

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 [1] [2]. 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. [1]
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. [3]

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:

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... [4]

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* [5]. 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 electric charge in the conventional view flow in an exponential manner? 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

In the Reciprocal System, current is not a flow of “electric charge” but rather the flow of uncharged electrons: rotating units of space through the time displacement of the atomic system. An uncharged electron is 0-0-(1), which moves through the net time-displacement of the atom. Since this is an electric space displacement, the ideal channel for the electron to flow is through the electric displacement of the atom, and when that is unavailable, through the magnetic displacement of the atom. The overall resistance to the flow occurs predominantly in the electric displacement unit, since this can take on space-displacements, and space-to-space is not motion. It is in this context that one has to examine the differences between conductors, insulators and semiconductors.

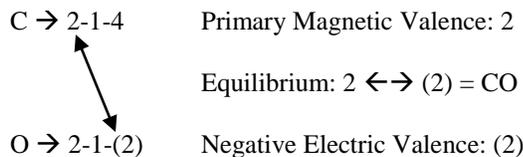
Larson mentions semiconductors only in one place [6]:

*Where there are two dimensions of rotation in space, as in many of the elements of Division IV (see [7]), 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.

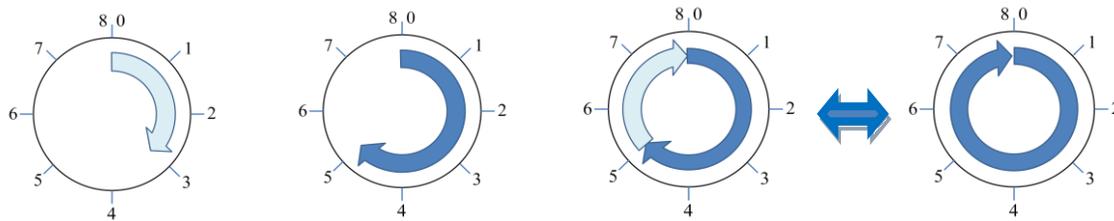
When looking at the atomic a-b-c notation in the Reciprocal System, the a-b rotation consists of magnetic 2D rotation while the c rotation is the electric 1D rotation. In the combinations that exist in the solid state, there are many possibilities: the electric valence can take on the normal positive (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 [8]).

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. 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. An example for this is carbon monoxide:



The more interesting situation is the neutral valence. According to Larson, this happens when both the electric valences do not cancel out, but rather combine to form either an 8 unit or an 18 unit displacement. According to the

relationship between electric and magnetic units, n magnetic units are equivalent to $2n^2$ electric units. Hence, a sum total of 8 or 18 units result in an electric displacement which is ineffective *as an electric unit*, since it has been brought back to its zero-point. An example is aluminum phosphide AlP. Aluminum is 2-2-3 and phosphorus is either 3-2-(3) or 2-2-5. In the neutral valence, a good proportion of the phosphorus picks up the 2-2-5 structure, and as a result, the combination on the electric valence is $3+5=8$.



Aluminum 2-2-**3** + Phosphorus 2-2-**5** = AlP **8** Electric Resultant = 0

Magnetic Resultant $\neq 0$

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 rotational displacement of 2, i.e. $2n^2$ with $n = 2$. Even though the equilibrium is established by the electric displacement units are due to a net zero effect in the electric displacement, the resulting effect in the magnetic displacement is not zero. However, there is no real magnetic displacement caused by the magnetic displacements of the constituent elements, since they are not involved in generating the equilibrium. This is the peculiarity of the neutral valence: the quality of this valence is *in between* a magnetic and electric valence. *The electrons that flow along the channel of the electric displacements hence have a “door” in the form of an unfilled magnetic rotation to transition into a 2D form.*

This feature turns out to be extremely crucial for the behavior of a semiconductor: by altering electricity between a 1D and a 2D “flow” or “state”, there is a possibility for those large changes in resistance which is characteristic of semiconductors. A quick check with respect to Table 7 in [8] 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

