Bachelor thesis

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Benchtop conductance quantization

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Abstract

Quantum conductance is a phenomenon associated with nanowires / quantum point contacts where the current through a wire is quantized. Experiments have shown that this phenomenon can be manifested at room temperature using macroscopic wires. This project is aimed to recreate these experiments with emphasis on simplicity. By briefly contacting gold wires and measuring the current using an oscilloscope, current quantization can occasionally be seen as the contact breaks.

Acknowledgements

I would like to thank my advisor Magnus Paulsson for offering a project well in line with my interests as well as being helpful throughout the process. Especially with regards to the derivation on page 6.

I also thank Luma Metall, a company in Kalmar which specialises in manufacturing fine wires, for kindly providing me with the metal wires used.

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1. Introduction

1.1 History and context of quantum conductance

The field effect transistor is an enormously important part of modern technological development. The miniaturisation of electronics components following Moore's law for more than 50 years, the devices have reached a high level of sophistication. A typical value for the distance between drain and source can be given as 25 nm as of 2020. Desiring to continue this trend of shrinking dimensions, it becomes relevant to ask what is expected to happen as the length of this channel between source and drain becomes shorter than the mean free path of the electron in the material. That is to say, what should be expected as electrons travel through a channel where they are not scattered by atoms in the material? When measuring resistance of such a wire, would any at all resistance be expected?
Electron transport in nanoscale devices without inelastic scattering is often called ballistic transport. Experimentally, work in this field can be said to have started in 1965 by Yuri Sharvin in Moscow[1]. Sharvin sent and detected a beam of electrons through point contacts in a single-crystalline metal. However, since this experiment used electrons of wavelength much shorter than the opening of the point contact, quantum effects do not play a large role. Instead, experiments examining quantum point contacts, where the wavelength of the electrons and the opening are comparable, were performed in 1988 by both Wharam et al and van Wees et al. [1]. These experiments examined the conductance of quantum point contacts by using a metal gate structure. This gate serves as the opening and by applying negative voltage to it, the opening is narrowed.

On the theoretical side, Rolf Landauer in USA contributed his formula in 1957:

$$G(\mu) = G_0 \sum_n T_n(\mu)$$

which gives the total conductance of a conductor as the sum of the probabilities of transmission for each conductance channel multiplied by the conductance quantum $G_0 = \frac{2e^2}{h}$. A simplified derivation of this value can be found in the next section.

Perhaps surprisingly, quantum conductance was observed at ambient conditions and at room temperature by Costa-Krämer et al[2] in Spain, 1995. Loose wire ends were arranged on a table and brought in and out of contact by knocking on the table. By applying a small voltage ~10 mV and measuring the current, conductance curves with steps matching integer multiples of G_0 were obtained. This was true for many types of materials including gold, copper, and platinum. However, gold produced the greatest number of steps and the clearest signals. The duration of the levels were approximately 1 ms.

A schematic illustration showing the conductance steps is shown in Fig. 1.1. The measured conductance starts at a high value, where the metal wires are in firm contact. However, as the contact is broken, the conductance sometimes decreases stepwise. In reality, the width and shape of the steps are not this uniform. The resulting curve takes on levels of constant conductance values with short jumps between them. This phenomenon is what is called conductance quantization. These levels are closely related to integer multiples of the value
$G_0 = \frac{2 \cdot e^2}{h} \approx 7.48 \cdot 10^{-5} \Omega^{-1}$ which corresponds to a resistance 12906 Ω.

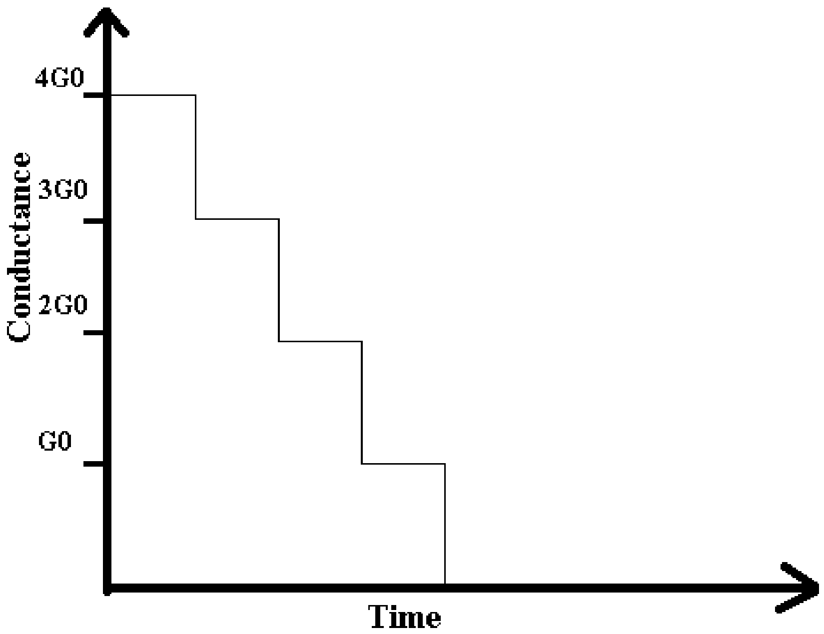


Figure 1.1. Sketch illustrating an ideal case of quantum conductance.

These steps are formed since the width of the constriction controls the number of electron transport channels that are able to exist. As such the phenomenon occurs at scales associated with quantum effect, that is when the width of the constriction is comparable to the wavelength of the electrons being transported. As the constriction decreases in width, but does not cross the threshold of removing a channel, the conductance remains unchanged. When the threshold is crossed, the conductance contributed from that channel suddenly goes away. This accounts for the shape of the curve.

1.2 A simplified derivation of conductance quantization

Following references [3] and [4] I make a simplified motivation for the value of G_0. A 1D wire is connected to two electron reservoirs with two different chemical potentials μ_1 and μ_2, where the difference is given by the applied voltage $\mu_1 - \mu_2 = - e \cdot V$. The resulting change in the electron density of the wire , δn, gives rise to an electric current:

$$I = (-e) v_g \frac{\delta n}{2} = (-e) \frac{v_g}{2} \frac{\partial n}{\partial E} \delta E$$

where I have made the assumption that only ½ of the electrons move in the current direction ($\frac{\delta n}{2}$) and the resulting current is simply the group velocity times the charge density. In a 1D wire: the electron group velocity is given by the bandstructure E(k):

$$v_g = \frac{1}{\hbar} \frac{\partial E}{\partial k}$$

Expressing the 1D density of states in the same way:

$$DOS = \frac{\partial n}{\partial E} = \frac{2}{\pi} \frac{\partial k}{\partial E}$$

Inserting these expressions in the current:

$$I = (-e) \left(\frac{1}{\hbar} \frac{\partial E}{\partial k} \right) \frac{1}{2} \left(\frac{2}{\pi} \frac{\partial k}{\partial E} \right) \delta E = (-e) \left(\frac{1}{\hbar} \right) \frac{1}{2} \left(\frac{2}{\pi} \right) \delta E = (-e) \left(\frac{2}{h} \right) \delta E$$

and finally the energy range:

$$\delta E = \mu_1 - \mu_2 = - eV$$

Gives the final expression for the current:

$$I = (-e) \left(\frac{2}{h} \right) (-eV) = \frac{2e^2}{h} V$$

Which gives the conductance as:

$$G = \frac{I}{V} \quad G = \frac{\left(\frac{2e^2}{h} V \right)}{V} = \frac{2e^2}{h}$$

Compared with the Landauer expression, this expression just gives the conductance of one perfect 1D metallic conductor. In reality a conductor consists of a large number of conduction channels, each of these with a not necessarily 100% probability of transmission.

1.3 Previous experiments

Landman et al (1996) both performed measurements using pin-plate equipment as well as molecular dynamics simulations[5]. This was done to investigate correlation between the mechanical response of the wires and the quantum ballistic electron transport properties. The measurements were done at room temperature. The junction consisted of a gold plate and a coaxial cable tip. Correlation between simulated conductance as a result of stretching the wire and conductance curves from the pin-plate equipment indicated mechanical stresses as an explanation for the shape of the conductance curves. In other words, the investigation proposes that the observed curves of quantized conductance at room temperature might have a cause other than quantum mechanics. G_0 levels seen were roughly ~500µs.

Huisman et al (2011) constructed a mechanically controlled break junction (MCBJ) setup where junctions were fabricated using electron-beam lithography[6]. This was done for the purpose of installing a public exhibit at the University of Groningen so that students as well as the public themselves can perform an experiment displaying quantum conductance. The experiment works by bending the junction in a very controlled fashion, achieving nanometer level of precision in the adjustment of the junction gap. The results display G_0 levels of several seconds.

Tolley et al (2012) constructed a MCBJ setup where the junctions consisted of macroscopic wires[7]. The purpose of the setup was to be a classroom experiment within courses at the physics department at Miami University. As with the previous MCBJ setup, atomic level precision is reached. G_0 levels of ~200ms were seen.

