SEMICONDUCTORS AND DOPING IN THE RECIPROCAL SYSTEM

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Introduction

Electrical conductivity is an important property of matter, and it has the distinctive property of varying by more than 10 orders of magnitude from insulators to conductors – one of the greatest ranges for physical magnitudes ever seen. In addition, the behavior of the class of materials called the "semiconductors" – materials whose properties are intermediate between conductors and insulators – has involved several unusual features almost since the beginning of their discovery. These features have resisted a clear explanation even in this Silicon Age where their use is widespread.

In order to understand their behavior, it is important to pay attention to all the observed phenomena and assemble them. Any attempt at describing the nature of semiconductor doping must shed light on *all* of the essential properties. A short summary of the properties are:

1. They have electric conductivities in between insulators and conductors, which are *very* sensitive to temperature variations. Both conductors and insulators rarely exhibit this sensitivity.
2. Normally resistance is assumed to increase with temperature, as seen in metals. In case of semiconductors resistance *exponentially decreases* with temperature.
3. Addition of small amounts of other elements to the semiconductor, usually those horizontally adjacent in the periodic table (for example, if the semiconductor is Si, Al or P can be used) in the "p-block", results in similar large *exponential* changes in conductivity. This is called "doping".
4. Conductivity can be both "p" and "n" type. In other words, the flow of current can be tuned to go either way, depending on the type of dopant.
5. If the amount of dopant added is increased, the conductivity gradually saturates, to become that of a conductor or metal.
6. Both crystalline and amorphous semiconductors can be "p" and "n"- doped. [1]

Any understanding of semiconductors has to explain all these properties, and provide a way of clarifying further properties of semiconductors.

Prior Knowledge

The distinctly different property that we have to deal with here is the great variation of resistance. It is mentioned, for instance, that [2]:

> *Clearly, the values appropriate to semiconductors do lie between those of metals and insulators but, perhaps the more striking observation is that semiconductor resistivities, themselves vary so much (roughly 13 orders of magnitude!) that it is hard to see this as a suitable parameter with which to 'pin them down'. We need an explanation for the origin of the resistivity if we wish to know what these numbers really mean…*

Not only were the material properties covering a wide range, but the variation in current with voltage, or with temperature, was also experimentally seen to be *exponential*. Traditional assumptions about the nature electricity flatly contradict this behavior, since an increase in temperature must create more resistance, not less. In addition, the response of electricity to applied voltages was predominantly linear, and not exponential.

The only place where exponential relationships were available was in thermodynamics, where transitions between energy levels involved exponential relations. Therefore, the exponential equations were imported for electrons from there, and then incorporated directly into the equations, completely leaving aside the question as to a possible mechanism for this bizarre dependence. How can electricity, which is linearly responsive, decide to follow a vastly different law in a different material? And how is this compatible with the ideal gas behavior of thermodynamics?

Semiconductors in the Reciprocal System

Larson mentions semiconductors only in one place [3]:

Where there are two dimensions of rotation in space, as in many of the elements of Division IV (see [4])*, the thermal motion, which requires two open dimensions because of the finite diameters of the moving electrons, is necessarily in time. In this case, zero temperature corresponds to zero motion in time. Here the resistance is initially extremely high, but decreases with an increase in temperature. Substances of this kind are known as insulators or dielectrics… The Division III elements of lower electric displacement follow a modified time motion pattern, with resistance decreasing from a high, but finite, level at zero temperature. These substances of intermediate characteristics are* ***semiconductors****.*

It is, however, entirely unclear how Division IV elements have "2 dimensions of rotation in space," since an electric rotation (rotation in space) is one-dimensional. This situation hence requires further clarification.

When looking at the atomic a – b – c notation in the Reciprocal System, the a – b rotation consists of magnetic 2D rotation while the c rotation is the electric 1D rotation. In the combinations that exist in the solid state, there are many possibilities: the electric valence can take on the normal positive (displacement in time), neutral or negative (displacement in space) orientation. The magnetic valence, which is always positive, can take on either the primary or secondary valence (see [5]).

