

# Electronic Properties of Carbon Film Resistors

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## Abstract

*Carbon film resistors have long been known to have strong temperature dependence at low temperature<sup>[1]</sup>, yet the mechanism by which these resistors conduct remains an area of active research. We have accurately measured the resistance of a 9.5M $\Omega$  carbon composite resistor from 8k to 301K and will illustrate the failings of modern band theory to accurately explain this behavior.*

## 1. Introduction

The electrical properties of a material can depend on temperature in any number of ways. Modern band gap theory can accurately explain the temperature dependence of both metals and semiconductors by relating the number of conduction electron to the number of phonon collisions as temperature decreases<sup>[2]</sup>, but lacks an insightful view into the behavior of semi-metals, such as carbon. Semi-metals have a band structure that leaves the chemical potential at zero temperature in such a way that conduction electrons remain mobile while also allowing for electron holes to exist, see Figure 1. The result of this, is interesting behavior that depends, not only on the material, but its crystalline structure. Carbon in the form of Graphite is shown to behave as a semiconductor along an axis parallel with the planes but shows zero Activation Energy at zero temperature<sup>[3]</sup>.

By studying the resistance of a Carbon Film Resistor we gain additional insight into the behaviors of Carbon at low temperature, as well as illustrate the need for further discussion into the possible mechanisms by which semi-metals conduct.

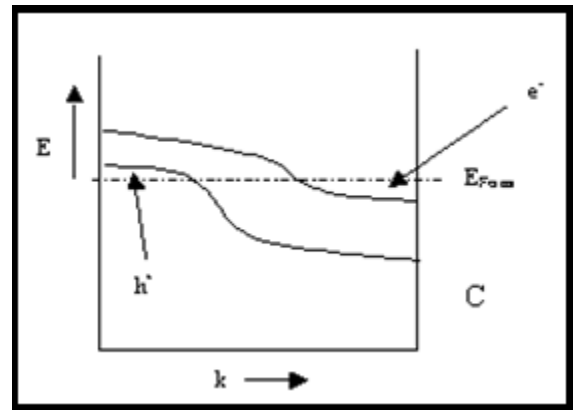


Figure 1: Dispersion relation for a semimetal.

## 2. Theory

### 2.1. Electrical Conductivity

The electrical conductivity of a material is intimately related to the charge ( $e$ ), effective mass ( $m^*$ ), and concentration ( $n$ ) of the mobile charge carriers, as well as the mean time between collisions ( $\tau$ )<sup>[2]</sup>.

$$\sigma = \frac{ne^2\tau}{m^*}$$

The concentration of charge carriers is equal to the density of states times the Fermi Function integrated from the conduction band edge to infinity and as a result the mobile charge density decreases as temperature decreases. For a metal at zero Kelvin, the Fermi level is above the conduction band edge, so mobile charge carriers remain and conduction is non zero. In a semiconductor, however, the Fermi level is at the top of the valence band resulting in a far greater drop in mobile charge density as temperature falls and zero conductivity at absolute zero, as shown in Figure 2.

The mean time between collisions is given by

$$\tau = \frac{m^* v E}{e} = \frac{m^* \mu}{e}$$

where  $v$  is the drift velocity,  $E$  is the electric field acting on the carrier, and  $\mu$  is the charge mobility which can be described by Matthiessen's Rule.

$$\frac{1}{\mu} = \frac{1}{\mu_{lattice}} + \frac{1}{\mu_{impurities}}$$

$$\therefore \sigma \propto \frac{1}{\mu_{lattice}}$$

A complete model for the electron mobility's dependence on temperature is still an active area of research but experiments have shown that as temperature decreases,  $\mu$  increases<sup>[4]</sup>. As the material cools the concentration of phonons in the crystal lattice decreases and vanishes completely at absolute zero. The result of this is that  $\mu_{lattice}$  vanishes at absolute zero<sup>[2]</sup>.

As temperature decreases  $n$  decreases and  $\tau$  increases causing a complicated dependence of  $\sigma$  on temperature that varies for materials with different Fermi energies and band structures. Metals exhibit an increase in conductivity as temperature drops resulting from the minimal drop in carrier density, while semiconductors show a significant decrease with the end result of zero conductivity at absolute zero.