Foley et al (1998) presented results from the experiment performed in the context of an undergraduate course [8]. Macroscopic wires were arranged in such a way that small disturbances, such as tapping on the table, brings them in and out of contact.The purpose of the experiment was to introduce undergraduate students to the concept of quantum conductance as well as the way in which basic research is carried out. G_0 levels of ~200µs were seen.

Comparing these experiments, it seems that an important parameter is the degree of control with which movement of the two parts of the junction is performed. Foley et al uses loose wires arranged so that tapping the table moves them in and out of contact, typical duration 200µs. Landman et al describes the contact between tip and surface as “coarsely controlled by a micrometer screw”, typical duration 500µs. The two experiments using the MCBJ technique see typical durations of a higher order, Tolley using macroscopic wires: typical duration 100ms, Huisman using fabricated junctions: typical duration 1 second.

1.4 Aim of this project

Considering which of previous experiments to recreate: it is understandable that the two setups intended to be some kind of exhibit make a greater investment, resulting in higher quality curves. However, I do not have access to MCBJ equipment or any substantial amount of money. Also, for my purposes, emphasis lies more in the direction of producing results which believably display quantum conductance rather than making these results outstandingly high quality. Recreating anything similar to the work by Tolley et al or Huisman et al is therefore not an alternative. While I find the setup by Landman et al to be interesting, again, I do not have access to such a thing as a gold plate.

The experiment which I will use as a rough guide is therefore the one by Foley et al. Not only because it is the only remaining alternative but also because of its design - it is intended to be simple & cheap. Being guided by it, I will not be simply copying it entirely.
Similar to the case of Foley et al, I am exploring this experiment in the context of (my own) undergraduate education. There is an interest at my university, Linneaus University in Sweden, of incorporating this type of experiment into the education. Because of this, I would like to be able to present an experimental setup which is as simple as possible, while also consistently displaying quantized conductance. While doing this, I have also tried to explore this experiment for the effect of changing various parameters in order to gain experience/understanding. While I would want to find a setup which gives as high quality results as the original experiment, I also realise the limitations of performing this work at home and with no prior knowledge/experience. As such, I will be exploring, observing and speculating rather than making authoritative claims or drawing far reaching conclusions. Also, in exploring the experiment and presenting what I have done I will try to be as complete as possible.

2. Experimental setup

2.1 Circuit to measure current

The goal of the experiment is to measure the conductance across a junction consisting of two briefly touching gold wires. In the schematics, see Fig. 2.1, this junction resistance is given by R_j. The small applied voltage is generated from a 7 V battery, by voltage division over two resistors 220 kΩ and 270Ω respectively. The resulting voltage $U_j = 7 \cdot \frac{270}{220270} \approx$ 8.5 mV is chosen to give a measurable current through R_j while hopefully not heating the wires.

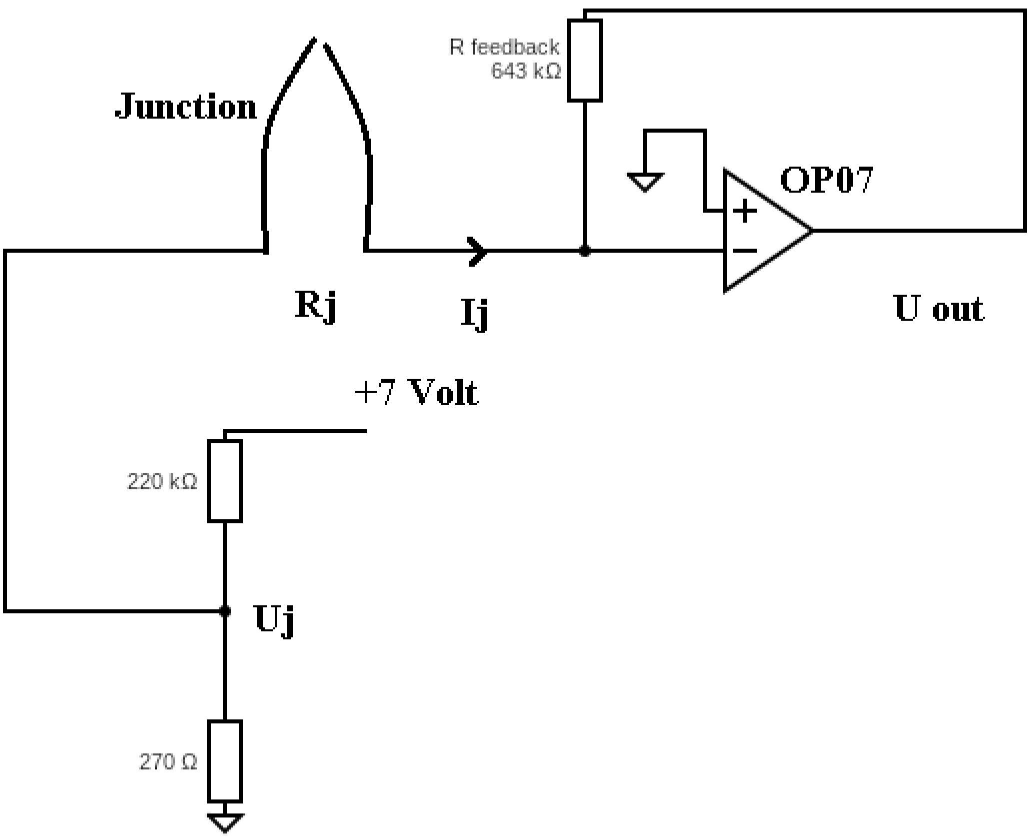


Figure 2.1. Circuit diagram of the circuit used to measure the resistance of the junction R_j. Supply voltage and offset pins for the operational amplifier are not shown.

To measure the small resulting current, i.e., 8.5 mV/12.9 kΩ ~ 0.66 µA, I use an operational amplifier (OP-amp) as a current to voltage converter, see Fig. 2.2. The effect of this device is to make the current through the junction measurable as a voltage. The operation can be understood by considering a small positive voltage on the "-" input pin will give a large negative voltage out U_{out} which will adjust itself until all the current through the junction (Iin) is pulled through the feedback resistor and U- is very close to zero.

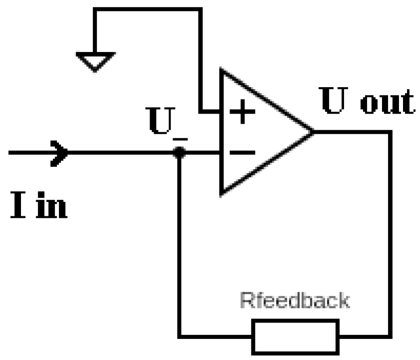


Figure 2.2. Operational amplifier in negative feedback mode. The amplifier also needs to be connected to a negative and a positive supply voltage but for the sake of clarity this is not shown.

This current to voltage converter consists of an operational amplifier connected in negative feedback mode. The incoming current, I_{in}, has 2 paths to split between, through the feedback resistor and into the negative input. However, the OP-amp input has a very high impedance (The parameter describing the deviation from this assumption, "bias current", is 1.2 nA for OP07, ~500 times smaller than the currents involved). Therefore it is assumed that all of the incoming current flows into the amplifier output. This current creates a voltage difference across $R_{feedback}$:

$$U_{-} - U_{out} = I_{in} \cdot R_{feedback}$$

The amplifier works by setting

$$U_{out} = U_{diff} \cdot A_0$$

where U_{diff} is the difference between the positive and negative inputs, A_0 is the open loop gain of the amplifier. And since the positive input is grounded:

$$U_{diff} = - U_{-}$$

$$U_{out} = - A_0 U_{-}$$

U_{out} and U_{-} can now be expressed as:

$$U_{out} = \frac{-R_{feedback} I_{in}}{1+\frac{1}{A_0}}$$

$$U_{-} = - \frac{U_{out}}{A_0}$$

A_0 for OP-amp OP07 is given as ~500 000 in the datasheet. Because this value is so large:

$$U_{out} \approx - R_{feedback} I_{in}$$

$$U_{-} \approx 0$$

In other words, for a given input current the amplifier will give an output voltage of opposite sign and amplified by the value of the feedback resistor. This is true within the constraint of which range of voltages the amplifier is able to output. In this case the supply voltages are +7V and -7V, so those are the maximum and minimum values. An appropriate value must be chosen for the amplification factor, $R_{feedback}$. The input current will be the current flowing through the junction. The amplification factor is chosen sufficiently large so that the measured voltages will be well within the ranges supported by the oscilloscope and sufficiently small so that the amplifier is able to provide this amount of amplification. In the case of the experiment performed in this report, the value for amplification is chosen as 643 kΩ. The output voltage U_{out} from the amplifier is then - 643 kΩ x 0.66 µA ~ - 0.42 V for each conductance step measured in the experiment.

