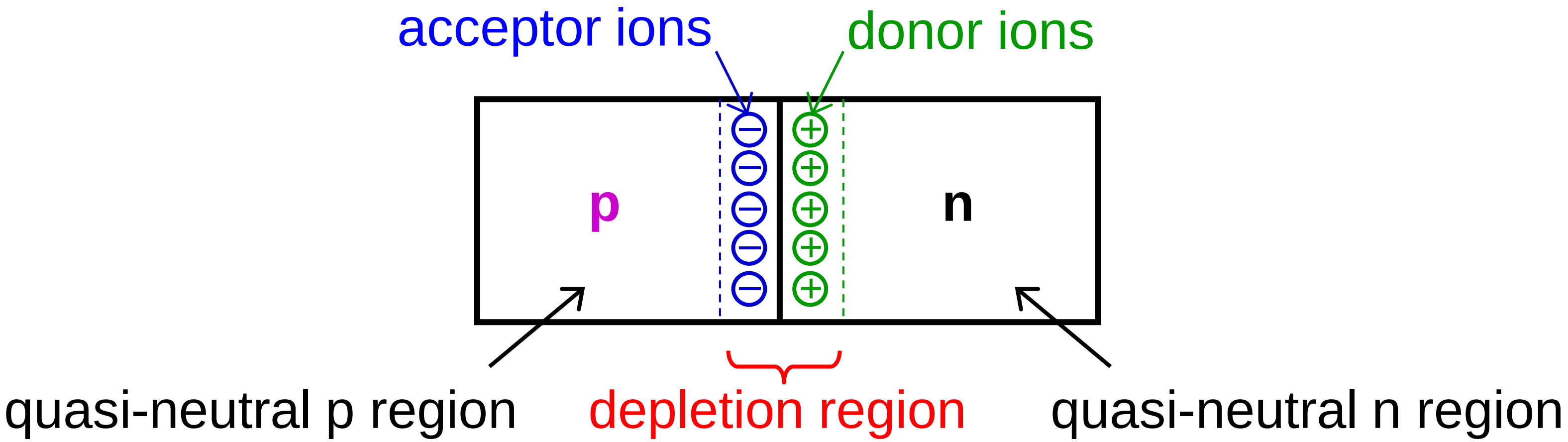
- Holes on the right are “**drifters**”, aimless wanderers coasting along who find themselves being moved by forces of the universe beyond their control
- Holes on the left are “**diffusers**”, a rare breed so aimless that they defy physical obstacles

One last analogy



- Billions of hobos at the base of Mount Everest and a few at the top, all randomly wandering

Hole Drift and Hole Diffusion Current



acceptor ions

donor ions

p

n

quasi-neutral p region

depletion region

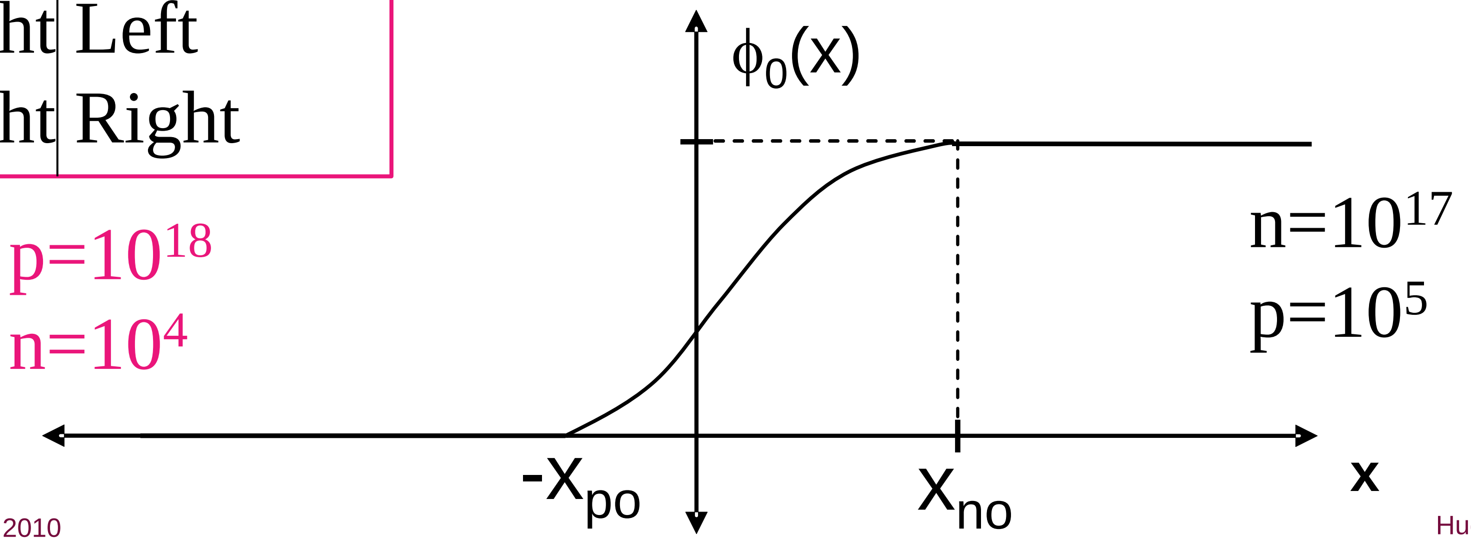
quasi-neutral n region

- Hole drift current: ←
- Hole diffusion current: →

iClicker Time

- **If electrons roll uphill**, what direction is the net movement of electron drift? What direction is the net movement of electron diffusion?