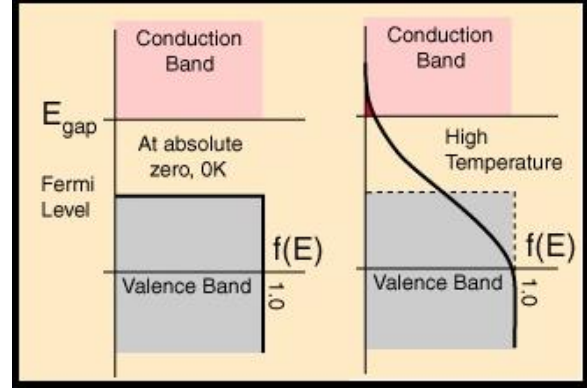


Figure 2 Fermi function for a semi conductor at 0K and high T respectively.

## 2.2. Activation Energies

Activation energy is defined as the minimum energy required in order to initiate a process. When referring to electrical conduction in semiconductors, the activation energy at zero temperature is taken to be the band gap<sup>[2]</sup>. To measure the activation energies of our resistor we have noted that the energy supplied to the resistor is proportional to the voltage ( $V$ ) and that the number of carrier activated over the barrier is proportional to the current ( $I$ ), therefore:

$$I = Ve^{\frac{-E_b}{kT}}$$

$$\text{Log}\left[\frac{I}{V}\right] = \frac{-E_b}{kT}$$

$$\text{Log}\left[\frac{V}{I}\right] = \frac{E_b}{kT}$$

$$\text{Log}[R] = \frac{E_b}{kT}$$

An activation energy can be found by finding the slope of the plot of the Log of  $R$  vs.  $1/KT$ . To find the deferential activation energy we note that:

$$E_b(T) = \frac{\partial \text{Log}(R)}{\partial \frac{1}{k_b T}}$$

Taking the limit of this function as  $T \rightarrow 0$  yields the band gap.

### 3. Experiment

A 9.5MΩ carbon film resistor was placed in a vacuum and cooled to various temperatures where current-voltage plots were taken and linearly fit in order to extract resistances. I-V curves were used to measure resistance as opposed to single V/I readings to verify that Ohm's Law is still valid at low T.

#### 3.1. Temperature Controller

An electrical feed trough was inserted into a vacuum cryostat and cooled down to 8.5K with the aid of a liquid helium 4 refrigerator. A Labview script was designed to convince a heater to step the temperature from the starting value of 8.5K to 151K in 0.5K steps then from 151K to 301K in 2.5K steps while continually measuring the temperature of the sample.

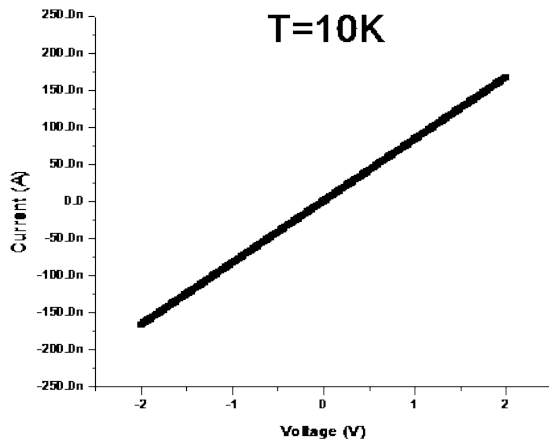


Figure 3: I-V curve taken at 10K. It is important to note that even at 10K Ohm's Law holds for this device

#### 3.2. Voltage Controller

In taking I-V curves, a Keithley voltage source and multimeter was controlled by Labview to increment potential across the carbon film resistor from -2V to +2V in 25mv steps while the device was beneath 151K and from -1V to +1V in 100mv step while the device was above 151K.

If at any point a jump in voltage was required (eg. Jumping from +2V back down to -2V) the source was ramped between voltages in 100mv steps to prevent any damage to the resistor as well as to minimize false readings due to bulk electron relaxation times. Two voltage sweeps were done at each temperature point to reduce statistical error.

