**Non-equilibrium Properties**

Yes.

**Conductivity**

Unlike with metals, conductivity actually goes up with increasing temperature, because the number of mobile carriers goes up. But they are still much less than metals of course. Resistivities of semiconductors are ~ 10-3Ω·cm’s at best I think. I’m going to mostly reproduce the analysis from the RTA approximation in the Stat Mech folder. We’ve got two bands to work with this time: the conduction band, and the valence band. I guess I’ll start with the former,

**Conduction band**

So for electrons in the conduction band, we have:



where,



Working out that derivative,



Now we’re usually interested in just the *first order* response to the **F**nc (i.e., electric field

in this case) But δn is already first order in these gradients and so we do the trajectory equations to zeroth order in the gradients. So:



and solutions are:



and so we have:



We can presume a linear combination of harmonic dependences: **F**n.c.(t) = eRe**E**(ω)e-iωt. Further, presume the scattering constant to be independent of position:



So altogether,



Now recall nleq = nF as we have electrons, so,



Note it is spin-independent. So now we can now work out the current,



In last line, ρc(ε) is the density of states of the conduction band, which includes spins, and I kind of presumed our system was isotropic. So the (complex) conductivity of the conduction band is:



We’ve been implicitly presuming our system is isotropic, so we have ε = k2/2mc. So then the result of the integration over ε will give zero for the off-diagonal components of the tensor. And also the diagonal components will be all the same. This amounts to being able to make the replacement **v**2 = (v2/3)**1** =2(ε-εc)/3mc·**1**. Now let’s fill in our distribution function, and presume that τ(k) is independent of energy, and go to the ω → 0 limit,



We did this integral when we calculated Heat Capacity. Guess we’ll do it again. Let’s fill it in, and I’m going to drop the **1** now.



And now fill in the density of states, remembering we committed to isotropy,



So,



Well,



So we can say,



Taking note that:



we have:



So we can say,



That looks familiar.

**Valence Band**

99% of this is going to be redudant. Now for electrons in the valence band, we have the same general result as above,



where now, due to ε << μ,



Note this makes the hole density,



where,



In the Metals/Free Day folder, we showed that the current in a band may be written in terms of holes.



So,



In last line, ρv(ε) is the density of states of the conduction band, which includes spins, and I kind of presumed our system was isotropic. So the (complex) conductivity of the valence band is:



We’ve been implicitly presuming our system is isotropic, so we have ε = εv – k2/2mv. So then the result of the integration over ε will give zero for the off-diagonal components of the tensor. And also the diagonal components will be all the same. This amounts to being able to make the replacement **v**2 = (v2/3)**1** =2(εv-ε)/3m­v·**1**. Now let’s fill in our distribution function, and presume that τ(k) is independent of energy, and go to the ω → 0 limit,



Let’s fill in the density of states, and drop the **1** now. And I think we’ll take note that eh = -e, so we can write:



And now fill in the density of states, remembering we committed to isotropy,



So,



And as we saw,



So we can say,



Taking note that:



we have:



So we can say,



This also looks familiar.

**All total**

So adding our two results together, we get:



This is a sensible result. If we’re dealing with an intrinsic semiconductor, where (nc,pc) ~ (ni,ni), and ni ~ T3/2e-βE\_g/2, then can see this would be an increasing function of temperature. In the extrinsic case, where (nc,pv) ~ (Nd,0) or (nc,pv) ~ (0,Na), we can see this wouldn’t change too much with T, but would go up a little, as ni2/ΔN or something.

Since semiconductors’ conductivity is highly dependent on carrier density, it doesn’t serve as a good indication of the ‘mobility’ of the electrons in the semiconductor, unlike how it does for a metal, in which the carrier density is basically constant w/ temperature. So it is customary to define the ‘mobility’ of electrons in a semiconductor. It’s the proportionality between their drift velocity, v, and the Electric field.



Since **j** = ne**v**, we can see from the formulas above that the mobility of the conductance and valence bands is:



Last thing I’ll mention? Even in the T = 0 case, where there is no intrinsic carrier density, and really, no extrinsic carrier density either, since all the electrons will be in the donor or acceptor levels, we can still get some residual conductivity. This essentially comes from electrons in the impurity sites tunneling from one impurity to another. Needless to say, the conductivity resulting from this mechanism will be quite small.

**Example**

A piece of silicon semiconductor has length L = 0.01cm and cross-section in a square shape with an area of A = 5×10-4cm2. The semiconductor is doped with 1012 cm‑3 Phosphorus atoms and 1017 cm-3 Boron atoms. An external electric field E = 1.5×104N/C is applied to the silicon piece along the length direction, through the cross section. What is the total current in the silicon at T = 300K? Assume the mobility of silicon is 1400 cm2V-1s-1 for electrons and 450cm2V-1s-1 for holes. Assume the intrinsic carrier concentration in silicon is 1010cm-3.

Phosphorus is the donor, and Boron the acceptor. And we’ll recall our formulas for the conduction and valence band concentrations at room-ish temperature.



Filling in the numbers,



These results correspond well to our approximation,



So then we can get the current density, j, via:



Then we can get the current by using,

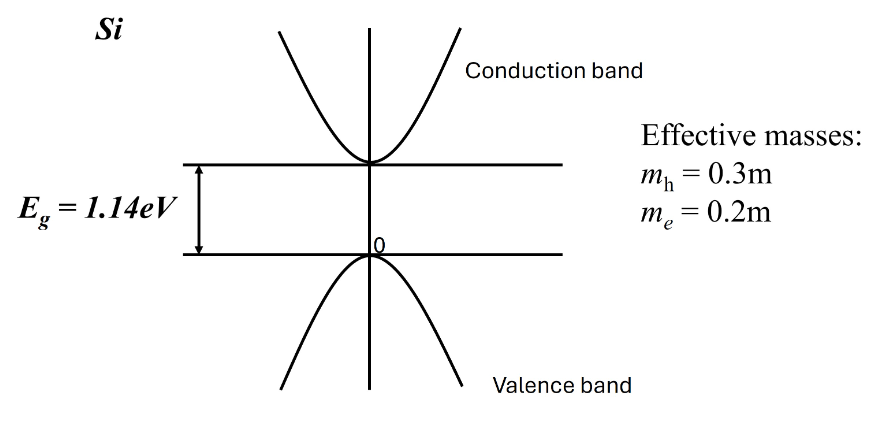


**Example**

For crystaline silicon, what concentration Nd of pentavalent As donors must

be added to make the extrinsic conductivity 104 times greater than the intrinsic

conductivity at room temperature?



The conductivity is given by:



where mc = 0.2m, and mv = 0.3m. Intrinsically,



which is given by, assuming a spherical density of states at the extrema of the valence and conduction bands:



So,



Extrinsically,



And ΔN = Nd in this case. So effectively,



So we need to solve:



Which brings us to:



So there.

**Absorption by Free electrons in Crystal Potential**

Don’t think impurities change much as far as absorption is concerned, considering how close the donor and acceptor levels are to the conduction and valence bands.