3.7 Physical Operation of Diodes

Reading Assignment: *pp. 190-200, 203-205*

A. Semiconductor Materials

Q: So, what exactly is a junction diode **made** of?

A:

HO: Intrinsic Silicon

Q: We call Silicon a **semi**-conductor. Can current flow in a semi-conductor?

A:

HO: Drift Current

HO: Diffusion Current

Q: So, is a junction diode just a **single** hunk of **intrinsic** Silicon?

A:

HO: Doped Silicon

B. p-n Junction Diode Operation

Q: So, exactly **how** is a junction diode formed?

A:

HO: The *p-n* Junction Diode

Q: How does this **simple** device result in the **complex** diode *i-v* characteristic that we studied earlier?

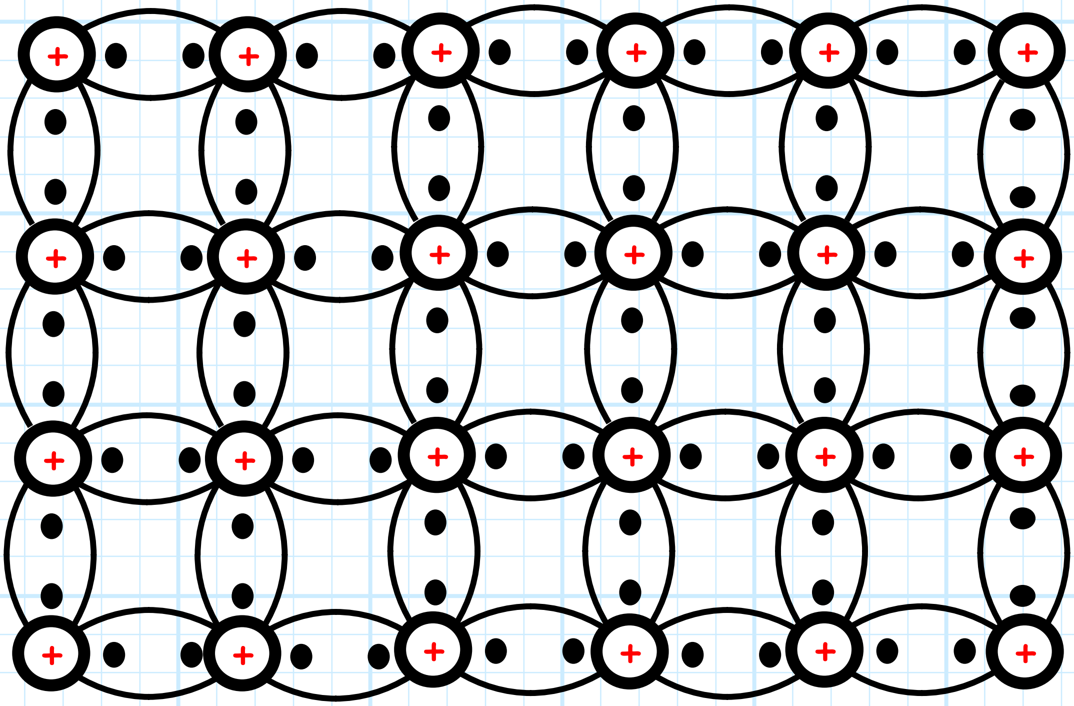
A:
- HO: The *p-n* Junction Diode in Forward Bias
- HO: The *p-n* Junction Diode in Reverse Bias
- HO: The *p-n* Junction Diode in Breakdown

Intrinsic Silicon

Silicon has **4** electrons in an outer valence shell that requires **8** electrons!

Each Si atom therefore forms a **covalent bond** with 4 other Si atoms—they **complete** their outer valence shell by "sharing" electrons.

A Silicon **crystal lattice** is created!



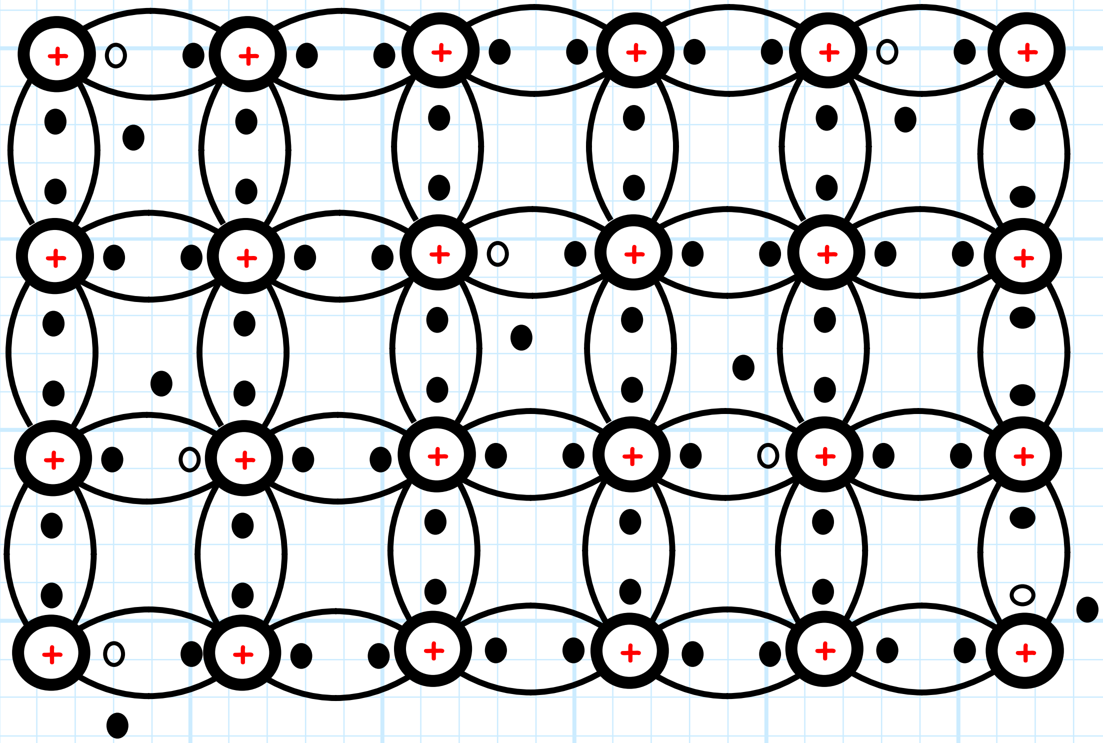
● = electron

BUT, thermal agitation **breaks** covalent bonds.

→ Electrons break free from lattice !!

A **hole** is left where the **bound** electron used to be.

We now have both **free electrons** and **holes** existing in Silicon.



○ = hole

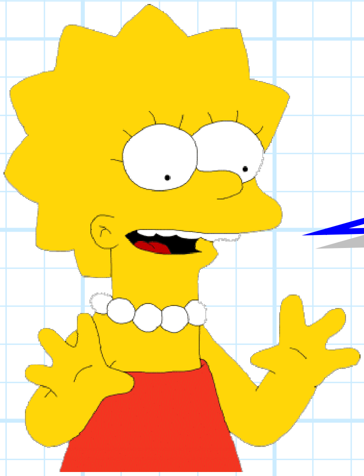
* The warmer the Silicon, the more free electrons (and thus holes) are produced. We can therefore define a **particle density,** defined as either holes/unit volume, or free electrons/unit volume.

* In pure Silicon, the number of holes **equals** the number of free electrons.

* Note however, silicon is electrically **neutral**. In other words, the **net charge density** within the material is **zero**, as the number of electrons equals the number of protons (in the nucleus).

Drift Current

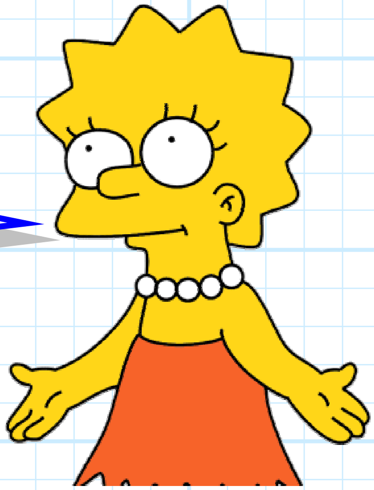
Say an **electric field** is applied to pure Silicon.



Q: *An electric field* $\mathbf{E}(\bar{r})$*! Tell me, what will happen?*

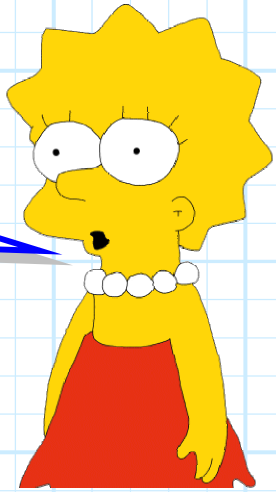
A: From EECS 220 we know what happens ! Since electrons and protons have electric **charge**, the electric field applies a **force** on them; a force that is proportional to the magnitude of the charge.

Q: *A force ! So, the electrons and protons* ***move****, right ???*



A: Not necessarily ! The protons, as well as (generally speaking) the **bound** electrons, are held **in place** by the lattice.

→ The electric field pulls at them, but atomic forces **hold** in place the charged particles **within** the lattice.



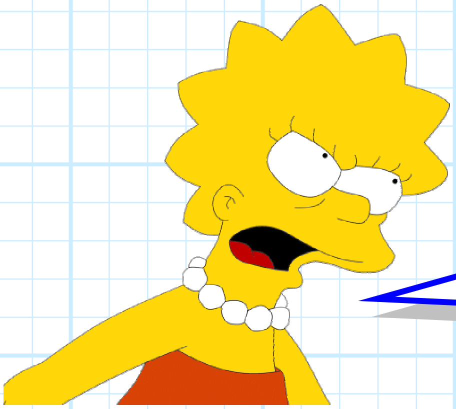
Q: *Within the lattice? The **free** electrons do not reside within the lattice. Do **they** move ??*

A: **YES !** Free electrons are free to **move**—they are not bound by atomic forces to the lattice.