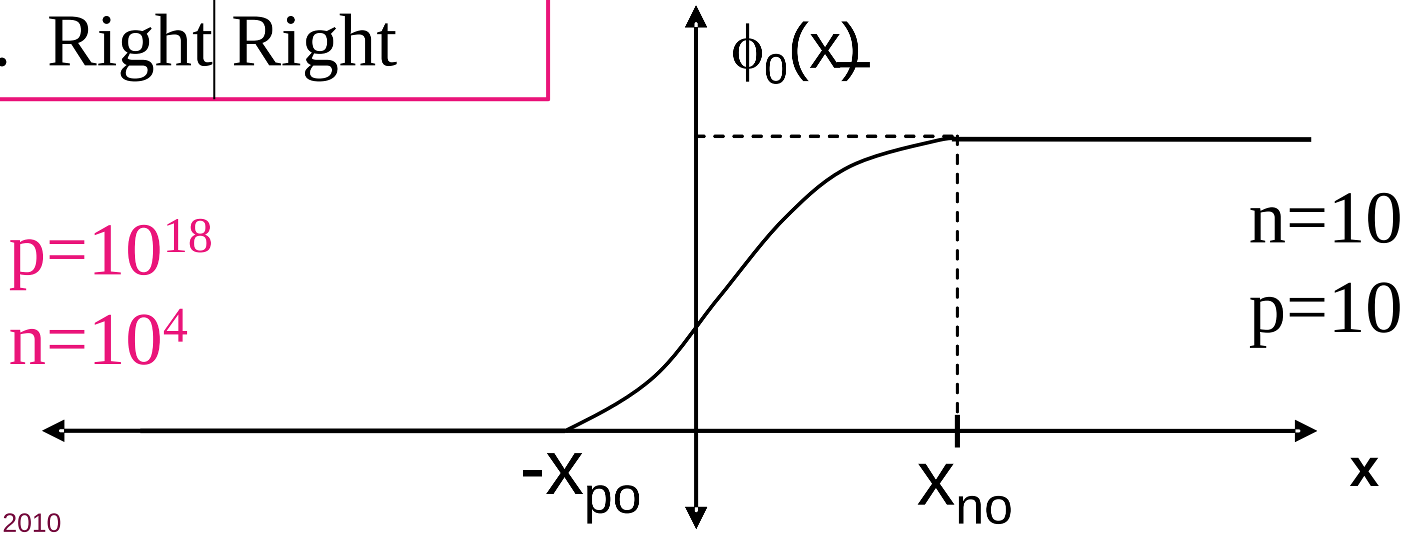
	Drift	Diffusion
A.	Left	Left
B.	Left	Right
C.	Right	Left
D.	Right	Right



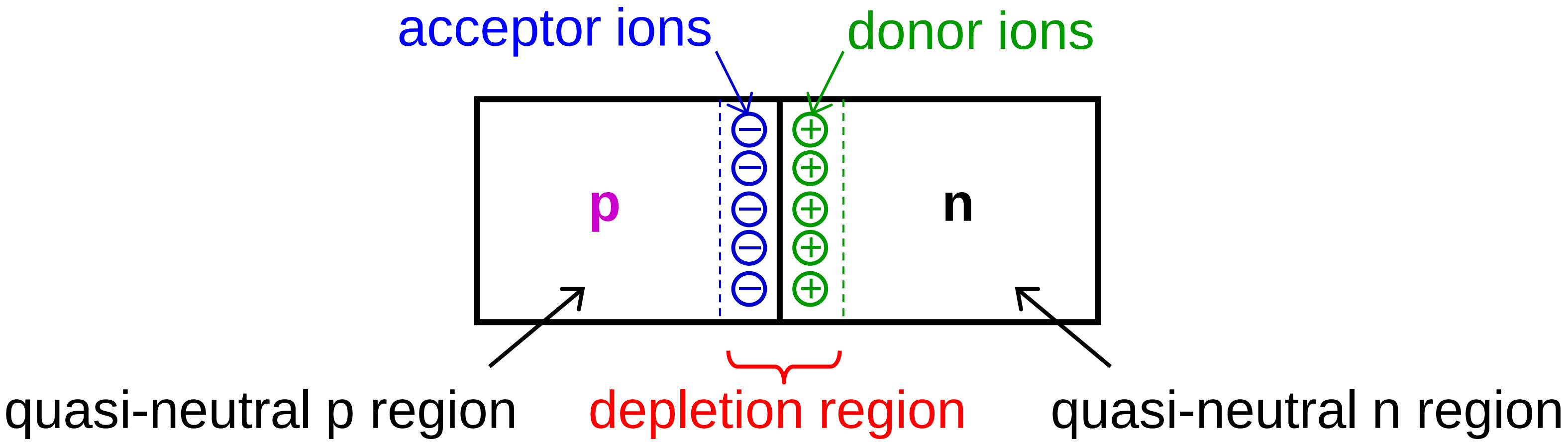
iClicker Time

- If electrons drift right and diffuse left, which directions are electron drift CURRENT and electron diffusion CURRENT?

