

Nature and Properties of Materials
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Lecture 37
Electric Properties 1

Other than the mechanical properties of materials, we have also discussed about the thermal properties of materials and the optical properties of materials. Now today, we are going to look into another interesting set of properties, which are known as the electrical properties of the material. As I told you that, materials are becoming more and more multifunctional today okay. In fact, very shortly they are also called functional materials, so functional materials actually solve more than one purpose, they not only solve the mechanical purpose, but they also solve some electrical or may be thermal or maybe optical or maybe magnetic functions they actually take care.

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So, in this particular talk we are going to talk about the Ohm's law which you all know, but for the sake of completeness we should discuss it, the electrical conductivity, energy band structure of solid materials and then conductivity in metals, semiconductors, ionic ceramics particularly that group of ceramics which has the Ionic bonds and the polymers, so this is what we are going to talk about in today's lecture. So let us 1st start our life with the Ohm's law.

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Ohm's Law

$V = IR$

Resistance (Ohms)
current (Ampere = Coulomb/s)
Voltage drop (Volts = Joule/Coulomb)

- Material's **electric resistance (R)** is an **extrinsic** property i.e., it depends on object geometry.
- Resistivity (ρ)** is independent of specimen geometry (**intrinsic** property) but related to R through the expression

$$R = \frac{\rho l}{A}$$

l : Distance between voltage measuring points
 A : Cross-sectional area perpendicular to the direction of the current
Unit of ρ = Ohm-metre

Reference: W.D Callister, 7 Ed.

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Now, this from your school days that the voltage drop in a circuit, let us say this is our circuit here okay and we have a battery which is the power source and then we have a resistor, it can be a variable resistor which means you can change the resistance of a resistor, we have an ammeter which can actually measure the current and then a part of, so this is the current that is flowing in the loop okay and you need to complete the loop. Now there is one part here where you are actually putting a new material let us say whose resistance is what you are interested to find out.

So what is the cross-sectional area of the material and what is the length of the material and as the current I and you can also find out what is the voltage across it okay through a voltmeter as you mean that the voltmeter is going to take minimum amount of resistance so that it is going to actually measure the voltage drop between the 2 without adding to the voltage drop and then the circuit is complete once it is coming back to the battery.

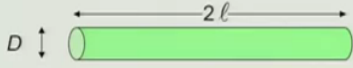
So with this kind of a simple circuit system if you actually note down that what is the voltage drop okay and what is the current from the ammeter, then you will be able to find out that what is the resistance of that particular length of the particular material. Now, this resistance is an extrinsic property because it not only depends on the material property, but also on the professional area on the length, et cetera. So the intrinsic material property that you should go for is called resistivity which is also denoted by Rho, so Rho for density Rho for resistivity we should not actually confuse between the 2 because the unit here is Ohm meter okay.

Now with respect to the extrinsic of property resistance, the relationship is simply given here as $R = \rho \frac{L}{A}$ that is the relationship okay. So once I know this material property of resistivity, once I know the length of the material in the wire form and the cross-sectional area, I can find out what is the actual resistance it will be or the it will be offering when you pass a current across it.

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Electrical Properties

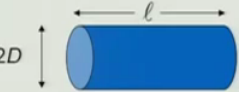
- Which will have the greater resistance?



D ↑

← $2l$ →

$$R_1 = \frac{2\rho l}{\pi\left(\frac{D}{2}\right)^2} = \frac{8\rho l}{\pi D^2}$$

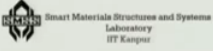


$2D$ ↑

← l →

$$R_2 = \frac{\rho l}{\pi\left(\frac{2D}{2}\right)^2} = \frac{\rho l}{\pi D^2} = \frac{R_1}{8}$$

- Analogous to flow of water in a pipe
- Resistance depends on sample geometry and size.



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Now then suppose I take 2 wires, one of diameter D and length $2L$ and in the other case it is of diameter $2D$ and length L okay. So what is the extrinsic resistance in the 1st case? Well, in the 1st case the length is $2L$ and the resistivity is same ρ and the wire cross-sectional area is $\pi D^2/4$, so it will become $8\rho L/\pi D^2$. On the other hand, if you consider the resistance of this one R_2 , then resistance is same again ρ , length is now L and diameter is double now $2D$, so that you substitute and you will get it as $\rho L/\pi D^2$.

So what it means is that R_2 is actually $1/8$ th of R_1 . So what it means is that if I double the diameter, my resistance come down by $1/8$ th. On the other hand, if I go for doubling the length, then my resistance increases. This is actually analogous to flow of water in a pipe and this also demonstrates that the resistance depends on samples geometry and size, but resistivity is an intrinsic material property.

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Electrical Conductivity (σ)

□ Indicative of the ease with which a material is capable of conducting an electric current.