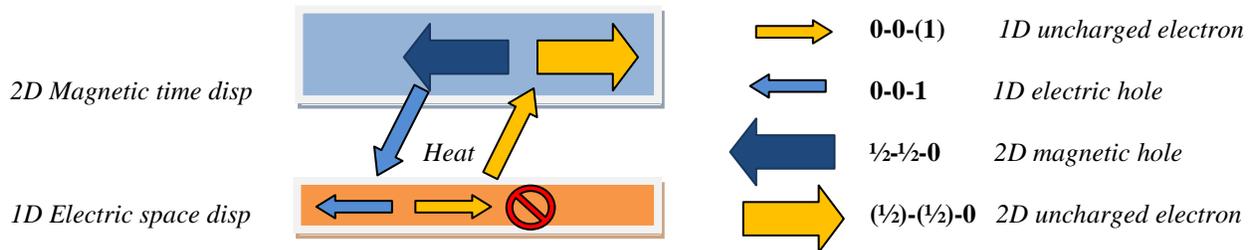
1. Electron-hole currents

The changing dimensionality of electrical motion can now be analyzed to see the expected properties. For one thing, a magnetic rotation is normally oriented *vectorially opposite* to an electric rotation. Therefore, the 1D current flow will be opposite to the 2D magnetic state.

In this paper, the term *positive* would be used to refer to temporal displacements 0-0-1 or $\frac{1}{2}$ - $\frac{1}{2}$ -0, and the term *negative* to the spatial displacements 0-0-(1). The sign of the displacement would hence be positive instead of negative (electrons). As already brought out in a previous paper [9], when a positive magnetic motion occurs, this is currently called “hole” current. Therefore, uncharged electrons and “holes” are oriented opposite to each other. Electrons are plentiful in the material environment, but holes are less plentiful, since they are time-displacements and can only move through space-displacements. Just like uncharged electrons, holes also move at the speed of light unless a space displacement is available to harness their motion. Therefore, either an uncharged electron current in the material, or spatial electric displacements in the material are necessary for the existence of holes. Since experimentally, most holes and electrons move in the bulk of the material and not on its surface, it is clear that there is no charge involved in the process.

With a supply of energy, an uncharged electron transitions from 1D => 2D. *Since the electric dimension is mostly “blocked” due to the net rotational equilibrium, when an electron “becomes” 2D, this space dimension allows a hole (2D) to move through the material.* Let us consider an uncharged electron moving in the material. Since an electron is 1D, it normally prefers to move through the electric displacement. When its movement is blocked by another space displacement the following sequence of events occur:

1. Electron cannot move through the electric displacement, looks for an alternative
2. If heat is available, and the “door” of a magnetic rotation is available due to neutral valence, it becomes 2D.
3. Electron flows as a 2D structure through the magnetic time displacement.
4. The 2D space displacement of the electron allows an equal and opposite movement of 2D time displacement.
5. Thus, hole units of $\frac{1}{2}$ - $\frac{1}{2}$ -0 move through the available electron channel $(\frac{1}{2})$ - $(\frac{1}{2})$ -0 in the material.
6. Some holes also move through the available negative electric displacement in 1D with expenditure of energy.
7. Each electron that transitions to 2D generates one hole.



The electron motion hence moves in the extra dimension it has gained, while the hole moves as a 2D displacement transitioning into a 1D 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 ([10], [11]). 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:

$$\frac{-e}{-m} = \frac{e}{m} \quad (1)$$

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.

$$n = p \quad (2)$$

Since the electric and magnetic movements have opposite space time characteristics, 2D electrons and 2D holes do not usually interact (s-s-0 passes through t-t-0), 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” (note that the traditional mechanism of an electron and an absence of an electron orbiting one another makes no sense).

It must be noted that the identification of the hole as $\frac{1}{2}$ - $\frac{1}{2}$ -0 makes it identical to Larson’s concept of the massless neutron [12]. However, Larson’s treatment and the subsequent development of this concept have focused on the presence of this particle *outside* a crystal lattice, as a decay product. The presence of this motion in the crystal lattice shows that it occurs through the conventional nucleus.

2. Exponential Behavior

The basic equation of exponential behavior is of the form:

$$v(t) = v_0 e^{-kt} \quad (3)$$

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:

$$\frac{dv}{dt} = -v \quad (4)$$

The sign is opposite due to the nature of the inversion of direction from electric to magnetic and vice versa [13]. In case this relation is not expressed in natural units, but in arbitrary ones, the relation becomes:

$$\frac{dv}{dt} = -kv \quad (5)$$

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

$$v(t) = v_0 e^{-kt} \quad (3)$$

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:

$$v(t, T) = v_0 e^{-t/T} \quad (6)$$

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

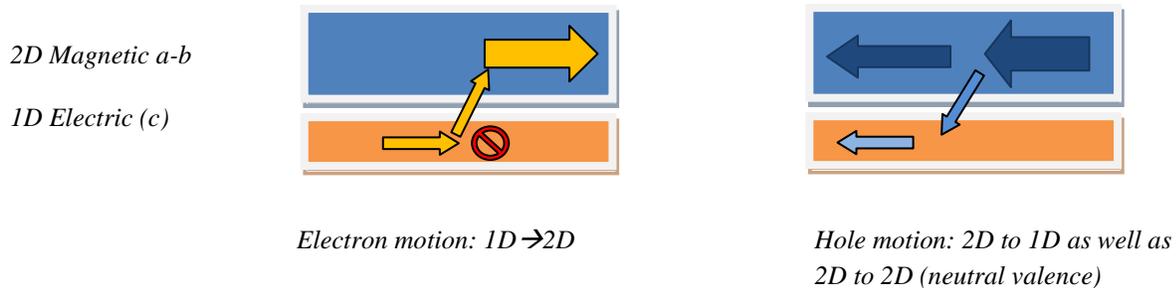
Since the electric displacement in its neutral valence has access to an extra dimension, and the hole has access to both magnetic dimensions, when other elements are added to a given semiconductor with either 0-0-(1) or 0-0-1 displacement off from the constituent material, these enter directly into the electric and magnetic dimensions respectively and therefore enhance the availability of electrons or holes. The nature of the displacements decide which one – electron or hole – is incorporated into the system. For example:

System: Aluminum Phosphide AlP, Al: 2-2-3 and P: 3-2-(3) or 2-2-5

1. Aluminum gets doped by Beryllium 2-1-2. The difference between the two is 0-0-(1). This allows 0-0-1.
2. Aluminum gets doped by Silicon 2-2-4. The difference between the two is 0-0-1. This allows 0-0-(1).

However, since the atomic structure as a whole has a major time displacement due to the magnetic component, the 0-0-1 component allowed access by Beryllium changes into the $\frac{1}{2}$ - $\frac{1}{2}$ -0 component: the *hole*. This is also called positive or *p-type* doping. Silicon on the other hand allows the flow of 0-0-(1) or uncharged electrons. This is hence called negative or *n-type* doping.

The electron and hole thus have opposite behaviors from a dimensional standpoint: an electron prefers to be 1D, while the hole prefers to be 2D. Let us take an n-type material with excess uncharged electrons made possible. Here, a specific amount of energy separates the 0-0-(1) from the $\frac{1}{2}$ - $\frac{1}{2}$ -0, which has to be supplied by the thermal energy. The probability of this happening is much higher due to the doping. This then would move through the magnetic displacements of the substance. A p-type structure will have the 0-0-1, which, being unstable in the temporal environment, switches over to $\frac{1}{2}$ - $\frac{1}{2}$ -0 and needs the *same* amount of energy to then move back through the negative electric displacements of the atom. The 0-0-1 to $\frac{1}{2}$ - $\frac{1}{2}$ -0 conversion would be “downhill”, and it is uphill to move back into the electric displacement channel. This would be the (c) of the a-b-(c) structure. There is also an additional channel available for holes due to the presence of magnetic rotation of the neutral valence. Diagrammatically, it looks like this:

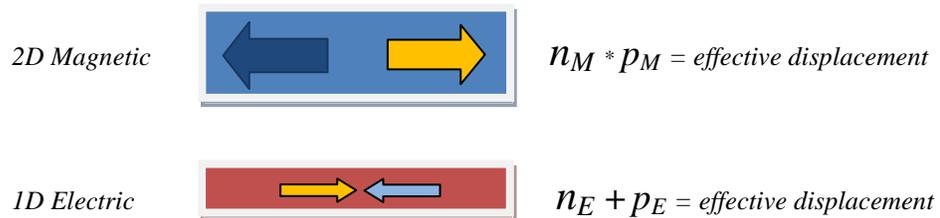


Before adding a dopant both semiconductors have a large resistance, since for electrons *s/s* is not motion and for holes, *t/t* is not motion. Adding a “dopant” of either type will hence make the excess electrons and holes available and exponentially decrease the resistance. Naturally, the exponential 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:



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 resistance is low, 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, viz. $1:c$, where c is speed of light. 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. As we have seen, both electron motion and the hole motion face this barrier: electron in the $1D \rightarrow 2D$ transition and hole in the $2D \rightarrow 1D$ transition. Since they are symmetric, the barrier will be calculated by assuming electron motion.

