Physics of Semiconductors

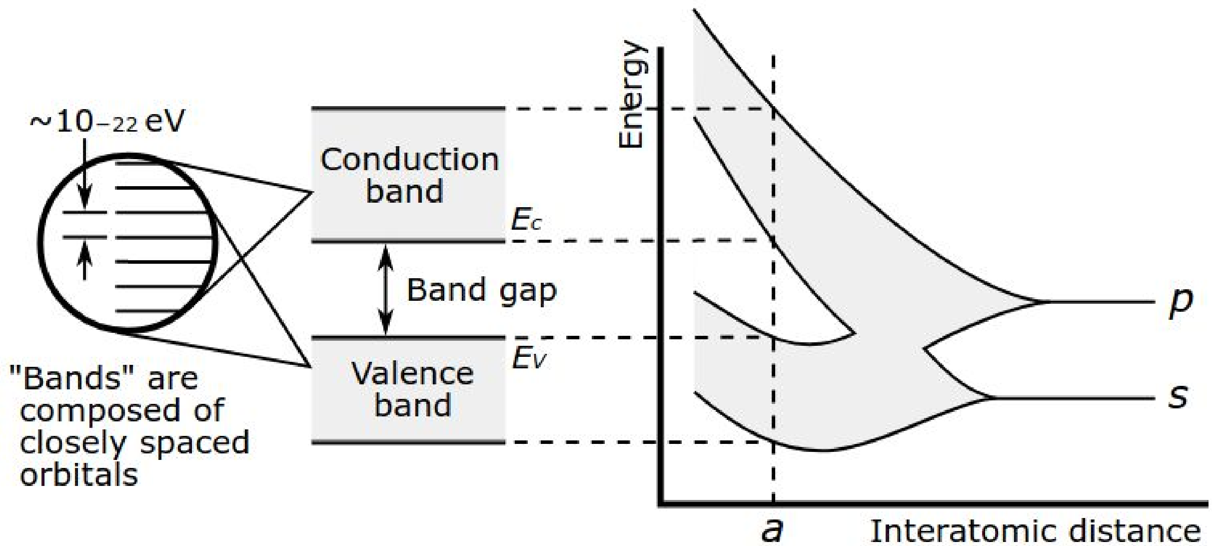
Charge Carriers

- **Charge carriers** are particles which are "free to move, carrying an electric charge, especially the particles that carry electric charges in electrical conductors".
    - There are two particular **charge carriers** present in **semiconductors**:
        - **Electrons**, negative particles.
            - Denoted by e^-.
            - Usually indicated with a black dot.
            - For reference, this is the only **charge carrier** in **metals**.
        - **Electron holes**, deficiencies of **electrons**.
            - It is useful to study **electron holes** as if they are particles (they are, in fact, quasiparticles), due to the net positive charge that their existence causes.
            - Denoted by h^+.
            - Usually indicated with a white dot.
    - The most abundant **charge carrier** is the **majority carrier**, and less abundant the **minority carrier**.
    - One way of looking at these (particularly relevant when studying generation and recombination) is to view them as **electron-hole pairs**.
    - In any kind of **semiconductor**, "Recombination and generation are always happening … both optically and thermally." This is not enough to induce desirable amounts of conduction.
    - "Unlike in metals, the atoms that make up the bulk semiconductor crystal do not provide the electrons which are responsible for conduction."
        - Rather than, say, Si **electrons** carrying the current (which they don't, as they are not mobile), either an **electron** from a **pentavalent atom**, or an **electron hole** will. We achieve conduction with semiconductors by this method, **doping**.