Electrical Conductivity, $\sigma = \frac{1}{\rho}$, Unit: (Ohm - metre)⁻¹ or Siemens/metre

□ Ohm's Law can also be expressed in terms of current density (J, Current per unit cross-sectional area), conductivity(σ), and applied electric field (E, unit-V/m or N/C).

$J = \sigma E$


$\sigma = \frac{1}{\rho}$

$J = \frac{I}{A} = \frac{V}{AR} = \frac{V}{A \times \frac{\rho L}{A}}$

$V = IR$ $R = \frac{\rho L}{A}$

$I = \frac{V}{R}$ $J = \frac{V}{\rho L} = \sigma E$

$E = \frac{V}{L}$



Now, similar to the real stability there is another very important term that we use that is called conductivity, which is the inverse of the resistivity. So electrical conductivity is $\sigma = 1/\rho$ and hence its unit is Ohm meter inverse or sometimes people also call it as Siemens per meter. So this is indicative of the ease where a material is highly conductive and what is its level of conductivity corresponding to electric current, we can measure it with respect to σ .


Now that we know that this σ is there with us, we can actually get a better form of the Ohm's law now in terms of the current density J , which is current per unit cross-sectional area, $J = I$ current per unit cross-sectional area. And voltage you already know that voltage = $I R$, so which means that I can write $I = V$ over R , so I can write this as V over $A R$, right. Also, I can write R in terms of resistivity, which is ρ times L divided by cross-sectional area A . So if I substitute this expression here, I am going to get V over A times ρL over A .

I can cross area and area, so as a result I am getting $J = V$ over ρL . And also, I have already said by definition $\sigma = 1/\rho$, we already said that. So we can write that as σ and this voltage per unit length is in meter, you can call it as the applied electric field E , so I can write it as $J = \sigma E$ okay, where $E =$ voltage over the length. So thus, we can actually get this beautiful relationship where the J the current density can be related to the applied electric field with the help of electrical conductivity and that is a new form of the Ohm's law.

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On the basis of Conductivity, solid materials can be classified as:

- ❖ **Conductors** : $\sigma > 10^7 (\Omega\text{-m})^{-1}$
- ❖ **Semiconductors** : $10^6 < \sigma < 10^4 (\Omega\text{-m})^{-1}$
- ❖ **Insulators** : $\sigma < 10^{-10}(\Omega\text{-m})^{-1}$



Now on the basis of this conductivity, solid materials can be classified into 3 parts; conductors, where the conductivity is greater than 10 to the power 7 per Ohm meter. Semiconductors, where it is in between 10 to the power - 6 and 10 to the power 4 per Ohm meter, and insulators, where it is actually less than 10 raise to the power - 10 per Ohm meter, so let us look into each one of this now.

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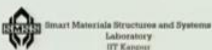
Conductivity: Comparison

- ❖ **Conductors** : $\sigma > 10^7 (\Omega\text{-m})^{-1}$
- ❖ **Semiconductors** : $10^4 < \sigma < 10^6 (\Omega\text{-m})^{-1}$
- ❖ **Insulators** : $\sigma < 10^{-10}(\Omega\text{-m})^{-1}$

Metal	Electrical Conductivity [($\Omega\text{-m}$) ⁻¹]
Silver	6.8×10^7
Copper	6.0×10^7
Gold	4.3×10^7
Aluminum	3.8×10^7
Brass (70Cu-30Zn)	1.6×10^7
Iron	1.0×10^7
Platinum	0.94×10^7
Plain carbon steel	0.6×10^7
Stainless steel	0.2×10^7

Material	Electrical Conductivity [($\Omega\text{-m}$) ⁻¹]
Graphite	$3 \times 10^4 - 2 \times 10^5$
Ceramics	
Concrete (dry)	10^{-10}
Soda-lime glass	$10^{-10} - 10^{-13}$
Porcelain	$10^{-10} - 10^{-12}$
Borosilicate glass	$\sim 10^{-13}$
Aluminum oxide	$< 10^{-13}$
Fused silica	$< 10^{-16}$
Polymers	
Phenol-formaldehyde	$10^{-9} - 10^{-10}$
Poly(methyl methacrylate)	$< 10^{-12}$
Nylon 6.6	$10^{-12} - 10^{-13}$
Polystyrene	$< 10^{-14}$
Polyethylene	$10^{-15} - 10^{-17}$
Polytetrafluoroethylene	$< 10^{-17}$

Material	Electrical Conductivity ($\Omega\text{-m}$) ⁻¹
Si	4×10^4
Ge	2.2
GaAs	10^6
InSb	2×10^4



Reference: W.D Callister, 7 Ed.

