Experiment 4: Quantisation Of Conductance In Nanowires

PHYS-C0258: Quantum Labs

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Table of Contents:

1. Introduction

In classical mechanics, the flow of current through a conductor is described by Ohm's Law I = V/R, where R is the resistance of the Ohmic conductor and V is the voltage difference across the ends of the conductor. The resistance of an Ohmic conductor can be represented by the formula $R = \rho L/S$ where ρ is the resistivity, L is the length of the wire and S is the transversal area of the conductor. The conductance is defined as $G = R^{-1}$ and it depends on the material and it is not affected by the microscopic flow of electrons in the conductor. As the area approaches zero, we expect the conductance to drop smoothly to zero, however it is experimentally shown that in sufficiently narrow wires, the conductance decreases in quantised steps of $Go = 2e^2/h \simeq 7.7 \cdot 10^{-5}\Omega^{-1}$ [1]. It is independent of the material, depends on electron charge, and is called the quantum of conductance.

In this experiment we aim to experimentally observe the quantisation steps of conductance by measuring the conductance of a loose electrical contact formed between two oscillating gold nanowires [2].

2. Methods

The experiment setup consisted of three main parts: a metal box which had all the electrical components needed for the experiment, a holder for the nanowires and an oscilloscope.

The metal box has a circuit inside it that has the following components: a current to voltage converter (an operational amplifier), and a tunable voltage source. The voltage source is powered by a 9v battery and it is connected to the BNC connector (1) on the box. The oscilloscope channel 1 (Ch1) is connected to the box at BNC connector (4) and channel 2 (Ch2) to BNC connector (5). Ch1 measures the applied (source) voltage and Ch2 the output of the converter. The wires are connected to the box from BNC connectors (2) and (3). The current flowing through the nanowires can be measured by Ch2 due to the property of the current to voltage converter which generates a voltage signal proportional to the current flowing through the wires. The figure is on the next page.

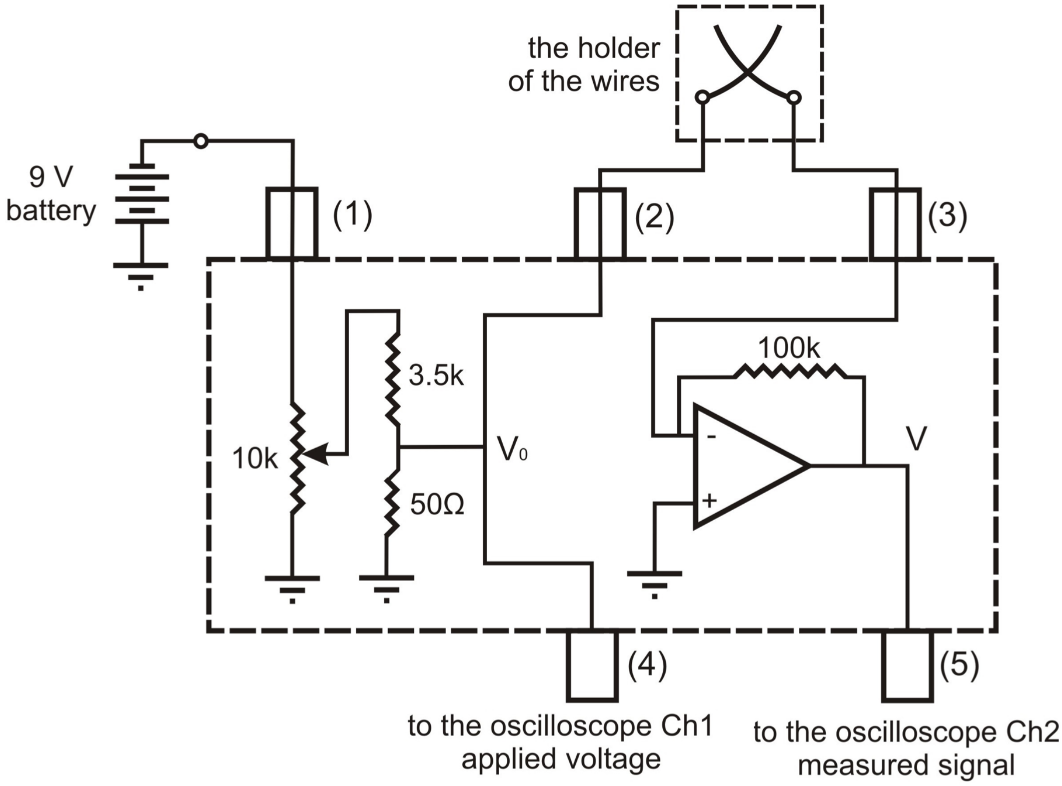


Figure 1: Experimental setup [3]

An oscilloscope is a device that displays how electrical signals change over time [4]. The experiment required us to collect data through the oscilloscope and we were required to apply some settings to make sure the device was ready for use.