Band Theory

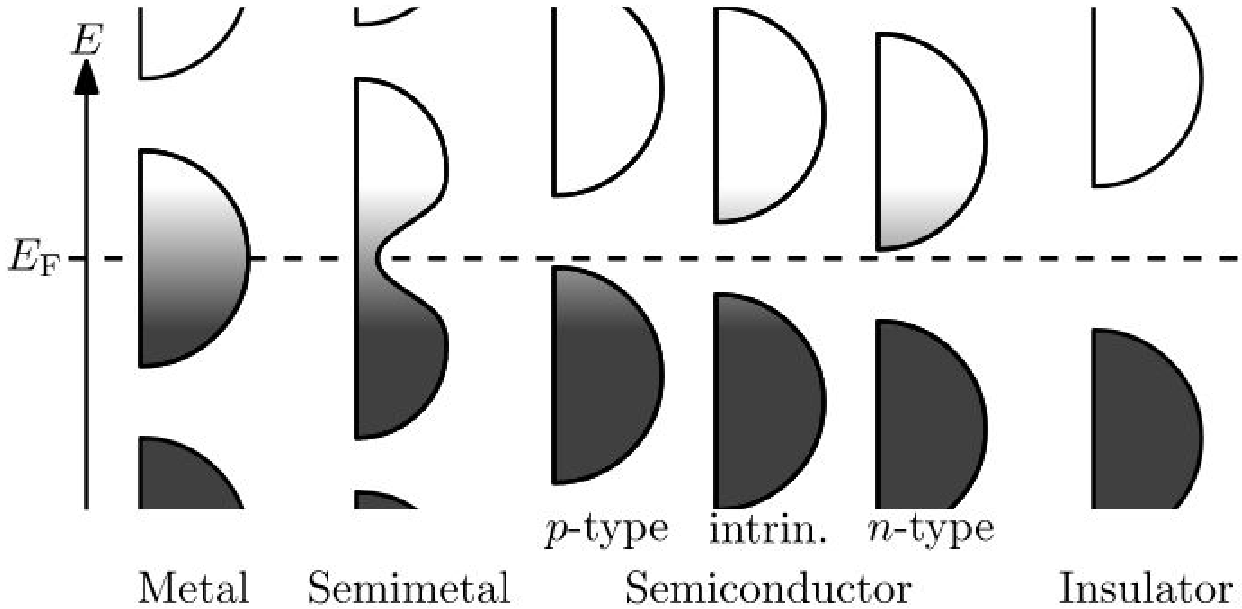
- The study of the electrical conductivity of different materials falls within the field of solid-state physics, itself a member of condensed matter physics.
    - One model that can be used to understand the energy levels of a solid or rigid matter is **band theory**, describing an **electronic band structure**.
        - Used to understand arrays of atoms, like so:
            - An atom - say, an Si atom - starts off with two molecular orbitals, p and s.
            - The Si is bonded to another Si to become a homonuclear diatomic molecule.

- Due to the [Pauli exclusion principle](), no two electrons may have "the same values of the four quantum numbers: n, the principal quantum number, ℓ, the azimuthal quantum number, m_ℓ, the magnetic quantum number, and m_s, the spin quantum number."
- In order to not violate this principle, "each atomic orbital splits into two molecular orbitals of different energy".
    - The p orbitals and s orbitals are still distinct.
    - The like orbitals have a very similar amount of energy, and so are grouped together, into **bands**.
- This orbital splitting repeats as more atoms are introduced:



- "A solid has an infinite number of allowed bands, just as an atom has infinitely many energy levels. However, most of the bands simply have too high energy, and are usually disregarded under ordinary circumstances."
- "Conversely, there are very low energy bands associated with the core orbitals (such as 1s electrons). These low-energy core bands are also usually disregarded since they remain filled with electrons at all times, and are therefore inert."
- Thus, the distinguished **bands**, **band gaps**, and levels are:
    - The **Fermi level**, the theoretical energy level of an **electron**, "such that at thermodynamic equilibrium this energy level would have a 50% probability of being occupied at any given time."
        - This is equivalent to the **work** required to *add* one **electron** to a **solid-state body**.
    - The **valence band**, the **band** nearest to the **Fermi level**, closer to the **atom**.

        - In **semiconductors**, this consists of the **valence orbitals**.
    - The **conduction band**, the **band** nearest to the **Fermi level**, further from the **atom**.
    - The **band gap/energy gap**, a space where **electrons** cannot exist.
        - This exists between the **valence band** and **conduction band**.
- The **band structure** varies depending on the material (noting that *intrin* is an **undoped semiconductor**). These are examples at **equilibrium**, where white represents unfilled states, and black filled states:



    - "the low energy states are completely filled with a fixed limit on the number of electrons at all times, and the high energy states are empty of electrons at all times."
        - In this case, the **conduction band** is mostly filled with **electrons**, and the **valence band** has a little bit filled.
- ["Only electrons in energy levels near or above the Fermi level are free to move within the broader material structure, since the electrons can easily jump among the partially occupied states in that region."]() - In order to conduct electricity, we have to get **electrons** past the **Fermi level**!
    - In the case of **metals**, **charge carriers** can move past the **Fermi level** with ease.
    - As for an **undoped semiconductor**, there are not many energy levels near the **Fermi level**, that is, it falls within the **band gap**.