Idealised assumptions have been made about such parameters as bias current and offset voltage. The amplifier still does behave in the expected way but a small zero offset which I believe to be due to offset voltage will be noticeable in the results.

As U_{out} is measured over time, plots of R_j over time can be made. It is in these plots that one hopes to observe quantum conductance as a pattern of jumps rather than continuous change.
Specifically, by examining plots of conductance

$$G = \frac{1}{R}$$

quantum conductance would show as staircase-like steps of integer multiples of G_0. As a consequence of the derived relation between R_j and U_{out}, the values corresponding to G_0 become U_{out} = ~ -0.42V and I_{in} =~0.66µA.

Being an operational amplifier, OP07 is limited in how fast its output voltage can change with time. This "slew rate" of OP07 is specified as ~ 0.3 V/µs. Because of this limitation, I should not try to find steps in conductance on the order of microseconds. By restricting measurements to longer timescales like 500µs/div, our results will be comparable to previous experiments and observed changes in output voltage will be unrelated to the slew rate.

2.2 Data collection

U_{out} was measured using the oscilloscope Agilent DSO6104A, set to triggermode(rising), 500µs/div, 1V/div, trigger level at ~ -0.9V. Since a time setting of 500µs/div was used, data is captured 2.5ms before voltage rises above -0.9V as well as 2.5ms after. “High resolution” (averaging) mode was used. Voltage was measured between the output pin of the amplifier and ground. Data was transferred from the instrument via ethernet cable and a python script to PC where it was saved as a file. Plots and histogram were produced from this data in MATLAB. The script can be found in the appendix.

2.3 Practical considerations

The question of shielding against electromagnetic noise should be discussed. Since Foley et al mentions this as an important problem, I was prepared to construct the setup in such a way as to provide significant shielding. An “RF-proof aluminium box”[1] was purchased for this purpose. I first noticed the presence of electromagnetic noise when constructing the circuit on breadboard. It is reasonable to expect this type of circuit to be sensitive since it is built to detect currents of microamperes and amplify them $5x10^5$ times into ~1 volt. By shortening the length of wire from the input pin of the amplifier to the junction, a lower level of noise was reached. Some noise was still present, observable when the junction is in its disconnected state. This amount of noise is illustrated in the image below, see Fig. 2.13. The curve shows the from the connected state of the junction to the disconnected state. Noise is seen in the disconnected state.

1 According to the website selling it.

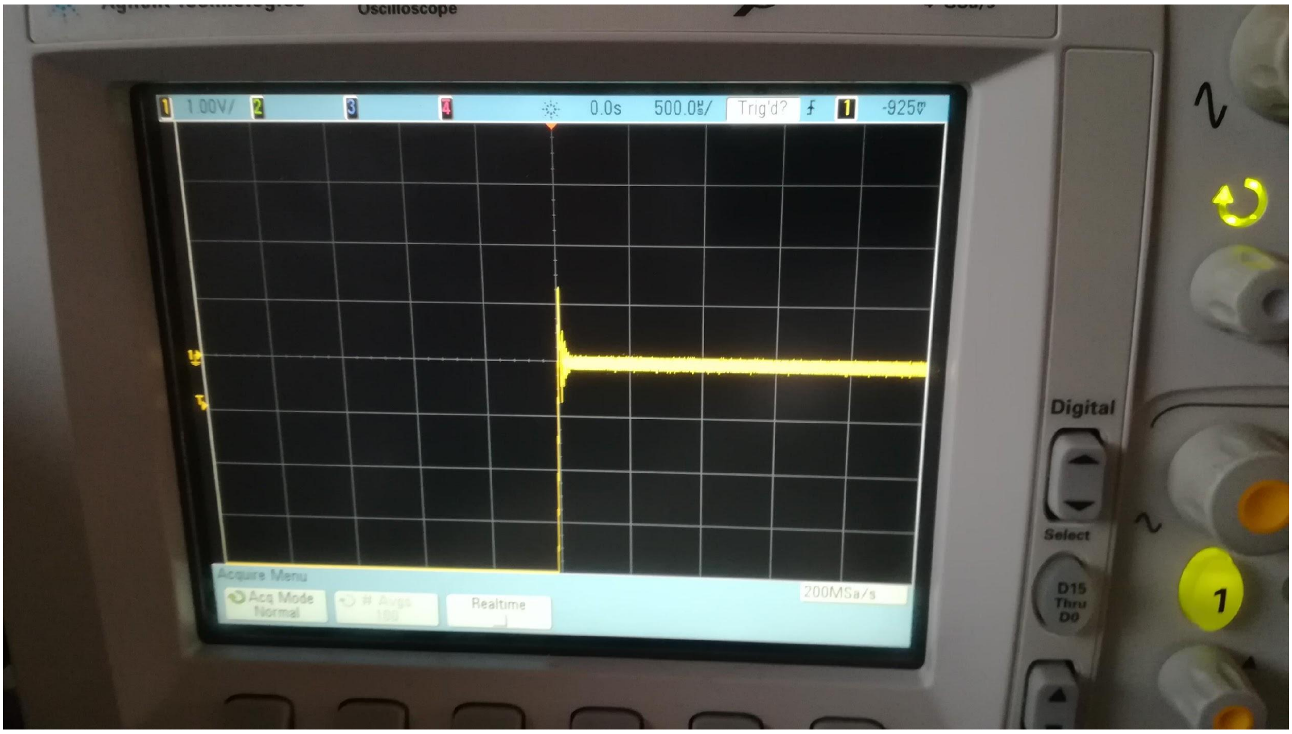


Figure 2.3. A curve with both the connected and disconnected state of the junction. No metal box and without using averaging.

By putting the circuit inside an RF-proof aluminium box, I expected this noise to be further reduced. The amount of noise when using the metal box is illustrated in the image below, see Fig. 2.14.

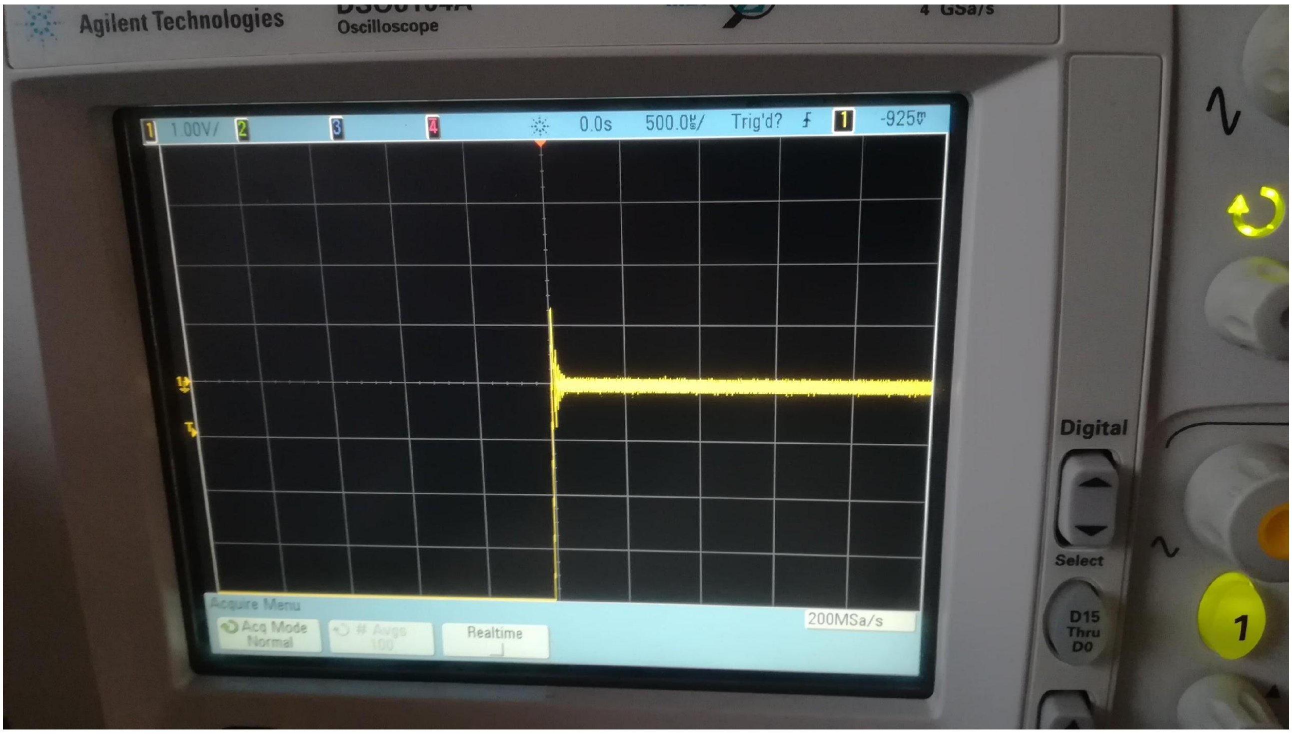


Figure 2.4. A curve with both the connected and disconnected state of the junction. Inside metal box and without using averaging.