Suppose, if I look into the conductivity of the metals where we, well one of the highest conductivity is silver which is 6.8 into 10 to the power 7. And interestingly, all the almost all the generally the metals that we use, all of them have 10 to the power 7 range of conductivity, but next to silver is copper which is 6.0, gold 4.3 into 10 to the power 7 every case,

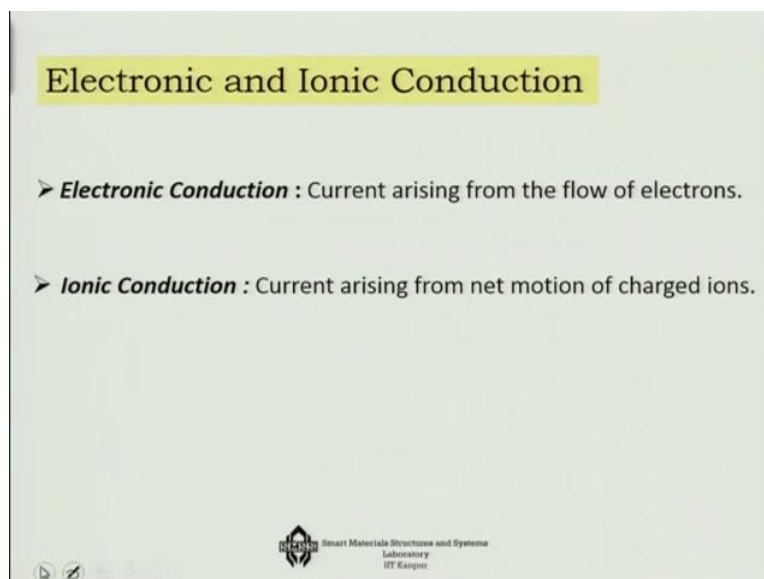
aluminium 3.8, brass 1.6, iron 1.0, platinum 0.94, then carbon steel, further lower than iron because of the alloying 0.6, stainless steel because of the addition of the carbon it is even lower 0.2, so that is the level of electrical conductivity.

Now, if you consider some of the materials which are like semi conductive materials, silicon 4×10^{-4} , germanium 2.2×10^{-6} , gallium arsenide 10^{-6} and InSb that is Indium based alloy, 2×10^{-4} . So we can see here that really the semiconductors are between 10^{-6} to 10^{-4} per Ohm meter and conductors are greater than 10^{-7} per Ohm meter.

And if you consider the insulators in this list, then graphite 3×10^{-4} to 2×10^{-5} , then concrete it is 10^{-9} so it is so low okay. Except graphite, everything else graphite is only having a good conductivity, not as well as metals but still quite a good conductivity, soda lime glass 10^{-10} to 10^{-11} , Porcelain - 10^{-12} , borosilicate 10^{-13} , aluminium oxide 10^{-13} , fused silica 10^{-18} .

And if you consider the polymers where are we like phenol formaldehyde 10^{-9} to 10^{-10} , for PMMA 10^{-12} , nylon - 10^{-12} to 10^{-13} , polystyrene - 10^{-14} , polyethylene - 10^{-15} to 10^{-17} and Polytetrafluoroethylene - 10^{-17} . Having said that again there are some polymers like Polypyrrole, et cetera, which shows much higher degree of conductivity, but we will come to it when we will discuss about the polymers.

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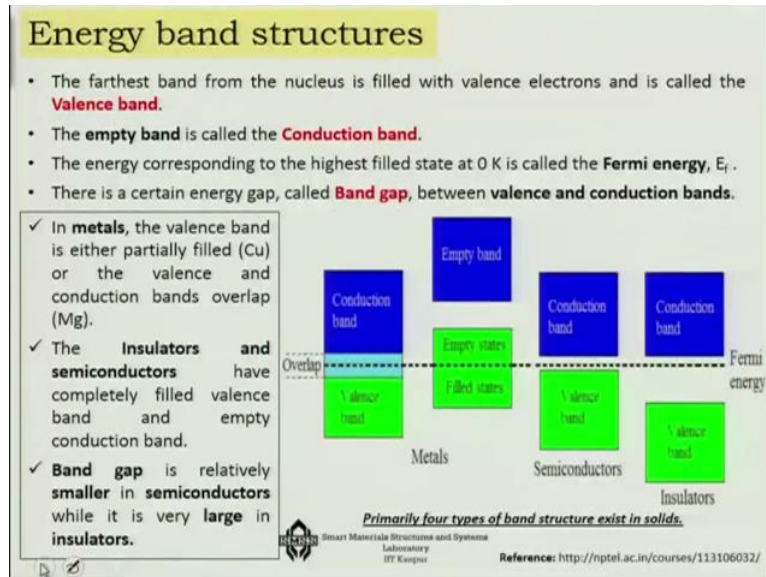
Electronic and Ionic Conduction

- **Electronic Conduction** : Current arising from the flow of electrons.
- **Ionic Conduction** : Current arising from net motion of charged ions.

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Now, the next point is electronic and the ionic conduction. How basically the conduction takes place, there are 2 ways; one is that conduction due to the flow of electrons and another is the ionic conduction, where current is arising from net motion of the charged ions, so in order to explain that we have to know little a bit about the energy band structures.