            - Using **doping**, we can move the **valence** or **conduction band** closer to the **Fermi level**, making it behave like a **metal**.

Semiconductors

- **Semiconductors** are materials with an intermediate electrical conductivity.
    - Elements with this classification include:
        - Silicon.
            - Advantages (From "Silicon Detectors") include:

"Very well developed technology (simplified version of IC's)
Fair signals created, "easily" detected (3.6 eV for the creation of an electron/hole pair)
Operation close to Room Temperature (RT)
Possibility to finely segment the electrodes down to few tens of μm"

            - Has an electron configuration of $1s^2 2s^2 2p^6 3s^2 3p^4$.
        - Germanium.
    - "Silicon and germanium are used here effectively because they have 4 valence electrons in their outermost shell which gives them the ability to gain or lose electrons equally at the same time."
    - There are two categories of **semiconductors** w.r.t. the presence of **doping species**:
        - **Intrinsic semiconductor/i-type semiconductors**, pure material "without any significant dopant species present" .
            - "the number of excited electrons and the number of holes are equal: n = p"
            - Allows for a small amount of electrical conductivity "due to crystallographic defects or electron excitation". These events create charge imbalances, but on a smaller scale than when doping.
                - Part of why these events don't have a larger effect is that, in carrier recombination, **charge carriers** may be made stationary, nullifying their imbalancing effects.
                    - This occurs when the smallest unit, an **electric-hole pair**, is joined together.
        - **Extrinsic semiconductors**, substances which have had impurities injected into them.
            - Created with **doping**.
            - Relatively **conductive**.
            - Has two types:
                - **N-type semiconductors**, where the **majority carrier** is the **electron**.
                    - Formed by **doping** with an **electron donor**.
                    - Free **electrons** are donated to the **conduction band**.

- Can be denoted with n^+ or n^-, to indicate the extent of the doping.
- **P-type semiconductors**, where the **majority carrier** is the **electron hole**.
  - Formed by **doping** with an **electron acceptor**.
  - **Electrons** are accepted from the **valence band**, creating **holes** in the **valence band**.
  - Can be denoted with p^+ or p^-, to indicate the extent of the doping.
- The **elements** that may be used as an **intrinsic semiconductor** to dope, and **donor** or **acceptor** vary (Source):