#### 3.3. Measurements

Current was measure by a Keithley picoammeter, which averaged each measurement 50 times to reduce statistical error. Once all parameter were met (temperature, voltage, and equilibration times) Labview collected the following data from their respective devices:

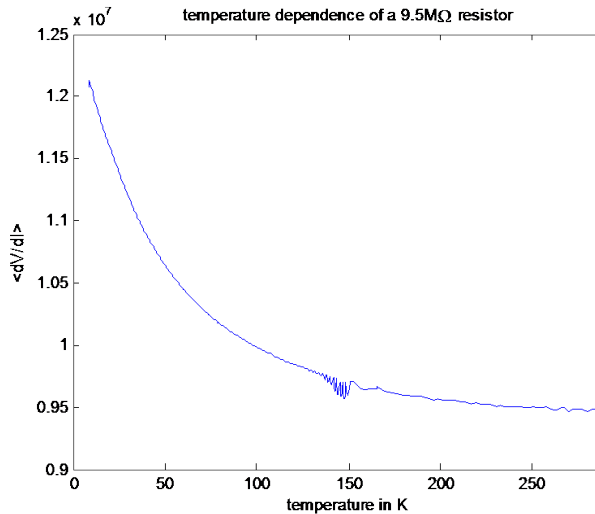
- Temperature set point
- Measured temperature value at the resistor
- Voltage set point
- Measured voltage across the resistor
- Measured current across the resistor

These values were recorded twice for every combination of temperature and voltage and logged into a data sheet which could be processed in MatLab.

### 4. Results

#### 4.1. Temperature Dependant Resistance

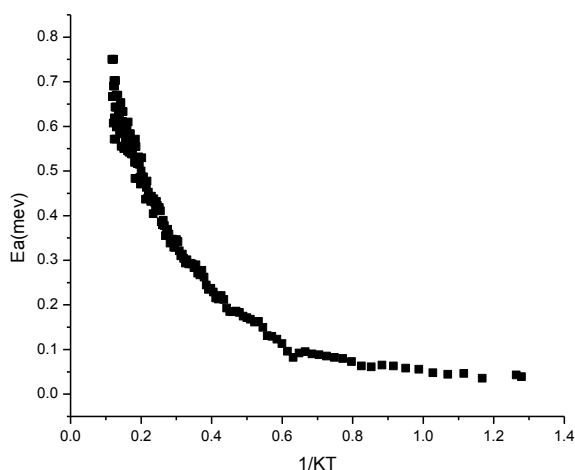
The output from Labview was a series of I-V curves, like the one in figure 3. These curves were loaded into MatLab, where they were linearly fit to extract a resistance.



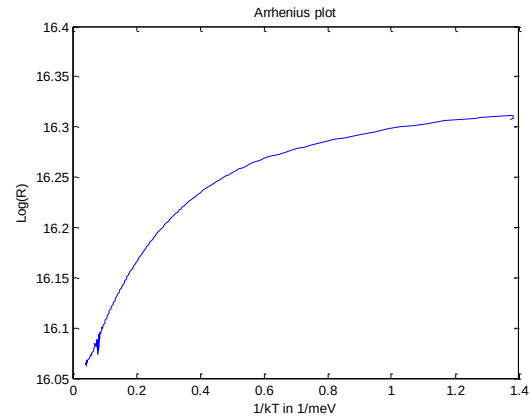
**Figure 4: Resistance vs. Temperature of a Carbon Film Resistor from 8.5K to 301K**

Two I-V curves at each temperature point yielded two resistances, which were then averaged together to give the most accurate value for the resistance at a particular temperature. The result is seen in Figure 4.

As temperature drops, resistance increases which indicated that the loss of conduction electrons plays a more prominent role in the temperature dependence than the increase in collision time. This behavior closely resembles that of a semiconductor at high T but as we cool the resistor down we see that at 0K, resistance will be approximately  $1.25\text{M}\Omega$  to  $1.35\text{M}\Omega$ , not infinity!



**Figure 5 Differential Activation Energies vs 1/KT**



**Figure 6 Log[R] vs 1/KT**

## 4.2. Activation Energies

To extrapolate activation energies we must plot the  $\text{Log}[R]$  vs  $1/KT$ , see figure 5. It is apparent that the activation energy is not constant in T, figure 6 shows the differential activation energy as a function of  $1/KT$ . We see that at low T we appear to be leveling out at a value of approximately  $0.5\text{meV}$ . If standard band gap theory could apply to a device of this type it would claim a band gap of less than  $0.1\text{meV}$ <sup>[2]</sup>.