This sheds more light on the dimensions of rotation. When the positive electric displacement interacts with the negative electric displacement to establish equilibrium, then they both act in their 1D capacity. However, in the case of magnetic valence compounds, the equilibrium is between a *2D* magnetic displacement and a *1D* electric displacement (for example, carbon monoxide CO). In this case, even though the electric displacement is 1D, in its combination with a magnetic displacement it acts effectively as a 2D displacement. This is what Larson meant by his phrase "two dimensions of rotation in space," that makes a substance insulating.

The more interesting situation is the neutral valence. Here, the electric displacements do not cancel out, but rather combine to form an 8 unit displacement, which is equivalent to zero displacement since 8 electric units complete the electric rotation available bring it back to the zero point again. However, there is a subtlety here that has to be recognized. Even though the 8 unit displacement is *equivalent* to a zero displacement in terms of equilibrium, it is not *equal* to zero displacement. 8 units of electric displacement are equal to a magnetic displacement of 2, which is makes the quality of this valence *in between* a magnetic and electric valence. This feature turns out to be extremely crucial, since allows a range of conductive behavior between the electric and magnetic rotation, thus altering electricity between a 1D and a 2D "flow" or "state".

A quick check with respect to Table 7 in [5] shows that almost all the elements that are found in semiconductors viz. C, N, Si, P, S, Cu, Zn, Ga, As, Se, Ge, Ag, Cd, In, Sn, Sb, Te, I, are those that form neutral valence compounds. It is quite a significant result that it is possible to identify semiconductors simply based on their a-b-c rotations. The conventional way has been either to use empirical data, or to carry out intensive band structure calculations on a computer using the equations of quantum mechanics with several empirical input parameters.

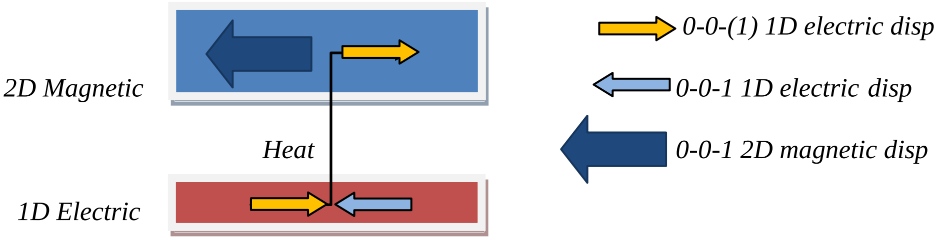
Therefore, we can characterize a semiconductor in the Reciprocal System as follows:

A semiconductor is a compound which contains elements capable of exhibiting the neutral valence, and whose conductivity can be altered between 1D electric state and 2D magnetic state.

Basic Properties of Semiconductors

1. Electron-hole currents

The changing dimensionality of electrical motion can now be analyzed to see the expected properties. For one, a magnetic rotation is normally oriented as a time displacement, while an electric rotation is oriented as a space displacement. Therefore, the 1D electric-state electricity flow will be opposite to the 2D magnetic state. The sign of the displacement would hence be positive instead of negative (electrons). As already brought out in a previous paper [6], when a positive magnetic motion occurs, this is currently called *"hole" current*. Therefore, electrons and "holes" are oriented opposite to each other, and with a supply of energy, an electron state (1D => 2D) and a hole state (2D) can be created. *Since the electric dimension is mostly "blocked" due to the net rotational equilibrium, the electrons and holes, when an electron "becomes" 2D, this disturbance naturally creates a hole.*



In this figure: 0 – 0 – (1) is the electron, and 0 – 0 – 1 2D magnetic displacement is the hole.