Moving Charge ! → *Moving charge is **current** !*

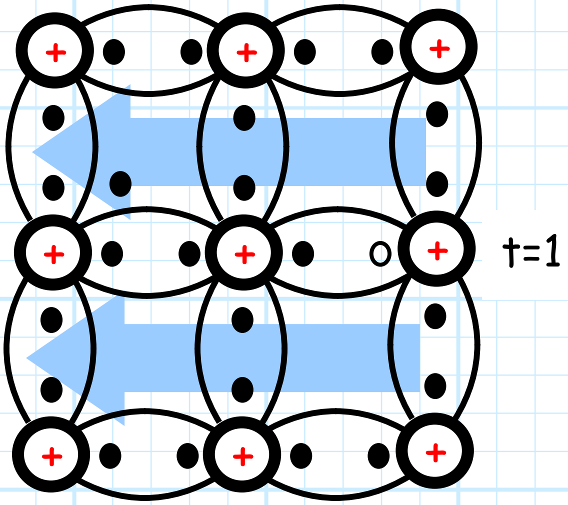
* Charge that moves in response to an applied electric field is known as **Drift Current**.

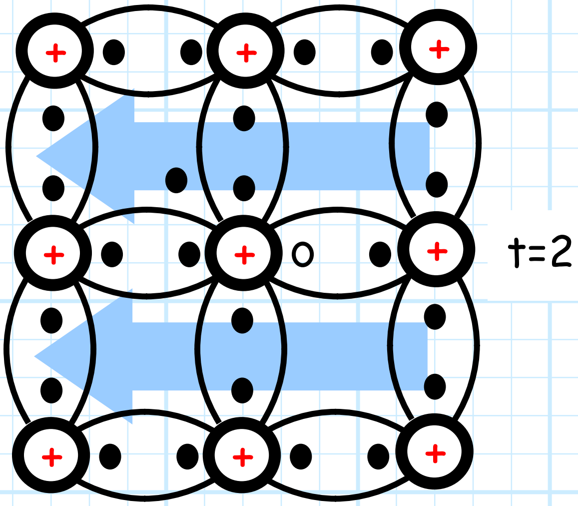
* Drift current in Silicon has **two** components—current due to moving free electrons, and current due to moving **holes**.

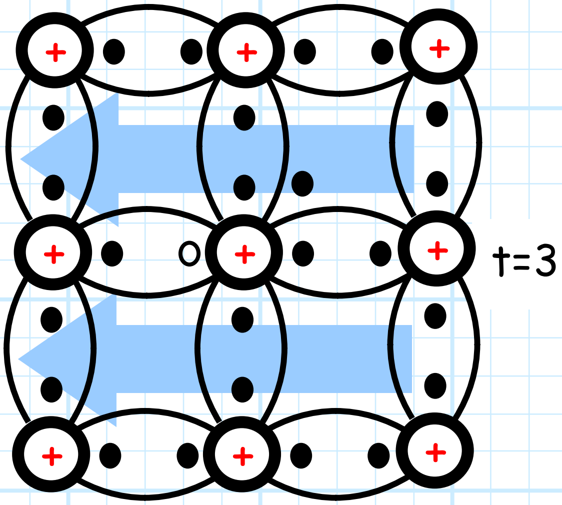


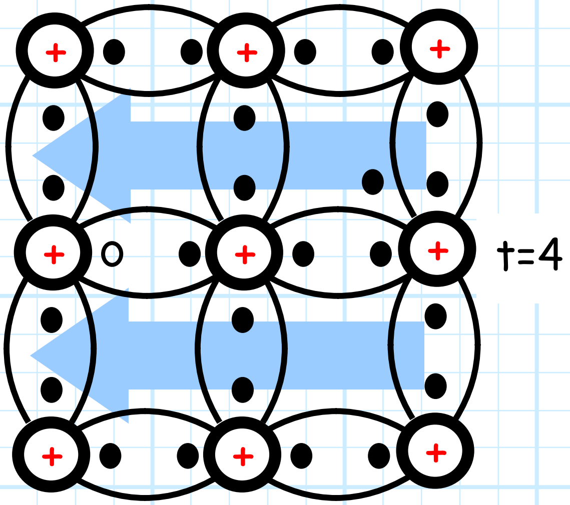
Q: *Moving **holes** !? How can moving holes create **current**? A hole is **nothing!***

A: Let's examine a Crystal Lattice as a function of **time**, while an electric field ← is applied to it:









* Note over time, the **free electrons** move from **left to right**, in response to the electric field.

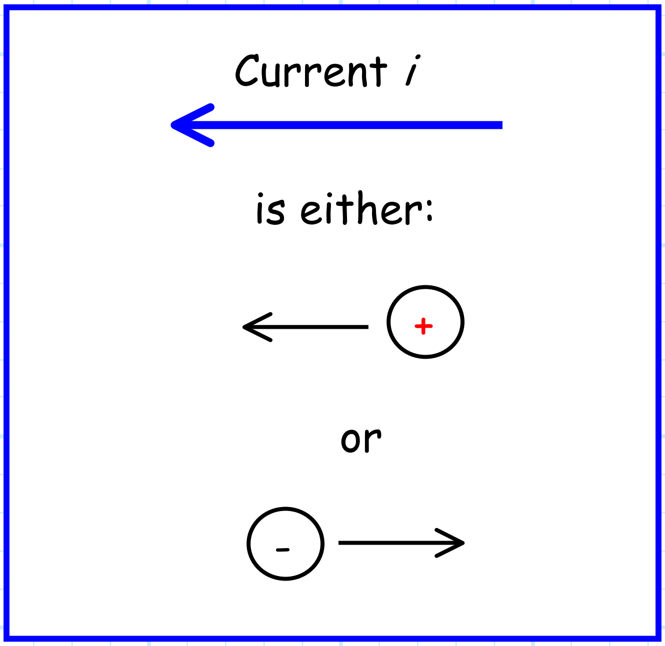
* But note also that some of the **bound** electrons **also** move from left to right, provided that there is a **hole** in the lattice for them to move into.

* As a result, the **hole** appears to moving from **right to left** !

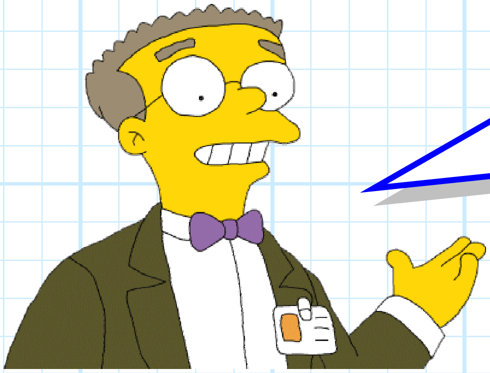
* A **positive** charge would move right to left in the applied electric field—the **hole** appears to have **positive charge**!

* In fact, holes behave as if they are positively charged particles, with a charge equal to that of an **electron** (only positive !).

So, we have **negative** charge (free electrons) moving left to right, and **positive** charge (holes) moving right to left. **Both** result in (drift) current moving from **right to left.**



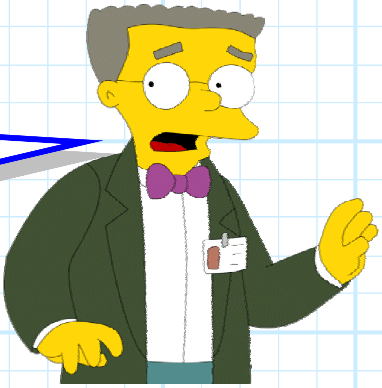
Diffusion Current



Q: *So, it seems to me that, **if** there is **no** electric field present, there can be **no** current flow in Silicon. Right??*

A: **NO** ! There **can** still be current flow in a Silicon lattice, even if there is **no electric field** applied to it! This kind of current is **different** from drift current—we call this current **diffusion current**.

Q: *But, how can a charged particle **move** if there is no **force** applied to it ?!?*



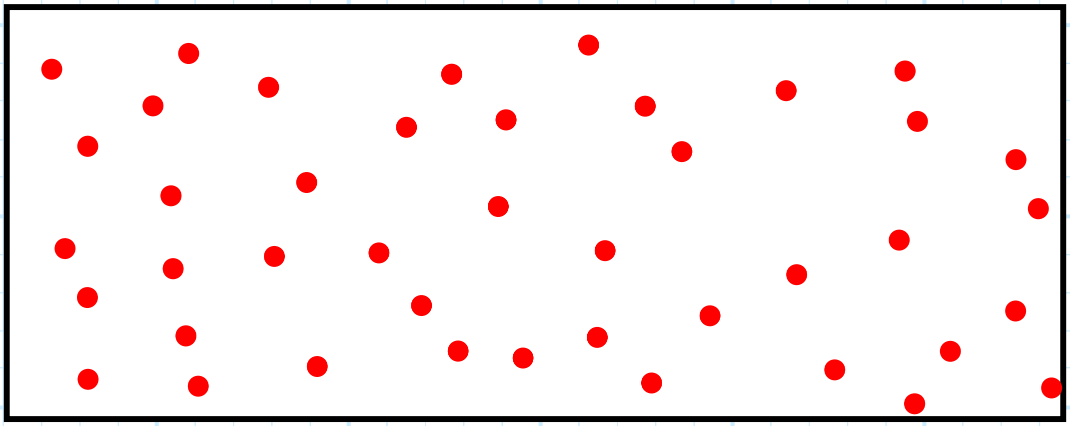
A: Electrons, whether free or bound, have both a charge and a **mass**. There is a source of **energy** within the Silicon lattice that can move **particles**, independent of their charge. This energy is **heat** !