## 5. Uncertainties

### 5.1. Statistical Errors

In order to limit the effect of statistical errors in our measurements, the following steps were taken:

- Sensitive equipment was used to precisely measure events
- Each current measurement was averaged over 50 cycles
- Each I-V curve was measured twice

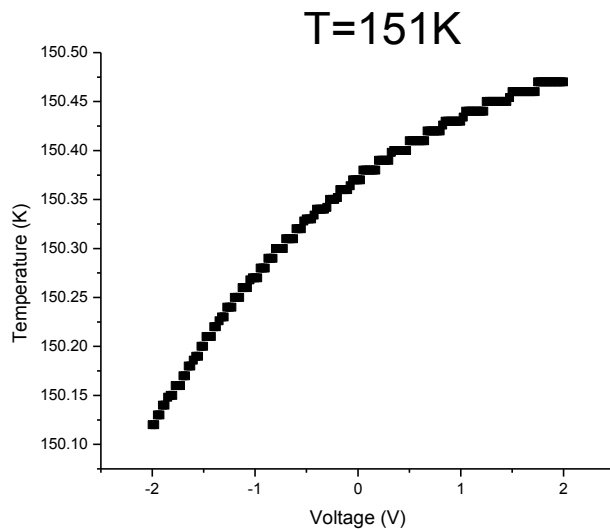
The result of these steps produced the following uncertainties:

- Current :  $(5 \text{ e-}13)/(\sqrt{50} \cdot \sqrt{2}) \approx 5\text{e-}14$
- Voltage:  $(5 \text{ e-}6)/(\sqrt{2}) \approx 3.5\text{e-}6$
- Temperature:  $(5 \text{ e-}5)/(\sqrt{2}) \approx 3.5\text{e-}5$

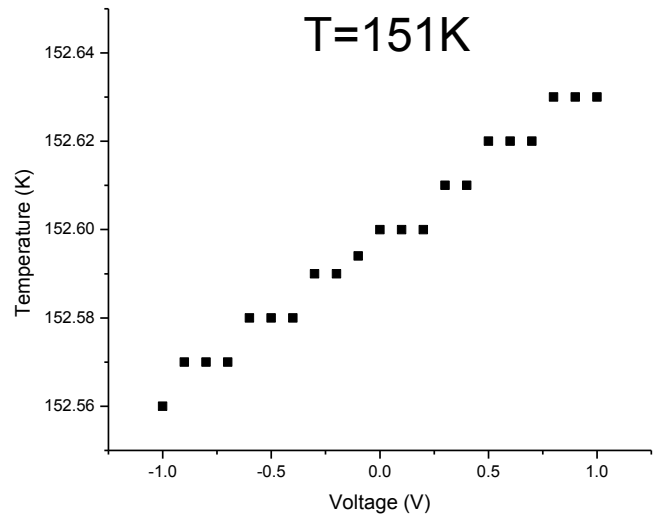
This cause a statistical error on the resistance measurement of only  $0.0004\%$  @  $1\text{V}$ ,  $150\text{nA}$ ,  $30\text{K}$ . This is negligible when compared with the systematic errors

### 5.2. Systematic Errors

With statistical errors as low as they were, our uncertainties were heavily dominated by systematic errors. Primarily, the temperature fluctuations during the I-V collection process. At low T sufficient time was allowed for the sample to thermally equilibrate resulting in a very well behaved resistance, but as T increases, the allotted equilibration time becomes insufficient and the temperature varies greatly from one voltage to the next, see figure 7. This produces huge errors in our data around  $\sim 150\text{K}$ . To fix this we quickened the I-V collection process while allowing for greater thermal equilibration time, this reduced our temperature fluctuations from  $\sim .4\text{K}$  @  $150\text{K}$  to  $\sim .08\text{K}$  @  $151\text{K}$ , see figure 8.



**Figure 7 Temperature fluctuations @  $T=151\text{K}$ .  
fluctuation  $\sim .4\text{K}$**



**Figure 8 Temperature fluctuation after fix,  
fluctuation  $\sim .08\text{K}$**

## 6. Conclusions

The material that composes a carbon film resistor cannot be treated as a pure metal or a pure semiconductor in the current models of solid state physics. At high T, the resistance exhibits semiconductor behavior in its dependence on temperature, but as the system cools the unique behavior of a semi-metal emerges. Like a metal, the conductivity is finite at  $T=0\text{K}$ , but the absolute zero resistance is higher than at room temperature. Further research is needed to develop a more accurate model for semi-metal behavior with an emphasis on low T.

## References

- [1] W. S. BOYLE and K. F. RODGERS, JR., "Performance Characteristics of a New Low-Temperature Bolometer," J. Opt. Soc. Am. 49, 66-69 (1959)
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