Since there is no discernible effect from using the metal box on this noise, I suspect that it does not come from the environment but instead from the circuit itself.

The shielding box is shown in figures 2.15, 2.16. The small stick which manipulates the wires is also shown.

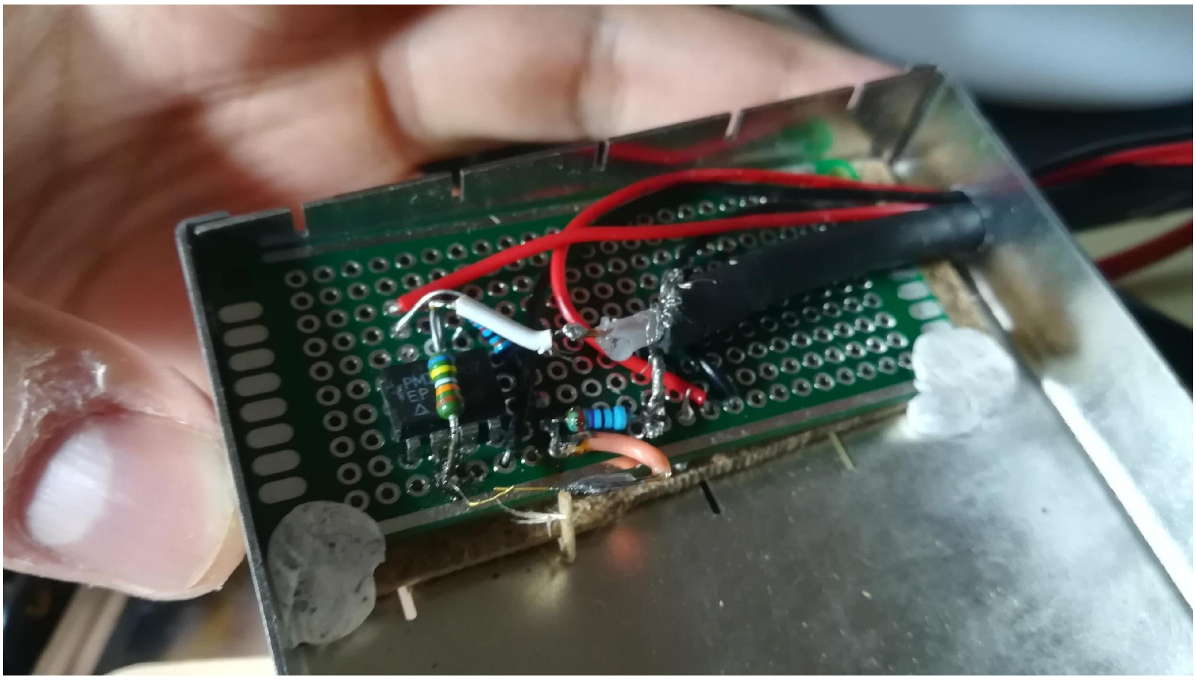


Figure 2.5. Circuit and junction inside the metal box. The junction can be manipulated from outside by the small piece of wood.

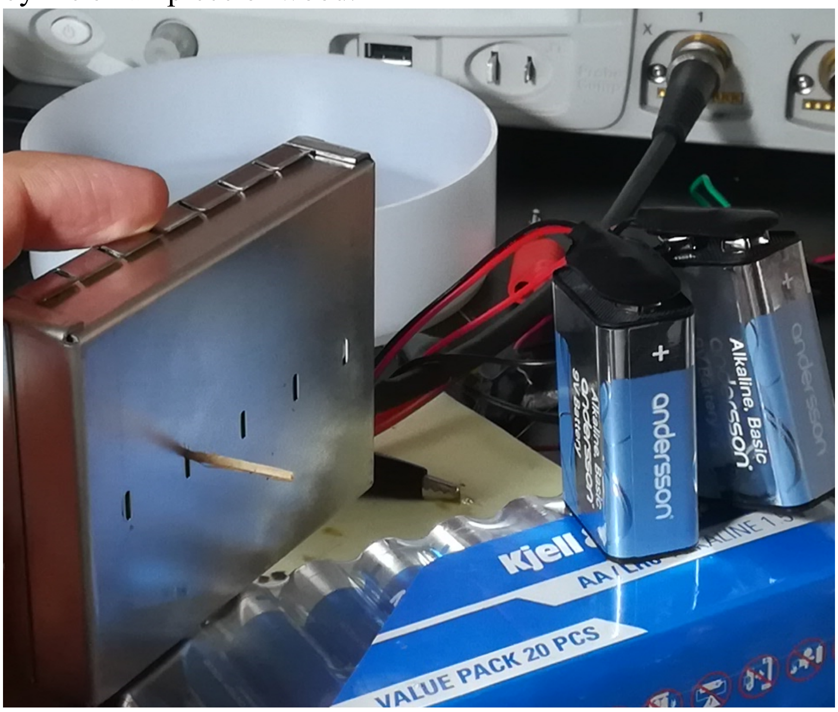


Figure 2.6. Outside of the metal box. The only wires leading out from the box are to the batteries and to the oscilloscope.

It was possible to set the oscilloscope to "high resolution" (averaging) mode and since the sample rate is 4Gsa/s while the timescale measured is ~5µs, it follows that an average can be taken over more than 10000 samples for each point.

The result of using averaging mode is shown below.

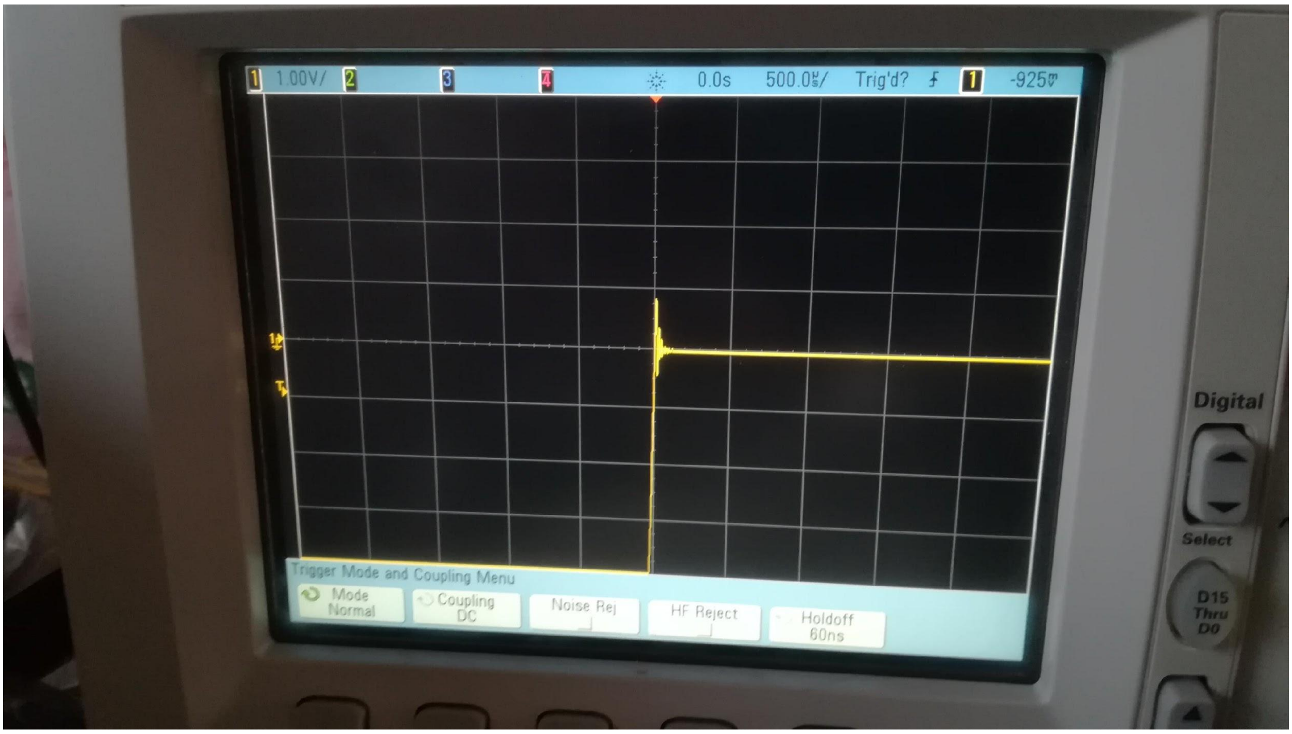


Figure 2.7. A curve with both the connected and disconnected state of the junction. No metal box and averaging is used.

The noise has effectively been overcome by averaging.