	Drift	Diffusion
A.	Left	Left
B.	Left	Right
C.	Right	Left
D.	Right	Right



Hole Drift and Hole Diffusion Current



acceptor ions

donor ions

p

n

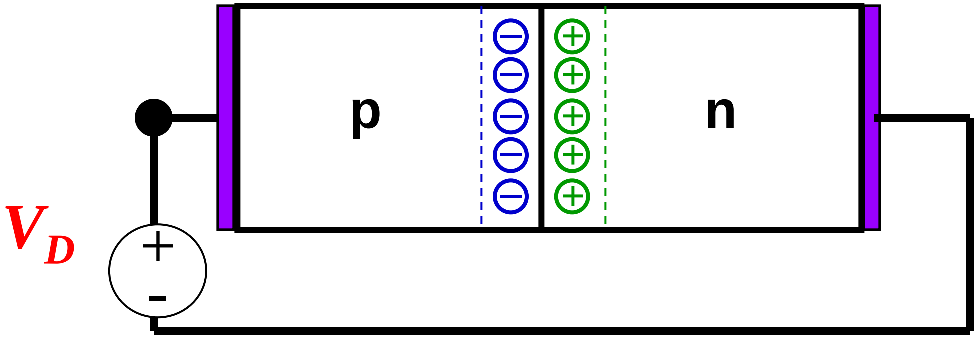
quasi-neutral p region

depletion region

quasi-neutral n region

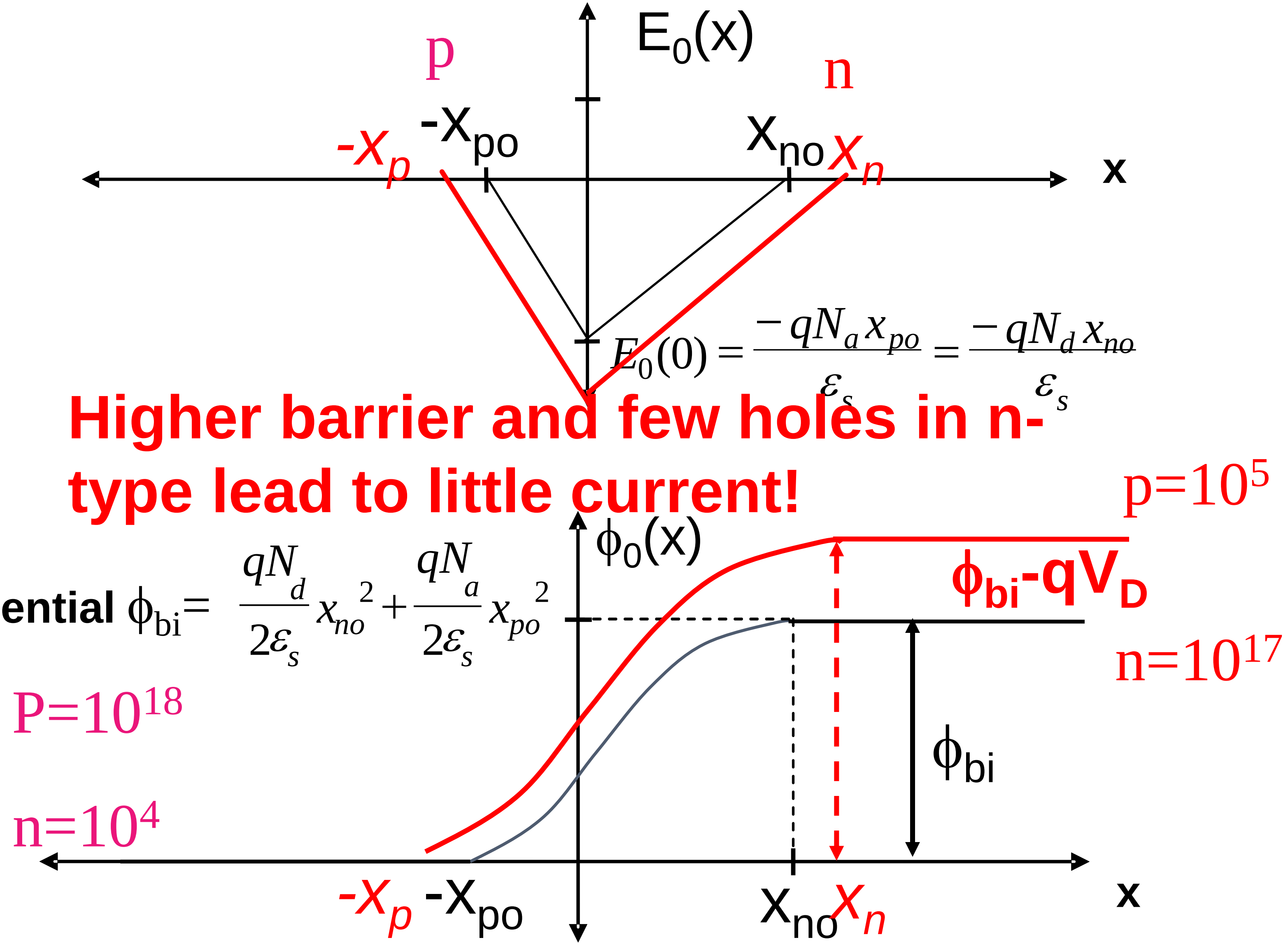
- Hole drift current: ←
- Hole diffusion current: →
- Electron drift current: ←
- Electron diffusion current: →

Effect of Applied Voltage



- The quasi-neutral p and n regions have low resistivity, whereas the depletion region has high resistivity. Thus, **when an external voltage V_D is applied across the diode, almost all of this voltage is dropped across the depletion region.** (Think of a voltage divider circuit.)
- If $V_D > 0$ (***forward bias***), the potential barrier to carrier diffusion is reduced by the applied voltage.
- If $V_D < 0$ (***reverse bias***), the potential barrier to carrier diffusion is increased by the applied voltage.

Depletion Approx. – with $V_D<0$ reverse bias

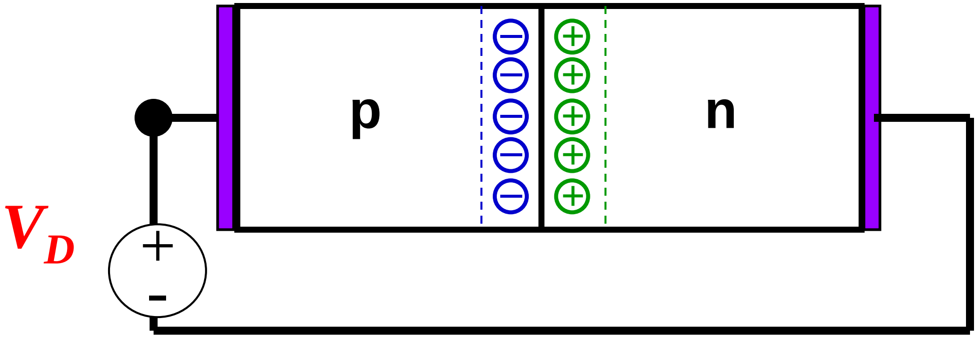


$$E_0(0)=\frac{-qN_a x_{po}}{\varepsilon_s}=\frac{-qN_d x_{no}}{\varepsilon_s}$$

Higher barrier and few holes in n-type lead to little current!

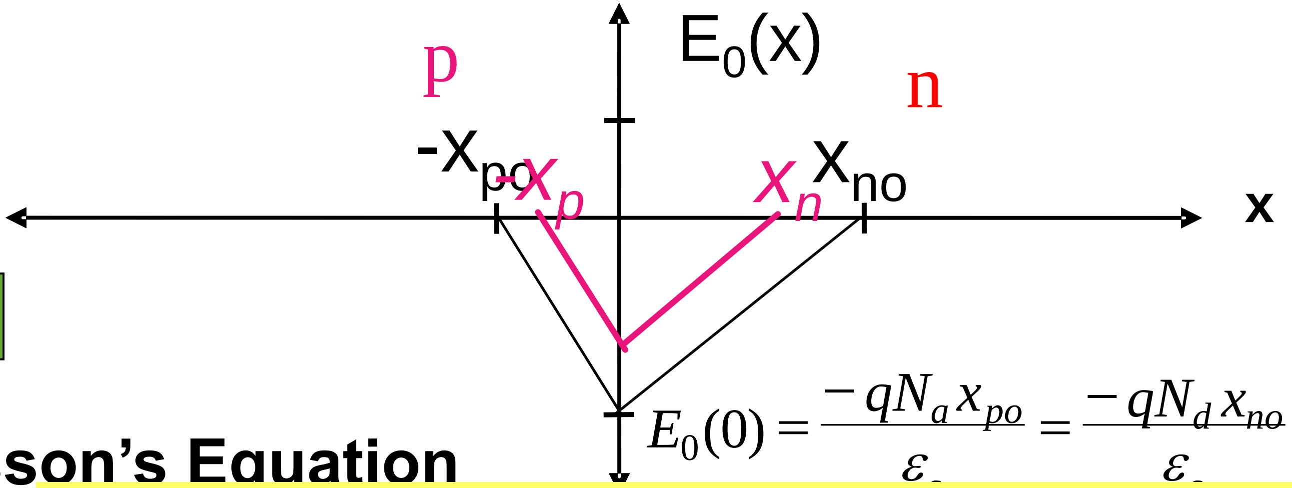
Built-in potential $\phi_{bi}=\frac{qN_d}{2\varepsilon_s}x_{no}^2+\frac{qN_a}{2\varepsilon_s}x_{po}^2$

Hobonalogy



- If $V_D < 0$ (***reverse bias***), Mount Everest becomes steeper
- Hordes of hobos at the bottom have a smaller chance of making it
- The few hobos at the top plummet like stones