Q: ***HEAT! Seems like** heat would result in the particles moving **randomly** in the lattice, as opposed to moving in a **specific** direction. The **average** current would be **zero** right??*

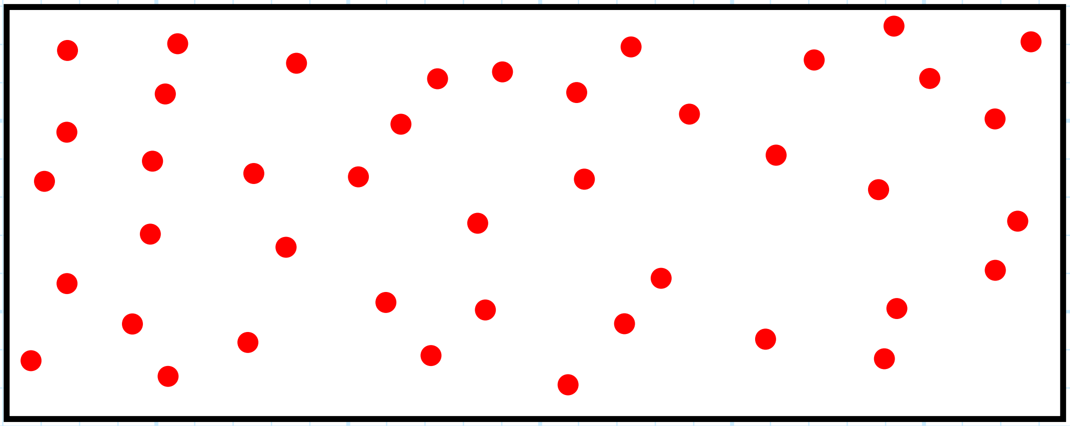
A: It **is** true that **if** the particles are **uniformly** distributed within the lattice, then the particles will remain **uniformly** distributed—the average current is **zero**.

However, if (for some reason) the particles are **concentrated** in one region of the lattice, **entropy** will ensure that they **move** from the region of **high** concentration into regions of **low** concentration. Moving **particles** mean moving **charge**—in other words **current**.

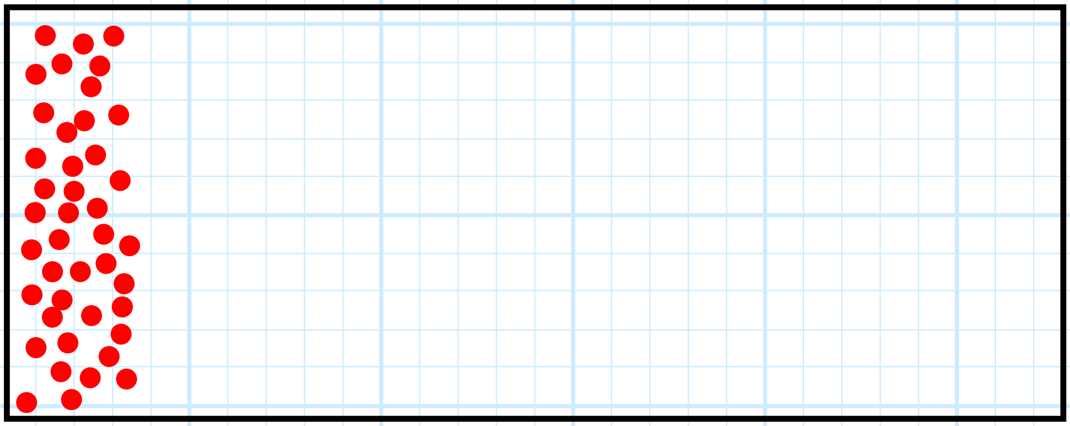
For example, consider the situation below, where a collection of particles (e.g., holes or free electrons), are **uniformly** distributed throughout the volume:



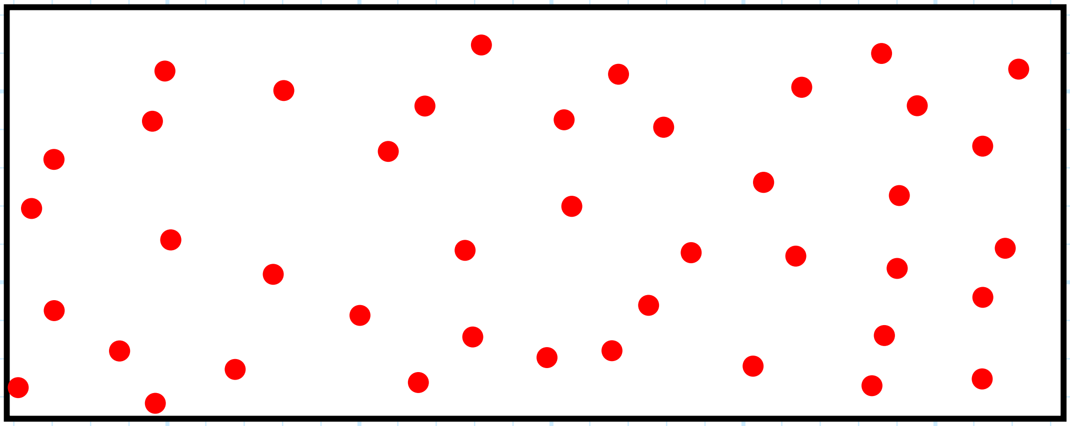
However, since these particles posses **thermal energy** (i.e., heat) they are moving randomly. As a result, at some **later time**, the particles have **all moved**, but are **still** uniformly distributed throughout the volume:



In contrast, consider the situation where the particles are **not** uniformly distributed, but instead are **concentrated** in one region of the volume:

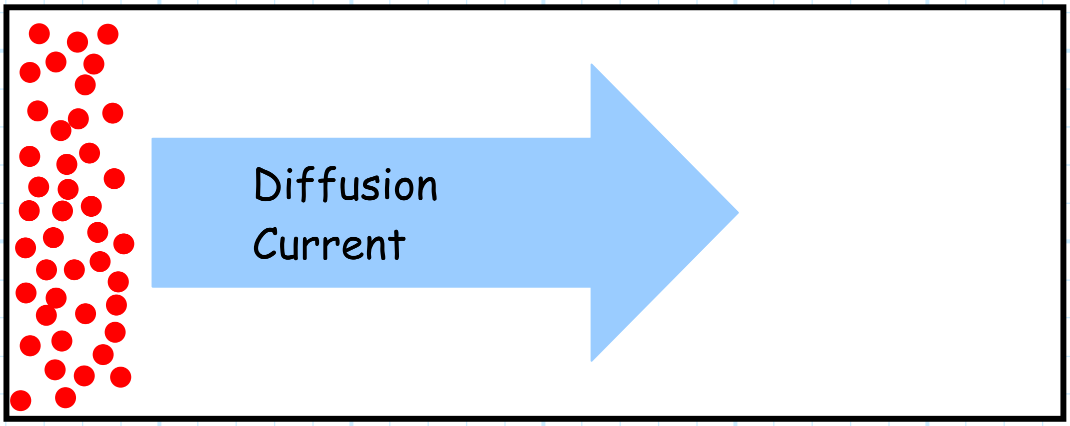


If there is no **other** force holding them in place, then thermal energy will cause these particles to **randomly redistribute** themselves over time, again **uniformly** across the volume:



Said another way, the thermal energy will maximize the **entropy** (i.e., randomness) of the volume !

But, notice what has happened. The charged particles have moved from one region of the volume into another. This movement, although having nothing to due with electromagnetics, is current!



Current generated by this mechanism is referred to as **Diffusion Current**.

Recapping:

1) **Drift current** is a result of electrons having **charge**. They move due to energy supplied by an **electric field**.

2) **Diffusion current** is a result of electrons having **mass**. They move due to energy supplied by **heat**.

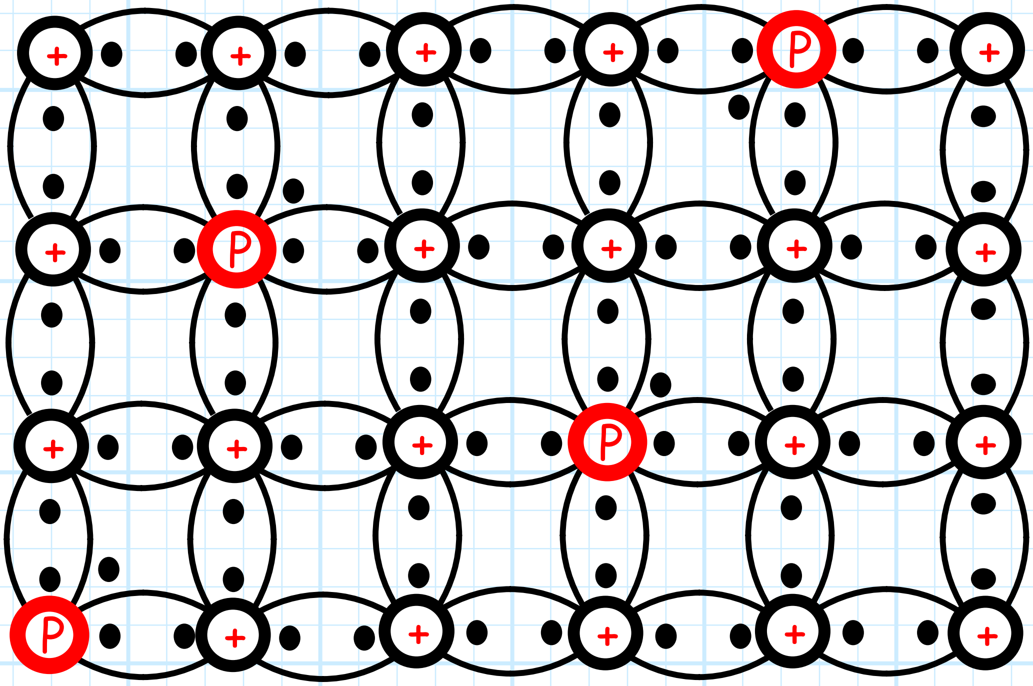
Doped Silicon

We can add **impurities** to Silicon to change the lattice characteristics.

