Quantum Conductance Lab - Prof. Haas, NYU, created Feb. 24, 2017

When two gold pieces are separated slowly, a tiny, very thin, “nanowire” is formed, often just a few atoms wide. (Gold is especially good at this since it does not oxidize, so the surface is pure.) Before the nanowire breaks, current in it is quantized, since the electrons carrying the current are confined in a small volume[1]. In other words, the conductance (G) of this nanowire is quantized. We will attempt to observe this, and measure the value of the quanta of conductance, which should be $G=2e^2/h$, about 7.748e-5 Siemens. The quanta of resistance (R=1/G) is thus about 1/7.748e-5 ~ 12.9kOhm. Some more info is here:
https://en.wikipedia.org/wiki/Conductance_quantum

To bring the gold wires into contact and then pulled apart in a controlled, repeatable way, a piezoelectric device is used. The piezoelectric device is a special crystal that expands proportional to the voltage applied to it. Thus for high voltage (~50V) the wires will be in contact, and at 0V the wires will be separated. A signal generator is used to control the voltage, which is then amplified by 10, and then applied to the piezoelectric device. A triangle wave is best to apply, since it most gradually separates the wires (as opposed to a square wave, for instance). A frequency of the triangle wave of about 10 Hz works well, since this again separates them slowly, while still allowing for a large number of separations in a few minutes. (The separation rate, given by the slope of the triangle wave, is proportional to frequency.)

To measure the resistance (and thus conductance) of the wire junction, we supply a known voltage across the junction (V in) and use an amplifier to measure the voltage produced (V out). The amplifier used is a small device known as an “op-amp”, and we’ll be setting it up as an inverting amplifier, meaning the input to measure goes into the negative input. The gain or amplification of the amplifier (V out / V in) is given by -R1/R2 (at low frequencies!), where R1 is the resistor feedback resistance going from output to negative input, and R2 is the resistance of the gold wire connection (what you’re trying to measure!). You should read more about op-amps here:
https://www.allaboutcircuits.com/technical-articles/a-practical-introduction-to-operational-amplifiers/

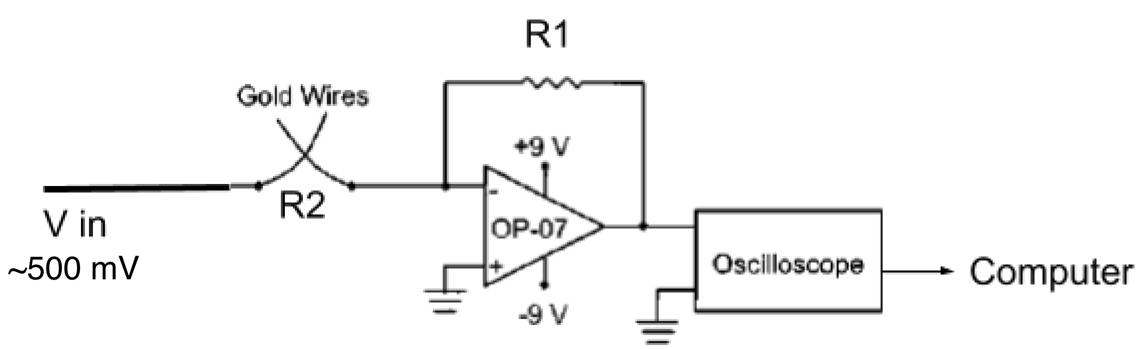
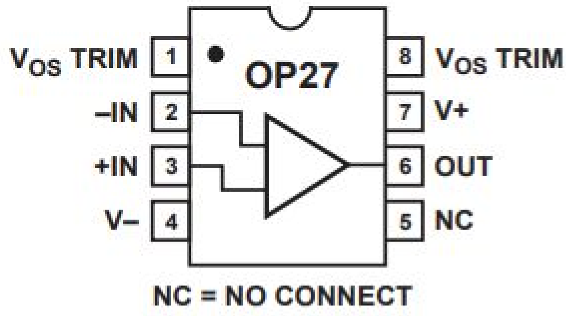


Fig. 1, adapted from E. L. Foley, D. Candela, K. M. Martini, and M. T. Tuominen.

The circuit can be put together on a simple breadboard. A value of R1 of ~100 kOhm works well[2]. Note that +9V must be put to one input power pin, and -9V put to the other! The positive input should be tied to ground (0V). The output voltage should go from 0 when the wires are disconnected, to 9V when they’re connected. It’s

[1] There is still debate as to whether this is really why the conductance is quantized, or if it is the atomic contacts involved.
[2] You should calculate (and measure as a crosscheck) what V out you’ll get for V in = 500 mV, and R2=12.9 kOhm. You want to choose R1 such that the gain of the amplifier will give ~2 steps (4.5V each) for this V in. V in can then be lowered, to observe more steps.

important to use an op-amp with a fast enough “slew rate”, which is how fast the output voltage can change. Your nanowires will only live for ~100 us (microseconds) or so before breaking. So on the oscilloscope we’ll need to look at this time range, and see the voltage change quickly. We thus need the output voltage to change by 9V in just a few us, or a slew rate of at least ~3V/us. For instance, we can use the OP27: http://www.analog.com/media/en/technical-documentation/data-sheets/OP27.pdf



One should also beware that the gain of the op-amp is only -R1/R2 at low frequencies (below ~1kHz or so, for a typical op-amp). At higher frequencies (higher rates of change of the input signal voltage), the gain is smaller, usually inversely proportional to the frequency. How much gain can be achieved at how large a frequency is given by the “gain-bandwidth product” for the amplifier. You can find details on this in the datasheet for the op-amp you are using. It will be important to measure and calibrate the actual gain you have for your setup, at various frequencies similar to those in the signal you are trying to measure, using a known value of R1. Just replace the gold wire setup with a resistor (~10k, similar to the quanta of resistance you’re trying to measure), and measure Vout RMS / Vin RMS vs the frequency of V in. The Vin frequency can be generated as a sin wave from the signal generator you already have in the setup - just disconnect it temporarily from the piezo setup. The oscilloscope can be setup to measure Vin RMS, Vout RMS, and Vin frequency simultaneously.