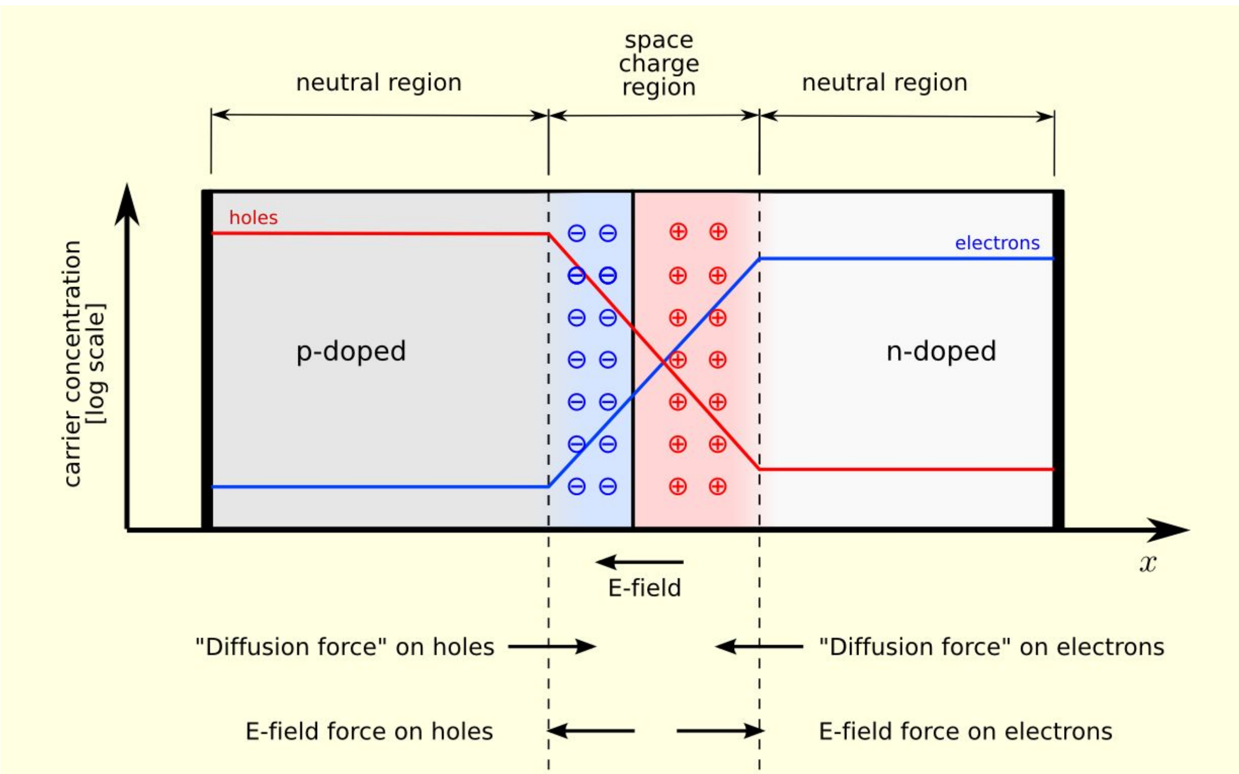
	Intrinsic semiconductor	Donor atoms	Acceptor atoms
Group IV semiconductors	Silicon, Germanium	Phosphorus, Arsenic, Antimony	Boron, Aluminium, Gallium
Group III–V semiconductors	Aluminum phosphide, Aluminum arsenide, Gallium arsenide, Gallium nitride	Selenium, Tellurium, Silicon, Germanium	Beryllium, Zinc, Cadmium, Silicon, Germanium

- The **doping agents** all are **pentavalent** or **trivalent** elements.

P-n junctions

- A **p-n junction** forms when the two respective **extrinsic semiconductors** are put together.
  - "A depletion region forms instantaneously across a p–n junction." As this area has been "depleted" of **charge carriers**, it is **nonconductive**.
    - This process is the aforementioned **recombination**. **Electron-hole pairs** meet, with free **electrons** from the **n-type** filling the **electron holes** from the **p-type**.
    - But, we doped the Si so that we *could* have some **conductivity**!
    - In order to **conduct** electricity across the **p-n** interface, we must supply a sufficient potential energy difference between the sides.
    - There are different **biases**, applications of **voltage** across **p-n junctions**, that can be applied:
      - **Zero bias**, when there is no external applied voltage, so the potential difference is just the **built in potential**, V_{bi}.
        - This is created due to the following process:
          - The two sides interface.
          - The **electrons** from the **n-type** are attracted to the **electron holes** from the **p-type**.
          - The **electrons** diffuse into the **p-type**, recombining the **electron-hole pairs**.

- Both the **donor** and **acceptors** are a part of the crystals, and don't move.
- There is now a negatively charged region on the **p-side** and positively charged region on the **n-side**.
    - This isn't throughout the whole **p-n junction**, there are neutral regions on both sides (even though the entirety *is* **doped**.).
- This results in an electric field being created, going from the **n-side** to the **p-side**.
- At the point between the **neutral region** and the **space charge region**, there is a "**diffusion force**" on the **electron holes**, as they are attracted to the **n-side**.
    - Unlike the recombinant **electron-hole pairs**, these **holes** will not get recombined, as there is now the **E-field** to oppose the **diffusion force**.
- Diagram of what the **p-n junction** looks like now:



- **Forward bias**, when the **p-type** is connected with the positive terminal, and **n-type** with the negative terminal.
    - This is created due to the following process, on top of what has been mentioned for **zero bias**:

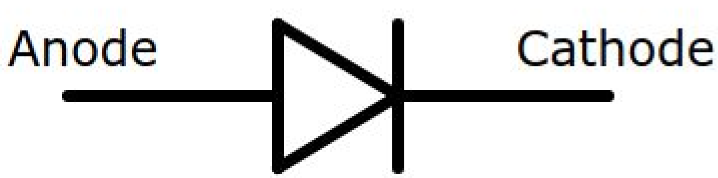
            - The **holes** and **electrons** are both pushed towards the **depletion region**.
            - The **depletion region** is somewhat neutralized.
            - The change in **potential energy** from the **p-side** to the **n-side** increases, changing the sign if the external **voltage** is great enough.
            - As the external **voltage** increases, the **depletion region** becomes diminishingly small, taking the **E-field** with it. This is imposed by a force exerted by the **forward bias**.
            - With the **E-field** small enough, the **diffusion force** can now have **majority charge carriers** cross the **p-n junction**.
            - Both **electrons** and **holes** begin crossing over, without stopping.
            - A consistent current flow is created.
    - **Reverse bias**, when the **p-type** is connected with the negative terminal, and **n-type** with the positive terminal.
        - This is created due to the following process, on top of what has been mentioned for **zero bias**:
            - The **electrons** and **holes** are pulled away from the **depletion region** due to how the terminals are arranged.
            - The **depletion region** is widened.
            - The **voltage barrier** is increased, increasing the **resistance**.
            - The **p-n junction** starts to function more like an **insulator**.
            - As a result, “very little current flows until the diode breaks down.”
- As a result: **currents** only really flow with a **forward bias**, and electrons can only flow from **n** to **p**!
    - This is the principle that unidirectional devices operate on.

Application of Semiconductors

Diodes

- “A **diode** is a two-terminal electronic component that conducts **current** primarily in one direction (asymmetric conductance); it has low (ideally zero) resistance in one direction, and high (ideally infinite) resistance in the other.”

- Potential uses include converting from alternating current to direct current, and measuring temperature and voltage differences.
- Historically made with **vacuum tubes**.
- Now most commonly made as **solid state diodes**, often **p-n diodes**.
    - Consists of a crystal of a **semiconductor**, doped to where there is a **p-n junction**.
        - Usually made with silicon.
    - With **zero bias**, no current flows through the **diode**.
    - With **forward bias**, a **diffusion current** is present.
    - With **reverse bias**, **leakage current** is present.
        - This is very weak current which arises from "generation-recombination defects in this region"
        - At a great enough voltage, can cause an **avalanche breakdown**.
            - This happens as follows:
                - As V increases, the depletion zone widens, and the electric field within it becomes stronger.
                - Because of this, the **minority charge carriers** moving from the **n-side** to the **p-side** start moving faster.
                - These **minority charge carriers** can knock **electrons** off of atoms in the **depletion zone**, which causes a chain reaction of **minority charge carriers** flowing back and forth.
                - A large current is created by the **mobile charge carriers**.
            - This occurs at $V_{breakdown}$ (V_b).
            - For normal **diodes**, this is generally a bad thing, and will break the component.
            - Covered in this video.
- Electronic symbol:

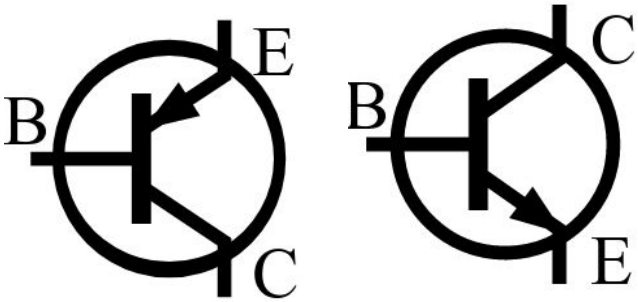


- Covered in this video.
- Covered in this textbook chapter.

Transistors

- A **transistor** is a three-terminal electrical component which controls the **current** through a pair of the terminals by applying **current** to the third terminal.

- Not the focus of this research, but interesting to mention as **bipolar junction transistors** use a p-n-p arrangement or n-p-n arrangement.
    - Usually made with silicon.
    - Electronic symbols:



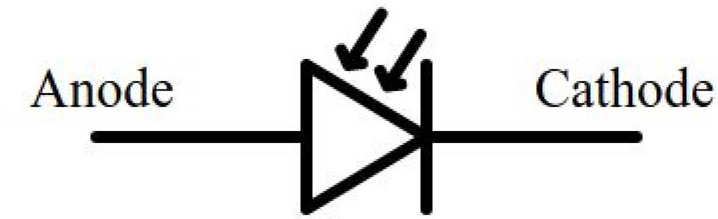
    - Covered in this video.

Photomultiplier

- A **photomultiplier** is an electric component which allows for the detection of **photons**, with an electric signal.

