Low temp resistance

- Filled dewar with ice to provide a 0°C refence point for the thermocouple.
- Checked ice was melting so sample is ≈ 0°C
- Changed current flow to be through the thermocouple to get a reading for the voltage across it.
  This was 0.87mV. This corresponds to the room temp reading RT was 21°c from thermometer

fitting a function to the thermocouple data gave $y = 0.0419x$ between 0 → 100°c

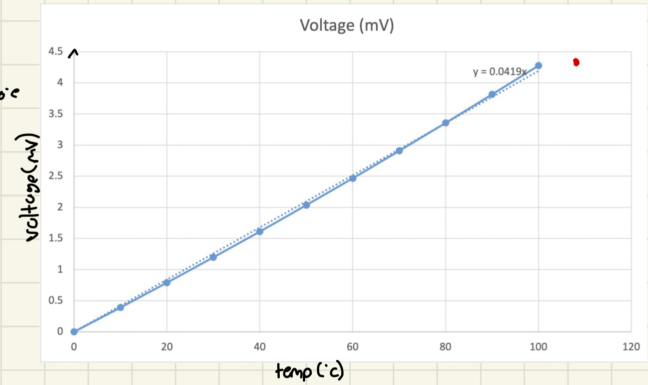
y: Voltage (mV)

x: temperature (°c)

$$\frac{1}{2\times10^{-2}} = \frac{1}{2}\times10^{2}$$

$$= 0.5\times10^{2}$$

$$\underline{\underline{50}}$$



dotted line is data, Solid line is fit function

So the thermocouple gave a reading of 0.87mV, from the fit function this gives a Temperature of T: 20.76°C which is close to measured room temperature of 21°C so we say the thermocouple is calibrated.

We started with room temperature Copper. RT was 21°C

We decided to take 8 measurements across a large range of current.

This was acheived by varying the resistance from 0.1 kΩ to 100 kΩ.

This gave a range of current from 1 μA to 10 mA which gave very spread out data.

Therefore we isolated the resistance to 100 kΩ

We varied the Voltage (V_1) which varied the input current from 1 μA to 17 μA

The current was calculated using $I = \frac{V}{R}$ using the voltage (V_1) and fixed resistance.

As only V_1 had an error, which was the smallest inciment on the voltmeter (0.001 V)

The error on the current was $\sigma_{I_i} = I_i \left(\frac{\sigma_{V_i}}{V_i} \right)$

We took a reading for the voltage across the Copper with an error of the smallest inciment of the voltmeter

this varied between results.

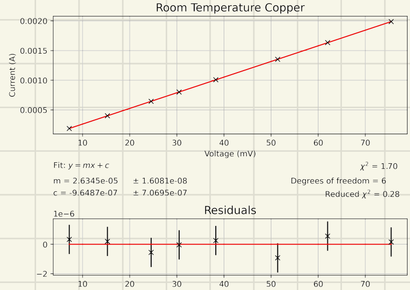
Copper						
Resistance (KOhms)	Voltage1 (V)	Error on V1 (V)	Calculated Current (A)	Error on Current (A)	Voltage Reading (mV)	Error (mv)
100	1.081	0.001	0.00001081	0.00000001	0.41	0.01
100	0.940	0.001	0.0000094	0.00000001	0.35	0.01
100	0.740	0.001	0.0000074	0.00000001	0.30	0.01
100	0.114	0.001	0.00000114	0.00000001	0.05	0.01
100	1.730	0.001	0.0000173	0.00000001	0.65	0.01
100	1.501	0.001	0.00001501	0.00000001	0.57	0.01
100	0.408	0.001	0.00000408	0.00000001	0.14	0.01
100	1.242	0.001	0.00001242	0.00000001	0.49	0.01

data for Room Temperature Copper.

Upon taking these readings we realised that a smaller percentage error on the voltage across the metal could be acheived by using a smaller resistance. This is because a larger resistance arm of a parallel circuit will have a greater fraction of the overall voltage. A smaller resistance will mean more voltage can be supplied to the metal and as the error on this voltage is roughly constant (resolution of voltmeter) this makes percentage error smaller. Also as the fluxuation of the voltage were a higher percentage of the readings for low voltage, a high voltage eliminated this problem.

However it was also important to have a low percentage error on the current readings. As V and I are inversely proportional, a resistance in the middle will give a good percentage error on current and voltage.

Copper						
Resistance (KOhms)	Voltage1 (V)	Error on V1 (V)	Calculated Current (A)	Error on Current (A)	Voltage Reading (mV)	Error (mv)
1	1.988	0.001	0.001988	0.000001	75.49	0.01
1	1.633	0.001	0.001633	0.000001	62.00	0.01
1	1.353	0.001	0.001353	0.000001	51.39	0.01
1	1.007	0.001	0.001007	0.000001	38.25	0.01
1	0.802	0.001	0.000802	0.000001	30.48	0.01
1	0.645	0.001	0.000645	0.000001	24.54	0.01
1	0.401	0.001	0.000401	0.000001	15.25	0.01
1	0.188	0.001	0.000188	0.000001	7.16	0.01



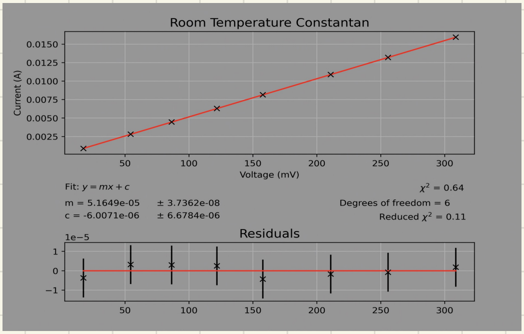
$m = 2.63 \times 10^{-5} \pm 1.6 \times 10^{-8}$; $R = 38.02 \pm 0.02\ \Omega$

