Quantized Conductance Lab Report

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1 Introduction

It has been shown that quantum point contacts act as electron waveguides through which transverse electron modes, N = 2×(width of constriction)/(Fermi wavelength of the point contact material) can propagate [1]. Landauer's Formalism can be used to understand these electron transverse modes/channels through narrow constrictions – electrons are modelled to be laterally confined by a two-dimensional infinite potential in the x and y. Hence, solving the Schrödinger equation for this electron system, one obtains discrete number of eigenstates (or 'modes') for this two-dimensional system [2]. $\therefore$ Depending on the width of the point contact constriction, the number of these modes change; and if the length this constriction (in z) becomes way less than the mean free path of the electron - electron conductance in all the modes transitions from diffusive to ballistic. Thus by decreasing the cross-sectional area of a point contact, one reduces the number of electron modes available for conduction, leading to ballistic quantized conductance (QC) through the point contact, and eventually no conductance when the contact breaks. It is reported that both QC and atomic rearrangements at the point contact contribute to experimental conductance steps [3].

2 Experimental Section

The objective of this experiment is to observe these quantized steps in conductance (and hence in voltage / current, $\because G = I/V$). Transient gold (Au) nanocontacts are known to reproduce QC at room temperature and under 10-70 mV bias, and this is suspected due to Au's malleability and/or the freedom from surface oxidation [4], [2].

Measurement Equipment Setup

1. A 9V battery in the negative bias and connected to a voltage divider is used to set the desired bias voltage across the Au wires (30mV in this experiment, V_4 in Table 3.1.1). Resistances in voltage divider (such as R_3 and R_4 in Table 3.1.1) such that the bias voltage (V_4) is neither too high to cause electron-heating effects, and neither too low make adjustments in shielding of the circuit [4].

2. A piezoelectric controller is used to establish and vary nanocontact junction area of these Au wires, by applying the desired voltage bias.

Voltage step	Transient time
From 0 to 1V	4.33 ms
From 0 to 10V	65 ms

Table 2.0.1: Piezo controller voltage changing times.

3. An operational amplifier in the negative feedback mode and powered by 2×9V batteries (reduces external noise), is used to measure the current flowing through the transient Au nanocontact junction under bias (recorded as a voltage signal in a digital oscilloscope with normal-mode dc triggering).

3 Results

3.1 Voltage drop over the resistors and expected steps

	Calculated values	Measured values
V_1 = voltage over R_1 (10 kΩ)	-8.4796V	7.6V
V_2 = voltage over R_2 (3.6 kΩ)	-0.5204V	0.5V
V_3 = voltage over R_3 (690 Ω)	-0.4853V	0.45V
V_4 = voltage over R_4 (49.9 Ω)	-0.0351V	0.03V
One conductance step $G_0 = 2e^2/h$	77.4810 μS	24.0833 μS *
One current step $I_{in} = 2e^2/h \times V_4$	-2.7196 μA	0.7225 μA *
One voltage step at $V_{out} = -R_F \times -I_{in}$	-0.0544V	0.0144V *

Table 3.1.1: Comparison between theoretically calculated and experimentally measured values. * V_{out} (and hence $I_{in} = V_{out}/R_F$, and $G_0 = I_{in}/V_4$) measured using Table 3.3.1 and Equation 3.4.1 in the subsequent sections. R_F (feedback resistance) = $20k\Omega$.