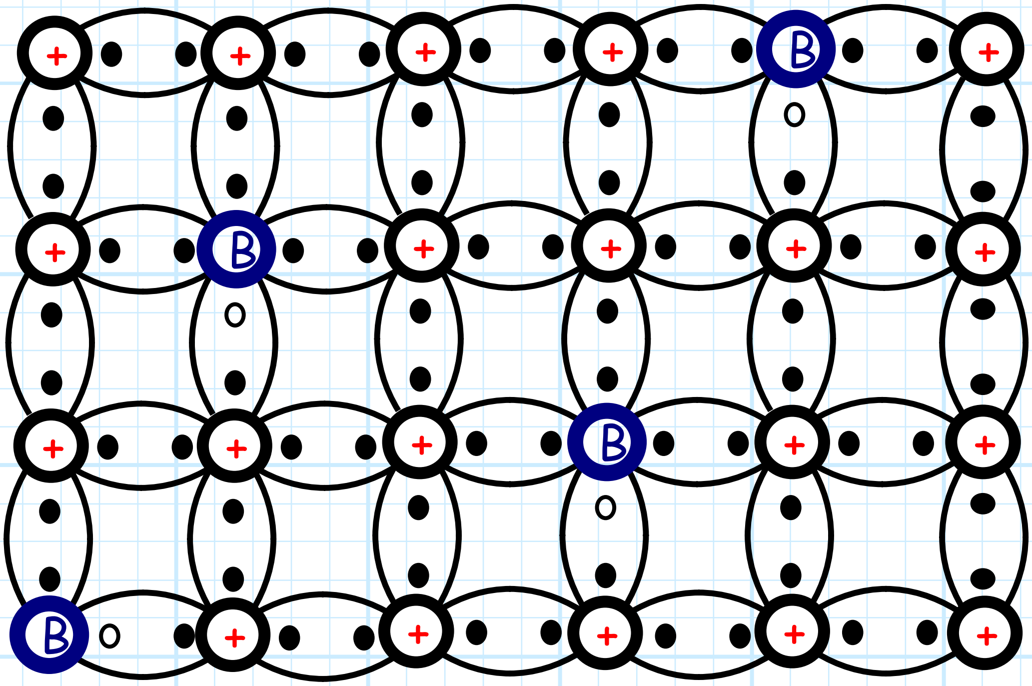
Specifically, we can alter the **particle densities** (i.e., either hole or f.e. densities) of the lattice, such that there are **more** holes than free electrons, or **more** free electrons than holes.

For example, we can add **Phosphorus** (P) to Silicon. Phosphorus has **5** valence electrons (**one more** than Silicon).

Problem !!! There is **no room** for this **extra** electron in the lattice! As a result, a Silicon lattice that has been **"doped"** with Phosphorus has an abundance of **free electrons**!



Or, we can dope the Silicon with **Boron** (B). Boron has **3** valence electrons (one **less** than Silicon). As a result, there are **holes** left in the lattice. An abundance of holes is the result !!!



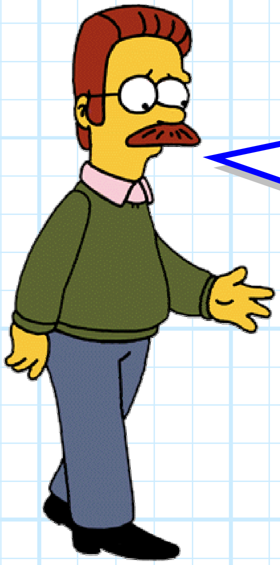
Silicon doped with Phosphorus, such that there is an abundance of free electrons, is called ***n*-type Silicon**. Likewise, Silicon doped with Boron is called ***p*-type Silicon**.

But note that due to **thermal** agitation, there are still **holes in *n*-type** Silicon, and **free electrons in *p*-type** Silicon.

1) For **n-type** Silicon we call free electrons the **majority** carrier, and holes the **minority** carrier.

2) **Conversely**, holes are the majority carrier in **p-type** Silicon, and free electrons the minority carrier.

Therefore, **unlike** intrinsic (i.e., pure) Silicon, the particle density (i.e., concentration) of free electrons **does not equal** the particle density of holes !



Q: *We learned that holes have* ***positive*** *charge, and of course free electrons have* ***negative****. Since in doped Silicon the concentrations of each are* ***unequal****, isn't the* ***charge density*** *of doped Silicon non-zero ??*

A: NO! Remember, a Phosphorus atom has one more **electron** that a Silicon atom, but it **also** has one more **proton** ! Likewise, a Boron atom has the **same** number of electrons as protons. In other words, the lattice remains electrically **neutral**—no **ions** are present!

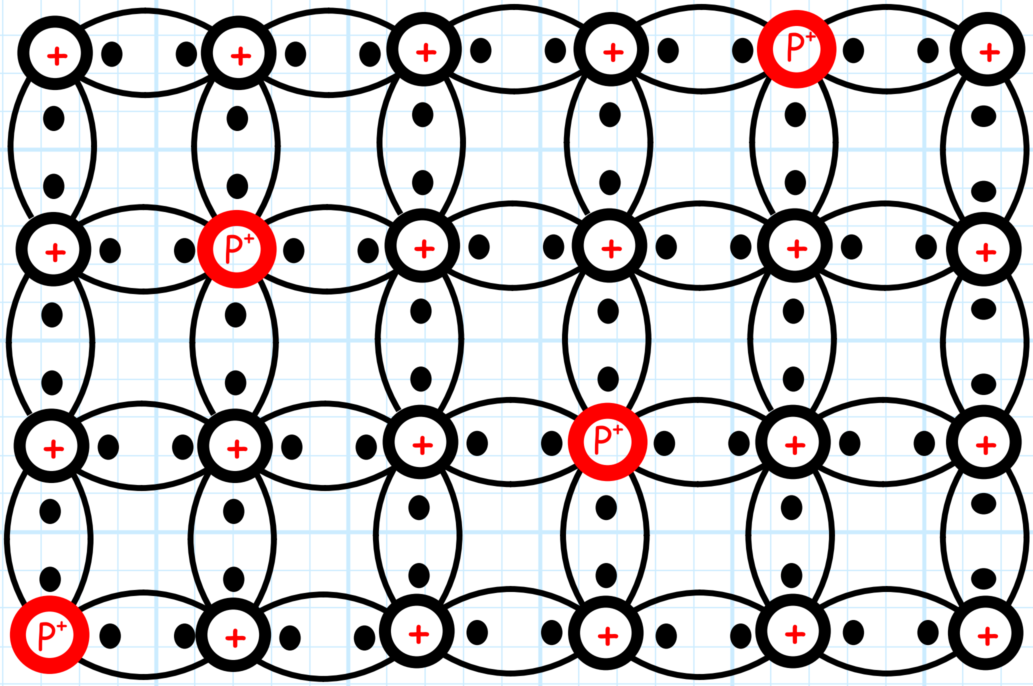
So, generally speaking, in doped Silicon the **charge densities** (electrons and protons) are in **balance**, but the **particle densities** (holes and free electrons) are **out of balance**.

Now, lets consider the case where the particle **concentrations** in Silicon become **rebalanced** !

Q: Rebalanced! *How could* ***this*** *possibly occur ?*

A: The majority carriers **can** move out of a region of the lattice. Recall moving charge is **current**. We now **know** that holes and free electrons can flow in the lattice due to either **drift** current or **diffusion** current.

So, for example, **n-type** Silicon might look like this:



Note the free electrons are gone. We say that this region of the lattice has been **depleted**.

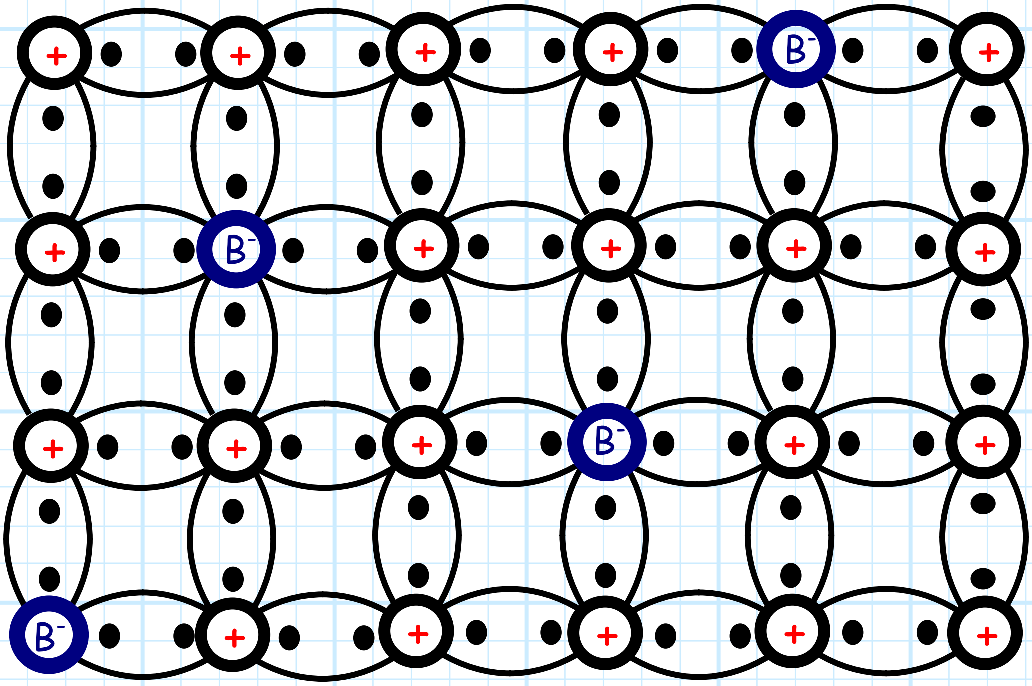
This looks a lot like **intrinsic** Silicon, in that the **particle** densities are now **equal**—there are as many holes as free electrons.

But, **think** about what has happened. The free electrons associated with the Phosphorus atoms have **left**, but no protons left with them—positive Phosphorus **ions** are created !!!

Now the particle densities are **balanced**, but the charge density is **not**—the charge density is now **positive**!

When a free electron is removed from a region of n-type Silicon, we say that a positive **ion** has been **uncovered**.

Now, let's consider what a **depleted** region of **p-type** Silicon would look like:



Note what has happened here is that the **holes** have left, leaving the **concentration** of holes and free electrons **equal**.

But, the "holes left" when **electrons** took their places in the lattice. Each Boron atom therefore has an **extra electron**.

→ **Negative** ions have been **uncovered** !

What's more, the **charge density** within the lattice is now **negative** !