The electron motion hence moves in the extra dimension it has gained, while the hole moves as a 2D displacement. There is hence an asymmetry between the electron and the hole, where their mobilities, masses, Hall coefficients, and concentrations are all different – a fact impossible to explain logically based on the conventional model of the electron as the only "real" particle. Something that has misled researchers regarding the right "carrier" of current has been the attempt to obtain the charge-to-mass-ratio (e/m) for both electrons and holes. Since this ratio was obtained to be the same, it was mistakenly concluded that only electrons are the true charge carriers ([7], [8]). What has been neglected in such attempts is the possibility that both e and m have effects in the opposite direction, so when a ratio is taken, their effects cancel out:

$$\frac{-e}{-m} = \frac{e}{m}$$

This overlook is surprising since conventionally holes are said to have "negative effective mass". However in the Reciprocal System, since the effective direction of magnetic rotations is opposite to that of electric, both "charge" and "mass" in conventional terms will be opposite, and electrons (n) and holes (p) are distinct entities in their own right, and are created in equal numbers.

$$n = p$$

Since the electric and magnetic dimensions are distinct, electrons and holes do not usually interact, unless there is a primary photon that has a vibrational displacement in both aspects that can hold the motions together. This combination is called "exciton" (although the traditional mechanism of an electron and an absence of an electron orbiting one another makes no sense).

2. Exponential Behavior

The basic equation of exponential behavior is of the form:

$$v(t) = v_0 e^{-kt}$$

How is this related to a phase transition? The relation between electricity and magnetism in bulk properties is related by the *changes* i.e. change of magnetic field produces electric current and vice versa. The change is because we are speaking about a universe of motion, which only consists of speeds or changes in speeds. Hence, when crossing from 1D to 2D or 2D to 1D, there is a time derivative or a space derivative involved. In case of electricity, which is a relation of rotational space to time, it is the time derivative that is important. However, note here that in contrast to the usual meaning of clock time for *t*, here *t* is the net effect of the temporal displacement.

The condition for the motion to remain equal in magnitude even after the change in dimension is the relation:

$$\frac{dv}{dt} = -v$$

The sign is opposite due to the nature of the inversion of direction from electric to magnetic and vice versa [9]. In case this relation is not expressed in natural units, but in arbitrary ones, the relation becomes:

$$\frac{dv}{dt} = -kv$$

The solution to this, which is a function that changes at a rate proportional to itself, is precisely:

$$v(t) = v_0 e^{-kt}$$

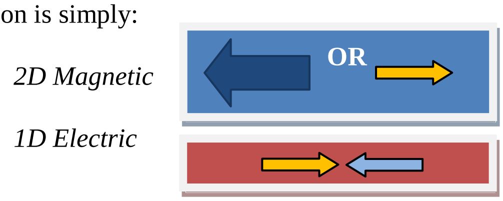
Therefore, the speed *v* varies exponentially with the value of the time displacement (*t*) that is involved in the transition. Since thermal energy opposes the net time displacement, the value for *t* is scaled down by the corresponding value of temperature *T*. Hence in natural units, we have:

$$v(t, T) = v_0 e^{-t/T}$$

Hence, if the temperature is increased, the value of the exponent also increases, leading to an exponential rise in the electricity available. This is the primary reason for the anomalous behavior of semiconductors where the electrical resistance decreases with temperature as more and more of the electric motion moves across to the extra dimension as a 2D electricity. For "hole" electricity, except for the direction of electricity, all the same relations hold. Therefore both the negative and positive currents are increased. Hence, whenever there is a crossover between 2D and 1D, the exponential relation appears on the scene.

