Quantized Conductance
Laboratory Experiment 3
SK2930-Quantum Technology

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Abstract

This experiment investigates the phenomenon of quantized conductance in a nanocontact formed between two gold wires. As the contact dimensions approach the atomic scale, the conductance deviates from classical behavior, instead displaying discrete steps governed by quantum mechanics. By gradually pulling the gold wires apart and observing the conductance through a piezo-controlled setup, we measured and recorded voltage steps corresponding to each quantized level. The conductance steps, each approximating the conductance quantum $G_0 = 2e^2/h$, confirm the quantized nature of electron transport in confined dimensions. Our results align closely with theoretical predictions, validating the transition from continuous to quantized conductance as a function of channel dimensions at the nanoscale.

1 Introduction

In the quantum regime, as conductive materials are reduced to dimensions near the atomic scale, they exhibit distinct phenomena, diverging from classical physics predictions. Quantized conductance is one such phenomenon, observed when the cross-sectional area of a conductor, like a gold nanocontact, becomes comparable to the electron wavelength. In this state, the conductance does not vary smoothly but instead in discrete steps due to the limited number of available electron transport channels.

This experiment involves creating a gold nanocontact by pulling apart two gold wires, forming a narrow conductive channel between them. As the nanocontact narrows, we monitor the conductance to observe these quantized steps, each approximately equal to the value of $G_0 = 2e^2/h$, where e is the electron charge and h is Planck's constant. This setup aims to measure and analyze the quantum steps in conductance to understand how electron transport is affected in constrained, near-atomic scale channels.

2 Measurements

To observe quantized conductance, a nanocontact was created between two gold wires using a piezo-controlled translation stage, operated through the Kinesis software. A constant voltage was applied across the contact, and an oscilloscope monitored conductance changes as the wires were carefully pulled apart to form the nanocontact. This nanocontact formed between the two macroscopic wires, leads to quantized steps in conductance. Gold wires tend to yield optimal results, likely due to their high malleability (or softness) and resistance to surface oxidation.

In the initial phase of the experiment, we examined the response time of the piezo controller to changes in voltage. By connecting the oscilloscope to the piezo controller and using the Kinesis software, we incrementally increased the voltage from 0 to 1V and from 0 to 10V to measure the delay in the piezo controller's response (see Table 1). As indicated in Table 1, the transient response time remained consistent across different voltage steps, showing independence from the magnitude of the voltage change.

We then built the circuit shown in fig 1, with $R_1 = 10k\Omega, R_2 = 3.6k\Omega, R_3 = 690\Omega, R_4 = 49.9\Omega, R_F = 20k\Omega$, two batteries of 9V and an operation amplifier. The electrical circuit connected

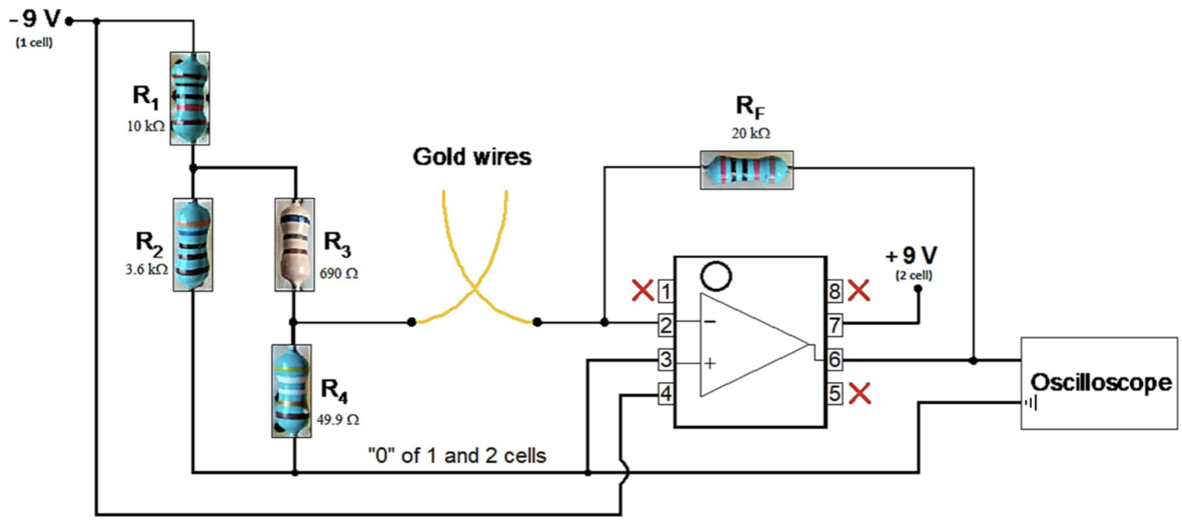

Figure 1: **Schematic diagram of the circuit used to observe quantized conductance**. Two 9V batteries are used along with four resistors to supply current through the one gold wire. The other wire is connected to the virtual-ground input of a transimpedance amplifier (current-to-voltage converter).[1]