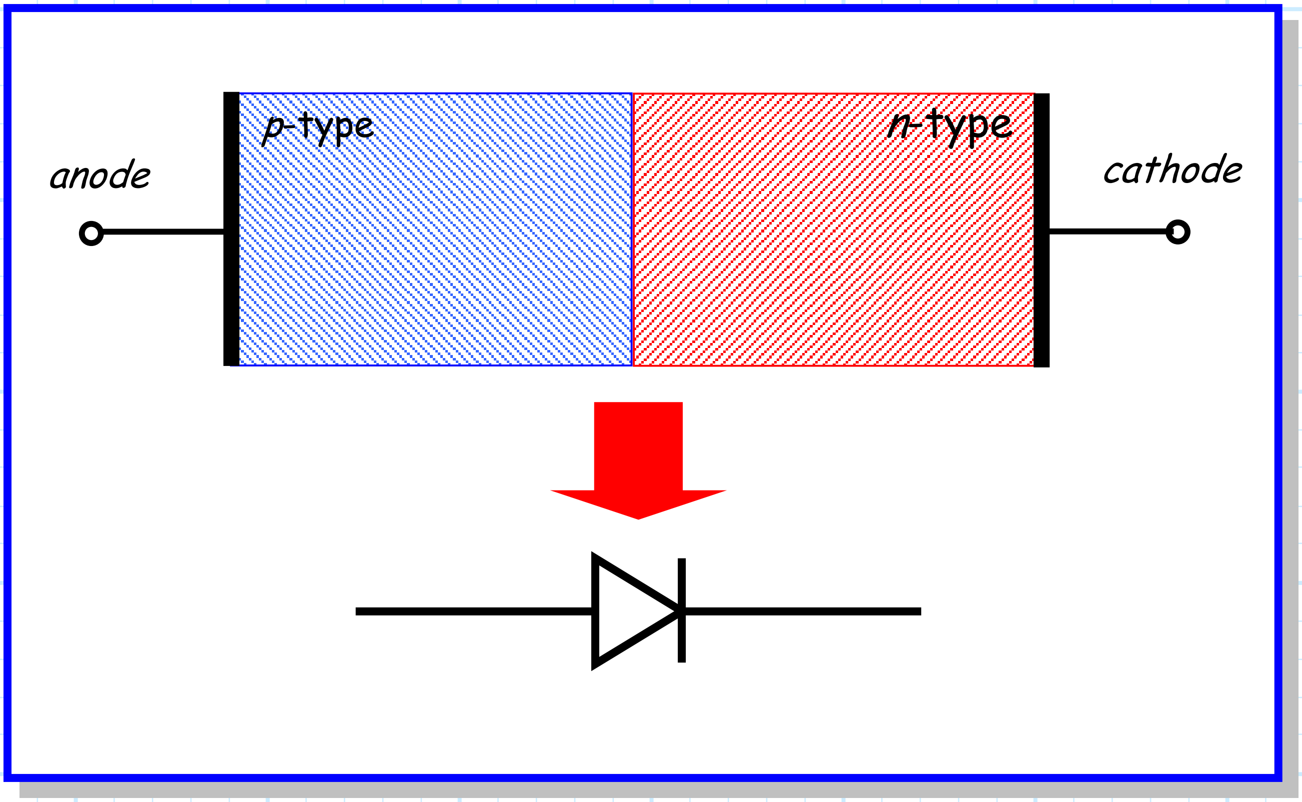
Recapping:

If we **dope** Silicon with impurities, then we create an imbalance in the number of holes and number of free electrons within the lattice—the **particle densities** are **unequal**. However, the **charge density** within the lattice is still **zero**.

If the **majority** carries are **depleted**, then ions are **uncovered**. The **particle densities** of holes and free electrons are now **equal**, while the **charge density** is now **non-zero**.

The *p-n* Junction Diode (Open Circuit)

We create a *p-n* junction diode simply by sticking together a hunk of ***p*-type** Silicon and a hunk of ***n*-type** Silicon!



Now, let's **think** about what happens here:

1) The **concentration** of holes in the anode is much greater than that of the cathode.

2) The **concentration** of free electrons in the cathode is much greater than that of the anode.

Diffusion is the result !

1) **Holes** begin to migrate (diffuse) across the junction from the **anode** to the **cathode**.

2) **Free electrons** begin to migrate (diffuse) across the junction from the **cathode** to the **anode**.

Q: *Oh, I see! This is **entropy** at work. This diffusion will occur until the concentration of holes and free electrons become **uniform** throughout the diode, right ?*

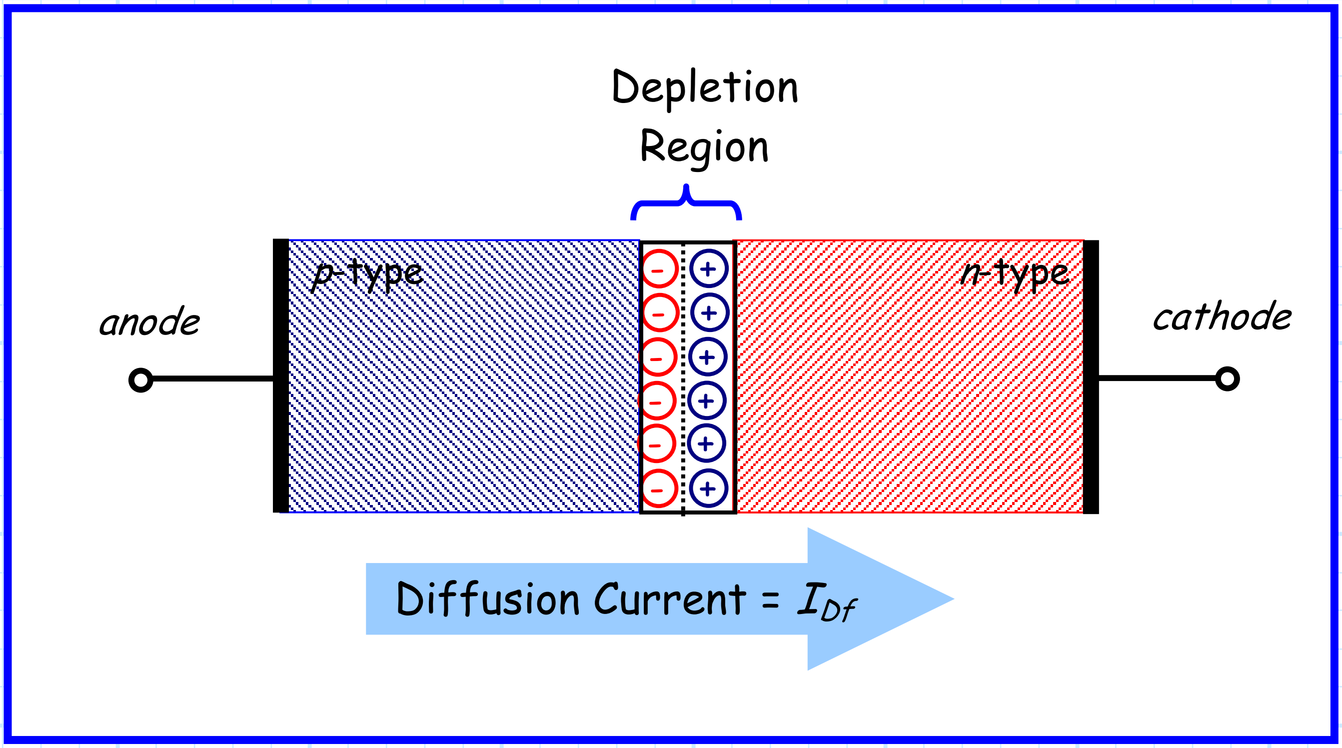
A: Not so fast ! There are **more** phenomena at work here than **just** diffusion !

For instance, **think** about what happens when holes **leave** the *p*-type Silicon of the anode, and the free electrons **leave** the *n*-type Silicon of the cathode:

→ They **uncover ions** !!!

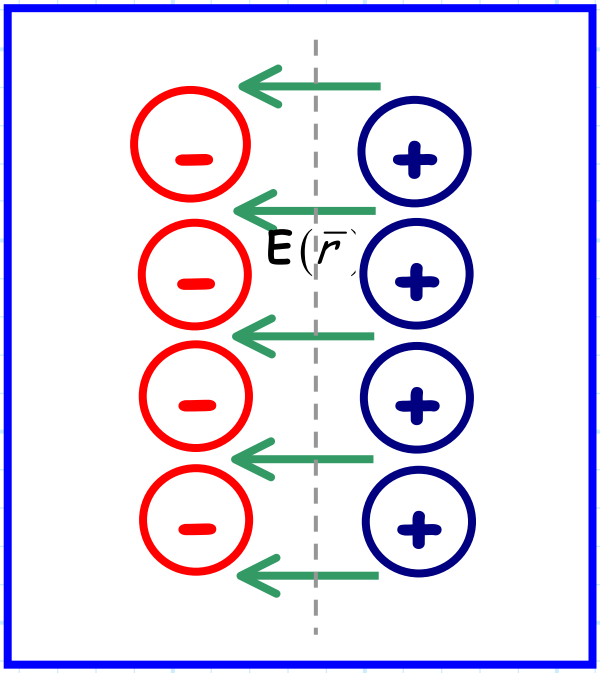
As a result, the **charge density** of the **anode** along the junction becomes **negative**, and the charge density of the **cathode** along the junction becomes **positive**.

This region of uncovered ions along the junction is known as the **depletion region**.



Now, something **really** interesting occurs!

The uncovered ions of opposite polarity generate an **electric field** across the junction.



Recall that an electric field exerts a **force** on charge particles—charged particles like **holes** and **free electrons**!