3. Results

I have performed many series of measurements, made variations to the setup in terms of:

- different types of wires (18K gold, molybdenum coated with pure gold, balls of solder)
- wires which are stiff / not stiff
- loose wire ends brought together by knocking on the table / stabilised wire ends brought together by gently touching the setup / wire ends stapled to a thin piece of wood where slowly bending the wood manipulates the wires
- no wire ends but instead a relay with gold plated leads
- attempted soundproofing the junction part of the circuit
- changing the size of the resistors in the voltage divider
- remaking the circuit with different amplifiers (OP07, OP27, LM318N, AD711,LM2902N)
- grounding / not grounding the circuit (via radiator)
- enclosing the circuit, including junction, inside an RF-proof aluminium box

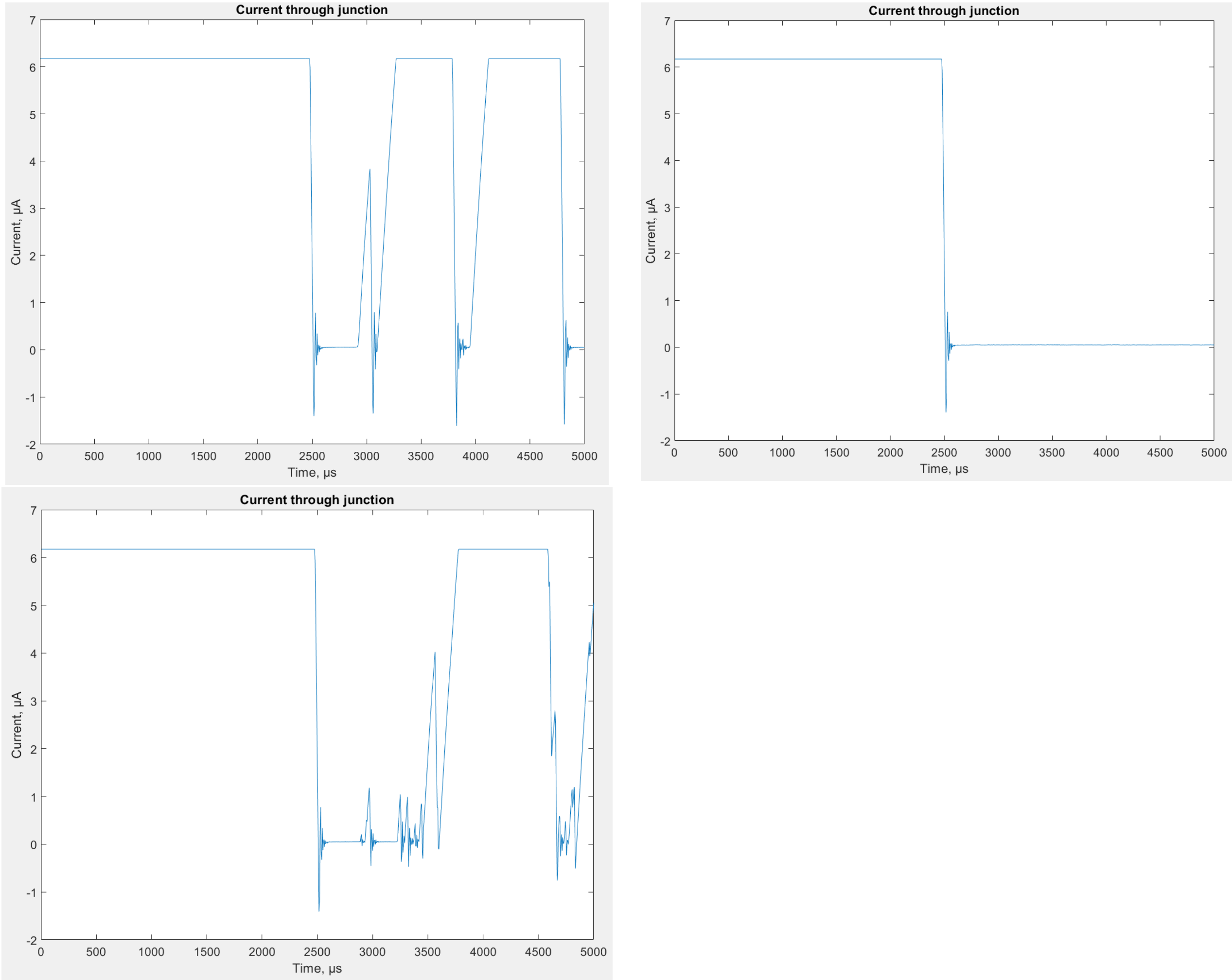
From these variations, general patterns observed were:

- curves showing conductance steps were obtained from all materials of wires
- slow, controlled separation of the wires gives curves with steps more consistently
- the relay did not give any curves with steps (across 20000 measured curves)
- OP07, OP27, LM318 were able to produce relevant curves. AD711, LM2902N were not (possibly because of higher offset voltage).
- No improvement observed from grounding
- No improvement observed from RF-proof box

For the rest of the report, results presented are from using the RF-blocking box, molybdenum coated with pure gold, stiff wires, wires gently pushed by a small piece of wood, no grounding via radiator. The voltage source was two 9 volt batteries with 7volts remaining. The experiment was performed in such a way that wires are placed into contact and the setup is then arranged so that the smallest possible disturbance will bring them out of contact.

I categorise the resulting curves under the three following headings:

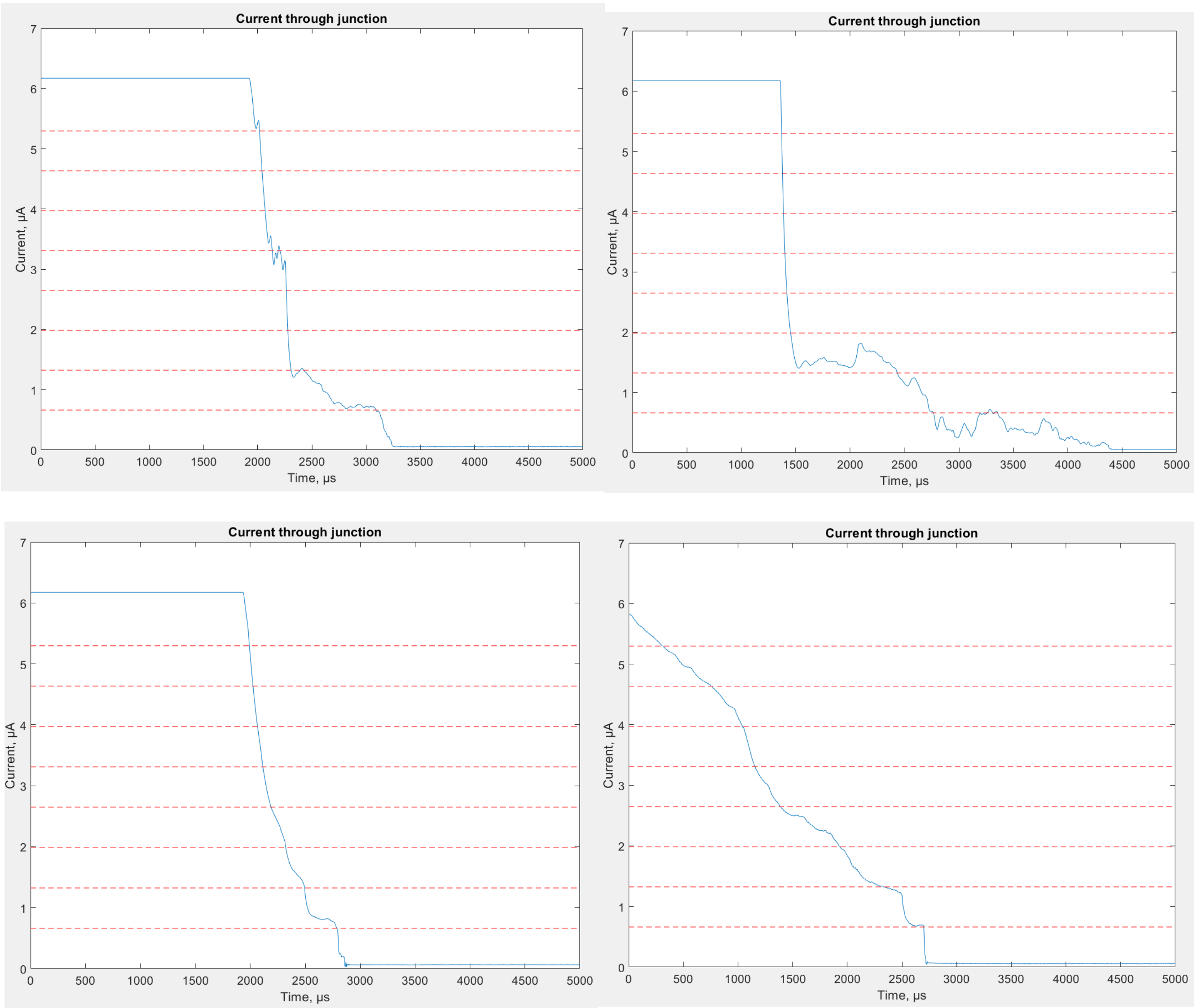
3.1 Fast disconnection



Figures 3.1-3. Plots showing the current through the junction over 5ms. Since the vertical scale is zoomed in in order to capture the behaviour close to 0 volts, the top of the curve at 6 µA is not the actual shape of the curve but only the bottom of the oscilloscope screen.