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. Therefore the bandgap is directly proportional to the electric displacement, and inversely proportional to the magnetic displacement. Electric displacement is calculated using the sum, while the magnetic displacement is calculated using the geometric mean of the two net magnetic speeds.

Consider two substances with *speeds* (not displacements alone) M_1 - M_2 - E and m_1 - m_2 - e . The reference level for the electric displacement is the neutral valence, viz. how much the displacement *differs* (Δ) from 4 or (4). An additional 2 units are required to account for the displacements from opposite zero points. Therefore, for two substances of

electric displacements E and e , the displacements from neutral valence is ΔE and Δe , and the net electric component of the bandgap will be $\Delta E + \Delta e + 2$. The physical dimension of this quantity is just space, or s .

On the other hand, the magnetic displacement occurs as a product. The electron moves through the magnetic displacement as a 2D rotation, and a 2D rotation occupies the full 3-dimensions spatially. Therefore the net magnetic rotation contribution from each of the two elements will be $M_1^2 M_2$ and $m_1^2 m_2$, as M_1 and m_1 are primary and M_2 and m_2 are secondary. However, since the electron is still in 1D before the transition, it will experience the three-dimensional magnetic effect that it would see in its 2D state as an equivalent 1D amount. Therefore, the physical *dimension* of both $M_1^2 M_2$ and $m_1^2 m_2$ is not t^3 , but just t , and only the numerical magnitude is enhanced. We can represent this net 1D effect of retaining magnitude only by the symbol $|m|$. Thus, for t_M and t_m :

$$t_M = |M_1^2 M_2| \quad (7)$$

$$t_m = |m_1^2 m_2| \quad (8)$$

Therefore, one can derive the relation in natural units for the band-gap energy E_g to be:

$$E_g = \frac{\Delta E + \Delta e + 2}{\sqrt{t_M t_m}} \quad (9)$$

Note that the dimensions for E_g are s/t . 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* [14]. This increases the strength of the magnetic contribution, by a factor of this rotation magnitude, or its square, depending on whether it applies to 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. It is similarly restricted to $1/3$ when the displacement is 1 (speed 2). *Two* of the dimensions become inactive. [15]

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 [16] and [17]. 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] [Online]. Available: <https://www.physics.byu.edu/faculty/christensen/Physics%202020/FTI/27%20Current%20and%20Resistance/27.11%20A%20typical%20semiconductor%20resistivity%20versus%20temperature%20curve.htm>.
- [2] [Online]. Available: http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C02/co/Contenu_02.html.
- [3] 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.
- [4] J. Orton, "Perspectives," in *The Story of Semiconductors*, New York, Oxford University Press, 2004, p. 7.

- [5] W. Shockley, in *Electrons and Holes in Semiconductors*, Princeton, NJ, D. Van Nostrand Company, 1959, pp. 17-28.
- [6] D. B. Larson, "Chapter 10: Electrical Resistance," in *Basic Properties of Matter*, Salt Lake City, International Society of Unified Science, 1996, p. 113.
- [7] D. B. Larson, "Chapter 10: Atoms," in *Nothing But Motion*, Portland, North Pacific Publishers, 1979, p. 137.
- [8] D. B. Larson, "Chapter 18: Simple Compounds," in *Nothing But Motion*, Portland, North Pacific Publishers, 1979, p. 227.
- [9] G. Vijaya, "Hall Effect in the Reciprocal System," unpublished, Salt Lake City, 2017.
- [10] 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.
- [11] G. G. Scott, "Inertia of the Carrier of Electricity in Cadmium," *Physical Review*, vol. 83, p. 656, 1951.
- [12] D. B. Larson, in *Nothing But Motion*, Portland, North Pacific Publishers, 1979, pp. 141, 165, 189.
- [13] D. B. Larson, "Chapter 9: Rotational Combinations," in *Nothing But Motion*, Portland, North Pacific Publishers, 1979, p. 122.
- [14] D. B. Larson, "Chapter 1: Solid Cohesion," in *Basic Properties of Matter*, Salt Lake City, International Society of Unified Science, 1996, p. 11.
- [15] 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.
- [16] [Online]. Available: <http://www.ioffe.ru/SVA/NSM/Semicond/>.
- [17] O. Madelung, *Semiconductors: Data Handbook*, Berlin: Springer-Verlag, 2004.