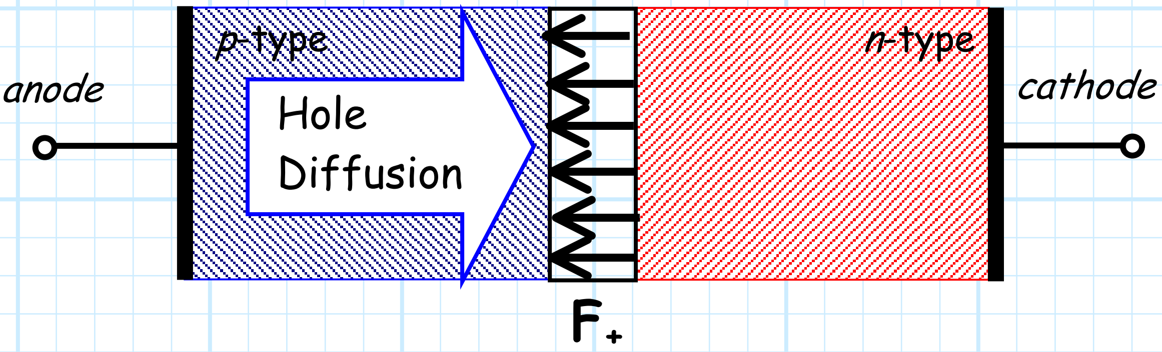
Let's see what this force **is** on both holes and free electrons:

For holes:

Using the **Lorentz force equation**, we find that the force vector $\mathbf{F}_+$ on a **hole** (with charge $Q_+ = -e$) located at position $\bar{r}$ is:

$$\mathbf{F}_+ = Q_+ \mathbf{E}(\bar{r})$$

Note that since the electric field vector in the depletion region is pointing from **right to left** (i.e., from the *n*-type Si cathode to the *p*-type Si cathode), and since the "charge" Q_+ of a hole is **positive**, the force vector likewise extends from **right to left**:



Look what happens! The electric field in the depletion region applies a **force** on the holes that is **opposite** of the direction of **hole diffusion**!

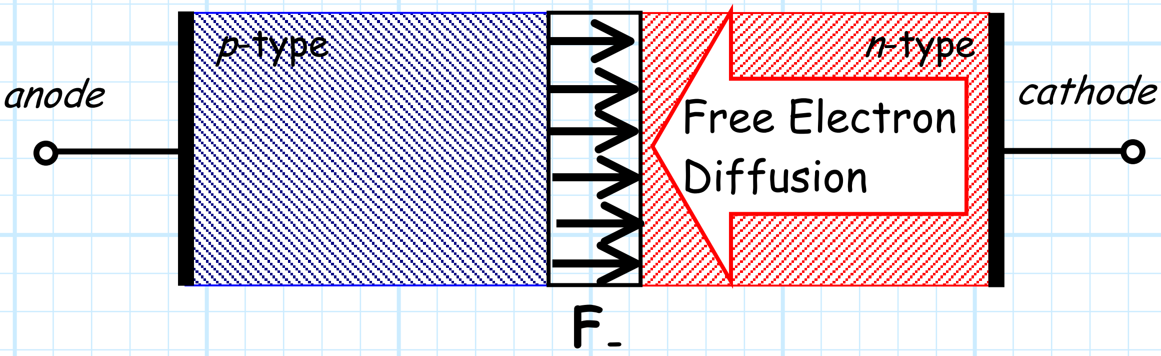
In other words, the electric field begins to "**hold back**" the tide of holes attempting to **diffuse** into the *n*-type cathode region.

For free electrons:

Now, let's see what effect this electric field has on **free electrons**. Using the **Lorentz force equation**, we find that the **force** vector $\mathbf{F}_-$ on a free electron (with charge $Q_- = e$) located at position $\bar{r}$ is:

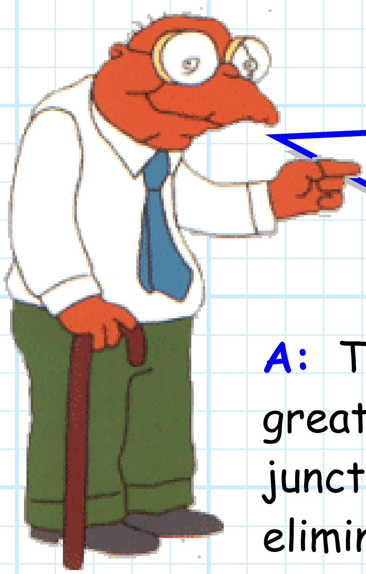
$$\mathbf{F}_- = Q_- \mathbf{E}(\bar{r})$$

Note that since the electric field vector in the depletion region is pointing from **right to left** (i.e., from the *n*-type Si to the *p*-type Si), and since the charge Q_- of a free electron is **negative**, the force vector extents in the opposite direction of $\mathbf{E}(\bar{r})$--from **left to right**:



Look what happens! The **electric field** in the depletion region likewise applies a **force** on the **free electrons** that is **opposite** of the direction of free electron **diffusion**!

In other words, the electric field begins to "**hold back**" the tide of **free electrons** attempting to **diffuse** into the *p*-type anode region .



Q: *So, does this electric field **stop** all diffusion across the junction ? Is the diffusion current I_{Df} therefore **zero**?*

A: Typically **NO!** The electric field will greatly **reduce** the diffusion across the junction, but only in **certain** cases will it eliminate I_{Df} entirely (more about **that** later!).

The **amount** of diffusion that occurs for a given electric field $\mathbf{E}(\bar{r})$ is dependent on how **energetic** the particles (holes and free-electrons) are!

Recall that these particles will have **kinetic energy** due to heat. If this energy is sufficiently **large**, a particle can still diffuse **across** the *p-n* junction!

To see why, consider the amount of **energy** E it would take to move a charged particle **through** this electric field. Recall from EECS 220 that this energy is:

$$E = -Q\int_C \mathbf{E}(\bar{r})\cdot\overline{d\ell}$$

For our case, Q is the **charge** on a particle (hole or free electron), and **contour** C is a path that extends **across** the depletion region.

Moreover, we recall that this expression can be simplified by using **electric potential**, i.e.,

$$V = -\int_C \mathbf{E}(\bar{r}) \cdot \overline{d\ell}$$

Where V is the difference in **potential energy** (per coulomb) between a charge at either end of contour C. This of course tells us how much **work** must be done (per coulomb) to move a charge from **one end** of the contour to the **other**.

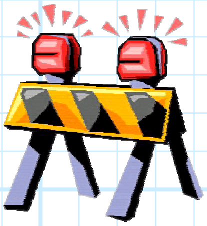
Of course V has units of **Volts**, but its more descriptive unit is **joules/coulomb**—energy per unit charge.

Therefore, the energy required to move a charge Q along some contour C can **likewise** be expressed as:

$$E = QV$$

Now, for our particular problem, the charge Q is either the charge of a **free electron** (Q_-) or the charge of a **hole** (Q_+).

The **voltage** (i.e., potential difference) across the depletion region is called the **barrier voltage** V_B (sometimes denoted V_0):



$$V_B = -\int_{C_{dr}} \mathbf{E}(\bar{r}) \cdot \overline{d\ell}$$

where the contour C_{dr} describes some contour **across** the depletion region.

Typically, we find that when the junction diode is **open** circuited (i.e., v_D=0 and i_D=0), this barrier voltage is approximately—**0.7 V** !

Thus, we find that the **energy** required for a **hole** to **diffuse** across the depletion region is:

$$E_B = Q_+ V_B$$

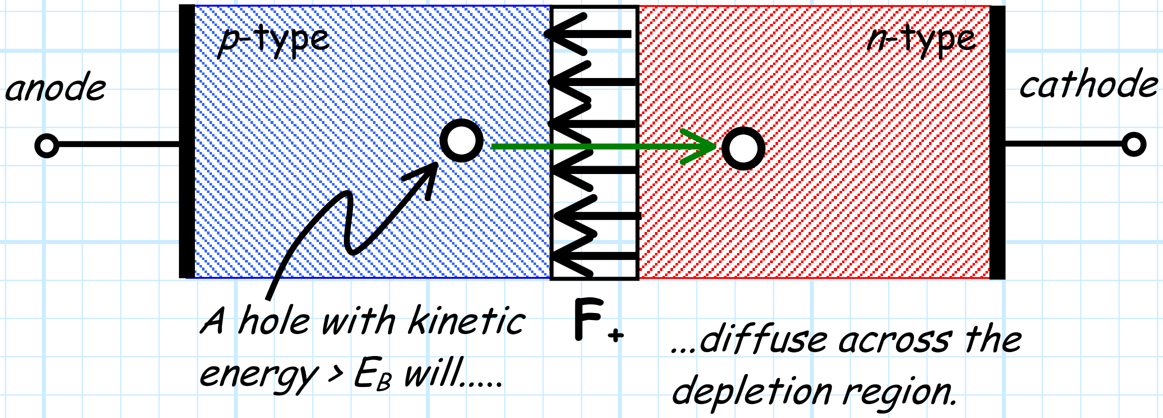
While the **energy** required for a **free electron** to **diffuse** across the depletion region is:

$$E_B = -Q_- V_B$$

Note that both these energies are the **same** (positive) value!

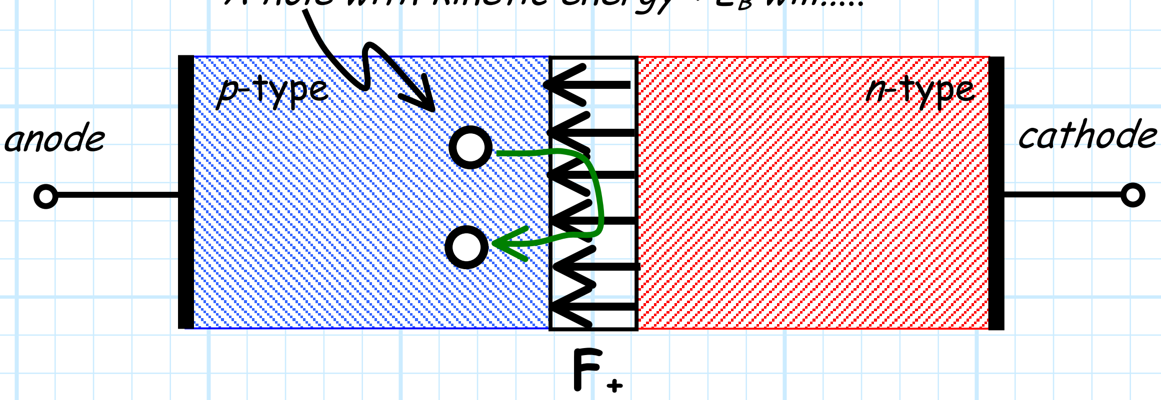
OK, here's the **important part**:

A. **If** the particle has kinetic energy **greater** than E_B, it can **diffuse** across the depletion region.



B. **If** the particle has kinetic energy **less** than E_B, then the electric field will "push" it **back** into either the *p*-type anode region (for holes) or the *n*-type cathode region (for free electrons).