The above type of curve, see Fig. 3.1-3 is what I choose to call a fast disconnection. The voltage jumps from the maximum negative output value of the amplifier to 0. Zooming in, this rise will be seen to be limited by the slew rate. Having reached zero, the voltage overshoots into the positive and rings for <50µs after which it centers around 0 with some low amount of noise. Across all setups, ~90% of curves have been this type of curve. Since they do not display any sort of quantum conductance, these curves are discarded. The vertical axis shows current but this is an artefact of dividing the measured voltage value by $R_{feedback}$. The change in voltage happens in such a short amount of time that I expect it to be limited by slew rate. Because of this, no statement can really be made about the current during this disconnection. It would also not be reasonable to expect the current to turn around to negative values as the curves indicate. It is also noticed that the zero level of the amplifier, where the contact has been completely broken, lies slightly below 0 volts at ~ -0.04V. I believe this effect to be due the offset voltage of the amplifier.

3.2 Fall with levels



Figures 3.4-7. Plots showing the current through the junction over 5ms. 4 examples of a decreasing current taking on levels as it heads to 0. The dashed lines indicate values of current corresponding to a conductance value being an integer multiple of G_0, that is, a line is drawn for every 0.66 µA.

The curves shown in Fig. 3.4-8, have been chosen to provide examples of both reasonably good fit with the expected positions of conductance levels as well as poor fit. With this type of curve, there is also a decrease of the current from high values towards 0. However the decrease is much slower and it also does not happen along a straight line. There are instances of definite conductance levels showing as well as levels where the curve slows its fall but then continues down. Also, ringing after it reaches 0 is not present. The majority of non- “fast disconnection” curves are “fall with levels” curves.

3.3 Other types

The previous two categories do not cover all of the curves obtained, there are more cases of curves with levels or otherwise unusual shape, see Fig. 3.9-11. I choose to not put these curves into any named category since I cannot provide a confident interpretation of them. I show these curves to give examples of things which do occur but which are not good illustrations of quantum conductance.

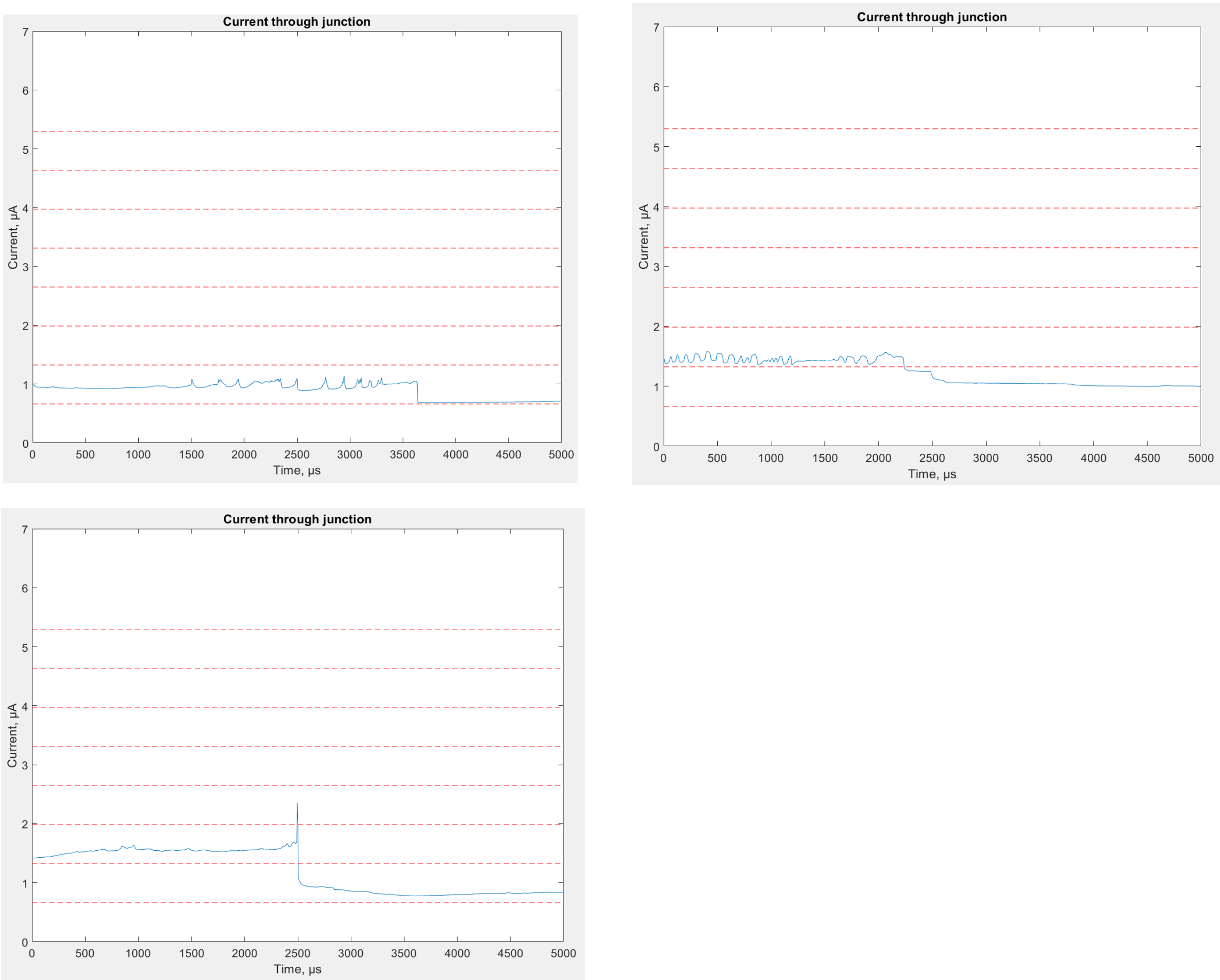


Figure 3.8-10. Some examples of more drawn out curves.

I also present a histogram of a set of curves to give a picture of the positions of the levels, see Fig. 3.12.