Depletion Approx. – with V_D>0 forward bias

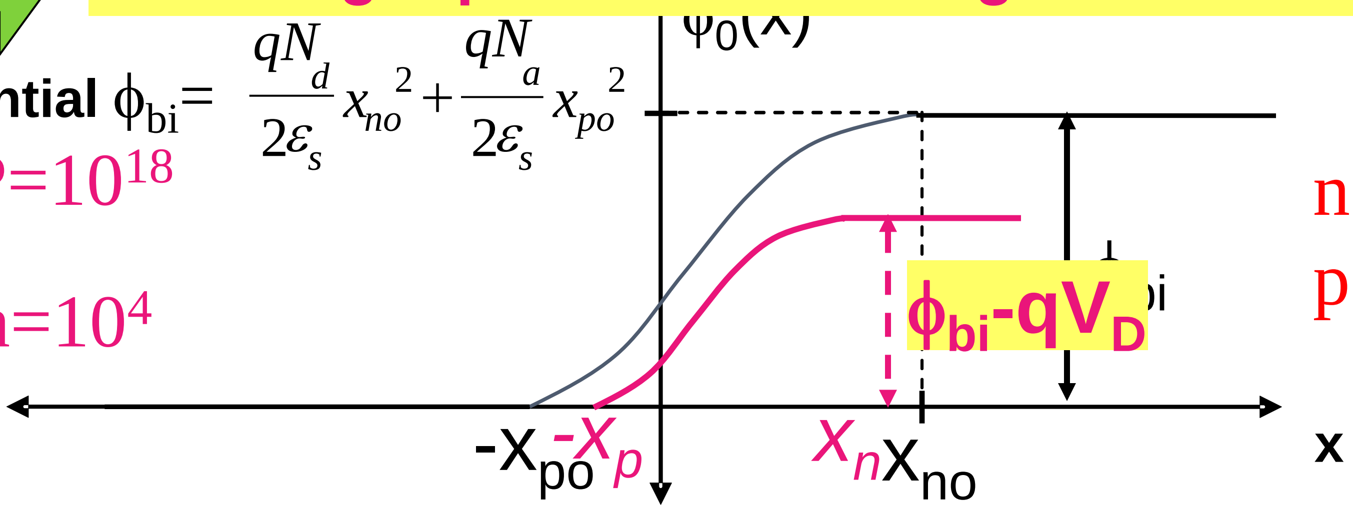


$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

Poisson's Equation

Lower barrier and large hole (electron) density at the right places lead to large current!

Built-in potential $\phi_{bi} = \frac{qN_d}{2\varepsilon_s} x_{no}^2 + \frac{qN_a}{2\varepsilon_s} x_{po}^2$



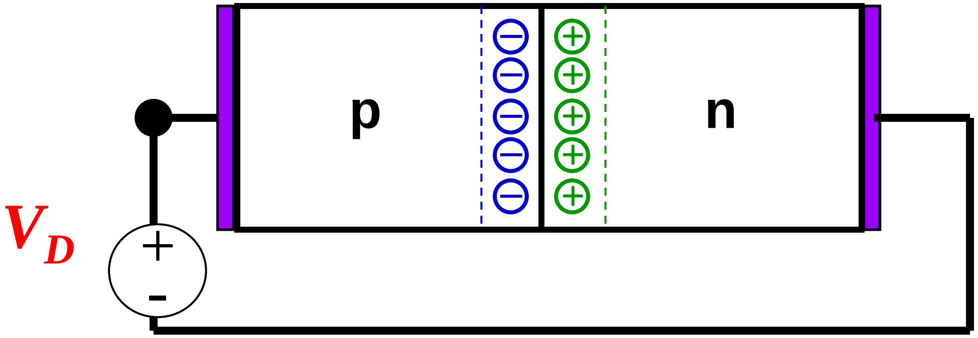
$P=10^{18}$

$n=10^4$

$n=10^{17}$

$p=10^5$

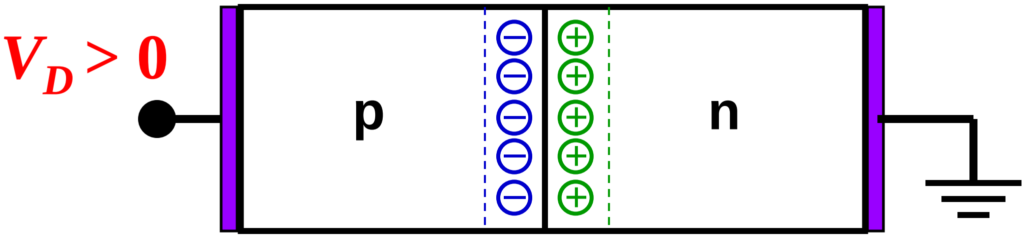
Hobonalogy



- If V_D < 0 (***reverse bias***), Mount Everest becomes a mere hillock
- Hordes of hobos at the bottom have a much better chance of accidentally ascending
- The few hobos at the top don’t fall quite so rapidly

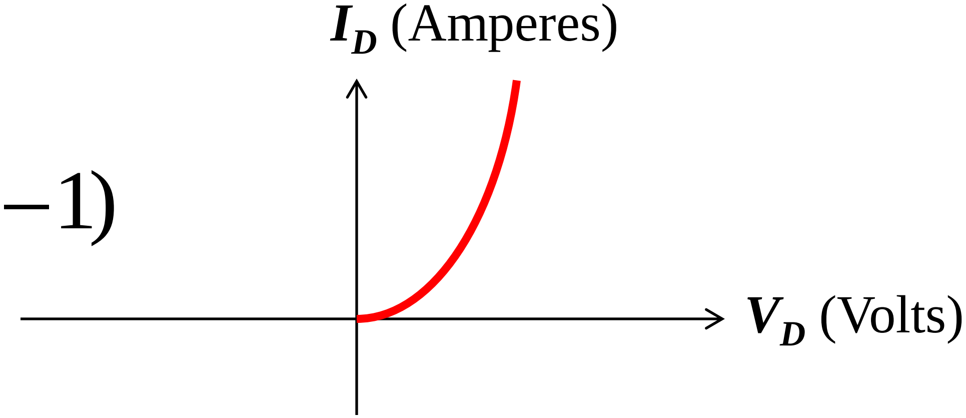
Forward Bias

- As V_D increases, the potential barrier to carrier diffusion across the junction decreases*, and current increases exponentially.