For Calculated values of V_1, V_2, V_3 and V_4, the following formulae were used –

$$I_1 \text{ current through } R_1 = \frac{-9}{R_1 + \frac{(R_3+R_4).R_2}{R_3+R_4+R_2}} \quad \therefore \underline{V_1 = I_1 \times R_1}$$

$$\underline{V_2 = -9 - V_1}$$

$$I_3 \text{ current through } R_3 \text{ } (= I_4 \text{ through } R_4) = I_1 - V_2/R_2 \quad \therefore \underline{V_3 = I_3 \times R_3} \text{ and } \underline{V_4 = I_3 \times R_4}$$

3.2 Illustrative transient for gold wires

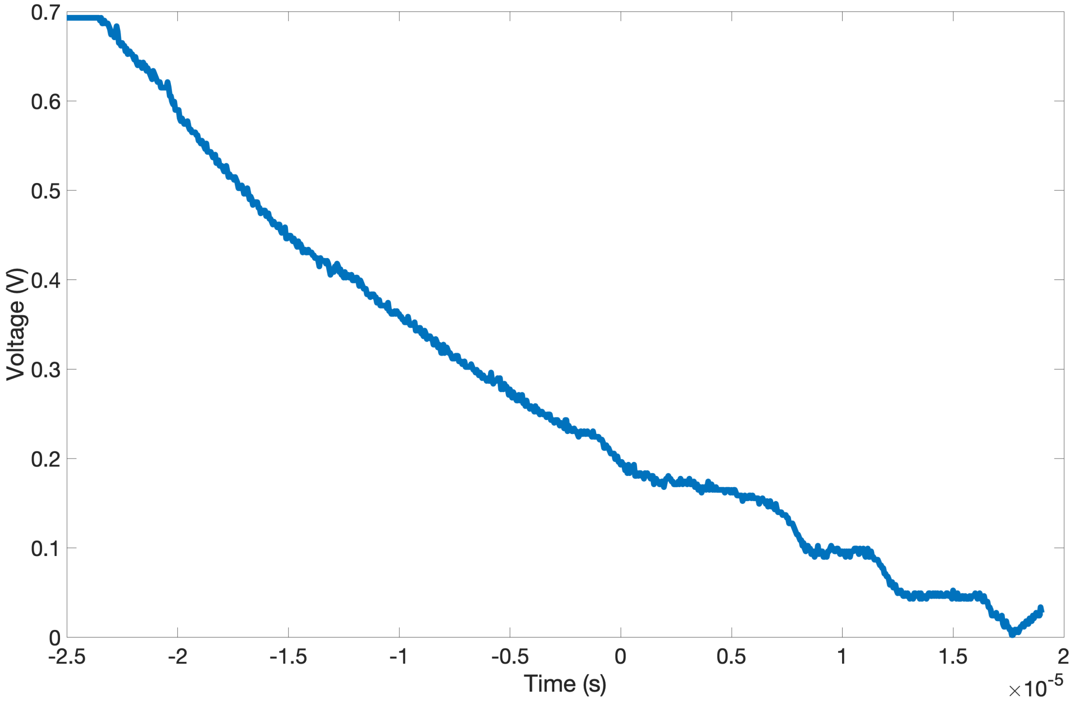

Figure 3.2.1: Experimental evolution of voltage across the Au Junction as it breaks (obtained from one of the 20 transient curves recorded in the lab). Voltage decrease in steps can be observed here as bias voltage is lowered from 0.2V.

