Conductance Quantization

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In this experiment, we measured the quantized conductance of atomic-scale gold nanowires formed by the mechanical break-junction technique. In atomic-scale regime, electrical conduction is governed by quantum mechanics and described by the Landauer formula, which predicts that the conductance is quantized in integer multiples of $G_0 = 2e^2/h$, where e is the elementary charge and h is Planck's constant. We measured the conductance through an inverting amplifier circuit that converts the junction conductance into a voltage recorded by a PicoScope USB oscilloscope. From the circuit parameters, we calculated an expected voltage step of $\Delta V = 1.21 \pm 0.027V$ per conductance quantum. We collected 39 triggered traces of breaking events and identified those containing clear voltage plateaus at the expected levels. A conductance histogram constructed from these step regions shows a prominent peak near $2G_0$. Our measured G_0 is $(7.972 \pm 0.681) \times 10^{-5}$ S. Theoretical $G_0 = 2e^2/h = 7.748 \times 10^{-5}$S falls into our error range.

I. INTRODUCTION

When a metallic wire is thinned down to just a few atoms at its narrowest point, its resistance is no longer described by classical Ohm's law. A macroscopic resistor has resistance inversely proportional to its cross-sectional area. However, this is not true at the atomic scale, where the physical width of the wire becomes comparable to the Fermi wavelength of the electrons. Transport in this regime is ballistic: electrons pass through the constriction without scattering. Therefore, the conductance is set by the number of quantum mechanical channels the wire can support [1].

Landauer formula gives the conductance of an atomic scale junction as

$$G = G_0 \sum_i T_i, \tag{1}$$

where $G_0 = 2e^2/h = 7.748 \times 10^{-5}S$ is the conductance quantum. T_i is the transmission probability of the i-th conducting channel. If the cross-section narrows gradually (the adiabatic limit), each channel is either fully open ($T_i = 1$) or fully closed ($T_i = 0$), and the conductance takes on integer multiples of G_0. Gold is very suitable in this situation: it has a single s-band at the Fermi level, so each atom in the narrowest cross-section contributes roughly one channel: $T_i = 1$. The conductance of a atomic scale gold nanowire is therefore $G = nG_0$ n is the number of atoms at the thinnest point [1].

In this experiment, we form and break atomic-scale gold wires by bringing two gold wire loops into gentle contact and tapping on the table. As the contact thins, the conductance steps down through integer multiples of G_0 before the wire breaks. We measure these steps electrically using an inverting amplifier circuit and a USB oscilloscope. In Section II, we describe the circuit design and measurement procedure. In Section III, we present and analyze the data collected, and calculate a measured value of G_0.

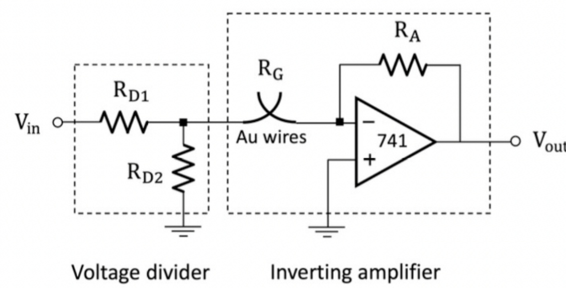

FIG. 1. Experiment circuit. Figure Adapted from [2]

II. EXPERIMENT AND APPARATUS

The measurement circuit is shown in Figure 1. The input voltage V_{in} passes through a voltage divider formed by R_{D1} in series with another resistor R_{D2}. The gold wire connects the output of the voltage divider and the inverting input of a 741 op-amp. The op-amp has a feedback resistor R_A. The non-inverting input of the op-amp is grounded. This configuration acts as an inverting amplifier with gain $A = -R_A/R_G$, where R_G is the resistance of the gold wire. The output of the op-amp, V_{out}, is recorded using a PicoScope USB oscilloscope running PicoScope 7 software.

The voltage divider serves to apply a small bias across the gold wire. The component values are $R_{D1} = 10.23\ \text{k} \pm 112\Omega$, $R_{D2} = 99.3 \pm 1.3\Omega$, and $R_A = 327.5 \pm 3.4\ \text{k}\Omega$. Since R_{D2} is far less than R_{D1}, the voltage at the junction is only about 48 mV, keeping the current through the atomic contact small enough to avoid disrupting the nanowire. At the same time, the large feedback resistance R_A ensures that the voltage shift per conductance quantum is large enough to resolve on the oscilloscope.

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The gold wire consists of two gold rings mounted on a vertical micrometer stage so that they are barely in contact. During the experiment, we tap lightly on the table or the apparatus, causing the rings to separate and reconnect over a few milliseconds. As the contact thins before breaking, a one-dimensional chain of gold atoms forms at the narrowest point, producing quantized voltage steps in V_{out}.

The circuit was built on a breadboard. The positive supply of the op-amp is 14.73 V and the negative supply is -14.91 V. The input voltage is $V_{in} = 4.96$ V.

Before connecting the gold wire, we tested the circuit by substituting the gold wire with a 9.7 kΩ resistor. This value was chosen because it is close to G_0^{-1}. After confirming that the circuit produced the expected output voltage, the gold wire was connected in place of the test resistor.