We then repeated this with Constantan:

Constantan						
Resistance (KOhms)	Voltage1 (V)	Error on V1 (V)	Calculated Current (A)	Error on Current (A)	Voltage Reading (mV)	Error (mv)
0.1	1.594	0.001	0.01594	0.00001	308.7	0.1
0.1	1.320	0.001	0.0132	0.00001	255.7	0.1
0.1	1.088	0.001	0.01088	0.00001	210.8	0.1
0.1	0.814	0.001	0.00814	0.00001	157.80	0.01
0.1	0.629	0.001	0.00629	0.00001	121.85	0.01
0.1	0.446	0.001	0.00446	0.00001	86.41	0.01
0.1	0.281	0.001	0.00281	0.00001	54.46	0.01
0.1	0.089	0.001	0.00089	0.00001	17.42	0.01

$V = IR$

$R = \frac{V}{I}$



$m = 5.16\times10^{-5} \pm 3.74\times10^{-8}$ A/mV

$R = \frac{1}{m\times10^{3}} = 19.38 \pm 0.01\,\Omega$

$R = \frac{1}{m}\times10^{-3}$ $\quad \sigma_R = R\times -1\times\frac{3.74\times10^{-8}}{5.16\times10^{-5}}$

$= 0.014$

And then with Germanium:

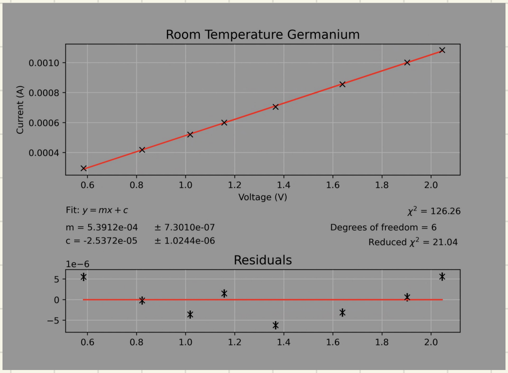
However a low resistance limited the Current range with Some samples So it was important to find the right balance

in this case we used $1k\Omega$

Germanium						
Resistance (KOhms)	Voltage1 (V)	Error on V1 (V)	Calculated Current (A)	Error on Current (A)	Voltage Reading (V)	Error (v)
1	0.295	0.001	0.000295	0.000001	0.58400	0.0001
1	0.418	0.001	0.000418	0.000001	0.82280	0.0001
1	0.520	0.001	0.00052	0.000001	1.0183	0.0001
1	0.705	0.001	0.000705	0.000001	1.3663	0.0001
1	0.855	0.001	0.000855	0.000001	1.6388	0.0001
1	1.001	0.001	0.001001	0.000001	1.9027	0.0001
1	1.083	0.001	0.001083	0.000001	2.0455	0.0001
1	0.600	0.001	0.0006	0.000001	1.1572	0.0001

$m: 5.39\times10^{-4} \pm 7.30\times10^{-7}$

$R: 1855.29 \pm 2.51\,\Omega$



We repeated this process for the following temperatures above room temperature:

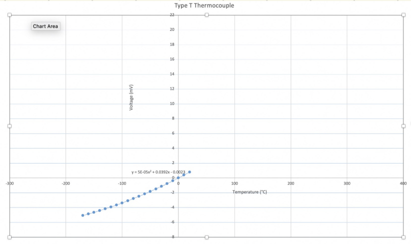
- 30°C ← only Germanium
- 42°C
- 50°C
- 70°C
- 80°C

This gave the following table:

	Resistance / Ohms					
Temperature	Copper	Error	Constantan	Error	Germanium	Error
21	38.02	0.02	19.38	0.01	1855.29	2.51
30	x	x	x	x	1422.48	1.26
42	42.02	0.03	19.38	0.01	922.33	0.87
50	42.92	0.03	19.42	0.01	729.93	0.57
70	46.08	0.03	19.42	0.02	346.02	0.23
80	47.62	0.03	19.42	0.01	245.70	0.16

each error was calculated as with copper.

- We also repeated the experiment for temperatures below Room Temperature.
- This was achieved using Liquid nitrogen which has a boiling point of about −200°C. The lowest temperature measured was roughly −165°C.
- We also used an exchange gas (Helium) to transfer this temperature to the specimin. Helium was used as it has a much lower BP than N so will remain a gas.
- We also put a fit to the thermocouple data to get accurate temperatures:



The fit model was $y = (5\times10^{-5})x^2 + 0.0392 - 0.0023$

from this accurate temperatures could be found from the voltage of the thermo couple.

So we repeated the experiment at:

- −165°C
- −119°C
- −73°C
- −15°C

This gave the following table:

	Resistance / Ohms					
Temperature	Copper	Error	Constantan	Error	Germanium	Error
-15	35.8	0.02	19.34	0.01	8544.45	5.89
-72	26.06	0.02	19.24	0.01	6971.78	4.78
-119	16.77	0.01	19.12	0.01	5241.49	3.20
-165	5.68	0.003	18.86	0.01	4456.04	2.55

From this data we worked out the thermal Coefficient of resistivity for each material by plotting a graph of the ratio of resistances against the difference in temperature.