For Ch1 and Ch2 the following were required: Coupling → DC, BW limit → Off, Probe →1xVoltage, Input → 1MΩ, Invert → Off, Fine → Off, Unit → V, 20 mV/div (Ch1) and 500mV/div (Ch2). For the trigger we had the following: Type → Edge, Source → Ch2, Slope → Falling, Mode → Auto, Coupling → DC.

We made the measurements by tapping the wire holder or the table to trigger vibrations on the wires, and then take traces of the voltage signal at random. We saved the signals that had clearly visible quantisation steps. The data obtained was analysed and processed using Matlab and the code is provided in the appendix. The voltage signals were first converted to conductance and then normalised using dividing by the quantum of conductance. The graphs were then plotted as Time versus Normalised Conductance. The last step of data processing was to plot a histogram of all the normalised traces we took with appropriate bin sizes.

3. Results

The I-V converter's conversion coefficient $k = 1/R$ can be approximated with the values Ro, Vo, and Vout. These were measured during the calibration of the setup.

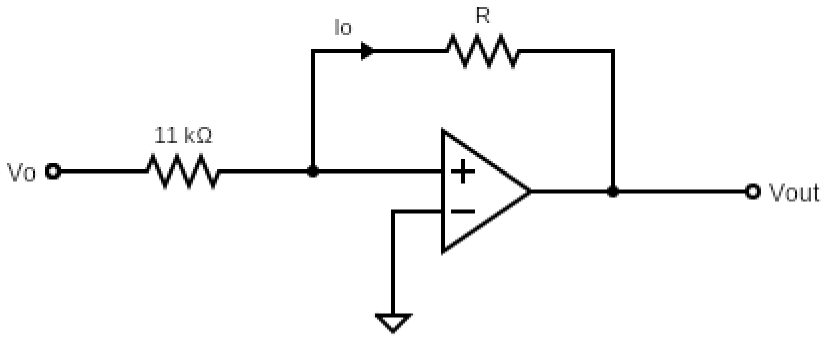


Figure 2: Operational amplifier setup when calibrating

$$R = \frac{Vout}{Io} \qquad Io = \frac{Vo}{Ro}$$

$$k = \frac{Vo}{Ro \cdot Vout}$$

From calculating average over time traces:

$Vo = -0.02005 \pm 0.00003578\,V$

$Vout = 0.17804 \pm 0.0001005\,V$

Measuring with the multimeter:

$Ro = 10.96 k\Omega$

Calculated value:

$k = 1.0275e - 05$

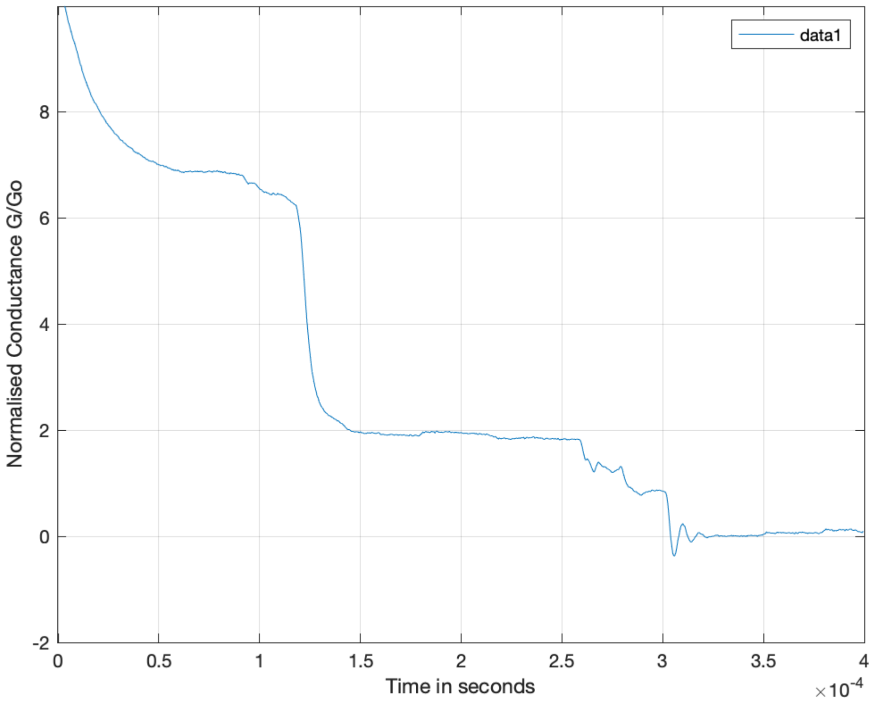


Figure 3: Voltage trace showing quantisation of conductance

In Figure 3, we can clearly see the step formation at integer multiples of the quantum of conductance Go. The voltage traces are transformed to conductance using the formula :

$$G = -k\frac{Vout}{Vo} \quad (1)$$

And then they are normalised by G/Go. This voltage trace matched what was described by the theory the best of all the traces we took during measurement. Many of our other traces had similar flat steps, and some had more steps, but none as clearly visible as this trace. Unfortunately a sizable portion of our traces had shifted zero points, the reasons for it are unclear, but they did impact the quantitative results for the histogram shown on Figure 4. Examples of the figures are attached in the appendix.

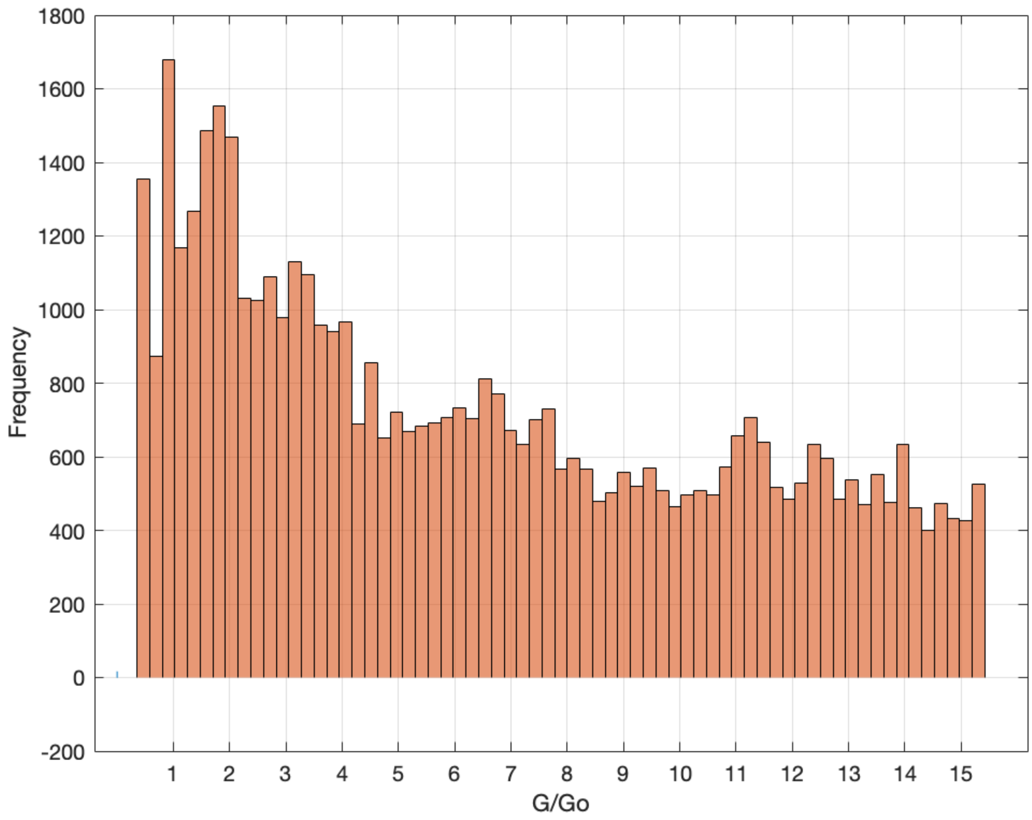


Figure 4: Histogram plot for all normalised voltage traces

Based on the theory, I would expect the frequency of occurrences to be higher around integer values of conductance as those are the allowed values of conductance. The figure obtained resembles the prediction very slightly. It is not immediately apparent. A closer look at the bins around the integer values can help us better recognise the higher frequencies around integers. The reason for poor resemblance could be because many graphs had some shifts in the zero point, which in turn shifted the values below or above the integer points. This can be rectified by closely examining each voltage trace and adjusting for the shift in values.