Photodiodes

- A **photodiode** (also see here) is an electrical component which converts **light** into **electrical current**.
    - Unlike other **semiconductor diodes** in that:
        - It is not packaged to block light.
    - Uses photoconduction, a phenomenon where the absorption of electromagnetic radiation results in increased conductivity.
        - Used to drive light sensitive processes, specifically “electrophotographic or xerographic processes” (Source).
        - Devices which operate on this principle are photodetectors.
    - Uses a **p-n junction**.
    - “The total current through the photodiode is the sum of the dark current (current that is generated in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device.”
    - Can operate in two different modes:
        - **Photovoltaic mode**, which operates at **zero bias**.
        - **Photoconductive mode**, which operates at **reverse bias**.
    - Electric symbol:



- Covered in [this](#) video.

Avalanche Photodiodes

- An **avalanche photodiode**/**APD** (also see here) is a **photodiode** which tolerates **avalanche breakdowns**, in order to amplify the **photocurrent**.
    - Operates at **reverse bias**.
    - Can be used for **proton counting** if in **Geiger mode**.
        - **APDs** specialized for this are **single-photon avalanche diodes**.
            - These have a lower **breakdown voltage**.
            - "At this bias, the electric field is so high [higher than 3×105 V/cm] that a single charge carrier injected into the depletion layer can trigger a self-sustaining avalanche."
                - After these avalanches, the **diode** is **quenched**, resetting its state.
            - Covered in this video.

Photoconductor

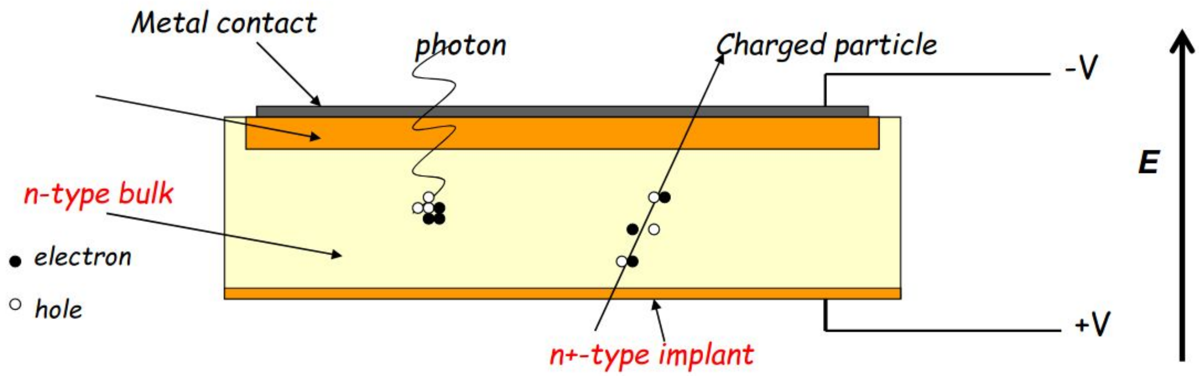
- A **photoconductive detector** is a **photodetector** which does not have a **p-n junction**, generally.
    - There are two main types of **photoconductors**:
        - **Intrinsic photoconductors** which use pure materials.
            - Can use "lead salt, cadmium sulfide and mercury cadmium selenide".
            - Only useful when "the photon energy is above the band gap energy, i.e., for sufficiently short optical wavelengths".
        - **Extrinsic photoconductors** which use materials with **impurities**.
            - Can use silicon and germanium.
            - Higher doping allows for stronger absorption.
            - Often used for **infrared detection**.
            - In its most basic form, it can be "a piece of semiconductor material with two attached metallic electrodes for sensing the resistance."
            - Doesn't necessarily use a **p-n junction**.
    - "It is desirable that a photoconductive detector has a high dark resistance, i.e., exhibits only a low electrical conductivity without incident light."

        - See here for a lead selenide **photoconductor** which features this characteristic.
    - Concerns with this include **thermal excitation** from high operating temperatures, or from background **thermal radiation**.
        - Cooling is especially important for **extrinsic silicon photoconductors**.
    - Can be made to be very responsive, more so than **photodiodes**.