$$R = R_{rt}\left[1 + \alpha (T - T_{rt})\right]$$

$$\frac{R}{R_{rt}} = 1 + \alpha (T - T_{rt})$$

$$y = c + m \, x$$

$$\frac{dR}{R} = \alpha \, dT \qquad dR = R_1 - R_{T_0}$$

$$\frac{dR}{R} = \alpha \Delta T$$

$$\frac{R(T) - R(T_0)}{R(T_0)} = \alpha \Delta T$$

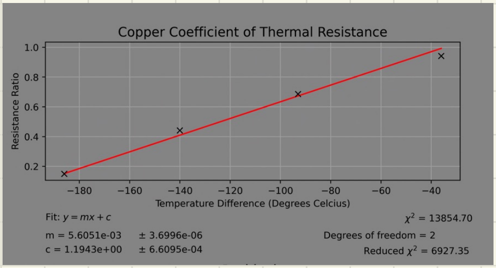
$$\frac{R(T)}{R(T_0)} - 1 = \alpha \Delta T$$

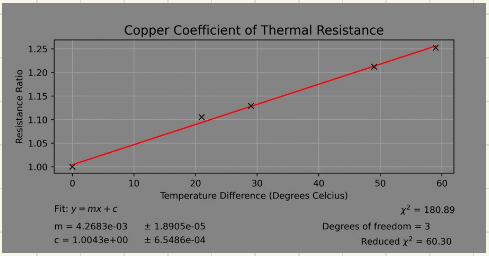
$$R(T) = R(T_0)(1 + \alpha \Delta T)$$

We took T_{rt} to be room temperature.

This gave a straight line graph with the gradient equal to the thermal Coefficient of resistivity.

For Copper we split the temperature into above room temperature and below.





We disregarded data below RT when calculating α as the quoted value is only given for 20°C:

For above Room Temperature:

$$\alpha = 4.27\times10^{-3} \pm 1.89\times10^{-5} \ {}^\circ C^{-1}$$

α for 20°C is: $\alpha = 3.93\times10^{-3} \ {}^\circ C^{-1}$ ← True Value

Our Calculated value for α above room temperature does not overlap with the true value.

This is most likely due to our data being taken over 20°C → 80°C, the temp. Coefficient may not be linear over this range but we have assumed it is.

The fact that this might not be a Suitable fit is reinforced by $\chi^2_{reduced} = 60.30$.

However this could also be due to underestimated errors.

However our Calculated value is only 7.5% greater than the true value.

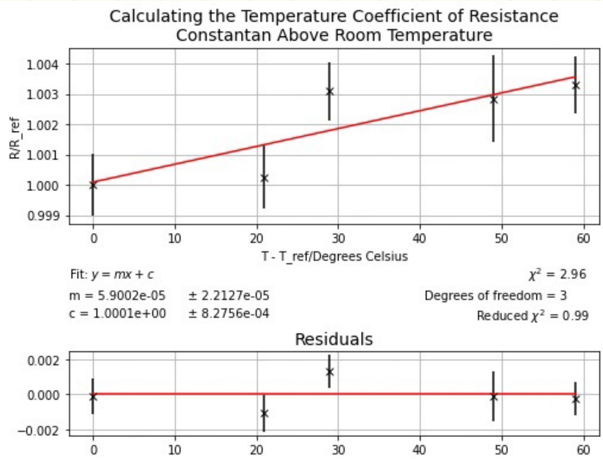
Data:

Temperature Difference	Resistance Ratio					
	Copper	Error	Constantan	Error	Germanium	Error
0	1	0.0007439	1	0.000729728	1	0.0019133
9	x	x	x	x	0.7667157	0.0012398
21	1.105207785	0.0009801	1	0.000729728	0.4971352	0.0008199
29	1.128879537	0.0009875	1.002064	0.000730482	0.3934318	0.0006146
49	1.211993688	0.0010144	1.002064	0.001154279	0.1865045	0.0002811
59	1.252498685	0.001028	1.002064	0.000730482	0.1324321	0.0001988
-36	0.941609679	0.0007225	0.997936	0.000728976	4.6054525	0.0069928
-93	0.685428722	0.0006377	0.9927761	0.000727097	3.7577845	0.0056994
-140	0.44108364	0.0003507	0.9865841	0.00072485	2.8251594	0.0041933
-186	0.149395055	0.0001114	0.9731682	0.000720005	2.4018024	0.0035281

The error on the ratio's of resistency were:

$$\sigma_{ratio} = ratio\sqrt{\left(\frac{\sigma_R}{R}\right)^2 + \left(\frac{\sigma_{R_{rt}}}{R_{rt}}\right)^2}$$

For Constantan:

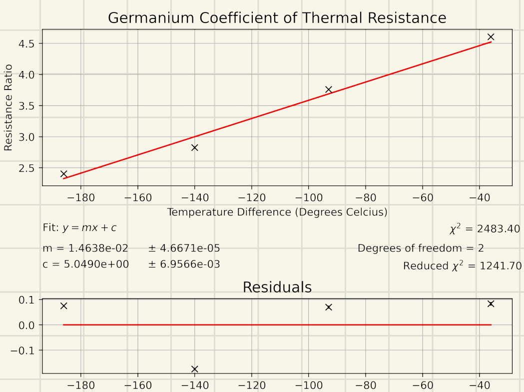


From this graph, $\alpha = (5.90 \pm 2.21) \times 10^{-5}\ °C^{-1}$

the true value is: $\alpha = 3 \times 10^{-5}\ °C^{-1}$

Again this doesn't overlap but no data could be found for the temperature range we used.
The values are roughly the same.