Voltage Step (V)	Transient Time (ms)
0 to 1	1.5
0 to 10	1.5

Table 1: Piezo Controller Voltage Change Delay

with gold wires is operated with the help of Kinesis software to gradually increase the voltage until a stable contact was established. Then, by gradually decreasing the voltage, we retracted the wires to break the contact and narrow the nanowire smoothly enough to observe conductance steps. The output voltage, proportional to the current through the junction, was recorded with a digital oscilloscope.

Figure 2 shows one set of voltage evolution, during the junction breaking process. A total of 23 transient spectra like Figure 2 were collected for statistical analysis. In the figure, voltage steps can be clearly seen in the lower region compared to the upper region. In some measurements upper steps can be clearly seen than the lower steps.

Figure 3, shows the histogram for the signal shown in fig 2. We can see at least two clear peaks one between 0-0.1 and another between 0.1-0.2 representing 2 voltage steps. Figure 4 represents the distribution for all of the measurements combined. Two peaks found at both ends of the distribution can not be considered as part of the voltage steps as they are the start and end of the signal.

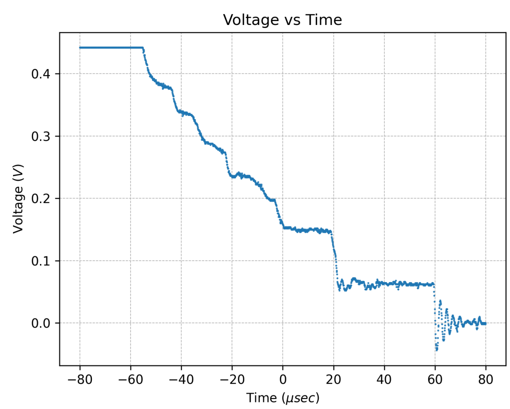

Figure 2: **Voltage-time signal for one measurement.** The measured Voltage signal can be converted to current by dividing with R_F. Quantized plateaus are visible in the signal.

Theoretically calculated values for voltage

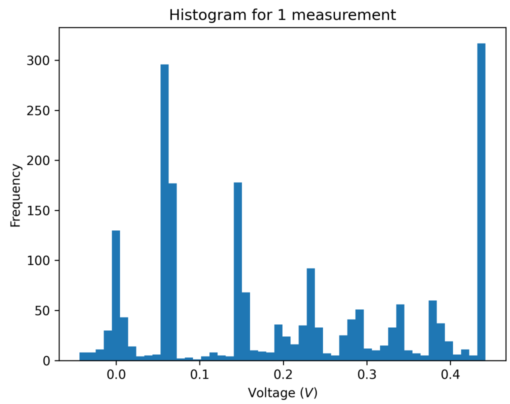

Figure 3: **Histogram of voltage data points for one measurement.**

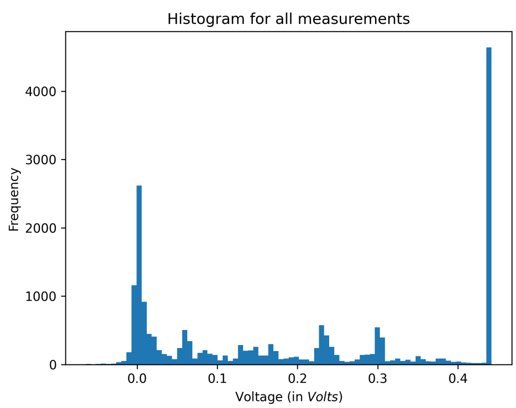

Figure 4: **Histogram of voltage data points for all measurement.**

across the resistors and the theoretical conductance step, voltage step and current step are provided in the table 2. To calculate these values, we first solve the simple electric circuit to find the voltage across R_1, R_2, R_3 and R_4. Other values can be calculated as follows, $G_0 = 2e^2/h = 77\mu S$, $I_{\text{in}} = G_0 \cdot V_4 = 2.72\mu A$ and $V_{\text{out}} = R_F \cdot I_{\text{in}} = 54mV$. We also measure the value of V_4 after building the circuit and applying the source voltage for the experimental measurement of the conductance step after the data analysis. This value is found to be $45mV$.