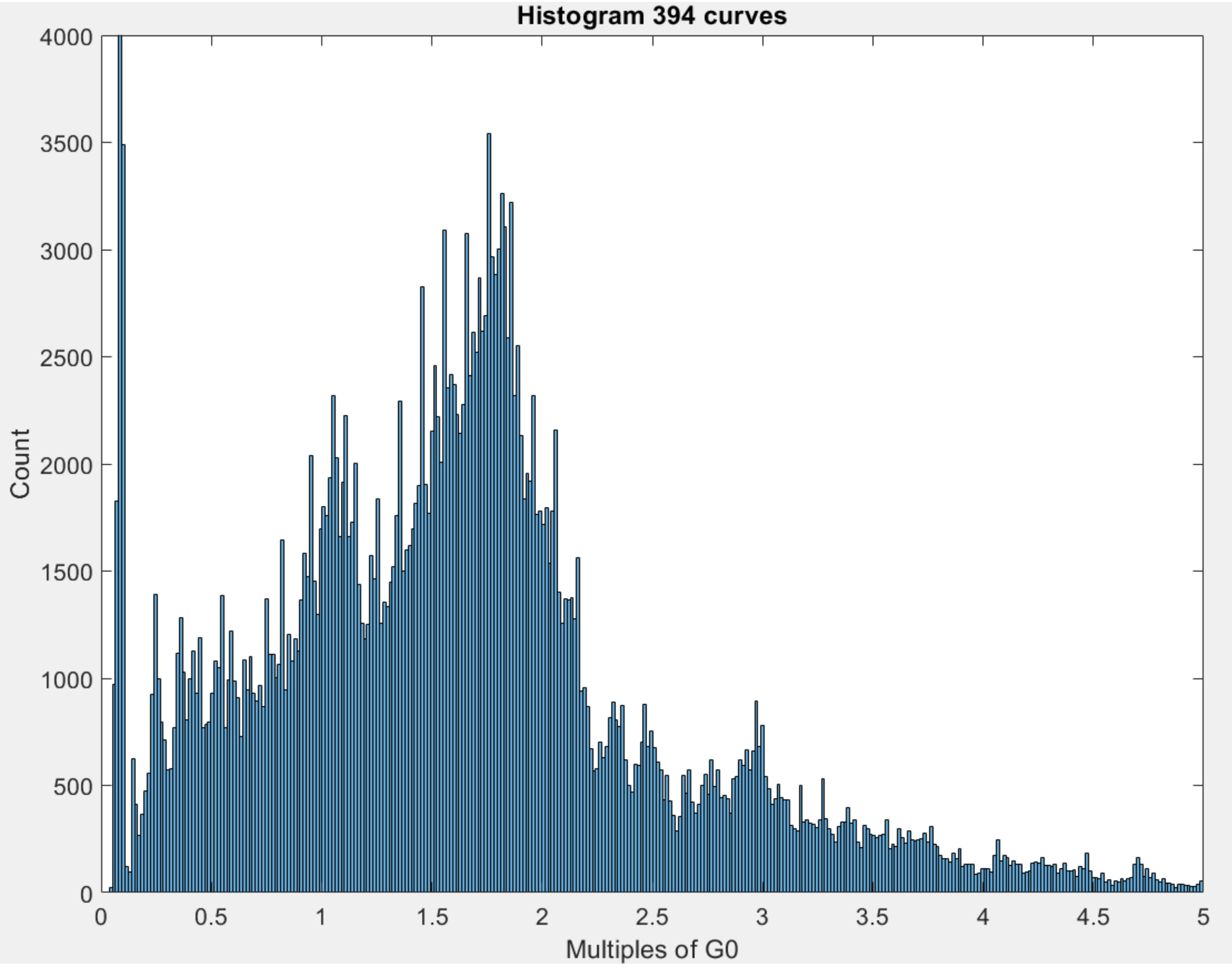


Figure 3.11. Counts of conductance values across 394 curves. The peak at 0.08 represents the disconnected state, therefore it is uninteresting. Conductance values beyond 5 not shown.

The above histogram is based on curves specifically selected to show levels. No fast disconnection type curves are included; Out of ~4000 curves these 394 were selected. The resulting histogram has its largest peak slightly below 2 multiples of G_0 and a less clear peak at 1 multiple of G_0. Other peaks are too unclear to mention. 394 curves contain 394000 points of measured voltages, these numbers are converted to multiples of G_0 and the distribution of these values is what is shown in the histogram. Ideally, the histogram would show sharp peaks at integer multiples of G_0. On the other hand, a histogram with a completely flat distribution would disqualify the data as having no connection with quantum conductance.

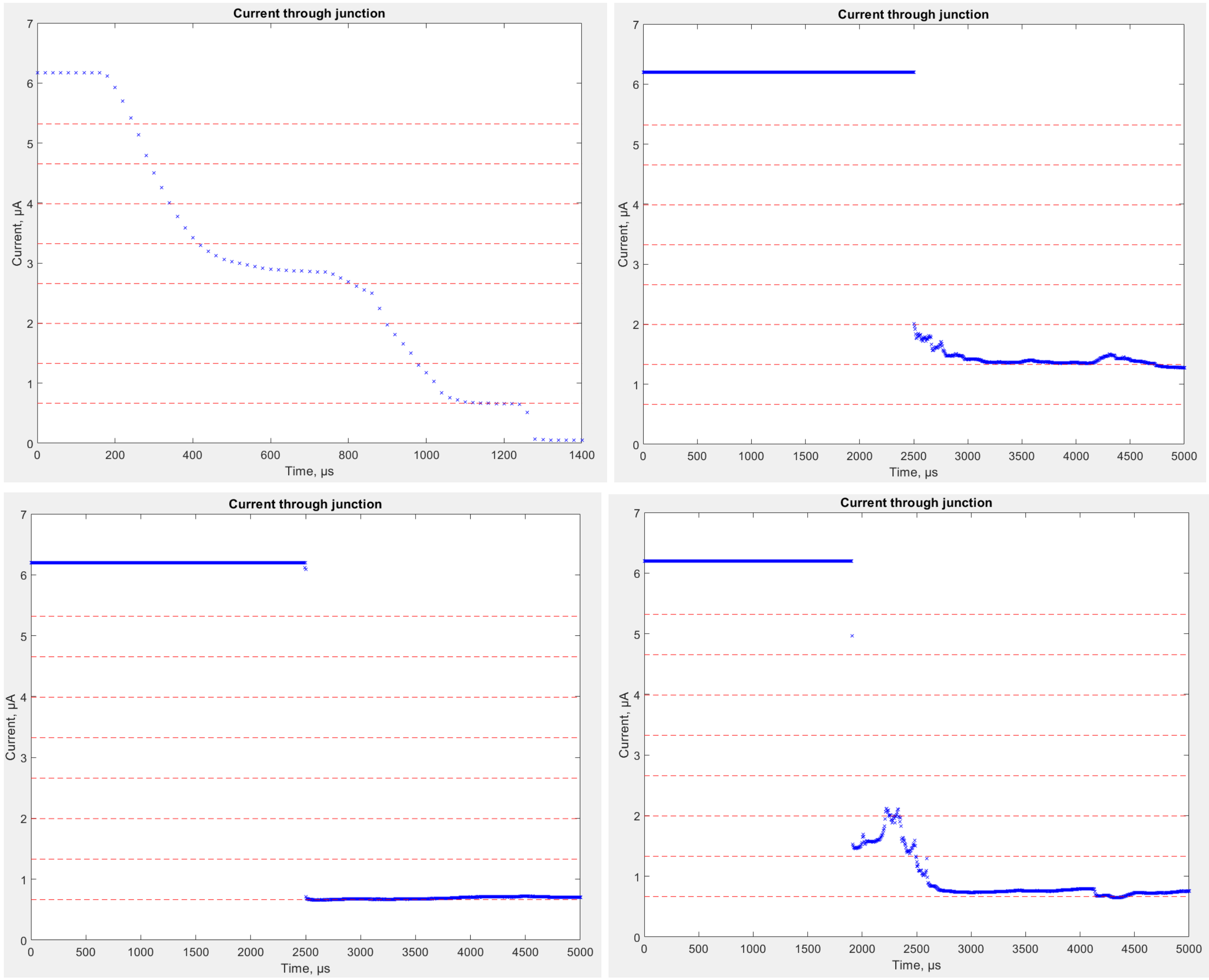
4. Discussion

As I wrote under “Aim of this project”, I have performed this task with exploration in mind rather than reaching any sort of statistically definitive conclusion.
As for finding a setup which shows the desired behaviour, I believe that I have succeeded.

Discussing the types of curves, I realise that my distinctions into “fast disconnection”, “fall with levels” and “other” are really a matter of the time during which the disconnection process takes place and how much of it is captured. With an instrument able to record voltage values on a µs resolution across for example 100ms, longer disconnection processes could be studied and what might have ended up in the “other” category instead might show long levels during its eventual fall to 0. Or, going to the other extreme, with an instrument able to react to very fast changes in current, shorter disconnection processes could be studied and what might have ended up in the “fast disconnection” category might instead show conductance levels with durations of for example 0.1 µs. By looking at this full range of possible curves, it would be possible to say whether there is some particular length of time for the entire process for which conductance levels are more likely to occur or more likely to match integer multiples of G_0.
While the fast disconnection- type should be discarded, I believe the “fall with levels” type shows quantum conductance the clearest. Translating these curves to the process they represent, they start out with the junction in its fully connected state where resistance is low. As disconnection begins and the wires gradually lose contact, resistance increases gradually. The fact that this increase in resistance slows or stops along plateaus is exactly what is expected when hoping to observe quantum conductance.
So why am I content to accept these curves as the quantized curves which I am supposed to find and which are supposed to be similar to the results by Foley et al? My answer is because at least some of them exhibit step-like behaviour at conductance levels sometimes positioned at integer multiples of G_0. The fact the curves have conductance levels of comparable length to the experiment of Foley et al, in an experiment set up in a similar way would indicate that we are looking at the same phenomenon.

Since the “other” types of curves do not show this process in its entirety, they are less good illustrations of what I hoped to observe. The “other” types also show unexpected behaviours such as slow increases between levels or levels maintained almost indefinitely. Meaningful discussion of this detailed behaviour is prevented by the fact that the measurements are done at room temperature, in air and using wires which cannot be guaranteed to be clean.

I would also like to discuss a few specific curves shown in figures 4.1-4.



Figures 4.1-4. Four particularly interesting curves.

While figure 4.1 is a more ordinary looking curve which happens to remain at the lowest multiple of G0 for ~200μs, figures 4.2-4 do not seem to have the same type of shape and the duration of the levels are much longer. One key difference is how quickly the transition down to the level occurs. While these four curves are all results of measurements performed in the same way, these differences make me suspect that the three last curves correspond to some different phenomenon than the first. In other words, I do not consider the three last curves to be representative results.