3. Doping of Semiconductors

Since the electric displacement in its neutral valence has access to an extra dimension, and the hole has access to both magnetic dimensions, when other elements are added to a given semiconductor with either 0 – 0 – (1) or 0 – 0 – 1 displacement, these enter directly into the free magnetic dimensions and therefore enhance the availability of electrons or holes respectively. However, the presence of holes or electrons in this case is not directly caused by the temperature, so the situation is simply:



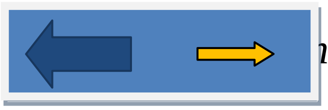
The transition caused by heat is no longer required. An example of doping is where GaAs, with Ga (3 – 3 – (5)) and As (3 – 3 – (3)), is doped either by Be (2 – 1 – 2) or Si (2 – 2 – (4)). Since the electric displacement of Ga (5) is equivalent to 3 (using 8-x), and that of Be is 2, there is a positive displacement. And since the electric displacement of Si is (4), with respect to Ga (5), there is a negative displacement. Arsenic is just providing the neutral valence. Hence, adding Be will create holes creating “p-type” material, and adding Si will create holes creating “n-type” material of gallium arsenide.

Adding a “dopant” of either type will hence exponentially increase the conductivity. Naturally, the exponential increase is not unlimited, as the semiconductor becomes metallic when either the electrons or the holes overwhelm the process. As a metal, conductivity is only limited by the net 3D time displacement.

4. Carrier concentrations

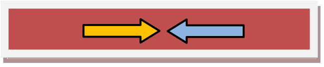
There is an extremely vital difference between the relations in the 2D magnetic dimension speeds and the 1D electric dimension speeds. Since the electric dimension has equilibrium established between positive and electric displacements (traditionally called carrier concentrations), they refer to two different zero points, and hence their net effect is the **SUM** of the two displacements. On the other hand, in the magnetic dimensions, the displacements interact geometrically; hence the net effect will depend on the geometric mean, or in other words, the **PRODUCT** of the two displacements. Let the electric displacement in the electric dimension be called n_E, while its opposite in the electric dimension be called p_E. Similarly, let the displacements in the magnetic dimension be n_M and p_M. Then the following relation holds:

2D Magnetic



$n_M * p_M$ = *effective displacement*

1D Electric



$n_E + p_E$ = *effective displacement*

This is also borne out by the exponential relation, since exponents add whenever expressions are multiplied. The displacements in the electric dimension hence have an exponential relation to the 2D magnetic dimensions. This feature will be important in describing the behavior of p-n systems, which will be described in another paper.

5. Band-gap

Since there are two “states” of electricity – a 1D and a 2D state – the physics of the transition between one to the other is the same as that of a phase transition from solid to liquid or liquid to gas. Hence, there the transition from a 1D to a 2D state is temperature-dependent, just like any other phase transition. An equivalent “latent heat” exists for this transition, which is the concept of “band-gap”. The 2D state is where resistance is high, and the 1D state where the conductance is high, according to the quote from Larson above. The transition from 2D state to 1D state hence involves not only a change in dimensions, but also a corresponding change in conductivity. The ratio of the two conductivities is similar to the ratio of magnetic and electric field strengths – 1: c, where c is lightspeed. In case of insulators, the ratio that applies is the full 1: c^2.This is the reason for the large range of values possible for resistivity in compounds.

The band-gap is the “barrier” from the 1D to 2D transition. By definition, the electron motion is opposed by electric displacement, since space to space is not motion. The greater the electric displacement available, the greater is the band-gap. The magnetic displacement facilitates it, hence the greater the magnetic displacement, the smaller the band-gap. Electric displacement is calculated using the sum, while the magnetic displacement is calculated using the geometric mean of the two net magnetic speeds. The reference level for the electric displacement is however the neutral valence: how much the displacement differs (Δ) from either 4 or (4). An addition of 2 units is required to account for the displacements from opposite zero points.

Therefore, one can derive the relation in natural units for the band-gap energy E_g, for two elements with *speeds* (not displacements alone) $M_1 – M_2 – E$ and $m_1 – m_2 – e$, to be:

$$E_g = \frac{\Delta E + \Delta e + 2}{\sqrt{M_1{}^2 M_2 m_1{}^2 m_2}}$$

Note that the dimensions in this case is not s/t^3, as the formula may suggest, but s/t. This is because the magnetic rotational units merely modify the time component as magnitudes and not as physical quantities. The overall quantity in questions is still just a velocity, or a frequency.