Germanium:

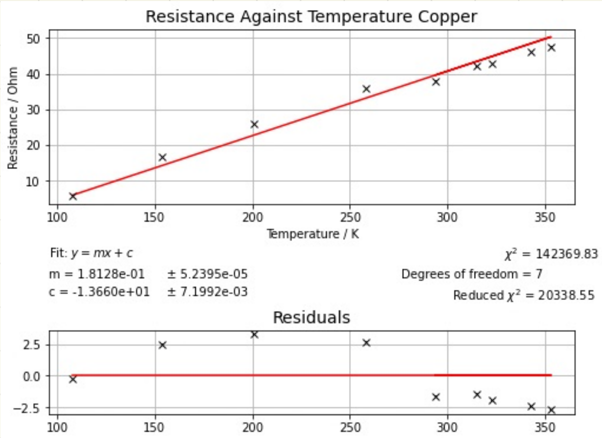


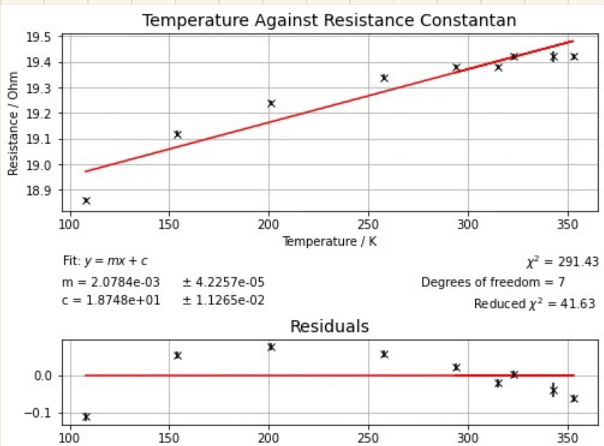
α for above room temperature was $(-1.05 \times 10^{-2} \pm 1.28 \times 10^{-5})\ °C^{-1}$

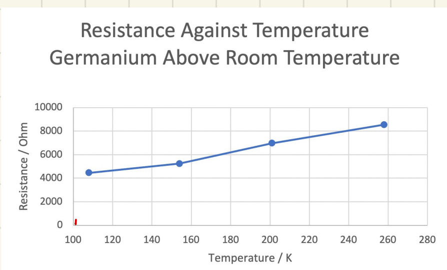
The true value is $\alpha = -5 \times 10^{-2}\ °C^{-1}$

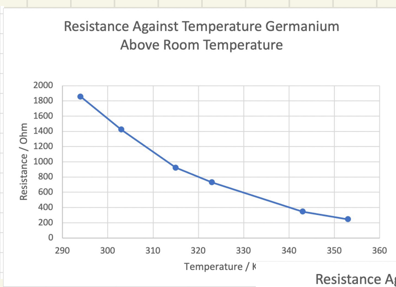
Again this doesn't overlap but no data could be found for the temperature range we used.
The values are roughly the same.

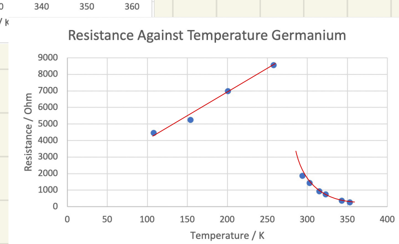
RT Graphs:











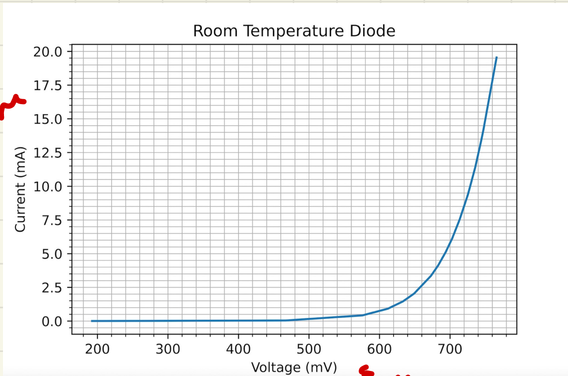
We note that the gradient changes direction for Germanium. This is explained in Conclusion

Diode:

For the diode we varied the resistances to get a large range of current ($2\,\mu A \rightarrow 20\,mA$)

We did this as voltage is roughly constant for small current but increases greatly after the threshold voltage is met a wide range of currents made both of these relations visible on a graph.

Silicon Diode						
Resistance (KOhms	Voltage1 (V)	Error on V1 (V)	Calculated Current (A)	Error on Current (A)	Voltage Reading (mV)	Error (mv)
0.1	1.955	0.001	0.01955	0.000010	766.10000	0.1
0.1	1.423	0.001	0.01423	0.00001	747.60000	0.1
0.1	1.340	0.001	0.0134	0.00001	744.4000	0.1
0.1	1.137	0.001	0.01137	0.00001	735.7000	0.1
0.1	0.937	0.001	0.00937	0.00001	725.4000	0.1
0.1	0.754	0.001	0.00754	0.00001	713.8000	0.1
0.1	0.612	0.001	0.00612	0.00001	703.1000	0.1
0.1	0.510	0.001	0.0051	0.00001	693.8000	0.1
0.1	0.412	0.001	0.00412	0.00001	683.2000	0.1
0.1	0.335	0.001	0.00335	0.00001	673.0000	0.1
0.1	0.204	0.001	0.00204	0.00001	649.2000	0.1
0.1	0.146	0.001	0.00146	0.00001	633.4000	0.1
0.1	0.092	0.001	0.00092	0.00001	612.1000	0.1
0.1	0.042	0.001	0.00042	0.00001	575.9000	0.1
1	0.041	0.001	0.000041	0.000001	467.1000	0.1
100	0.280	0.001	0.0000028	0.00000001	192.4000	0.1



This was then repeated for all temperatures that we used for the other samples.