Semiconductors in Sensors

Integrated Circuits

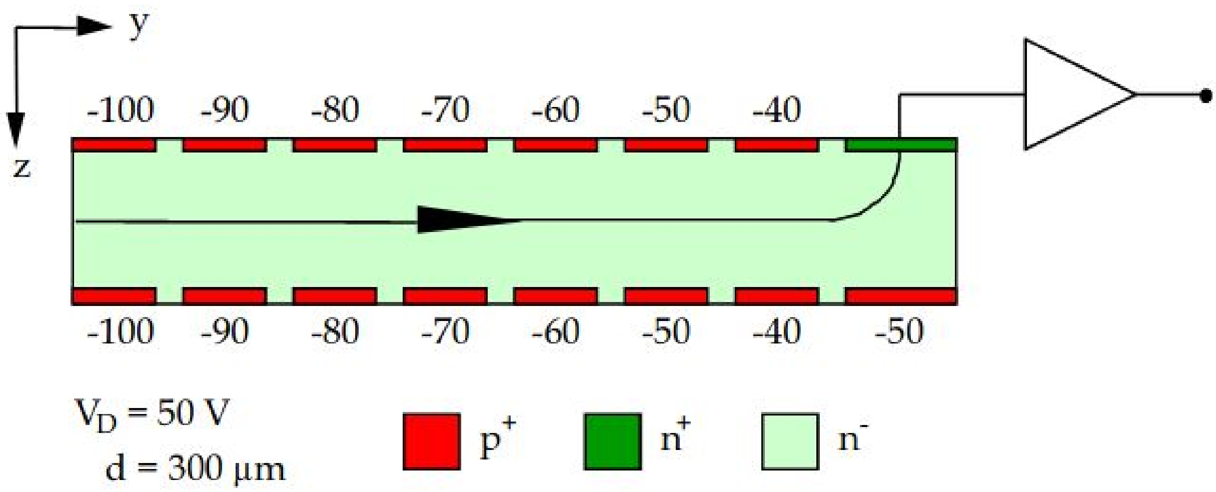
- **Integrated circuits** allow us to implement circuits in a cost and resource effective manner.
    - Usually made with silicon.
    - Essentially made by cutting silicon wafers, and **doping** them.
        - The process is covered in more detail here.
        - The fabrication process for **CMOS** chips in particular is covered here.
    - Makes use of **p-n junctions**, as in **diodes**.
        - This can be used to "emulate" components that wouldn't be on an IC.
    - Every chip starts as pure silicon (or, say, germanium).
        - The substrate is lightly doped, either as an **n-type** or **p-type semiconductor**.
            - This has a relatively low concentration of the **majority charge carrier**.
                - This is done to prevent the recombination of **charge carriers** (Source).
            - This may also be called the **bulk**.
        - An **n-well**/**n-implant** or **p-well**/**p-implant** of the opposite type is put in place.
            - For **CMOS** chips, **n-wells** in **p-substrate** are preferred for lower leakage currents.
        - The top layer has **electrodes**, used to receive pulses.
- A sensor can be constructed to detect radiation, as follows:



- There is an electric field present, because of the **p-n junction**.
    - Question: Unlike in a simple **diode**, there are two differently oriented **p-n junctions** here. How is the electric field still all upwards?
        - The electric field is given by $\frac{dE}{dx} = \frac{E(\Delta x) - E(0)}{\Delta x} - \frac{\rho}{\varepsilon}$, where ρ is **charge density**, and ε is **permittivity**, constant for a given material..
            - This is a form of **Gauss's law**.
- **Photons** or charged particles enter through the **n^+ implant**, and travel along the electric field *E* through the **n^- bulk**.
    - Question: Why don't they recombine with the **major charge carriers** in the **implants**?
        - Electrons won't really recombine in **n-type semiconductors**. When they do reach the **p-type semiconductor**, they are not recombined due to the **electric field** moving them along.
- The particles travel through **p^+ implant**, and make contact with the **electrode**.
- The **electrode** is part of a **read-out chip** or **readout integrated circuit**/**ROIC**, which processes the result.