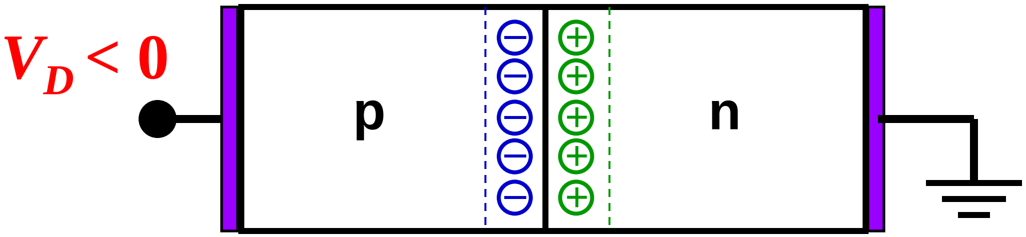
The carriers that diffuse across the junction become minority carriers in the quasi-neutral regions; they then recombine with majority carriers, "dying out" with distance.

$$I_D = I_S(e^{qV_D/kT} - 1)$$

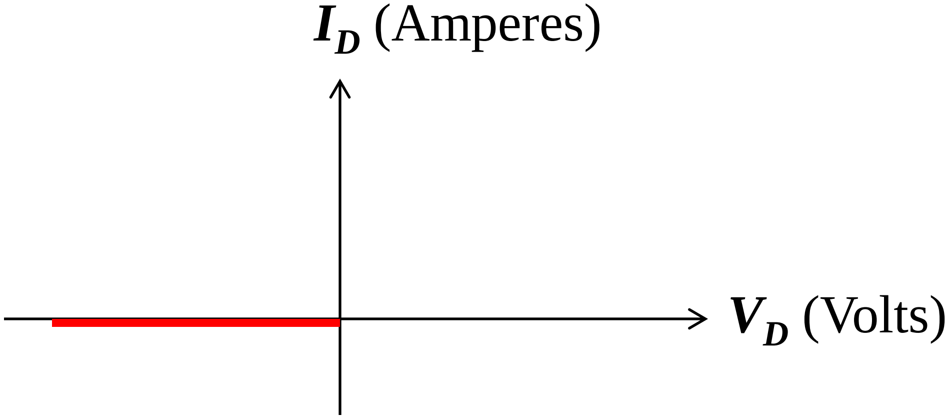


Reverse Bias

- As $|V_D|$ increases, the potential barrier to carrier diffusion across the junction increases*; thus, no carriers diffuse across the junction.



A very small amount of reverse current ($I_D < 0$) does flow, due to minority carriers diffusing from the quasi-neutral regions into the depletion region and drifting across the junction.

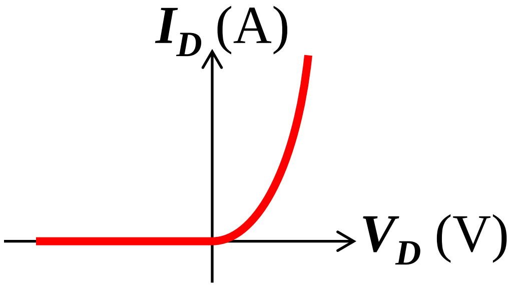


Summary: *pn*-Junction Diode *I-V*

- Under forward bias, the potential barrier is reduced, so that carriers flow (by diffusion) across the junction
  - Current increases exponentially with increasing forward bias
  - The carriers become minority carriers once they cross the junction; as they diffuse in the quasi-neutral regions, they recombine with majority carriers (supplied by the metal contacts)

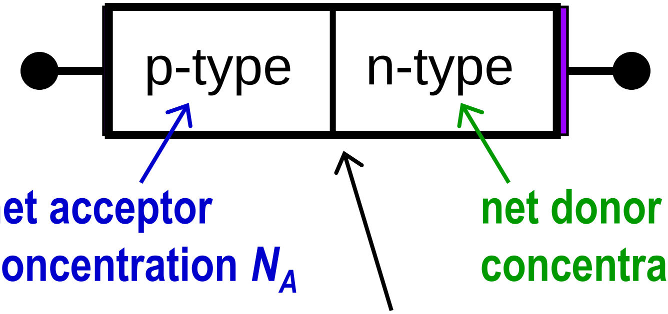
    “injection” of minority carriers
- Under reverse bias, the potential barrier is increased, so that negligible carriers flow across the junction
  - If a minority carrier enters the depletion region (by thermal generation or diffusion from the quasi-neutral regions), it will be swept across the junction by the built-in electric field

    “collection” of minority carriers → reverse current



Making a *pn* Junction Diode

Schematic diagram



p-type

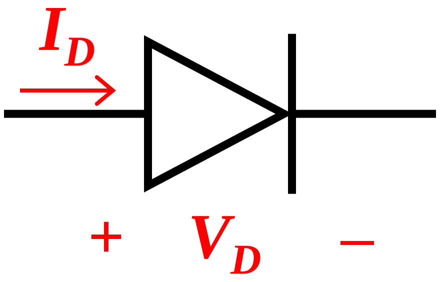
n-type

net acceptor concentration N_A

net donor concentration N_D

cross-sectional area A_D

Circuit symbol

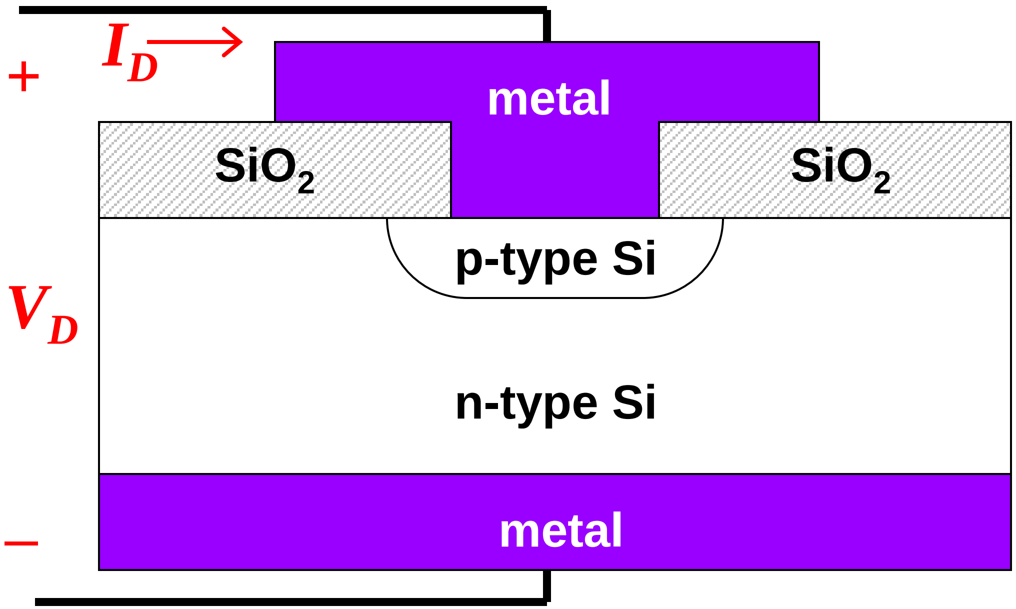


I_D

$+ \quad V_D \quad -$

Physical structure:

(an example)