The characteristic equation for a diode is: $I = I_0\, e^{-E_g/kT}\left(e^{eV/kT} - 1\right)$ for the range of temperatures we used, $e^{eV/kT} \approx 10^{60}$ So $e^{eV/kT} - 1 \approx e^{eV/kT}$

$$I = I_0\, e^{-E_g/kT}\, e^{eV/kT}$$

$$I = I_0\, e^{(eV - E_g)/kT}$$

$$\ln I = \ln(I_0) + \frac{eV}{kT} - \frac{E_g}{kT}$$

$$\frac{kT}{e}\ln I - \frac{kT\ln I_0 + E_g}{e} = V$$

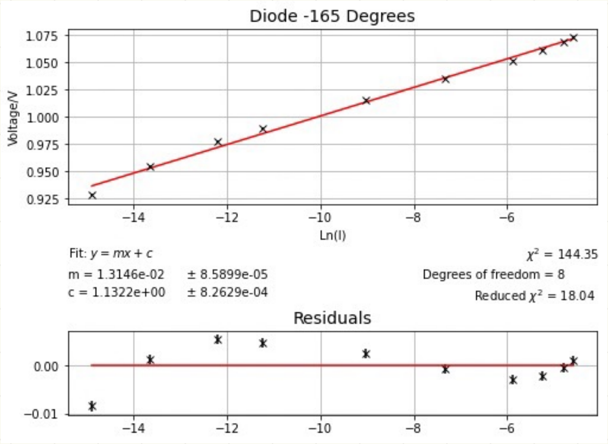
This can now be plotted as V against $\ln I$. From this the gradient will actually be $\frac{nkT}{e}$ as the diode is not theoretically ideal.

Therefore if we multiply the gradient by $\frac{e}{kT}$ we will get the ideality factor, n, of our diode. This was done for each temperature:

An example graph of ln I against V (with data) at $-165°C$:

Ln(Current)	Voltage (V)	Error
-3.974430466	0.6758	0.0001
-4.23360663	0.6578	0.0001
-4.435427411	0.6439	0.0001
-4.640797364	0.6302	0.0001
-4.820841722	0.6191	0.0001
-5.031348336	0.6057	0.0001
-5.417100903	0.5819	0.0001
-5.936976362	0.5519	0.0001
-6.868534566	0.4999	0.0001
-7.74477283	0.452	0.0001
-12.06805135	0.2008	0.0001
-13.81551056	0.1016	0.0001
-9.511445465	0.3532	0.0001

error on V was from resolution of voltmeter



We removed anomalous data points that tended to be at low currents.

The gradients for each temperature were calculated:

Temperature/K	Gradient	Gradient Error	Ideality Factor	Ideality factor error
108	0.013146	0.000085899	1.411272142	0.009221578
157	0.019867	0.00010325	1.467146681	0.00762485
201	0.02977	0.00010095	1.717211046	0.005823059
259	0.039831	0.000011769	1.783045157	0.000526842
294	0.049365	0.000024559	1.946761313	0.00096851
313	0.0352	8.17E-06	1.303884799	0.000302512
323	0.054141	8.66E-06	1.943410957	0.000310933
343	0.056595	9.13E-06	1.913043478	0.000308463
353	0.057781	9.14E-06	1.897803506	0.000300152

The ideality factor was calculated by: $n = \frac{me}{kT}$ for each temperature.

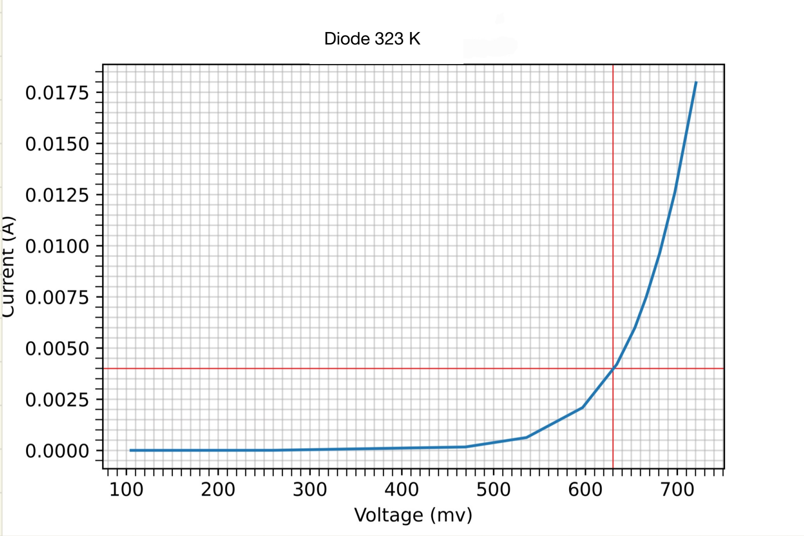
The error on this was calculated as: $\sigma_n = \frac{e}{kT}(\sigma_m)$

We did not take an average value of these as n varies with temperature.

However $1 \le n \le 2$ which all calculated values fit within.

For each IV graph for the Diodes at Varying temperature we read the Voltage at 0.004 A, this Current was fixed.

An example is shown:

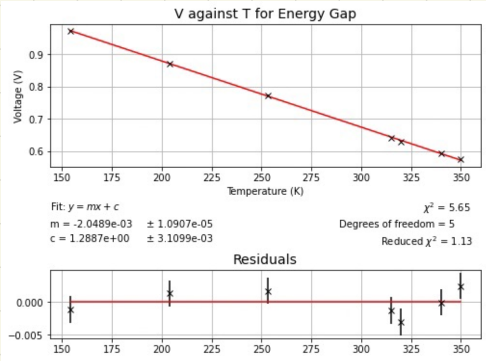


On this graph at $I = 0.004A$, $V = 630 \pm 2mV$ The error on this was taken to be $\frac{1}{5}$ of the smallest increment.

This was repeated for each temperature to give the following data:

T/k	Voltage/v	V_err/v
350	0.574	0.002
340	0.592	0.002
320	0.630	0.002
315	0.642	0.002
253	0.772	0.002
204	0.872	0.002
154	0.972	0.002

← After removing anomalies.