The PicoScope was configured to trigger on voltage transitions and automatically save each triggered trace as a separate CSV file. A 10 ms capture window (ideally ±5 ms around the trigger) was used. Over the course of the experiment, 39 traces were collected, each corresponding to one or more making and breaking events of the gold contact.

III. DATA

Each time we tap on the apparatus, the gold contact breaks and reforms, producing voltage steps in the output of the op-amp. Because the atomic-scale wire only survives for less than a millisecond, we setup PicoScope to capture 10 ms per trace, ideally centered around the trigger event. The sampling rate is around 10^6 Hz. This gives roughly 7800 data points per trace, balancing time resolution and file size.

We collected several hundred traces during the course of the experiment. Of these, 39 showed clear voltage plateaus at intermediate levels between the open-circuit baseline and the op-amp shorting. These 39 traces are shown in Figure 2. Our subsequent analysis is based on these 39 traces.

The voltage across the gold wire from the voltage divider is $V_G = R_{D2}/(R_{D1} + R_{D2}) \cdot V_{in} = 47.69$ mV. The op-amp output is related to the junction conductance G by $V_{out} = V_{open} - R_A \, V_G \, G$, where $V_{open} \approx 2.94$V is the open-circuit baseline measured from the data. We extract only the intermediate portions of each trace, which are the voltage transition intervals. We discard the flat regions at the op-amp shorting (wire fully connected) and at the baseline (wire fully broken). Several examples of the selected regions is shown in Figure 3. This help removing unrelated data points from the result.

To measure G_0, we convert the intermediate voltage data to raw conductance $G = (V_{open} - V_{out})/(R_A \, V_G)$ in Siemens. We then scan over trial values of G_0^{trail} and, for each trial, express the data in units of the trial G_0^{trail}. If the trial value is close to the real G_0, the conductance histogram should show peaks at integer values 1, 2, 3, etc. We quantify this by computing the total number of data points that falls with in ±0.15 of an integer, and select the trial G_0^{trail} that maximizes this number as measured G_0. This procedure produces

$$G_0 = (7.972 \pm 0.681) \times 10^{-5} \text{ S}, \tag{2}$$

corresponding to a voltage step of $\Delta V = G_0 \, R_A \, V_G = 1.22$V. The circuit components measurement uncertainties contribute an 2.2% of the total uncertainty. The other part comes from the uncertainty in peak measurement. We find all the trial G_0^{trail}s whose integer score is larger than half of the maximum integer score (reached by $G_0 = 7.972 \times 10^{-5}$ S). Then we can calculate the full width at half maximum (FWHM) by $G_0^{trail} right - G_0^{trail} left$. Assuming Gaussian distribution of measured G_0, or combined error, the standard deviation is then FWHM/2.35. The theoretical value $G_0 = 2e^2/h = 7.748 \times 10^{-5}$S falls within our uncertainty, representing a 2% deviation.

Figure 4 shows the conductance histogram evaluated at the measured G_0, with visible peaks near integer multiples confirming the quantization. We do notice that the peak around $1G_0$ is missing in this measurement. This is probably because of instability and uncontrollable factors in gold wire formation.

IV. CONCLUSION

In this experiment, we measured the conductance quantum G_0 using breadboard electronics and two gold loops. We were able to make atomic scale gold wires by knocking on the table and the apparatus. We observed voltage steps and calculated $G_0 = (7.972 \pm 0.681) \times 10^{-5}$ S based on our data. Our result matches the theoretical G_0 with a 2% deviation.

V. DATA AND CODE AVAILABILITY

[1] K. Hansen, Quantized conductance in relays, Physical Review B **56** (1997).

[2] Cornell university physics faculty, course website (2026).