Analysing the histogram from the results; while a slight peak can be seen at 1 multiple of G_0, the picture painted by the histogram is the same as by examining the curves: there are slight tendencies for levels at integer multiples but in general levels occur at almost any values.
Comparing these results to the results of the experiment used a guide: the observed duration of conductance levels are comparable, ~200µs in both cases. The interesting question is how often the experiment produces relevant curves. In my case these are what I call non-"fast disconnection" curves , roughly 10% of all traces. As a criterion for accepting a given trace, Foley et al mentions "for example, accepting all traces that fall to zero within a specified time interval." This is roughly similar to my selection criteria but it implies that the setup is reliable enough to provide curves which do not have to be manually sorted. Another sign illustrating the higher repeatability of the setup used by Foley et al is the histogram which certainly has more clearly defined peaks than my results. So, since we are performing a similar experiment and observing the same phenomenon but seeing different degrees of repeatability, something must account for this difference. A few candidates exist for this missing ingredient:

- Unclean wires: I fully acknowledge that the surfaces of the wires cannot be guaranteed to be clean. While soldering the gold wires to the rest of the circuit and generally handling them, the surfaces are likely to pick up some dirt. I have tried to counteract this by scratching the surface with a knife after putting the wires in place. In spite of this, the possible presence of dirt is not eliminated. The presence of dirt might also match the type of mismatch between expected results and obtained results. That is, the conductance levels often appear at values other than integer multiples of G_0. When measuring one trace, the dirt might be there, when measuring the next trace it might not. On the other hand, why should a drop of oil from a persons finger contribute any substantial amount of conductance? What makes me not really consider the factor of dirtiness is the fact that Foley et al never mentions this factor (any form of dirt). After all Foley et al describes relevant factors of this experiment to consider in the context of a laboratory session with groups of 3rd or 4th year undergraduate students. If wires dirtied by skin oil would create a major deviation in the results, such a factor could very well have come up in such a context.
- Specific setup of the junction: There is a distinction between setting up the wires so that contact is made sideways by both wires, sideways by only one wire or both wires head on. There is also a distinction between having the wires initially be in contact or not. One might also try to make the applied force which triggers a trace to be as small as possible or instead forcefully knock the one wire into the other. Since I early on perceived that small movements with the wires initially touching more often gave curves with steps, I mostly changed around the other parameters. Perhaps by putting the wires together with more force, after contact is made, the wires would be pulled apart by a restoring force which would be similar each time the measurement is performed.This as opposed to the "small force" method. Again referring to Foley et al their setup is described as "The gold wires must be supported in such a way that a slight vibration such as tapping on the table will bring them into and out of contact". This point might seem like a small detail but it might be the key difference.
- Material of the wires: At no point did I actually perform the experiment with pure gold wires. Foley et al describes the wires as "0.05mm diam gold wires". While I did try 75% gold wires, it is possible that 100% gold is required for best results. In the original experiment by Costa-Krämer et al the histogram obtained for the "amorphous" material does display a similar decrease in "quality" (peaks between integer multiples and peaks which are not much higher than the rest of the data).

With more time/resources, more variations could be tried, and so based on the above points what I think is the right answer would be:

Most likely answer: Using 100% gold wires. This occurs to me as an important deviation from previous experiments. Also it is a straightforward change to make which eliminates this variable. The molybdenum wires with gold coating which were the wires used in my measurements were expected to be a reasonable substitute for 100% gold since the surface is the important part. With hindsight this might have been an excessive assumption.
Next likely answer 1: Using a high quality voltage source. It is possible that some of the irregularities observed in the curves come from the fact that batteries were used as the voltage source instead of laboratory instruments made for the purpose of precise measurements. Perhaps the batteries also can account for the misplaced levels. Another case of a variable which can be easily eliminated.
Next likely answer 2: Knocking the wires into each other. It never occurred to me that while putting the wires close to each other does tend to produce step-like curves, maybe this happens at the cost of repeatability. Perhaps by performing a very large amount of measurements when forcefully knocking the wires together, repeatability is achieved.
Less likely answer: Electromagnetic noise. Foley et al does mention this factor and I did take the precaution of using an aluminium box. Despite this, the deviation from the expected results still occurs and noise is only visible while the junction is in its disconnected state. A strange possibility remains that the deviations are caused by an electromagnetic interference which is not directly seen in the measurements and also bypasses the aluminium box.

Things learned and advice

Before beginning to work on this experiment and simply reading about it, I intended to measure the quality of my own results by some parameters such as what time length of conductance levels are maintained in the curves. I have since understood that repeatability and being able to account in detail for the results are more important.

I should name a few points which I would give as advice for someone trying to recreate the experiment:

First ensure that the basics are in order: voltage across the junction is ~10mV, resistor across amplifier is sufficiently large (500k good value).
For dealing with electromagnetic noise from the environment, first try to make the wire on the negative input pin as short as possible, for example 2cm.
Use one of the proven amplifiers, OP07 or OP27.
The relevant timescale on the oscilloscope is 500µs/div.
Expect that the majority of curves to be of such types as to be discarded.

References

[1] van Houten, H and Beenakker, C.W.J. ‘Quantum Point Contacts’, Physics Today **49**, 22-27 (1996). doi:10.48550/arXiv.cond-mat/0512609.

[2] Costa-Krämer, J. L. , Garcia, N. , Garcia-Mochales, P and Serena, P.A. ‘Nanowire formation in macroscopic metallic contacts: quantum mechanical conductance tapping a table top’. *Surface science*. [Online] Volume **342**, Issues 1–3, L1144–L1149 (1995). doi: 10.1016/0039-6028(95)00967-1.

[3] Frolov,S. Quantum Transport, Lecture 5: Ballistic Transport Available at: https://www.youtube.com/watch?v=sh_8mh_e2H8 (Accessed: 16 June 2023).

[4] Das, M. P. , Green, F. ‘The Landauer Formula: a Magic Mantra Revisited’. In Proceedings of XXVI International Workshop on Condensed-Matter Theories, 2003. doi:10.48550/arXiv.cond-mat/0304573

[5] Landman, U. , Luedtke, W. D. , Salisbury, B. E. , Whetten, R. L. ‘Reversible Manipulations of Room Temperature Mechanical and Quantum Transport Properties in Nanowire Junctions’. *Physical Review Letters* **77**, no. 7 (1996): 1362–1365. doi:10.1103/PhysRevLett.77.1362

[6] Huisman, E. H. , Bakker, F. L. , van der Pal, J. P. , de Jonge, R. M. , van der Wal, C. H. ‘Public exhibit for demonstrating the quantum of electrical conductance’. American journal of physics, 2011, Vol.**79** (8), p.856-860. doi:10.1119/1.3593276

[7] Tolley, R. , Silvidi, A. , Little, C. , Eid, K. F. ‘Conductance quantization: A laboratory experiment in a senior-level nanoscale science and technology course’. American journal of physics, 2013, Vol.**81** (1), p.14-19. doi:10.1119/1.4765331

[8] Foley, E. L. , Candela, D. , Martini, K. M. and Tuominen, M. T.‘An undergraduate laboratory experiment on quantized conductance in nanocontact’, American Journal of Physics **67**, 389 (1999); doi: 10.1119/1.19273

Appendix

The script uses the library pyvisa which provides functionality for issuing commands within the "Virtual Instrument Software Architecture (VISA)" specification. The oscilloscope used is compliant with this specification. Pyvisa can be found at https://pyvisa.readthedocs.io/en/latest/.

Python script for transferring curves

```
import pyvisa
import time

RRMM=pyvisa.ResourceManager()
isse=RRMM.open_resource("TCPIP0::192.168.0.102::INSTR")
isse.timeout=2000
isse.read_termination="\n"
isse.write_termination="\n"




print(isse.write("ACQUIRE:MODE NORMAL"))
time.sleep(0.2)
print(isse.write("ACQUIRE:TYPE HRESolution"))
time.sleep(0.2)

print(isse.write("ACQUIRE:COUNT 100"))
time.sleep(0.2)
print(isse.write(":ACQ:COMPLETE 100"))
time.sleep(0.2)

alla=[]

forra=""

print(isse.write(":WAVeform:UNSigned 1"))
```

```
time.sleep(0.2)
print(isse.write(":WAVeform:BYTeorder LSBFirst"))
time.sleep(0.2)

print(isse.write(":WAVeform:FORMat ASCII"))
time.sleep(0.2)
print(isse.write(":WAVeform:SOURCE CHANNEL1"))
time.sleep(0.2)

print(isse.write(":WAVeform:POINTS 1000"))
time.sleep(0.2)

print(isse.write(":WAVeform:POINTS:MODE NORMAL"))
time.sleep(0.2)


for i in range(0, 500):


    try:
        isse.write(":DIGITIZE CHANNEL1")
        isse.clear()
        isse.write(":RUN")
        isse.write(":WAV:DATA?")
        time.sleep(0.2)
        denna =isse.read()
        print(str(denna))
        isse.clear()
    except:
        time.sleep(0.1)
        continue
    alla.append(denna+"\n")
    forra=denna
isse.close()
ff=open(str(time.time_ns())+"AAAAA.csv","x")
for s in alla:
    ff.write(s[10:])
ff.close()
exit()
```