We did this as from the characteristic diode equation: $I = I_o e^{-E_g/kT} e^{eV/kT}$ neglecting the +1,

$$\ln I = \ln I_o + \frac{eV - E_g}{kT}$$

$$kT \ln\left(\frac{I}{I_o}\right) = eV - E_g$$

$$V = \frac{k \ln\left(\frac{I}{I_o}\right)}{e} T + \frac{E_g}{e}$$

So plotting V against T

will give the energy gap, E_g, in electron volts

as the intercept.

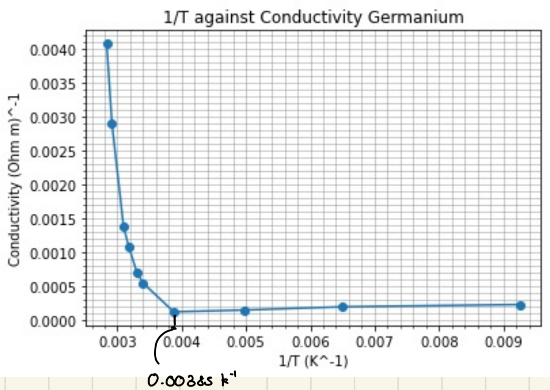
Therefore from the graph, $E_g = (1.2887 \pm 0.0031)$ eV

The true value for E_g at room temperature is $E_g = 1.11$ eV

These do not overlap but are close. The quoted value is for room temperature and as the energy gap varies with temperature a difference is expected

Germanium Conductivity:

Plot of $\frac{1}{T}$ against Conductivity:



$0.00385\ k^{-1}$

↓

260 K

↑

$E = 0.0336$ eV

This is an exponential relation, very dependent on T for large T but faint dependance on T for low temperatures.

The conduction proceeds through 2 distinct channels:

- At high temperature ($T > 260$ K) conduction is strongly dependent on T. As temperature is decreased conduction decreases very fast. This implies that at these temperatures the conduction is dependent on electrons in conduction band here. As above 260 K the conduction exponentially increases. This is expected to plateau but is outside our range of T. The increase in conductivity from conduction electrons dominates the decrease from increased vibrations

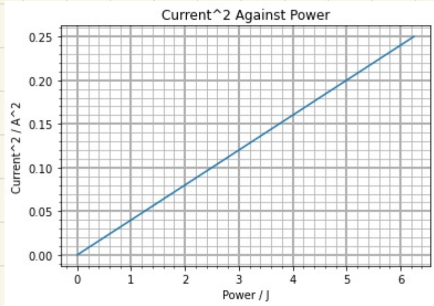
- However at low temperatures ($T < 260$ K) the energy required to move electrons into the conduction band is not met. Therefore an increase in temperature slightly decreases conductivity due to thermal vibrations.

Rate of heat change:

iv) due to heater (heat in)

$P = I^2 R$

↓ varies from $0 \to 6$ W depending on current.

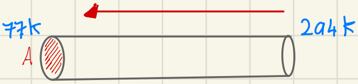


Gain

iii) Conduction along brass bar (heat loss)

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$$

$k = 109$ W/mk

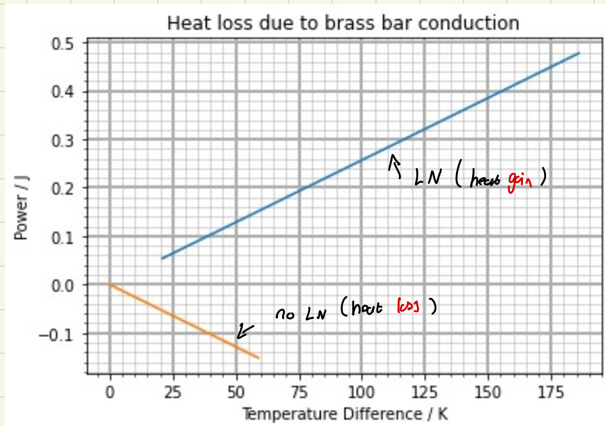


$A = \left(\frac{3}{2} \times 10^{3}\right)^2 \times \pi$

$= 7.07 \times 10^{-6} m^2$

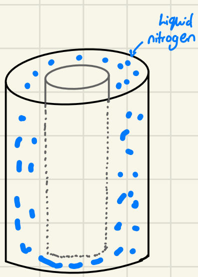
$$\dot{Q} = \frac{109(7.07 \times 10^{-6})(T_2 - 294)}{0.3}$$

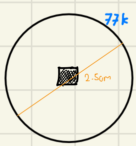
$$\dot{Q} = 0.00257 \ (\Delta T)$$



heat loss due to Conduction

ii) Radiation from and to Specimin holder (heat loss and gain)





$\frac{P}{A} = \sigma T^4$

from Specimin holder sides:

$= 5.67 \times 10^{-8} \times (77)^4$

$= \boxed{1.99 \ J m^{-2}}$

$A = \pi D L$

$A = 0.0314$

$P = 1.99 \times 0.0314$

$P = 0.0625$ W

Due to ends:

$= 5.67 \times 10^{-8} \times (294)^4$

$= 423.616 \ J m^{-2}$

$A = 2 \times \pi r^2$

$= 0.000982$ m

$P = 0.416$ W

rate of heat gain was constant from radiation of Specimin chamber. →

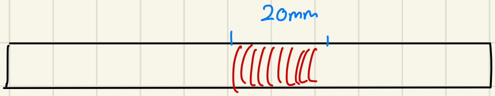
Total $= 0.4785$ W Gain

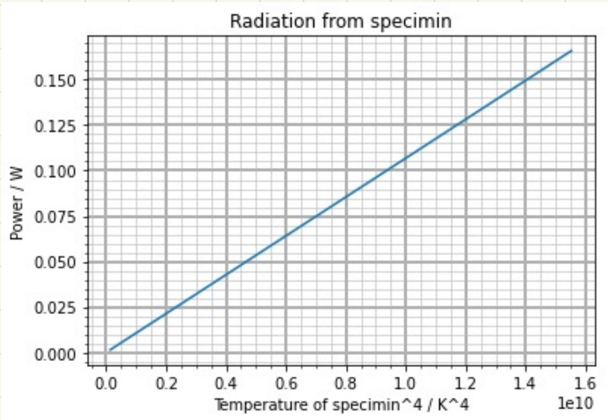
radiation from specimin to LN:

$$A = \pi(3\times10^{-3}) \times 20\times10^{-3})$$

$$P = \cancel{\varepsilon}A\sigma(T^4)$$

$(108 - 353)K$





loss

So as the temperature of the specimin increased the rate of heat lost increased.

i) Conduction through pressure of Heliums

For varying pressures we measured the average temperature increase of the sample when supplied with 6.25W from the heater.

We calculated the volume of the specimin chamber: $V_{Final} = V_1 - V_2 = L(A_1 - A_2) = L\pi((0.1)^2 - (0.025)^2)$

$= 2.95\times10^{-3}\,m^3$

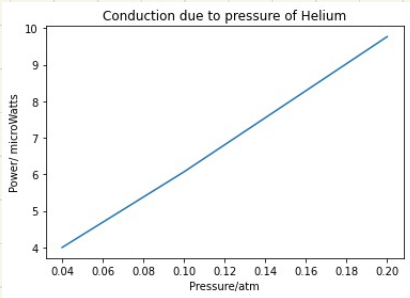
For each pressure we used $PV = NkT$ to find N using the average temp.

from which the mass could be found by multiplying by hydrogen mass.

The heat transfer was then calculated using $Q = mc\Delta T$

then dividing by 300 s to get $\dot{Q}$

We then plotted $\dot{Q}$ against P:



loss

So as pressure of Helium increases the rate of heat loss of the specimin increases.

Therefore from each of these 4 graphs for a constant pressure, temperature and current of heater, the heat loss or gain of the specimin can be found.

$$\boxed{\text{All graphs and data for materials : Desktop/uni/year2/lowtempresis/materials}}$$

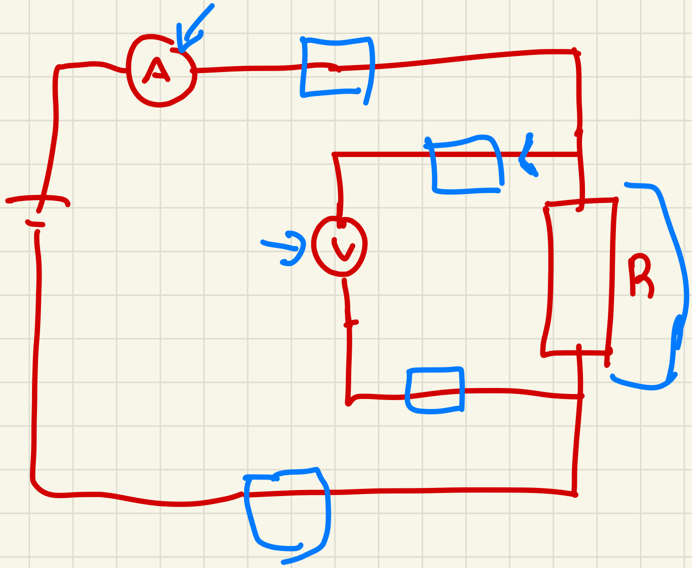
All graphs and data for diode: Desktop/uni/year2/lowtempresi./diode

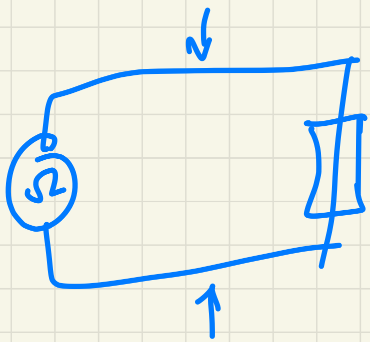
All graphs and data for R-T : Desktop/uni/year2/lowtempresi./RT

