Temperature Dependence of a Semiconductor Resistor

Objective:
- Determining the resistance $R$ of a semiconductor as a function of temperature $T$ in a Wheatstone bridge.
- Determining the “band gap”.

Apparatus:
1. Semiconductor resistor 586 82
1. Electric Oven, 220V 555 81
1. Thermometer
1. Demonstration measuring bridge, 1m 536 02
1. Resistance box 536 77
1. Connecting leads 501 20/25/33
1. Multimeter 531 52
1. Power supply 685 44

Theory:
The following relationship applies:

$$R_T \propto e^{-\frac{\Delta E}{2kT}}$$  \hspace{1cm} (1)

$\Delta E$ : energy gap
$R_T$ : electric resistance
$k : 1.38 \times 10^\text{J.K}^{-1}$ (Boltzmann constant)
$T$ : Absolute temperature

The specific resistance of a semiconductor falls with temperature.
The lower the band space between the valence and conduction bands in the band model, the lower the resistance.
The greater the ratio of to the thermal energy $k.T$ of the electrons, the fewer the electrons which can be moved from the valence band to the conduction band.
The number of thermally generated pairs of electrons and holes depends exponentially on
The following equation applies:
\[
\frac{E_g}{kT}
\]

where \( n \): Electron concentration in the conduction band
\( p \): Concentration of the holes in the valence band
since, \( n = p \) in the case of intrinsic conduction, it follows for the electric resistance that

\[
R_T = \frac{1}{n} e^{E_g/2kT}
\]

\[
\ln R_T = \ln R_o + \frac{E_g}{2kT}
\]

If \( \ln R_T \) is plotted against \( 1/T \) on a coordinate system, we obtain a straight line with the gradient

\[
slope = \frac{E_g}{2k}
\]

It is thus possible to determine the band space \( \Delta E \) form the temperature dependence of the semiconductor resistor:

\[
E_g = \text{slope} \times 2k
\]

The resistance is measured in a Wheatstone bridge circuit. If the Wheatstone bridge circuit is balanced at the set temperature, i.e. the bridge branch AB is currentless, the unknown resistance is given by:

\[
R_T = (L_1/L_2)R
\]

Carrying out the experiment:
1. Set up the experiment as shown in figure.
2. Set the battery voltage to 1.5V by using the d.c. voltmeter.
3. Look for the balancing point by sliding the free end of the galvanometer over the meter bridge.
4. Make the balancing point in the middle of the meter bridge by adjusting the resistance from the resistance box (this is the adjustable resistance in the Wheatstone bridge). Don't forget that the balancing point is the point at which the galvanometer points to zero.
5. Now, turn on the oven to heat the semiconductor resistance.

**CAUTION**: The noble metal resistance temperature must not exceed 180°C.

6. Measure \( L_1 \) at every 10°C decrease in temperature by looking for the balancing point.
7. Deduce \( L_2 \) and calculate \( R_T \) every time.
8. Plot \( R_T \) versus \( T \).
9. Linearize the relationship between $R_T$ and $T$ by plotting $\ln R_T$ versus $1/T$.

10. Calculate the slope and then the band gap energy for the semiconductor.

Evaluation and Results:

The gradient of the straight line in the graph in the above figure is:

$$\text{slope} = \frac{3.9}{1.4 \times 10^{-3} \text{K}^{-1}} = 2786 \text{K}$$

The energy gap:
\[ E_s = \text{slope} \times 2k = 2786K \times 2 \times 1.38 \times 10^{-23} J \text{ } K^{-1} \]
\[ = 7.69 \times 10^{-20} J \]
\[ = 0.48eV \]
\( (eV = 1.602 \times 10^{-19} J) \)

The semiconductor resistance decreases non-linearly with increasing temperature. In the case of non-pure semiconductors, \( \ln R \) as a function of \( 1/T \) is a linear relation only at higher temperatures, use intrinsic conduction is dominant there.