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Now, the farthest band from the nucleus is filled with the valence electrons and that is known as the valence band, so this is our valency point, okay. Then there is an empty band which is called the conduction band, so this is where our conduction is. The energy corresponding to the highest filled state at 0 degree Kelvin is called the firm energy level, so this is our Fermi energy level that is the highest energy state okay. Just keep in mind that your valency band is below this level in your conduction band is above this level.

There is a certain energy gap between the conduction band and the valence gap and that is known as the band gap as you can see the band gap here. Now, in metals the valence band is either partially filled like copper or the valence and conduction bands, they overlap like in case of magnesium, so there will be either an overlapping or they will be partially filled. On the other hand, the insulators and semiconductors have completely filled valence band and empty conductive bands like this that valence band completely filled and this is completely empty, this part is completely empty.

And the same thing is true for the insulators that this is empty and the only difference between semiconductor and the insulator is that this gap is even more in the case of the insulators. So, the band gap is relatively smaller in semiconductors, while it is very large in

the insulators. So you need to supply in case of metals only a little amount of energy so that the conduction band can then start to flow the electrons and cause the generation of the current.

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Energy Band Structures : Metals (Conductors)

- For metals, empty energy states are adjacent to filled states.
- Metals have high conductivities because of the large number of free electrons that can be excited into empty states above the Fermi energy.
- Very low thermal energy excites electrons into empty higher energy states.

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Reference: W.D Callister, 7 Ed.

So for metals, empty energy states are adjacent to actually filled states, they are very close. And metals have high conductivity because of the large number of free electrons that can be easily excited into empty space above the Fermi energy level. Very low thermal energy excites electrons into this empty higher energy states, so this is easy excitation through thermal energy is one of the tell-tale sign of the metallic conduction, which is the conduction based on electron flow.

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Effect of Temperature on metal conductivity

- Increasing temperature causes greater electron scattering due to increased thermal vibrations of atoms.
- Hence, resistivity of metals increases or conductivity decreases linearly with temperature.
- The total resistivity of a metal is the sum of the contributions from thermal vibrations (ρ_t), impurities (ρ_i) and plastic deformation (ρ_d), i.e. scattering mechanisms act independently of one another.

$$\rho = \rho_t + \rho_i + \rho_d$$

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Reference: W.D Callister, 7 Ed.

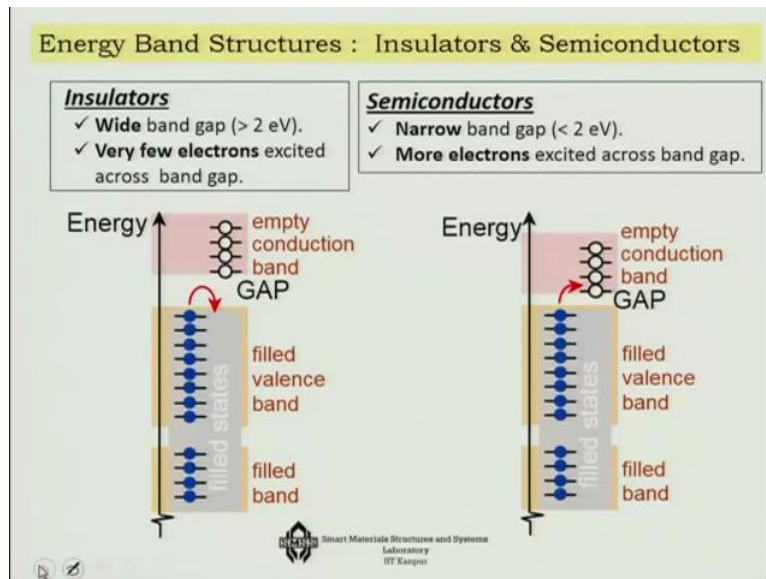
Now, definitely then temperature will should increase this effect. However, when you increase the temperature it would actually cause greater electron scattering due to the increased thermal vibration of the atoms. So hence, resistivity of metals increases or conductivity decreases linearly with the temperature. So instead of allowing the electrons to freely change this gap from the valence band to the conduction band, what happens is that it increases the electron scattering and as a result of this free flow actually gets hampered with the increase of the temperature.

And as you can see here this plot like pure copper, from - 200 onward how the resistivity is continuously increasing that is for pure copper. Similarly, we will see copper with nickel are smaller or bigger amount, each one of them has higher degree of resistivity, but the effect is almost similar that it is increasing the resistivity with respect to temperature. The total resistivity of a metal then is the sum of the contributions from thermal vibration and impurities, both of them are important right.