In some cases where the magnetic rotation reaches the value 4 in both species, a transition to *vibration two* begins to occur, as already brought out in *Basic Properties of Matter* [10]. This increases the strength of the magnetic contribution, by a factor of this rotation magnitude, or its square depending on the primary or secondary magnetic rotation. Also, depending on whether the vibration two is obtained in one of the elements or in both, there is a factor that enters into the magnetic rotation that is dependent on the available magnetic rotation. In addition when the displacement is 2 (equivalently, when the rotation is 3) in the magnetic rotation, the rotation is only effective in 2/3 due to the requirement that ln(t)>1. One of the dimensions becomes inactive. [11]

Including these relationships, one gets the following table for the band-gap calculations for some common semiconductors. References for the band-gap experimental values (w.r.t. the Γ–gamma point which is spherically symmetric) are from [12] and [13]. Those with vibration two values are indicated as V2.

Material	$M_1 – M_2 – E$	m_1-m_2-e	Crystal	E_g (nat. units)	E_g (Calc.) (eV)	E_g (Obs.) (eV)
AlN	3 – 3 – 4 (2/3)	3 – 3 – (4) (2/3)	WZ	0.2222	5.733	6.13
AlP	3 – 3 – 4 (2/3)	3½ – 3½ – (4)	ZB	0.1440	3.715	3.63
GaN	4 – 3 – 4	3 – 3 – (4) (2/3)	WZ	0.1361	3.511	3.50
AlAs	3 – 3 – 4 (2/3)	4 – 4 – (4)	ZB	0.1179	3.042	3.12
GaP	3 – 4 – 4	3 – 4 – (4)	ZB	0.1111	2.866	2.89
AlSb	3 – 3 – 4 (2/3)	5 – 4 – (4)	ZB	0.0943	2.410	2.38
InN	4 – 4 – 4 (V2)	3 – 3 – (4)	WZ	0.0680	1.754	1.94
GaAs	3 – 4 – 4	4 – 4 – (4) (V2)	ZB	0.0589	1.519	1.52
InP	4 – 4 – 4 (V2)	3½ – 3½ – (4)	ZB	0.0539	1.391	1.42
GaSb	4 – 3 – 4 (V2)	5 – 4 – (4) (V2)	ZB	0.0333	0.859	0.81
InAs	4 – 4 – 4 (V2)	4 – 4 – (4) (V2)^2	ZB	0.0156	0.402	0.42
InSb	4 – 4 – 4 (V2)	5 – 4 – (4) (V2)^2	ZB	0.0100	0.258	0.24
C	2 – 3 – 5 (1/3)	3 – 3 – (5) (2/3)	Dia	0.2357	6.081	6.02
Si	3 – 3 – 5 (2/3)	3 – 4 – (5) (1/3)	Dia	0.1361	3.511	3.35
Ge	4 – 4 – 5	4 – 4 – (5)	Dia	0.0313	0.806	0.89
SiC	3 – 3 – 5 (2/3)	3 – 3 – (5) (2/3)	Mix	0.2222	5.733	6.00
ZnO	4 – 4 – (7)	3 – 3 – (3)	WZ	0.1443	3.722	3.44
ZnS	4 – 4 – (7) (V2)	4 – 3 – (3)	ZB	0.0765	1.974	2.15
ZnSe	4 – 4 – (7) (V2)	4 – 4 – (3) (V2)	ZB	0.0468	1.209	1.42
CdTe	5 – 4 – (7)	5 – 4 – (3)	ZB	0.0600	1.548	1.48
HgS	5 – 5 – (7) (V2)	4 – 3 – (3) (V2)	ZB	0.0245	0.632	0.56
CuCl	4 – 4 – (8)	4 – 3 – (2)	ZB	0.1443	3.723	3.40
AgI	4 – 5 – (8)	4 – 5 – (2)	WZ	0.1000	2.850	3.02