Questions:
- Describe the relationship between the semiconductor resistor and the temperature?
- Explain why does the resistance of a semiconductor resistance decrease with increasing temperature?
A Wheatstone bridge is a measuring instrument invented by Samuel Hunter Christie in 1833 and improved and popularized by Sir Charles Wheatstone in 1843. It is used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component. Its operation is similar to the original potentiometer except that in potentiometer circuits the meter used is a sensitive galvanometer.

In the circuit at right, $R_x$ is the unknown resistance to be measured; $R_1$, $R_2$ and $R_3$ are resistors of known resistance and the resistance of $R_2$ is adjustable. If the ratio of the two resistances in the known leg ($R_2 / R_1$) is equal to the ratio of the two in the unknown leg ($R_x / R_3$), then the voltage between the two midpoints ($B$ and $D$) will be zero and no current will flow through the galvanometer $V_g$. $R_2$ is varied until this condition is reached. The current direction indicates whether $R_2$ is too high or too low.

Detecting zero current can be done to extremely high accuracy (see galvanometer). Therefore, if $R_1$, $R_2$ and $R_3$ are known to high precision, then $R_x$ can be measured to high precision. Very small changes in $R_x$ disrupt the balance and are readily detected.

At the point of balance, the ratio of $R_2 / R_1 = R_x / R_3$

Therefore,
\[ R_x = (R_2 / R_1)R_3 \]

Alternatively, if \( R_1, R_2, \) and \( R_3 \) are known, but \( R_2 \) is not adjustable, the voltage or current flow through the meter can be used to calculate the value of \( R_x \), using Kirchhoff's circuit laws (also known as Kirchhoff's rules). This setup is frequently used in strain gauge and Resistance Temperature Detector measurements, as it is usually faster to read a voltage level off a meter than to adjust a resistance to zero the voltage.

**Derivation:**

First, we can use Kirchhoff’s first rule to find the currents in junctions \( B \) and \( D \):

\[
\begin{align*}
I_3 - I_x + I_g &= 0 \\
I_1 - I_g - I_2 &= 0
\end{align*}
\]

Then, we use Kirchhoff’s second rule for finding the voltage in the loops \( ABD \) and \( BCD \):

\[
\begin{align*}
I_3 \cdot R_3 + I_g \cdot R_g - I_1 \cdot R_1 &= 0 \\
I_x \cdot R_x - I_2 \cdot R_2 - I_g \cdot R_g &= 0
\end{align*}
\]

The bridge is balanced and \( I_g = 0 \), so we can rewrite the second set of equations:

\[
\begin{align*}
I_3 \cdot R_3 &= I_1 \cdot R_1 \\
I_x \cdot R_x &= I_2 \cdot R_2
\end{align*}
\]

Then, we divide the equations and rearrange them, giving:

\[
R_x = \frac{R_2 \cdot I_2 \cdot I_3 \cdot R_3}{R_1 \cdot I_1 \cdot I_x}
\]

From the first rule, we know that \( I_3 = I_x \) and \( I_1 = I_2 \). The desired value of \( R_x \) is now known to be given as:

\[
R_x = \frac{R_3 \cdot R_2}{R_1}
\]
If all four resistor values and the supply voltage ($V_s$) are known, the voltage across the bridge ($V$) can be found by working out the voltage from each potential divider and subtracting one from the other. The equation for this is:

$$V = \frac{R_x}{R_1 + R_2} V_s - \frac{R_2}{R_3 + R_2} V_s$$

This can be simplified to:

$$V = \left(\frac{R_x}{R_3 + R_x} - \frac{R_2}{R_1 + R_2}\right) V_s$$

The Wheatstone bridge illustrates the concept of a difference measurement, which can be extremely accurate. Variations on the Wheatstone bridge can be used to measure capacitance, inductance, impedance and other quantities, such as the amount of combustible gases in a sample, with an explosimeter. The **Kelvin Double bridge** was one specially adapted for measuring very low resistances. This was invented in 1861 by William Thomson, Lord Kelvin. A "Kelvin One-Quarter Bridge" has also been developed. It has been theorized that a "Three-Quarter Bridge" could exist; however, such a bridge would function identically to the "Kelvin Double Bridge."

The concept was extended to alternating current measurements by James Clerk Maxwell in 1865 and further improved by Alan Blumlein in about 1926.