	Calculated values
V_1	$8.48V$
V_2	$0.52V$
V_3	$0.49V$
V_4	$35mV$
G_0	$77\mu S$
I_{in}	$2.72\mu A$
V_{out}	$54mV$

Table 2: Calculated (theoretical) Values for the experimental Set up

3 Analysis

To find the experimental values of current, voltage and conductance step we analysed the combined histogram of all of the measurements given in figure 4. We fitted a Gaussian curve over the experimental data using python with scipy library [2].

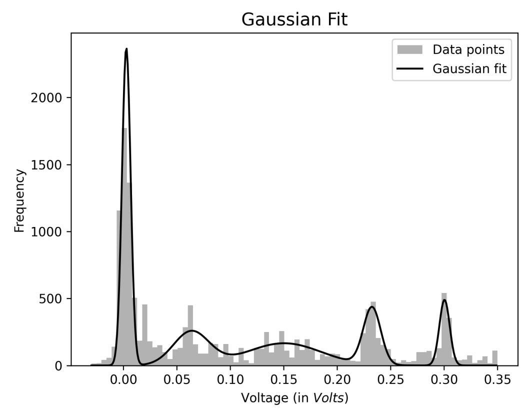

Figure 5: **Gaussian fit over voltage data points for all measurement.** Five Gaussian distribution can seen in the histogram represents four voltage steps peak along with the zeroth step.[2]

In the fitted curve fig.5 we could see four clear peaks corresponding to the zeroth, first, third and fourth voltage step and a little curve for the second voltage step. These peaks represent one of the voltage step values and differences in the peak values of these curve should give us the corresponding step values. These peaks can be better analyed in the fig. 6, which shows four voltage steps apart from the zero.

Using average V_{step} from experimental data we

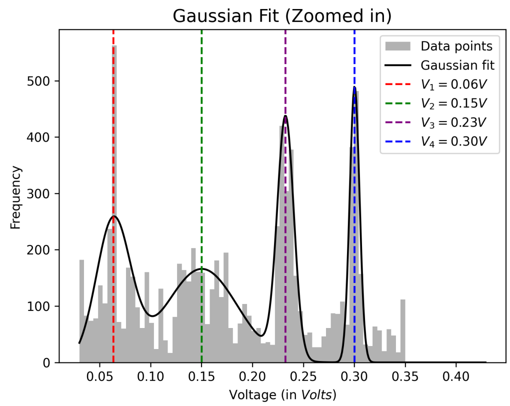

Figure 6: **Zoomed in Gaussian fit over voltage data points shows 4 peaks.**[2]

	$V \pm \delta V(V)$	*Steps*
$0^{th} Step$	0.003 ± 0.004	
$1^{st} Step$	0.06 ± 0.02	0.06 ± 0.01
$2^{nd} Step$	0.15 ± 0.03	0.09 ± 0.02
$3^{rd} Step$	0.23 ± 0.01	0.08 ± 0.02
$4^{th} Step$	0.30 ± 0.01	0.07 ± 0.01
$Average\ V_{\text{step}}$		0.075 ± 0.01

Table 3: Experimental values for Voltage step

get the $I_{\text{step}} = V_{\text{step}}/R_F = 3.75 \pm 1\mu A$ and using the measured value of $V_4 = 45mV$, we calculate $G_{\text{exp}} = I_{\text{step}}/V_4 = 83 \pm 20\mu S$. The observed value of the conductance step falls in the range of the theoretically expected value of $77\mu S$ within error. Therefore, our experimental results agree with the results obtained in the theory.

4 Conclusion

In this experiment, we observe a quantum phenomena at room temperature and in normal conditions known as quantized conductance. Our measurements and results from the experiment provides experimental confirmation for the theory. The experiment successfully demonstrated quantized conductance in a gold nanocontact, with conductance decreasing in discrete steps as the contact size was reduced. Each observed step corresponded closely to the theoretical conductance quantum $G_0 = 2e^2/h$, confirming the quantum model of conductance in nanoscale channels. We could see the transition from classical to quantum effects in electron transport when conductor dimensions approach the atomic scale. It could be interesting to see what would happen if we replace the gold wires with different material or if we change the temperature conditions.

5 Discussion

At room temperature, we successfully observed quantized conductance in the experiment, with results aligning well with the theoretical value of $G_0 = \frac{2e^2}{h}$. However, at higher temperatures, thermal broadening and increased electron-phonon scattering blur the distinct conductance steps, transitioning the system toward classical behavior. These effects highlight the importance of low-temperature conditions for clear quantization. Quantized conductance plays a critical role in quantum metrology, providing a universal standard for electrical resistance based on fundamental constants.

References

[1] Instructions for laboratory experiment on quantized conductance. Rinat Yapparov, Ilya Sychugov (2020).

[2] https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html