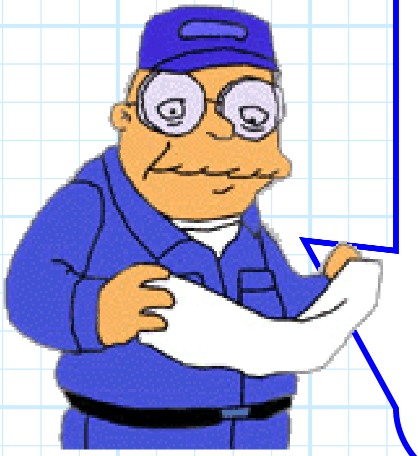
A hole with kinetic energy < E_B will.....



...be pushed back by the electric field (it will ***not*** *diffuse across the depletion region)!*

Thus, the diffusion current I_{Df} across the *p-n* junction will depend on three things:

1. **The majority particle concentration.** -The more holes or free electrons there are, the more particles will diffuse across the junction.
2. **The barrier voltage V_B.** – A lower barrier means less kinetic energy is required to diffuse across the depletion region, resulting in more.
3. **The diode temperature** – Higher temperature means holes and electrons have more kinetic energy and thus are more likely to diffuse across the depletion region.



Q: *Wait a minute! We've examined the behavior of holes in the p-type region and free electrons in the n-type region. These are the* ***majority*** *carriers for each of those Silicon types.*

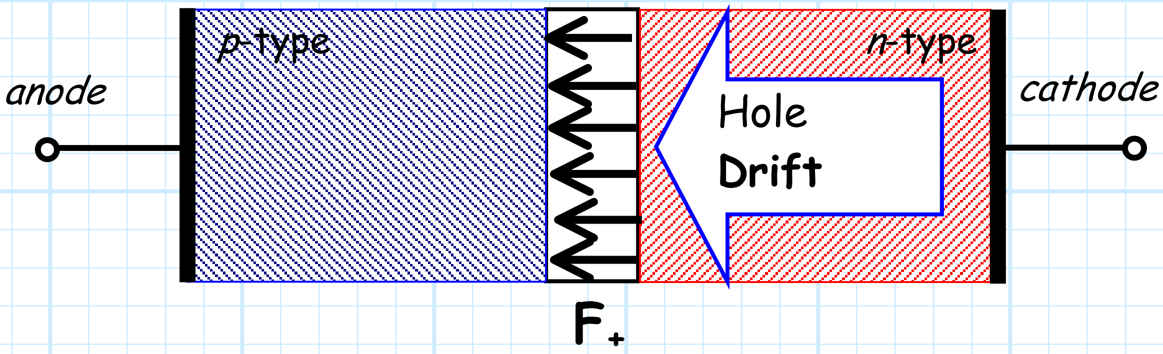
There are also ***minority*** *carriers present in each side. What does the electric field in the depletion region do to* ***them****?*

A: A great question! We will find that the electric field will have a profoundly **different** effect on **minority** carriers!

For **holes:**

Recall that the electric field in the depletion region applies a force on **positive** charges (holes) that is directed **from** the *n*-type (cathode) region **into** the *p*-type (anode) region.

This force of course **pushes** the holes in the *p*-type anode (the *majority* carriers) **back into** the *p*-type region. **However**, the same force will **pull** holes from the *n*-type region (the **minority** carriers) **into** the *p*-type region!



Any unsuspecting **minority** hole that "drifts" into the depletion region will from the *n*-type side will be **pulled** into the *p*-type side! Note that this result is **independent** of the kinetic energy of the particle—it takes **no** energy to "fall **downhill**".

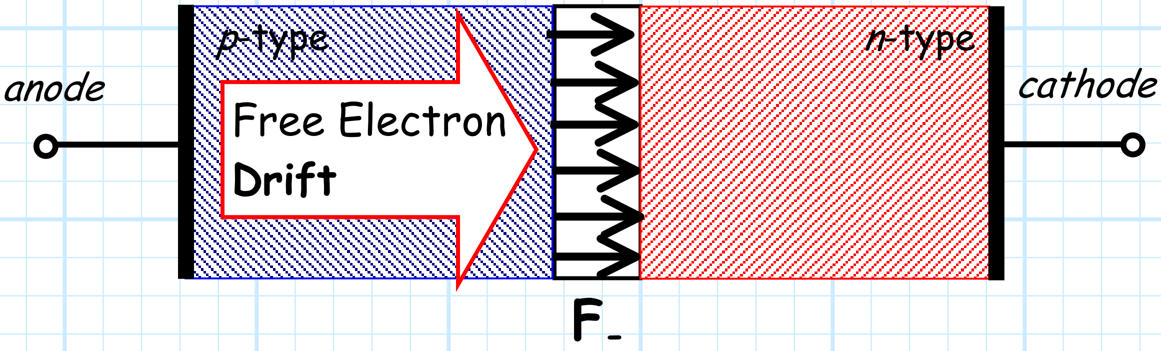
This movement of charge is completely **due** to the force applied by the **electric field**—this is **drift current** I_s!

Now, for **free electrons:**

Recall also that the electric field in the depletion region applies a force on **negative** charges (free electrons) that is directed **from** the *p*-type (anode) region **into** the *n*-type (cathode) region.

This force of course **pushes** the free electrons in the *n*-type region (the **majority** carriers) **back into** the *n*-type region.

However, the same force will **pull** free electrons from the *p*-type region (the **minority** carriers) into the *n*-type region!

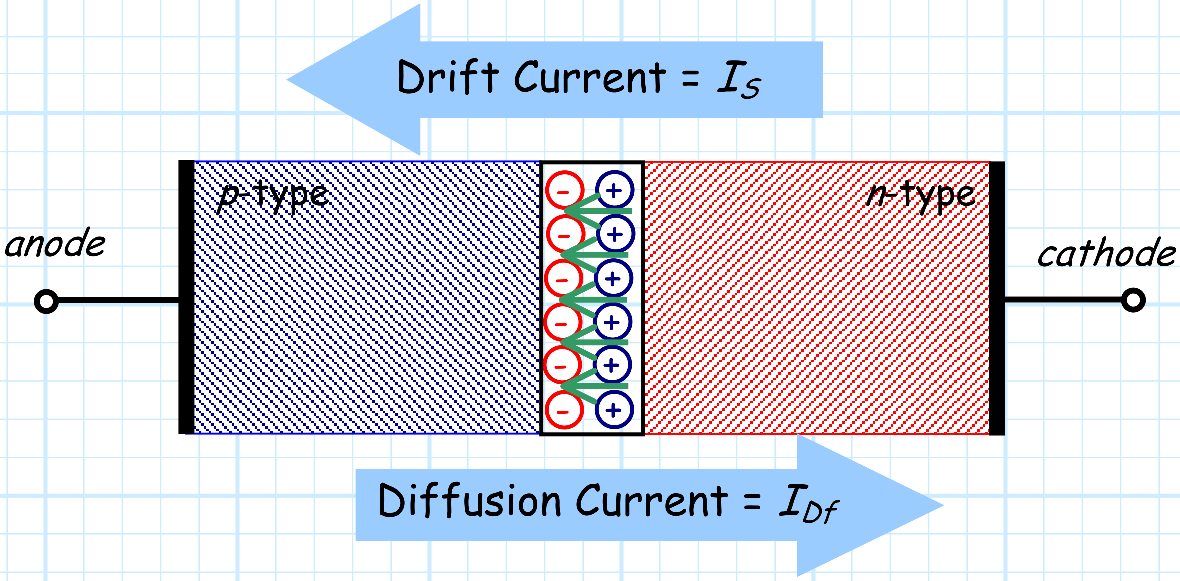


Any unsuspecting **minority** free electron that "drifts" into the depletion region will from the *p*-type side will be **pulled** into the *n*-type side! Note that this result is **independent** of the kinetic energy of the particle—it takes **no** energy to "fall **downhill**".

This movement of charge is completely due to the force applied by the **electric field**—this is also **drift current** I_S!

There are two very important **differences** between **drift** and **diffusion** currents in a *p-n* junction diode:

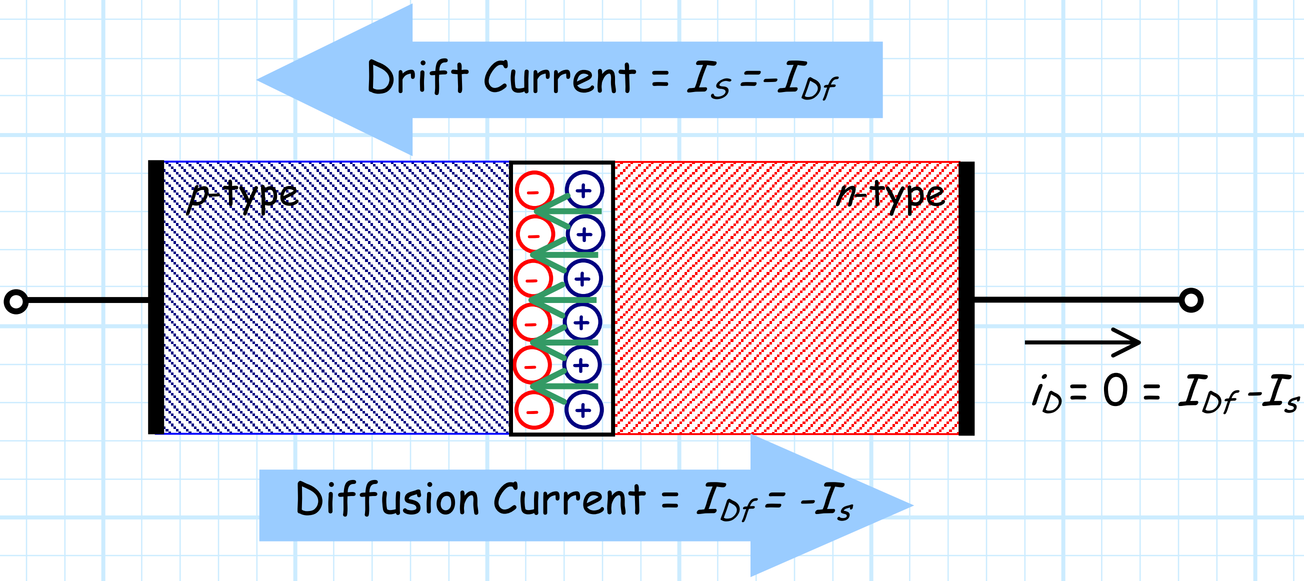
1. Drift and Diffusion current flow in opposite directions – The Diffusion current I_{Df} flows across the *p-n* junction from anode to cathode, while Drift current I_S flows across the *p-n* junction from cathode to anode.