Silicon Drift Detectors

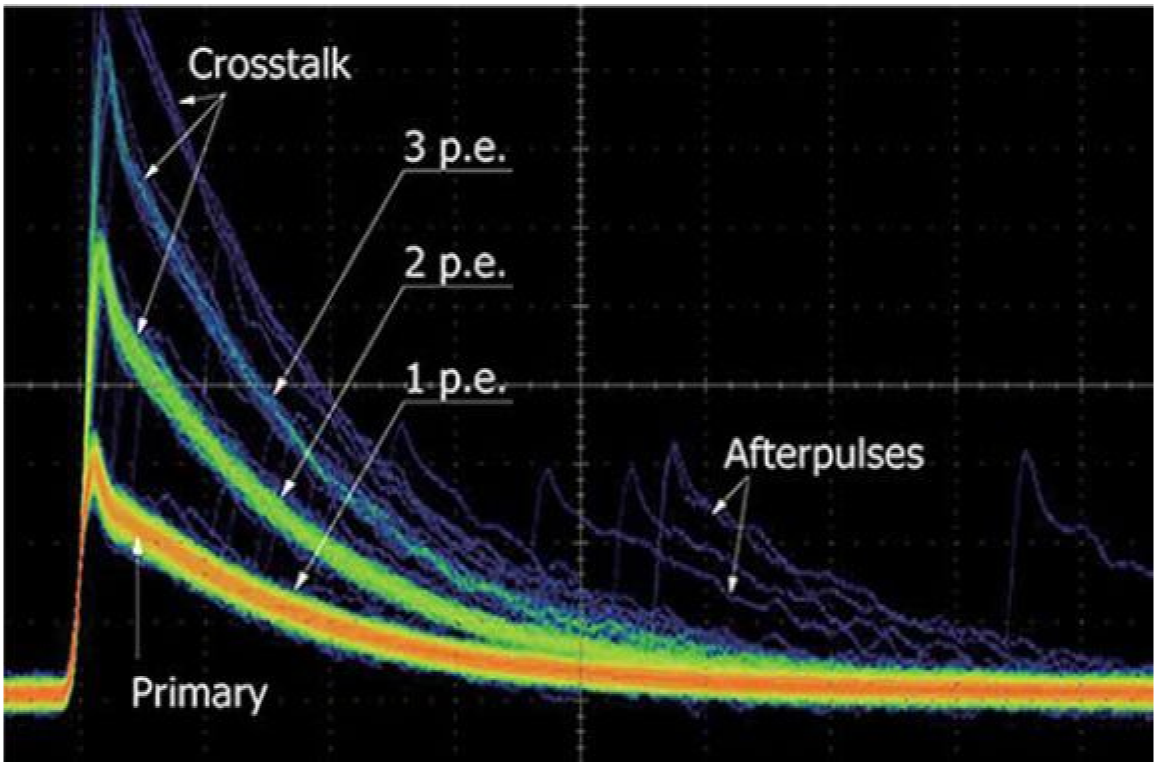
- **Silicon drift detectors** can be used to detect X-rays, and to deplete the substrate.



- "Anode connected to ROIC, while voltages applied to the cathodes create an electric field following which the electrons drift to and are collected by the anode."
- This seems to have two uses:
    - Measuring incoming radiation:
        - Incoming radiation "drifts" to the **anode**, as demonstrated here.
        - The radiation produces a varying amount of ionization in the substrate.
        - The anode can measure the amount of **ionization**, which can be used to determine the energy of the **radiation**, e.g. an incoming **photon**.
    - Reducing noise, by collecting free **electrons**.

Silicon Photomultipliers

- **Silicon photomultipliers/SiPM** are devices used to amplify signals, based on **SPAD**s.
    - Can be used to count **photons**.
    - Works on the principle of one **electron** being able to cause an **avalanche**.
    - Smaller and cheaper than the traditional **vacuum photomultiplier tubes**.
    - Measures in peaks of **photoelectrons**/**p.e.**:



Journal

7/19/20

- Question: How can you tell that this is actually 1e15 and not just 15?
- Question: what temperature is assumed when running simulations?
    - 300 degrees Kelvin. I just found this out by looking at the lattice temperature in the Xsection plot.
- Question: why is the chip said to be one-dimensional, if it has an x-axis?
    - Nothing along the x-axis is changed, so it is effectively 1-dimensional.
- Question: why is the aluminum at the bottom called the substrate?
    - It is in contact with the substrate.
- Question: what is the “cond” in cond current?
    - Conduction current.

7/20/2020

- Question: How should one go about collecting data from TonyPlot?
    - CSV and TonyPlot data exports.
- Poster title: “TCAD Simulations of a Photoconductor”

7/23/2020

- General goal: have the hole concentration flatten out.