$+$

I_D

metal

SiO_2

SiO_2

p-type Si

V_D

n-type Si

metal

$-$

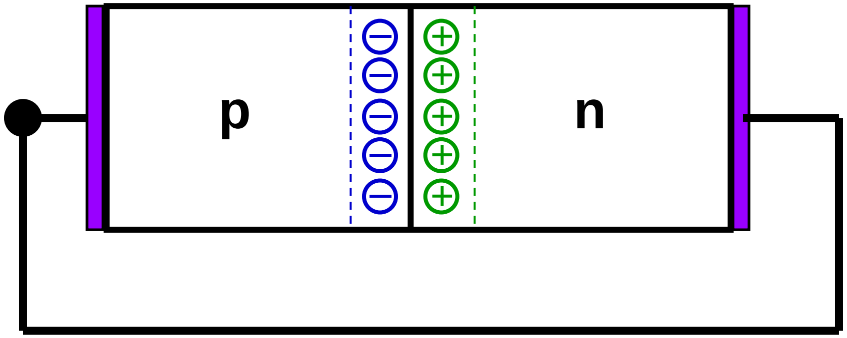
For simplicity, assume that the doping profile changes abruptly at the junction.

More than one way to get current flowing

- Or there’s more than one way to move hobos around mountains
- Electric field is the obvious way
- Can also create electron/hole pairs, for example, with light

Optoelectronic Diodes

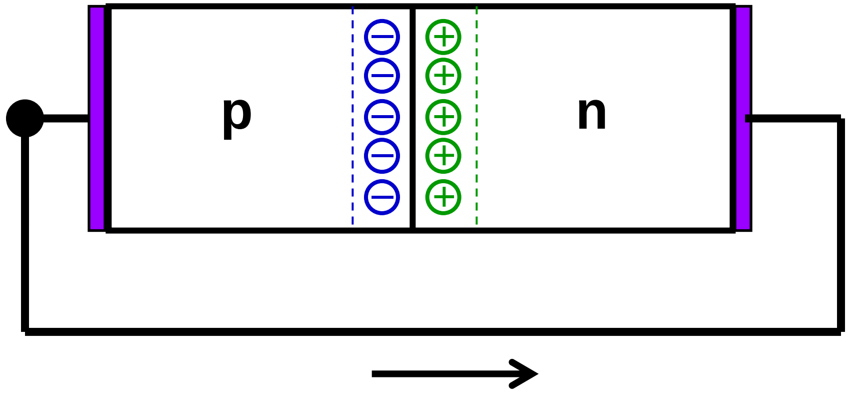
- Light incident on a pn junction generates electron-hole pairs
- Carriers are generated in the depletion region as well as n-doped and p-doped quasi-neutral regions.
- Electron hole-pairs generated on the n and p sides will happen at about the same frequency, and therefore will cancel out



- Electron-hole pairs formed at the junction will:
  - A. Result in no net current
  - B. Result in a net current to the left
  - C. Result in a net current to the right

Optoelectronic Diodes

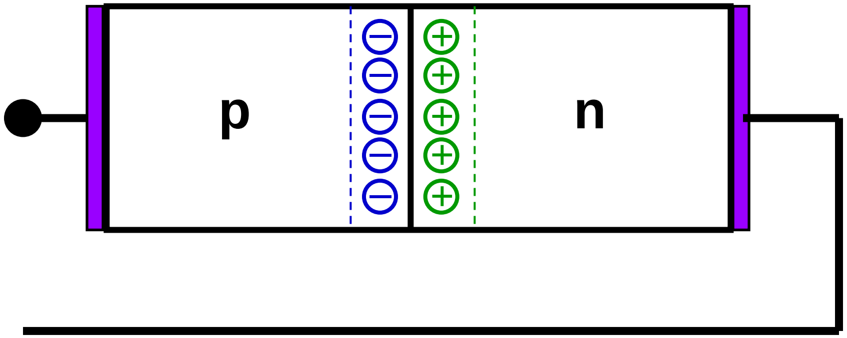
- Electron-hole pairs formed at the junction will:
  - **Result in a net current to the p-side**



- Solar cells are nothing but big photodiodes!
- Directly converts light into electricity

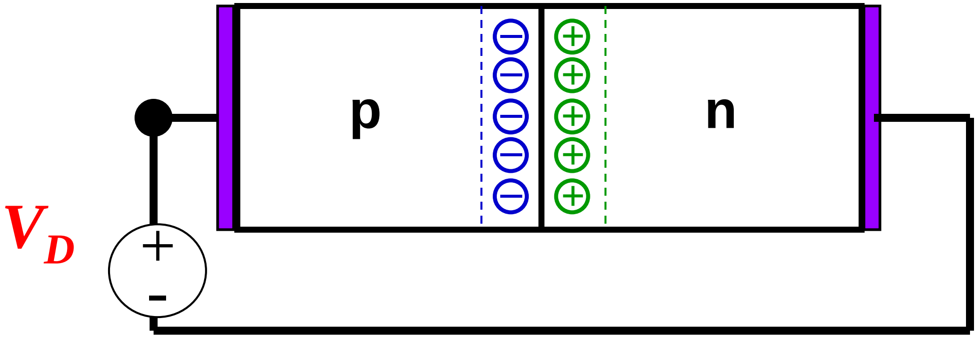
Open Photodiode

- If we leave our photocell open circuited, what happens?