2. Diffusion current depends on the barrier voltage V_B, but Drift Current does not. – As the barrier voltage increases, fewer and fewer of the majority carriers will have sufficient kinetic energy to cross the depletion region—the **diffusion** current will **decrease**.

Conversely, minority carriers require **no energy** to be swept across the depletion region by the electric field, the value of the **barrier voltage is irrelevant** to the value of drift current I_S.

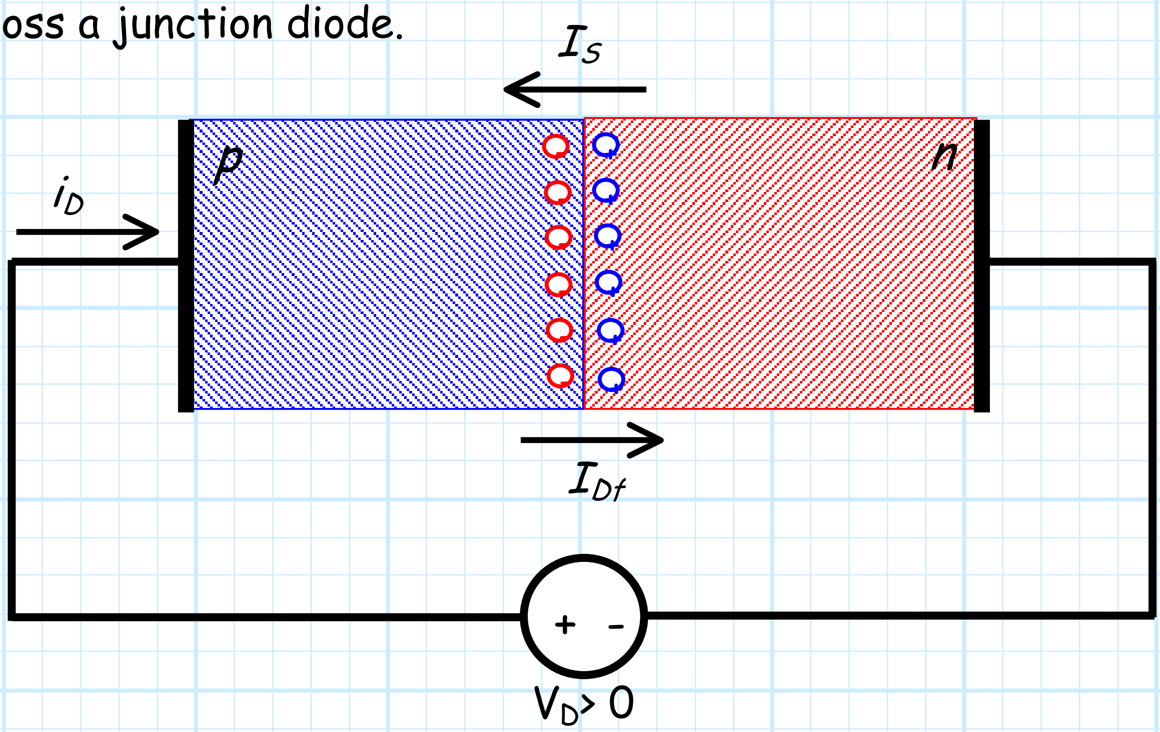
Now, for an open-circuited (i.e., **disconnected**) junction diode, the **total current** i_D through the device **must be zero** (**i_D=0**). In other words, the diffusion current I_{Df} must be **equal but opposite** that of the drift current I_S, such that $I_{Df} - I_S = 0$:



This is the **equilibrium** state of a **disconnected** junction diode. We find that typically this drift/diffusion current is **very small**, generally 10^{-8} to 10^{-12} Amps!

The *p-n* Junction in Forward Bias

Now consider the case where we place a **small, positive voltage** across a junction diode.



1) This voltage **reduces** the **barrier** voltage, i.e., the electric field that **holds back** the **diffusion** of holes from the anode to the cathode, as well as holds back the **diffusion** of free electrons from the cathode to the anode.

2) Thus, diffusion current **increases** as diode voltage increases. In fact, this increase is **exponential** with the diode voltage! :

$$I_{Df} = I_s \, e^{v_D / nV_T}$$

3) But, the **drift** current does **not** change if v_D is increased! The **reduced** electric field moves charges with **less** force, but the **number** of holes and free electrons swept across the depletion region does not change. Therefore, drift current I_S remains at its same **small** value, **independent** of diode voltage v_D.

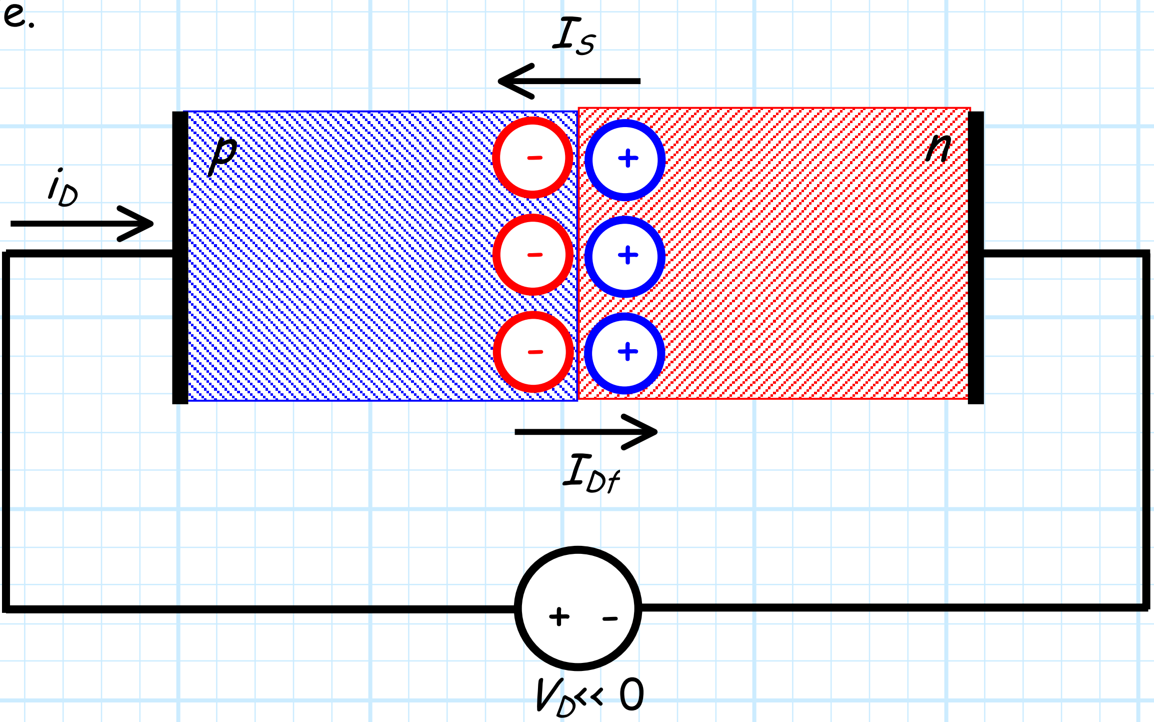
The total current i_D through the diode is therefore:

$$\begin{aligned} i_D &= I_{Df} - I_S \\ &= I_S\, e^{v_D / nV_T} - I_S \\ &= I_S\left(e^{v_D / nV_T} - 1\right) \end{aligned}$$

*Hey! this result is **very familiar** !!*

The *p-n* Junction Diode in Reverse Bias

Say we now place a significant **negative** voltage across the diode.



1) This negative voltage **increases** the electric field within the **depletion** region.

2) The **barrier voltage** is now so large that it **stops** virtually all **diffusion** across the junction.

3) Therefore, the diffusion current I_{Df} **= 0**:

$$I_{Df} = I_s e^{v_D / nV_T} \simeq 0 \qquad \text{for} \quad v_D \ll 0$$

4) As with the forward bias case, the **drift current** remains **constant**. The holes and free electrons are swept through the depletion region with greater energy, but the **number** these charged particles remains **unchanged**.

Therefore, the **total** diode current is:

$$\begin{aligned} i_D &= I_{Df} - I_S \\ &= 0 - I_S \\ &= -I_S \end{aligned}$$

This result should **likewise** be **very** familiar !

The *p-n* Junction Diode in Breakdown

If reverse bias too large (i.e., $v_D < -V_{ZK}$), the **covalent** bonds within the depletion region will **break**.

Therefore, **free** electrons are created (i.e., **conductivity** σ goes from zero to very high).

Large electric field **and** high conductivity:

→ This means **high current** ($\mathbf{J} = \sigma \mathbf{E}$) !!

Attempts to decrease v_D past $-V_{ZK}$ instead just causes further breaking of covalent bonds (i.e., conductivity σ increases). Therefore $|i_D|$ increases while $v_D \approx -V_{ZK}$.

There are **two** mechanisms for breakdown.

1) **Zener Effect** – Covalent bonds break because of large **E**-field.

2) **Avalanche Effect** – Bonds break due to kinetic energy of drift current.