4. Conclusions

The aim of the experiment was to observe quantuisation steps of conductance as described by results of quantum transport theory in the Landauer-Büttiker approach. These aims were met successfully and without facing any major issues while conducting the experiment. We also show quantitatively that the steps are quantised by plotting the histogram of all the normalised traces and observed peaks around integer quantisations that match what the theory describes.

We observed the quantisation steps as shown in figure 3 by taking output voltage traces when the nanowires are oscillating, and then converting it into conductance using formula (1), and finally normalising it with the known value Go (quantum of conductance). There were some errors in our data acquisition as the time length of the voltage traces were not consistent for all our data, and that some of our voltage traces were not zero centered. This did not affect the observation of the steps but did affect our histogram plot.

5. References

[1] - *CODATA value: Conductance quantum*. Available at: https://physics.nist.gov/cgi-bin/cuu/Value?conqu2e2sh

[2] - Keränen, A. *Quantization of conductance in nanowires*. Available at: https://mycourses.aalto.fi/mod/folder/view.php?id=934844

[3] - Essick, J. *An examination of quantized conductance in nanowires*, *AAPT Advanced Labs Website*. Available at: https://advlabs.aapt.org/items/detail.cfm?ID=11237

[4] - Vinci, A. (2021) *What is an oscilloscope?*, *Tektronix*. Tektronix. Available at: https://www.tek.com/en/blog/what-is-an-oscilloscope

Appendix

Contents


```
clear all
format long
```

Calculating Vo

```
data = readmatrix("/REPORT DATA/scope_0.csv");
vals = data(3:end,2);
stdvo = std(vals);
V0   = -mean(vals);              % -0.020049413489950
```

Calculating Vout

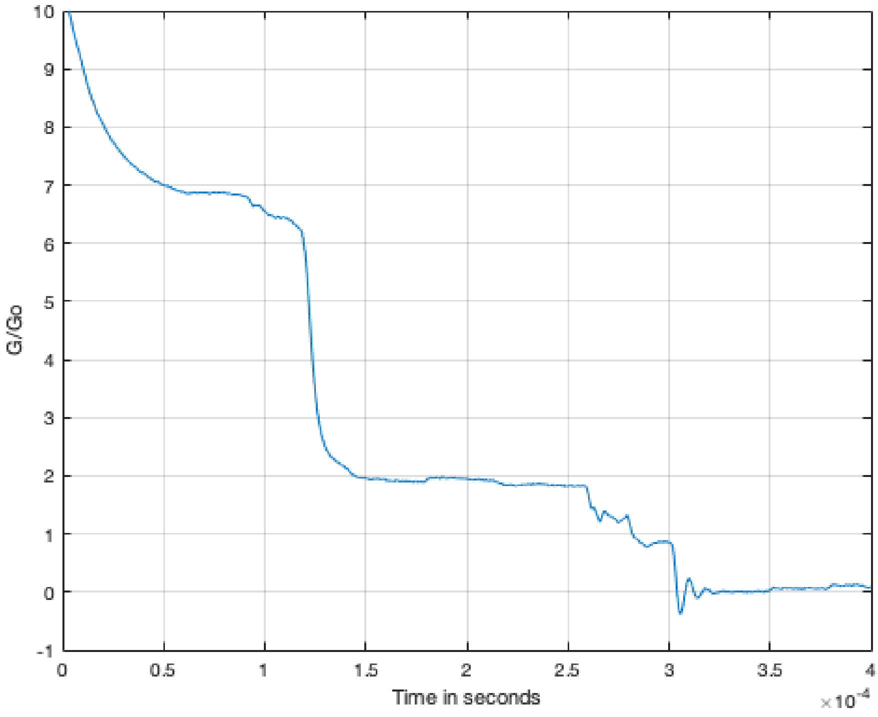
```
data = readmatrix("/REPORT DATA/scope_1.csv");
vals = data(3:end,2);
stdvout = std(vals);
Vout = mean(vals);              % 0.178043215200050
```