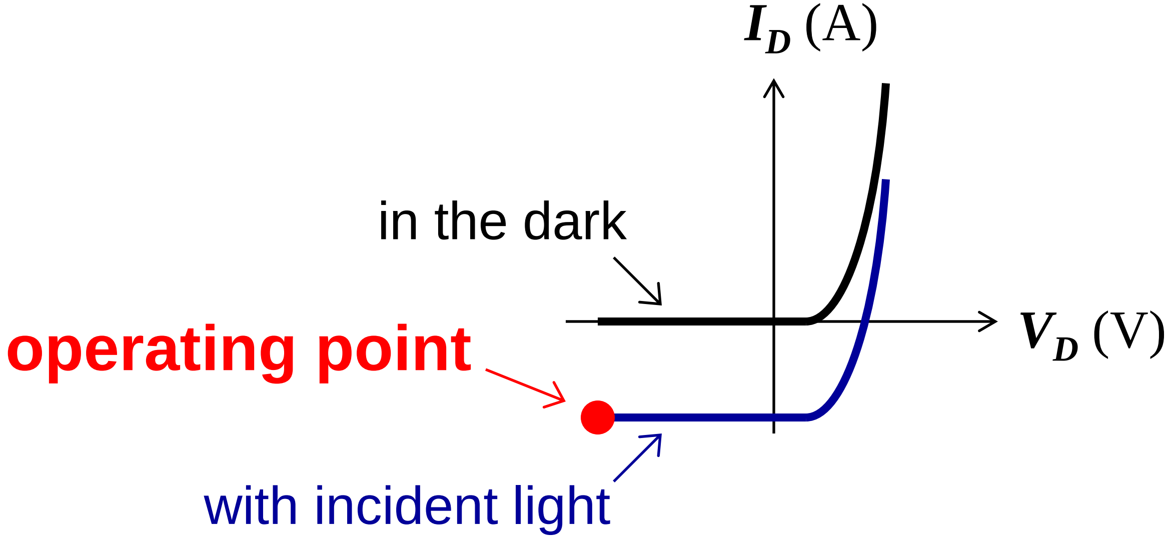


- Voltage is generated

I-V Characteristic of Optoelectronic Diodes



$$I_D = I_S(e^{qV_D/kT} - 1) - I_{optical}$$



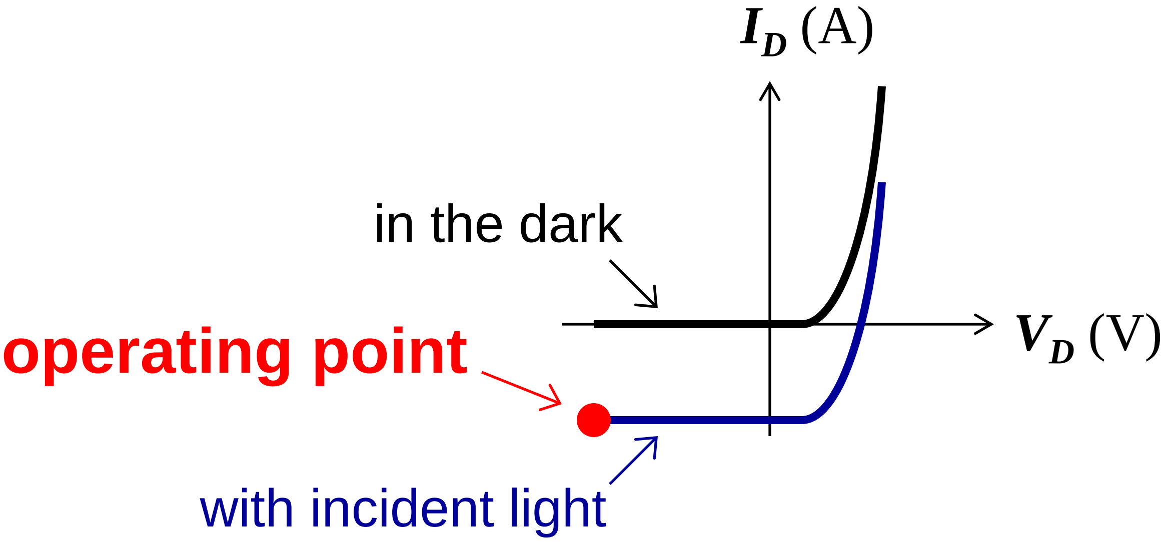
in the dark

operating point

with incident light

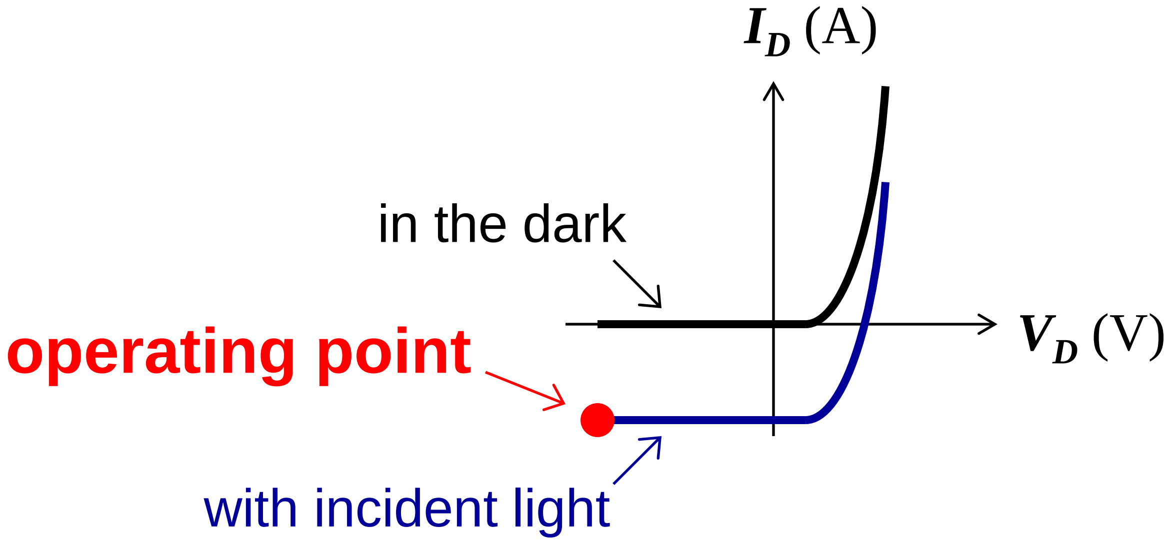
Photodiodes as Voltage Source and Current Source

- If we leave attach a very small resistor, does the solar cell act like a voltage source or a current source?
  - A. Voltage source
  - B. Current source



Photodiodes as Voltage Source and Current Source

- If we leave attach a very large resistor, the solar cell acts like a voltage source



That’s all for today

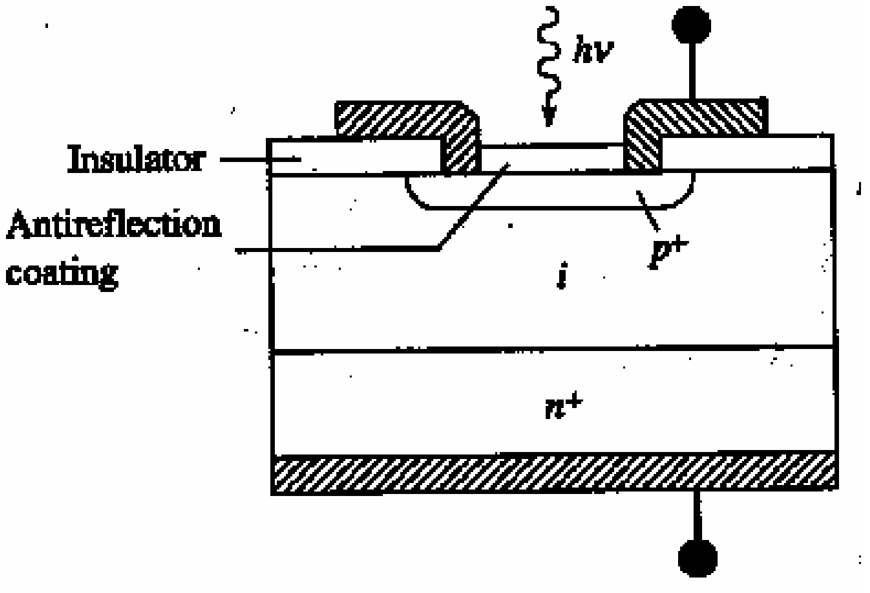
- Next time
  - Brief tiny look at MOSFET semiconductor physics (for ~5 minutes)
  - Course overview
  - Open Q&A: Send me questions beforehand for better answers
  - If somehow we aren’t done at this point, I’ll do a quick diode problem