So I increase the temperature, there is a thermal vibration contribution that is the ρ_t part of it okay and so that is the for example, the ρ_t part of it. And also, there is the effect of the impurities like copper I am writing 1.12% nickel, so that is the ρ_i part of it, the impurity part of it. Also, plastic deformation ρ_d sometimes, so if you further deform the same material, if you further deform it, it will further increase and that is the ρ_d .

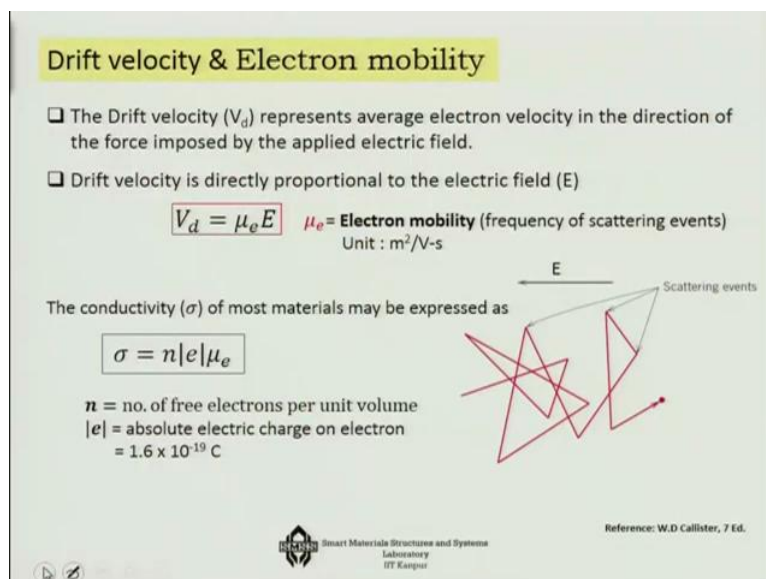
So basically, total resistivity is actually part of ρ_t that is the resistivity due to thermal vibration, ρ_i resistivity due to the impurities and ρ_d that is resistivity due to the plastic deformation, so these are the different things and they can act independently of one another that is very important thing we have to keep in our mind. Now let us look into the energy band structures of insulators and semiconductors.

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Insulators I told you that there will be a wide band gap greater than 2 electron volt and very few electrons will be excited across the band gap, so you can see here that there is a wide band gap here okay and the conduction band remains empty okay. On the other hand, if you consider the semiconductor material then there is a narrow band gap less than 2 electron volt and more electrons are excited across the band gap, so more electrons can actually go from here to here, but if they go then there will be a hole formation you know, so we will talk about it that is the good part of the semiconductors.

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So there is a drift velocity V_d , which represents the average electron velocity in the direction of the force imposed by the applied electric field okay. So electrons, the moment you are

applying the electric field then they will start to flow and then the average velocity of these electrons is measured with the help of the drift velocity V_d and this V_d is expressed as a function of μ_0 times the electric field E and where μ_0 is the electron mobility that is the frequency of scattering events, which is measured in terms of meter square per voltage second.

Now the conductivity σ of most materials may be expressed in terms of this μ term μ , which is the electron mobility and we can write it as the conductivity as n times magnitude of the absolute electric charge on electron, which is $1.6 \times 10^{-19} \text{ C}$ multiplied by the μ_e , which is the electron mobility. So, if you have more free electrons per unit volume, your conductivity will be more. If you have more electron mobility μ , because any way absolute electric charge on electron is not changing. If you have more electron mobility then also you will get a higher conductivity in a metallic system.

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Semiconductors

- Conductivity lower than metals but higher than insulators.
- Semiconductors have relatively narrow band gap generally below 2 eV.
- Therefore, it is possible to excite electrons from the valence to the conduction band.
- Every electron that is excited to the conduction band leaves behind a hole in the valence band.
- A hole is considered to have a charge that is of the same magnitude as that for an electron, but of opposite sign.

The diagram shows three energy bands: the top 'Conduction band' contains several electrons (represented by small circles with minus signs); the middle 'Band gap' is empty; the bottom 'Valence band' contains several electrons, with one missing, leaving a 'Hole' (indicated by a small circle with a plus sign). An arrow points from an electron in the valence band to the conduction band, and another arrow points from the hole in the valence band to the left.

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Now in the case of semiconductors, the conductivity is lower than metals but higher than the insulators we have seen it just now in the table. Semiconductors have relatively narrow band gap generally below 2 electron volts therefore, it is possible to excite electrons from the valence band to the conduction band. Every electron that is excited to the conduction band leaves behind a hole in the valence band.

So like 1 electron jumping from here to here, so there is a hole that is remaining here. A hole is considered to have a charge that is of the same magnitude as that for an electron, but of

opposite sign that is what we call them and the electron deficiency in that region and we call them as a hole.