3.3 Distribution diagram for 20 recorded transients

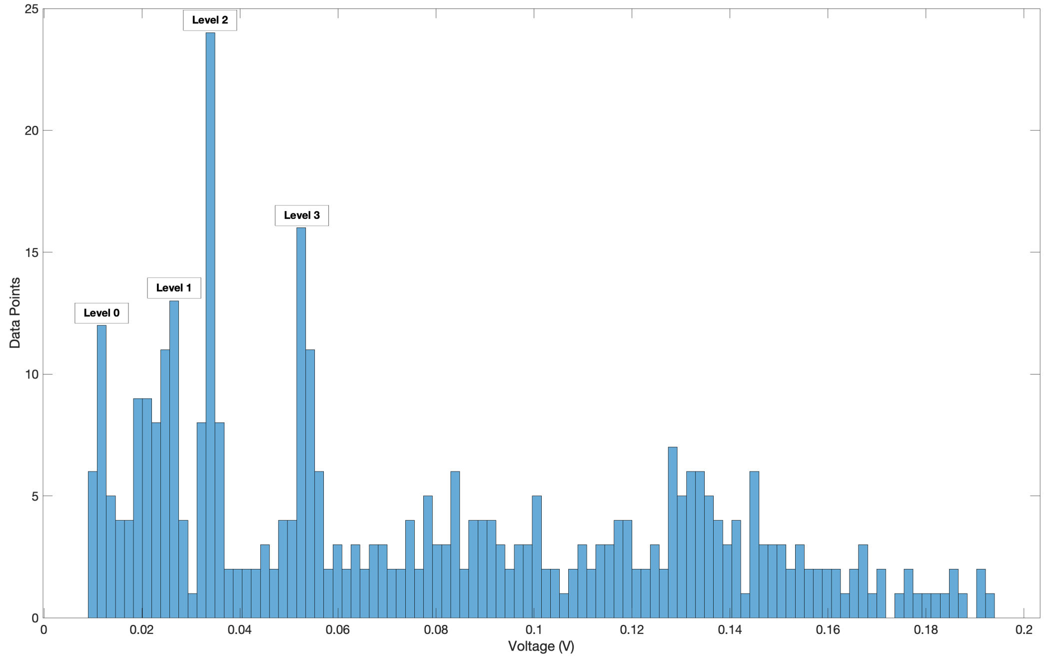

Figure 3.3.1: Histogram Plot (100 bins) of voltage values accumulated from 20 recorded Transient Curves.

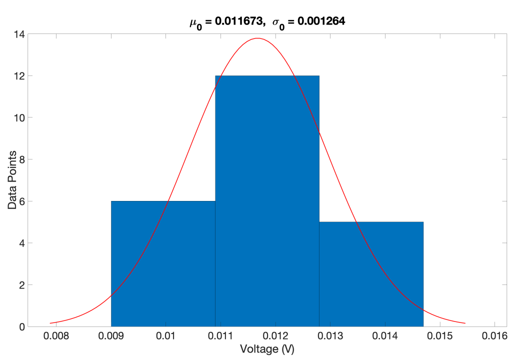

Figure 3.3.2: Resolved peak histogram for **Level 0** (from Figure 3.3.1), when fit with Normal Distribution.

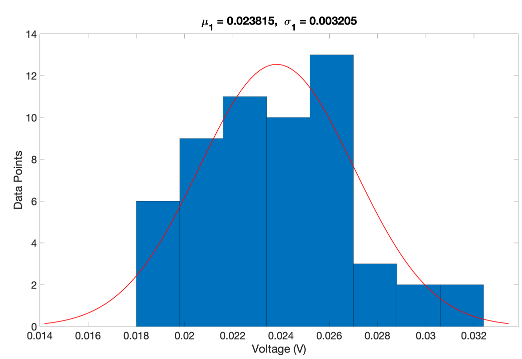

Figure 3.3.3: Resolved peak histogram for **Level 1** (from Figure 3.3.1), when fit with Normal Distribution.

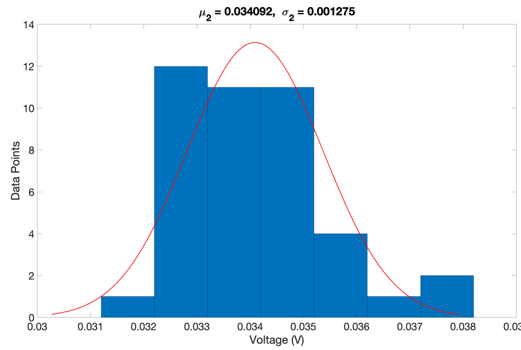

Figure 3.3.4: Resolved peak histogram for **Level 2** (from Figure 3.3.1), when fit with Normal Distribution.