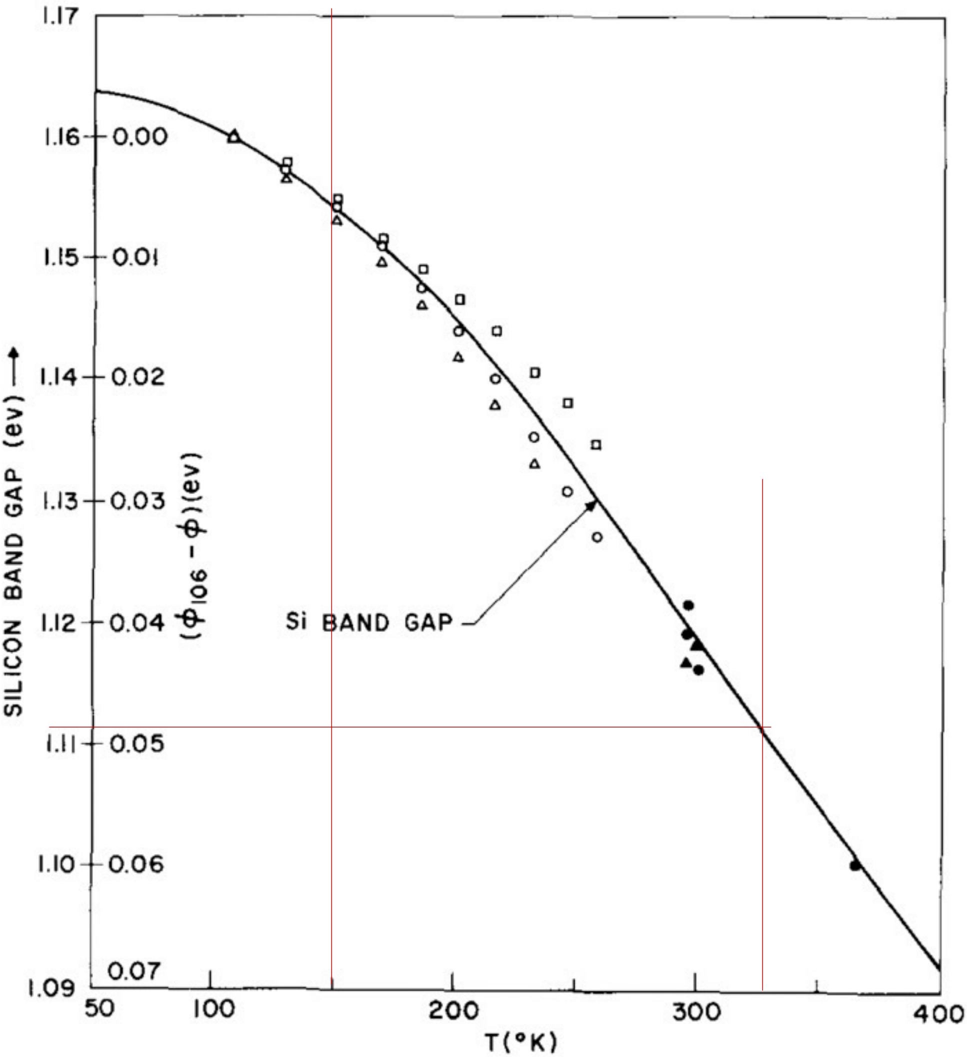
All graphs and data for TCOR : Desktop/uni/year2/lowtempresi./TCOR

All graphs and data for Heatloss: Desktop/uni/year2/lowtempresi./Heatloss

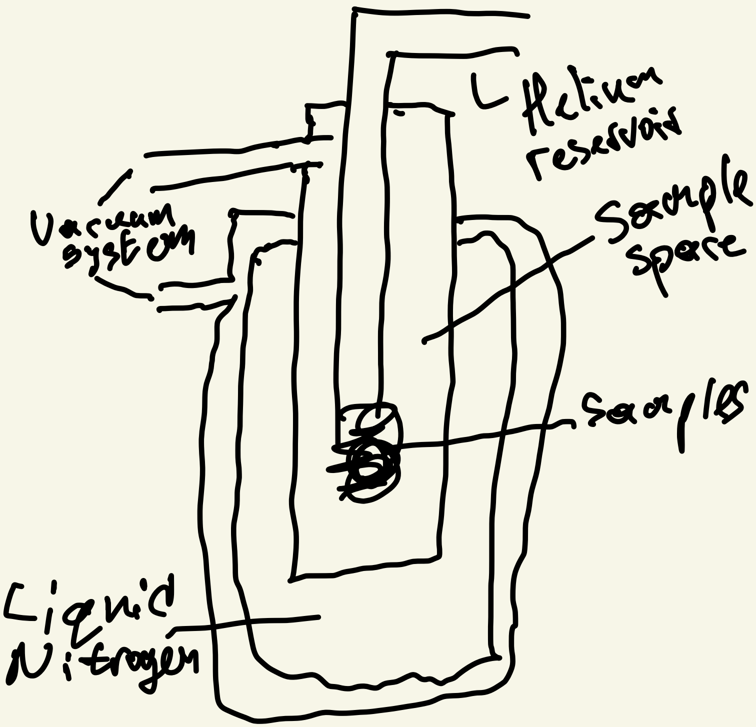
- TCOR for each material
- Energy gap
- Ideality factor


A
V
R

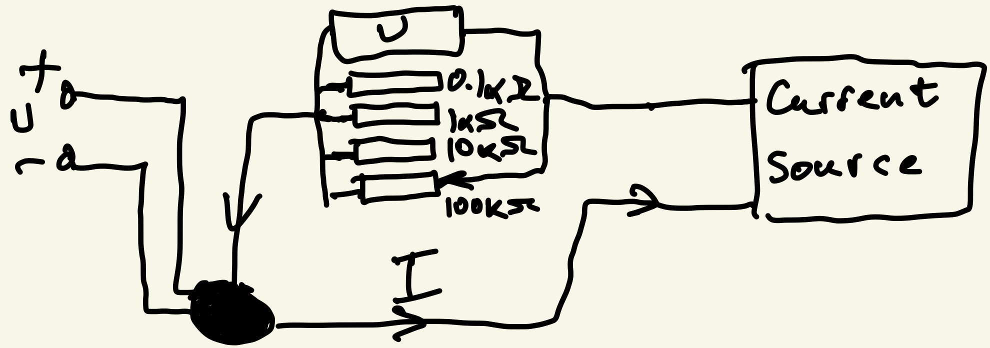

Ω



SILICON BAND GAP (ev)
$(\phi_{106} - \phi)$ (ev)
Si BAND GAP
T(°K)
1.17
1.16
1.15
1.14
1.13
1.12
1.11
1.10
1.09
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
50
100
200
300
400



Helium reservoir
Vacuum system
Sample space
Samples
Liquid Nitrogen


+
U
-
U
0.1kΩ
1kΩ
10kΩ
100kΩ
I
Current
Source