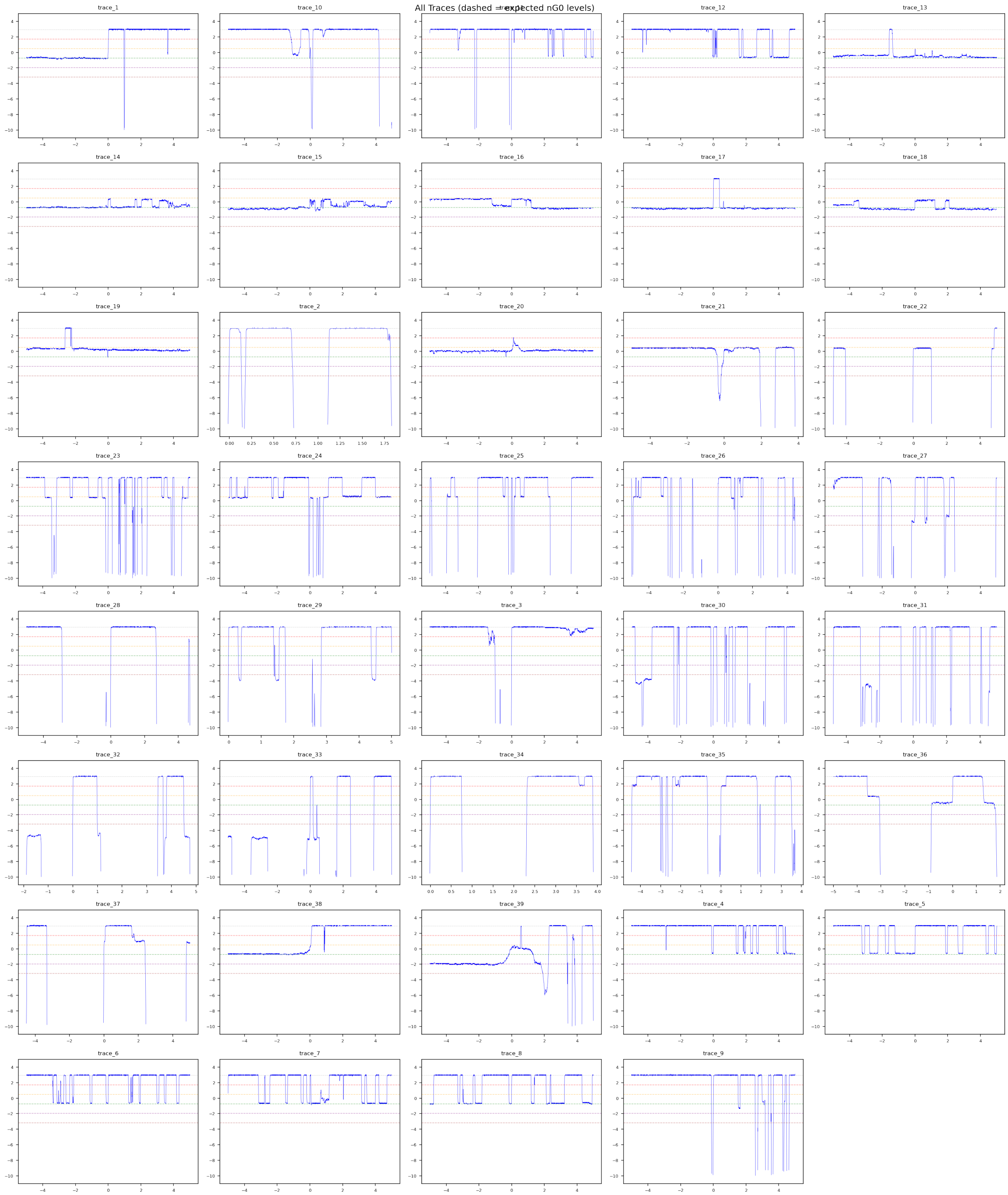

FIG. 2. All 39 working traces. Vertical axis is measured voltage [V], and horizontal axis is time [ms].

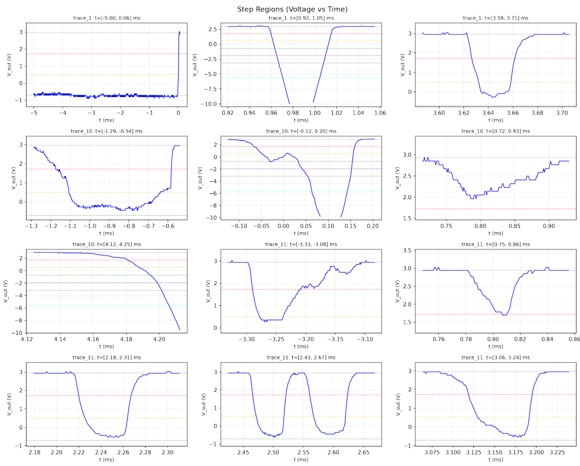

FIG. 3. Examples of selected intermediate regions.

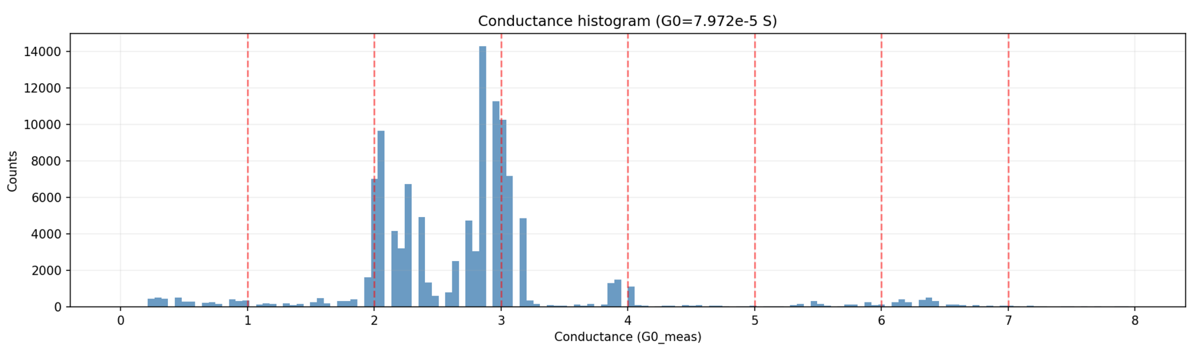

FIG. 4. Conductance histogram