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Intrinsic Semiconductors

- Electrical behavior is based on the electronic structure inherent in the pure material.
- **Example:** Si, Ge
- Intrinsic semiconductors have two types charge carriers, namely electrons and holes


$$\sigma_i = n|e|\mu_e + p|e|\mu_h$$

n, p = no. of free electrons and holes per unit volume
 $|e|$ = absolute electric charge = 1.6×10^{-19} C
 μ_e, μ_h = Electron and hole mobility, $\mu_e > \mu_h$

- For intrinsic semiconductors, each electron excited to conduction band leaves behind a hole in the valence band, then

$$n = p = n_i = \text{intrinsic carrier concentration}$$

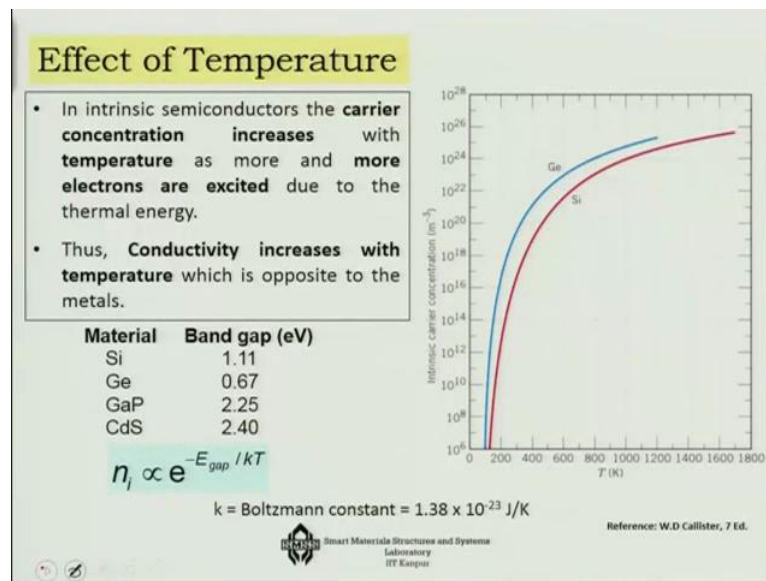
Therefore, **Electric conductivity, $\sigma_i = n_i|e|(\mu_e + \mu_h)$**


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Now intrinsic semiconductors if you consider, the electrical behavior here is based on the electronic structure inherent in the pure material for example, silicon, and germanium. Now intrinsic semiconductors have 2 types of charge carriers namely electrons and holes, so you can write it as n times, where n is the number of free electrons per unit volume, so n times e times Mu e electron charge mobility and p times e times magnitude of e times Mu h, where Mu h is the hole mobility.

So for intrinsic semiconductors, each electron excited to conduction band actually leaves behind a whole in the balance band, so you may say $n = p = n_i$ that is the intrinsic carrier concentration. In that case, you can simplify this expression further as $\sigma_i = n_i$ times modulus of e times Mu e + Mu h, this is the simplified relationship of electric conductivity for the intrinsic semiconductors.

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What happens for the semiconductors if I increase the temperature? Does it behave the same way as the metals? In intrinsic semiconductors, the carrier concentration increases with temperature as more and more electrons are excited due to the thermal energy and they are kind of encouraged to jump band gap and go to the valence band. So conductivity increases here with temperature, which is opposite to the metals so like silicon, the band gap is only 1.11 electron volt, germanium 0.67 GaP 2.25, cadmium sulphide 2.40.

In fact, you can write actually that n_i is proportional to exponential $e^{-E_{gap}/kT}$ and where k is the Boltzmann constant. So with respect to temperature, if you got this you will be able to see that the intrinsic carrier concentration how sharply it is increasing for silicon and then it is getting saturated with respect to temperature okay. So similar qualitative nature we will also see for germanium, so this is opposite to the behavior that you will see in the metals.

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Extrinsic Semiconductors

- ❑ Those in which electrical characteristics are imparted by impurity atoms.
- ❑ **Virtually all** commercial **semiconductors** are **extrinsic**.
- ❑ For example, an impurity concentration of one atom in 10^{12} is sufficient to render silicon extrinsic at room temperature.
- ❑ A higher valence dopant e.g. P (5+) in Si (4+) creates an extra electron (n-type) while a lower valence dopant like B (3+) creates a hole (p-type).
- ❑ This increases the charge carrier concentration and hence the enhancement in conductivity.

The diagram shows two silicon lattices. The left lattice is labeled 'n-type' and contains a phosphorus (P) atom with five valence electrons, one of which is shown as a 'Free electron'. The right lattice is labeled 'p-type' and contains a boron (B) atom with three valence electrons, leaving a 'Hole' in the lattice structure.

Now, very few semiconductors that we use today are intrinsic semiconductors, mostly they are extrinsic semiconductors, which means they are semiconductors because of the addition of impurity concentration, which is like something like of one atom in 10^{12} is sufficient to render silicon extrinsic at room temperature. Now a higher valence dopant example, P 5 + in Si 4 +, that creates an extra electron n-type, while a lower valence dopant or impurity like boron creates a hole of p-type.