Extra Slides

Design Problems

- **ALL WORK MUST BE DONE COMPLETELY SOLO!**
- Maximum allowed time will be **5 hours**
  - Will be written so that it can be completed in approximately 2 hours
- Allowed resources:
  - May use any textbook (incl. Google Books)
  - Anything posted on the EE40 website
  - Only allowed websites are Google Books, wikipedia, and EE40 websites
  - Not allowed to use other websites like facebook answers, yahoo answers, etc. even if you are reading other people's responses
  - When in doubt, email me or text me
  - We will be very serious about cheating on this!

Example: Photodiode



- An intrinsic region is placed between the p-type and n-type regions
  - Goal is so that most of the electron-hole pairs are generated in the depletion region

Depletion Approximation 3

$$\phi_0(x) = \int_{-x_{po}}^{x} -E_0(x)dx + \phi_0(-x_{po}) = \int_{-x_{po}}^{x} \frac{qN_a}{\varepsilon_s}(x + x_{po})dx + 0$$

$$= \frac{qN_a}{\varepsilon_s}\left(\int_{-x_{po}}^{x} x\,dx + \int_{-x_{po}}^{x} x_{po}\,dx\right)$$

$$\phi_0(x) = \frac{qN_a}{2\varepsilon_s}(x + x_{po})^2 \qquad (-x_{po} < x < 0)$$

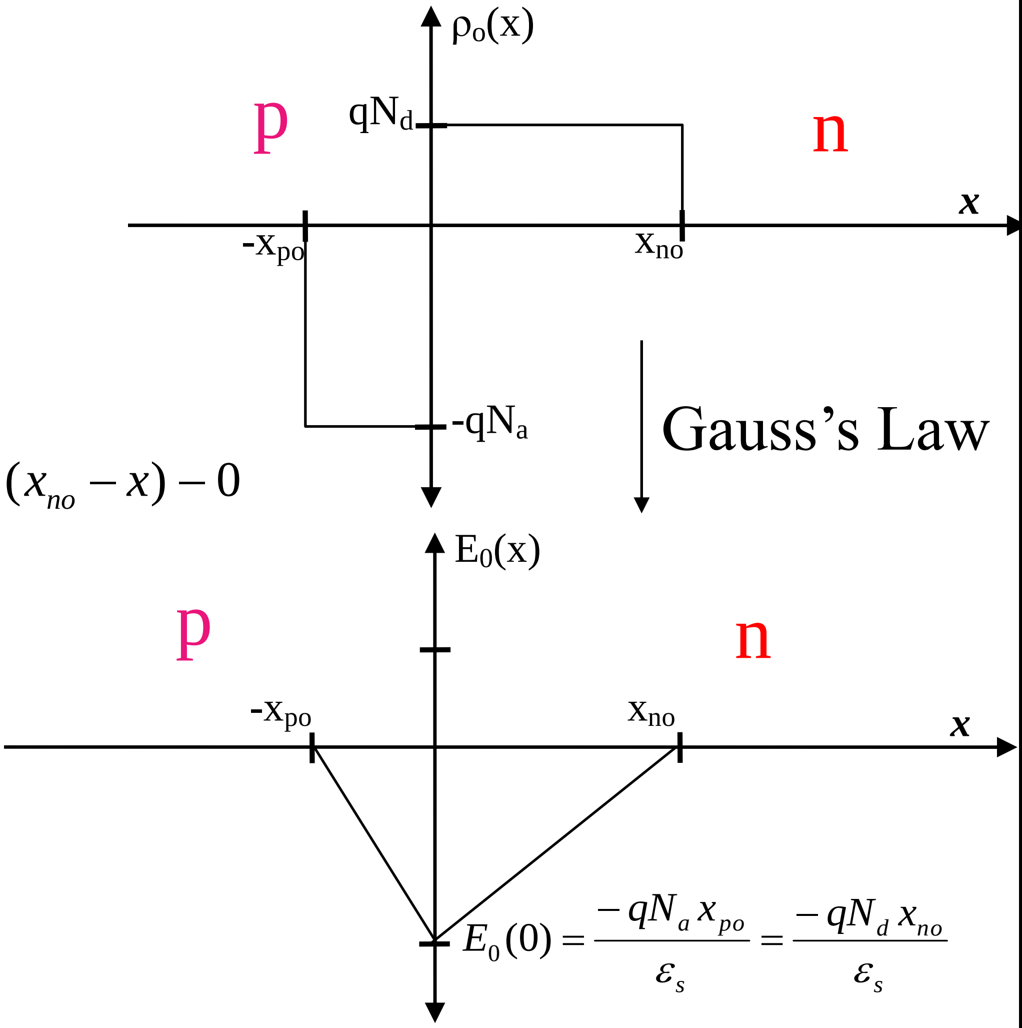
$$\phi_0(x) = \int_0^x - E_0(x)dx + \phi_0(0) = \int_0^x -\frac{qN_d}{\varepsilon_s}(x - x_{no})dx + \frac{qN_a}{2\varepsilon_s}(0 + x_{po})^2$$

$$= \frac{qN_d}{\varepsilon_s}\left(-\int_0^x x\,dx + \int_0^x x_{no}\,dx\right) + \frac{qN_a}{2\varepsilon_s}x_{po}{}^2$$

$$\phi_0(x) = \frac{qN_d}{2\varepsilon_s}x(2x_{no} - x)^2 + \frac{qN_a}{2\varepsilon_s}x_{po}{}^2 \qquad (0 < x < x_{no})$$

Depletion Approximation 1

$$\rho_0(x) \approx \begin{cases} -qN_a & (-x_{p0} \le x \le 0) \\ qN_d & (0 \le x \le x_{n0}) \end{cases} \quad \text{and} \quad \rho_0(x) = 0 \quad (x < -x_{p0},\ x > x_{n0})$$



$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

$$E_0(x) = \frac{-qN_a}{\varepsilon_s}(x + x_{po}) \qquad (-x_{po} < x < 0)$$

$$E_0(x) = \int_x^{x_{no}} \frac{\rho_0(x)}{\varepsilon_s} dx \; - E_0(x_{no}) \; = \; \frac{-qN_d}{\varepsilon_s}(x_{no} - x) - 0$$

$$E_0(x) \; = \; \frac{qN_d}{\varepsilon_s}(x - x_{no})$$

$(0 < x < x_{no})$