Other known data

```
R0   = 10.96*10^3;              % Given by TA
e    = 1.60217662 * 10^(-19);   % Electron charge in coloumbs
h    = 6.62607015 * 10^(-34);   % Planck's constant
G0   = 2*e^2/(h);               % Quantum of conductance = 7.748091594456254 * 10^(-05)
k    = 1/(10^5);                % Conversion coefficient given
k1   = -V0/(R0*Vout);           % Conversion coefficient from calculation = 1.027461813862249e-05
G    = -k*Vout/V0;    %8.880220625371224e-05
G1   = -k1*Vout/V0; %9.124087591240875e-05
```

Best trace

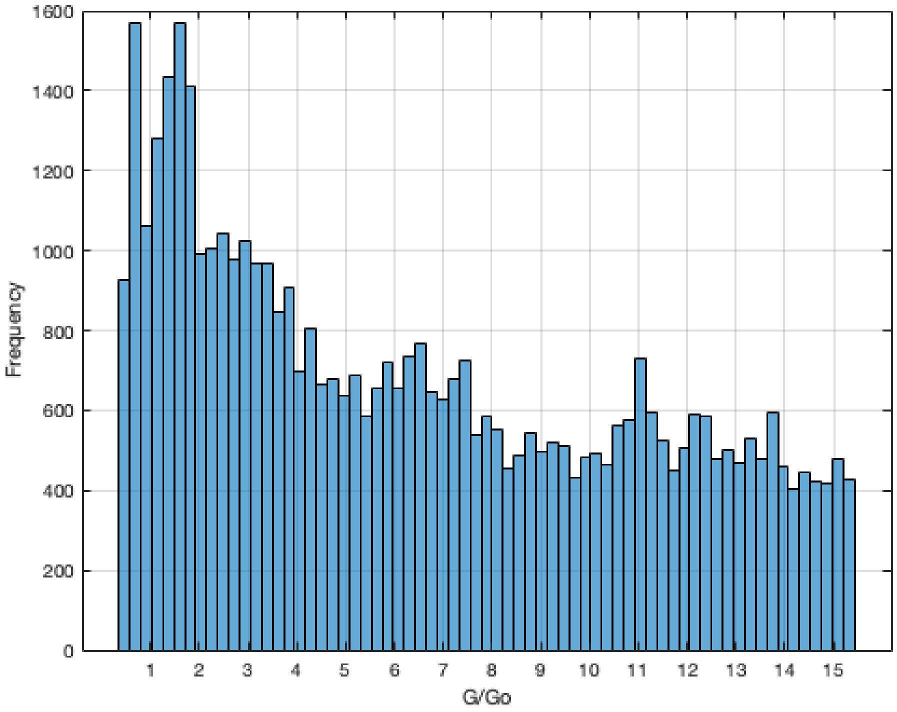
```
a = readmatrix("/REPORT DATA/scope_38.csv");
p = a(3:end,3);
p_n = a(3:end,3)+ 0.03;
figure(1);
plot( a(3:end,1) , ( -k1*p / V0  ) /G0);
xlabel('Time in seconds')
ylabel('G/Go')
axis([0 4*10^-4 -1 10]);
grid on;
hold on;
```



Histogram code

```
figure(2);
x = zeros(2000*50,1);
%x_n = zeros(2000*50,1);
for N = 4:54
    file = sprintf("/REPORT DATA/scope_%d.csv",N);
    f = readmatrix(file);
    ll = f(3:end,3) + 0.03;
    %x_n(2000*(N-2)+1:2000*(N-1),1) = (( -k1*ll) / V0 ) /G0;
    x(2000*(N-2)+1:2000*(N-1),1) = (( -k1*f(3:end,3)) / V0 ) /G0;
end
bins = 0.35:0.225:15.5;
%[0.75,1.35,1.75,2.35,2.75,3.35,3.75,4.35,4.75,5.35,5.75,6.35,6.75,7.35,7.75,8.35,8.75,9.35,9.75,10.35]


histogram(x,bins);
ylabel('Frequency')
xlabel('G/Go')
grid on;
hold on;
%histogram(x_n,bins);
xticks(1:15)
```



Zero shift error

```
er = readmatrix("/REPORT DATA/scope_52.csv");
figure(3)
plot( er(3:end,1) , ( -k1*er(3:end,3) / V0  ) /G0);
xlabel('Time in seconds')
ylabel('G/Go')
hold on;
grid on;
y = zeros(2000,1);
plot( er(3:end,1) , y);
```