So this increases the charge carrier concentration and hence the enhancement in terms of the conductivity. So as you can see it here that this is a silicon lattice structure and let us say you have actually added a phosphorus here okay, so this is a higher valence dopant okay so as a result this will create an extra electron okay. And on the other hand, if I add something like boron, so this is a lower valence dopant so electrons will travel from silicon towards this system. So thus, one is where it is actually giving the free electron then it is n-type and when it is contributing to the making of holes, then it is actually p-type, so this is the extrinsic semi conduction system.

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Extrinsic Semiconductors (contd.)

- In **n-type**, for each impurity atom one energy state (known as **Donor state**) is introduced in the band gap just below the conduction band.
- In **p-type**, for each impurity atom one energy state (known as **acceptor state**) is introduced in the band gap just above the valence band.

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So in n-type, for each impurity atom one energy state known as the donor state is introduced in the band gap just below the conduction band. Whereas, in the p-type for each impurity atom one energy state known as the acceptor state is introduced in the band gap just above the valence band okay, so like in the n-type if you look at it that as the electron has travelled up, so you are actually getting here the donor state that is introduced in the band gap. And on the other hand, in the p-type impurity you are actually getting an acceptor state as the band gap, so this is what the extrinsic semi conduction system is.

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- Large number of electrons can be excited from the donor state by thermal energy in n-type extrinsic semiconductors.
- Hence, number of electrons in the conduction band is far greater than number of holes in the valence band, i.e. $n \gg p$

$$\sigma \approx n|e|\mu_e$$

- In p-type conductors, on the other hand, number of holes is much greater than electrons ($p \gg n$) due to the presence of the acceptor states.

$$\sigma \approx p|e|\mu_h$$

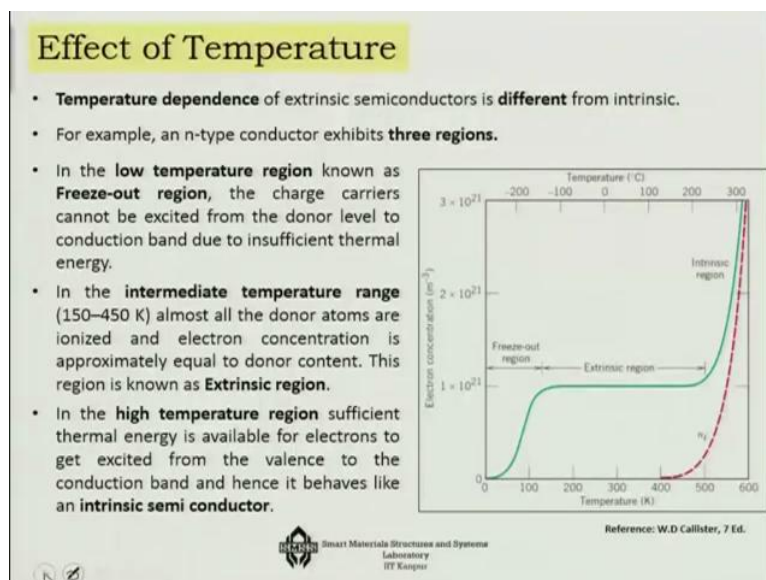
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Now large number of electron can thus be excited from the donor state by thermal energy in n-type extrinsic semiconductors. So further to this if you apply this actually, if you go to the

last slide that if you increase the temperature, then you can actually create large number of these donor states. So, number of electrons in the conduction band is far greater than number of holes in the valence band and that can be written in terms of n the magnitude of e times the μ_e .

In the case of p-type conductors on the other hand, number of holes is much greater than electrons, p much greater than n due to the presence of the acceptance states and hence the conductivity for such material is p times mod of e times μ_h . So one case it is μ_e and other case it is μ_h , so this point we have to keep in our mind. Now what is the effect of temperature in the case of extrinsic semiconductors?

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Here it is different from the intrinsic for example; an n-type conductor will exhibit 3 regions. In the low-temperature region, known as the Freeze-out region you will see that the charge carriers cannot be excited from the donor level to conduction band due to insufficient thermal energy. In the intermediate temperature range, what you are going to see, so this is the intermediate temperature range okay. Almost all the donor atoms are ionized and electron concentration is approximately equal to donor content, this region is also known as the extrinsic region.

In the high-temperature region, sufficient thermal energy is available for electrons to get excited from the valence to the conduction band and hence behaves like a intrinsic semiconductor. So with respect to temperature, you have these 3 regions, the Freeze-out region, extrinsic region and intrinsic region. In the extrinsic region as you can see that

electron concentration is remaining almost constant and then as you are increasing temperature, the intrinsic region is getting dominated in the system.