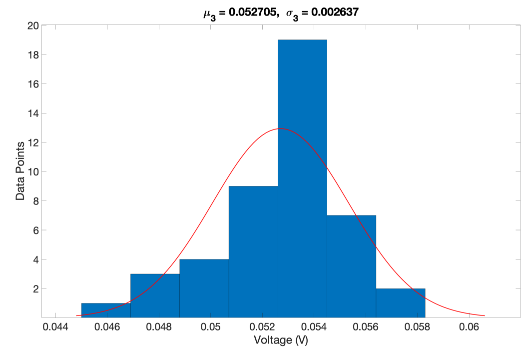

Figure 3.3.5: Resolved peak histogram for **Level 3** (from Figure 3.3.1), when fit with Normal Distribution.

Level i	Average μ_i (V)	Standard Deviation $\sigma_i(V)$
0	0.0117	0.0013
1	0.0238	0.0032
2	0.0341	0.0013
3	0.0527	0.0026

Table 3.3.1: Average values with standard deviations for peaks in Level 0, 1, 2 and 3; when fit with Normal Distribution (obtained from Figures 3.3.2, 3.3.3, 3.3.4 and 3.3.5).

3.4 Experimental voltage step size (V_{out})

$$V_{out} = \frac{(\mu_3 - \mu_2) + (\mu_2 - \mu_1)}{2} \pm \left(\frac{\sqrt{{\sigma_1}^2 + {\sigma_2}^2 + {\sigma_2}^2 + {\sigma_3}^2}}{2} \right) = 0.01445V \pm 0.0023V \tag{3.4.1}$$

4 Conclusion

1. From Table 3.1.1, it can be observed that there is $\approx 74\%$ difference between the measured and calculated absolute values of step sizes (voltage V_{out} / currentI_{in} / conductance G_0).

   1.1. This difference may be attributed to the relatively low number of recorded transient curves (20) used in our subsequent statistical analysis. In [2] and [4], about 100 transient curves were used to plot the histogram distribution, and conductance steps were then found to be near integer multiples.

   1.2. Conductance (and hence voltage or current) step sizes are also known to change due to the presence of a residual resistance (R_S), which is attributed to electron backscattering events at the entrance-exit of the Au wire constriction [1] and/or internal disorder in the (transient) Au nanocontacts [4]. This can be also be accounted for in the histogram distribution analysis, and modelling for this R_S parameter in the voltage step can help reduce the discrepancy in measured v/s calculated step values.

1.3. Noise from external sources (optical, mechanical and/or thermal) may also influence step sizes, hence appropriate shielding of the electronic equipment may be helpful in minimising discrepancy in measured v/s calculated step values.

2. Although the measured average voltage levels (2 and 3 in Figure 3.3.1) are not at perfect integral multiples of V_{out} from level 1, discrete voltage steps can still be seen (as in Figure 3.2.1) instead of a continuous spectrum in the transient curves, confirming the discreteness in quantisation of voltage / current / conductance through the Au nanocontacts.

References

[1] Henk van Houten and Carlo Beenakker. Quantum point contacts. *Physics Today*, 49(7): 22–27, 1996. doi: 10.1063/1.881503. URL `http://dx.doi.org/10.1063/1.881503`.

[2] Laetitia G. Soukiassian. Measuring the conductance of gold atomic wires: Quantized conductance of a break junction, June 2000.

[3] J. M. Krans, J. M. van Ruitenbeek, V. V. Fisun, I. K. Yanson, and L. J. de Jongh. The signature of conductance quantization in metallic point contacts. *Nature*, 375(6534): 767–769, Jun 1995. ISSN 1476-4687. doi: 10.1038/375767a0. URL `https://doi.org/10.1038/375767a0`.

[4] E. L. Foley, D. Candela, K. M. Martini, and M. T. Tuominen. An undergraduate laboratory experiment on quantized conductance in nanocontacts. *American Journal of Physics*, 67 (5):389–393, 1999. doi: 10.1119/1.19273. URL `https://doi.org/10.1119/1.19273`.