There are possible variations that may occur due to crystal geometries, namely Zinc Blende (ZB), Wurtzite (WZ), Diamond (Dia.) or even mixed (Mix). These are not pursued in this preliminary study, but it is clear from the table that the band-gaps are reasonably close to what is obtained in conventional literature. It is hence possibly from first principles of the Reciprocal System to obtain an estimate of the most crucial quantity in semiconductors: their band-gaps.

Summary

The connection of semiconductor behavior with a dimensional transition clarifies several puzzling features. For instance, it is determined that there is a phase transition between 1D and 2D electrical motion that can account for the sudden rise in its conductivity with temperature or doping. Since the currents depend mainly on the dimensional relation and not directly on the physical symmetry of the crystal, it is possible to get semiconductor action and doping both in crystalline and amorphous structures. The 1D to 2D transition implies that phase relations are exponential, as most phase transitions usually are. This is probably the reason why traditional thermodynamics was borrowed into solid state physics, and ideas of "electron gas" were entertained seriously for a very long time. The sensitivity to doping, impurities as well as the temperature is hence explained in coherent fashion. Electrons and holes get a clearer meaning as their asymmetry is linked to the dimensional difference.

The added dimensionality provides the reason for a different sort of interaction in the magnetic rotations vs. the electric rotation, where the magnetic behaves like a scalar and the product is important, while the electric sums like vectors. This dimensional transition is also the reason for the existence of a band-gap, which is an analogue of "latent heat" in terms of thermodynamics. With the help of theoretical considerations, the band-gaps for several common semiconductors have been calculated, showing that this is indeed a good start in predicting this important value.

Bibliography

[1] W. E. Spear, P. G. Le Comber, S. Kinmond and M. H. Brodsky, "Amorphous silicon p-n junction," *Applied Physics Letters,* vol. 28, no. 2, pp. 105-107, 1976.

[2] J. Orton, "Perspectives," in *The Story of Semiconductors,* New York, Oxford University Press, 2004, p. 7.

[3] D. B. Larson, "Chapter 10: Electrical Resistance," in *Basic Properties of Matter*, Salt Lake City, International Society of Unified Science, 1996, p. 113.

[4] D. B. Larson, "Chapter 10: Atoms," in *Nothing But Motion*, Portland, North Pacific Publishers, 1979, p. 137.

[5] D. B. Larson, "Chapter 18: Simple Compounds," in *Nothing But Motion*, Portland, North Pacific Publishers, 1979, p. 227.

[6] G. Vijaya, "Hall Effect in the Reciprocal System," unpublished, Salt Lake City, 2017.

[7] S. Brown and S. J. Barnett, "Carriers of Electricity in Metals Exhibiting Positive Hall Effects," *Physical Review,* vol. 87, no. 5, pp. 601-607, 1952.

[8] G. G. Scott, "Inertia of the Carrier of Electricity in Cadmium," *Physical Review*, vol. 83, p. 656, 1951.

[9] D. B. Larson, "Chapter 9: Rotational Combinations," in *Nothing But Motion*, Portland, North Pacific Publishers, 1979, p. 122.

[10] D. B. Larson, "Chapter 1: Solid Cohesion," in *Basic Properties of Matter*, Salt Lake City, International Society of Unified Science, 1996, p. 11.

[11] D. B. Larson, "Chapter 2: Inter-Atomic Distances," in *Basic Properties of Matter*, Salt Lake City, International Society of Unified Sciences, 1996, pp. 21-22.

[12] [Online]. Available: http://www.ioffe.ru/SVA/NSM/Semicond/.

[13] O. Madelung, Semiconductors: Data Handbook, Berlin: Springer-Verlag, 2004.