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Electrical conduction in Ionic ceramics

- Possess a relatively **large band gap**, usually greater than 2 eV.
- Thus, at normal temperatures only **very few electrons** may be **excited** across the band gap by the available thermal energy. Hence, very **small values of conductivity**.
- **Charge** can also be **conducted via ions**- called **ionic conduction**. This may occur **either in conjunction** with or **separately** from **electronic conduction**.
- Both **cations and anions** in ionic materials possess an **electric charge** which are capable of **migration** under **electric field**.
- Thus, for ionic materials, conductivity is equal to the **sum of electronic and ionic contributions**.

$$\sigma_{total} = \sigma_{electronic} + \sigma_{ionic}$$

- **Contribution** may **predominate** depending on the **material, its purity and temperature**.
- But still, most ionic materials **remain insulative**, even at elevated temperatures.

Any scope ???


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Now, in terms of the Ionic ceramics, it possess a large band gap usually it is greater than 2 electron volts like the semiconductor materials. Thus, at normal temperature only very few electrons may be excited across the band gap by the available thermal energy hence it has a very small value of conductivity. However, for the ceramics I told you this point earlier that it can also be conducted by ions called ionic conduction. This may either occur in conjunction with or separately from electronic conduction. There is a new thing that you have, which is ionic conduction.

Both cations and anions in ionic materials possess an electric charge which is capable of migration under the electric field. Thus, for ionic material conductivity equal to the sum of electronic and ionic contribution, so they have conductivity as an electronic contribution and an ionic contribution. Now, this contribution will predominate depending on the material, its purity and temperature. But still, most ionic materials remain insulative even at elevated temperature. So, can you think of any scope of applying this particular property?

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- ❑ By properly engineering the **point defects**, it is possible to convert ceramics into semiconductors.
Example :Indium tin oxide (ITO) - 74% In, 8% Sn and 18% O₂ by weight.
- ❑ ITO is often used to make **transparent conductive coatings** for displays such as **liquid crystal displays, flat panel displays**, plasma displays, **touch panels**, and electronic ink applications.
- ❑ ITO films **deposited on windshields** are used for **defrosting** aircraft windshields. The heat is generated by **applying voltage** across the **film**.



ITO defrosting coating on an Airbus cockpit window

Image: Wikipedia

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For example, we can tell you that one such interesting thing that by properly engineering the point defects, it is possible to convert ceramics into semiconductors. Example, if you make Indium tin oxide ITO, which has 74% Indium, 8% stannum and 18% oxygen by weight. ITO is often used to make transparent conductive coatings for display such as your LCD displays, flat panel displays, plasma, touch panels and electronic ink applications.

In fact, if you look at the aircraft, then on that window you use ITO films deposited on windshields which are used for defrosting aircraft windshields, the heat is generated by applying voltage across the film. So thus, by properly engineering point defects, you can actually convert the ceramics at least to the semiconductor level. And ITO defrosting coating on an Airbus cockpit window is what is can be taken as an example of the whole thing.


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Electrical Properties of Polymers

- ❑ **Polymers** are, in general, **insulators**. But some polymers can be **made conductive** in two ways:
 - Introducing an **additive** to the polymer to improve conductivity such as **carbon black**.
 - Creating polymers with inherent conductivity by **doping**
- ❑ **Example of Conducting polymers (CP)** - Polyparaphynylene, Polypyrrole, Polyaniline, Acetalpolymers.
- ❑ These polymers become conductive when doped with appropriate impurities such as AsF_5 , SbF_5 , or iodine.

Poly(pyrrole) has been tested as **microwave-absorbing "stealth" (radar-invisible)** screen coatings.

Nobel Prize in Chemistry (2000) was awarded for development of **electrically conductive polymers** to:
Professor Alan J. Heeger at the *University of California, Santa Barbara, USA*
Professor Alan G. MacDiarmid at the *University of Pennsylvania, USA* and
Professor Hideki Shirakawa at the *University of Tsukuba, Japan*

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Now, in terms of the polymers, polymers are in general insulators, they are much more insulators than the ceramics. But some polymers can be made conductive in two ways; one is introducing an additive to the polymer to improve conductivity such as carbon black, graphite plate or even silver flex you can use. The other is, creating polymers with inherent conductivity by doping. Examples of conducting polymers are like Polyparaphynylene, Polypyrrole, Polyaniline, Acetolpolymers, so these polymers become conductive when doped with appropriate impurities such as AsF_5 , SbF_5 or Iodine.

Polypyrrole has been tested as microwave absorbing, so “stealth” radar visible screen coatings. It is interesting to know that in 2000, a Noble prize was awarded for the development of electrically conductive polymers to Professor Alan Heeger, Alan MacDiarmid and Hideki Shirakawa. So thus, electrically conductive polymer is a very interesting application of the polymers. This is where we will come to an end, in the next lecture we will learn about the dielectric concept and we will solve a problem based on the Ashby approach, thank you.