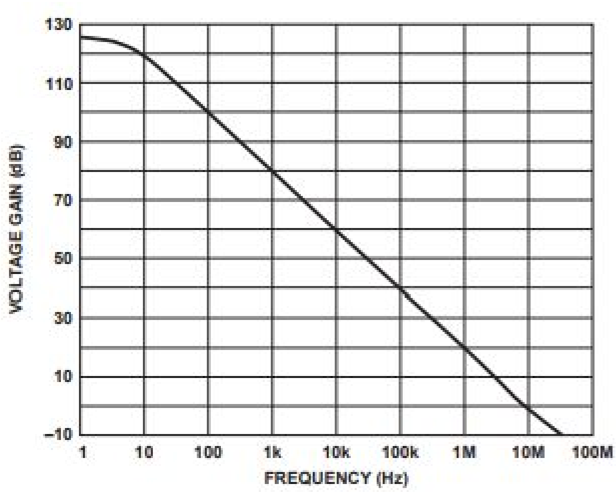


Figure 19. Open-Loop Gain vs. Frequency

You may also run into some noise issues with the op-amp. One is caused by the power supplies (+-9V) which do not completely remove all 60 Hz oscillations from the AC wall voltage. Filtering capacitors (~100 uF) can be placed across the power inputs to reduce this (beware they are *polarized* - make sure to have the positive lead at a larger voltage than the negative lead!). Another noise problem is ringing/oscillations due to out-of-phase feedback from the output to the input through the resistor, mostly due to output capacitance. This tends to happen past ~1 MHz, and when the input is disconnected (gold wires not touching). A resistor from input to ground of ~100k helps, providing a path to ground when the gold wires are not connected (but then you have to account for this in your gain calculations!). You can also try adding additional capacitance to op-amp feedback loop, in parallel with R1, to reduce the bandwidth of the op-amp circuit. (The *reactance* of a capacitor is ~1/fC, so is smaller at large frequencies. How big does C need to be to reduce R1 by a factor of 2 at f=1 MHz?)

The basic procedure is:

- Set the input voltage to ~500 mV and plot it using the oscilloscope to monitor it.
- Trigger the oscilloscope on edges of V out around 4.5 V and plot V out on the oscilloscope.
- Start the triangle wave at 10 Hz and adjust the piezoelectric device using the hand screws until it is just making/breaking contact of the gold wires at ~10 Hz. Leave the DC offset of the signal generator near 0, and adjust the amplitude to get good breaks.
- Hopefully you'll see some steps in the oscilloscope traces, as shown below.
- Once things are going well, start recording the oscilloscope traces to the computer (using a python script?)
- Then repeat for V in = 400 mV, 300 mV, etc.

Once you've collected the traces to the computer, they should be analyzed, separately for each V in, to find the average values of the conductance of the nanowires during the times when the nanowire is stable (the plateaus on the traces). A good way to do this is to histogram the calculated conductance (determined from V out), from the start of the break until it is broken. You can add together the data from all the traces of each V in. You should then see something similar to the histogram below. It may be necessary to "clean" your data before plotting it, to remove artifacts such as noise, etc. Try your algorithm on a few traces first, to see how they reduce the noise features, and accentuate the steps.

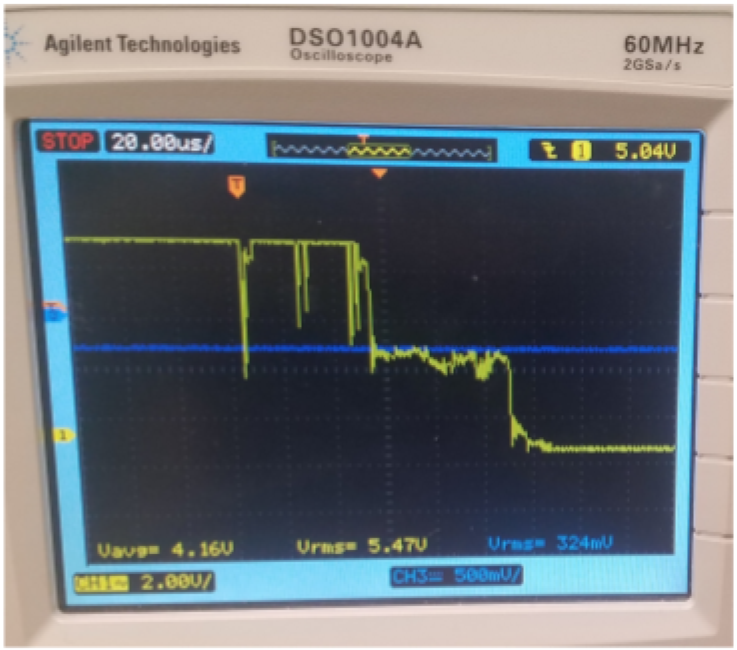


Fig. 2, an example oscilloscope trace showing one step.

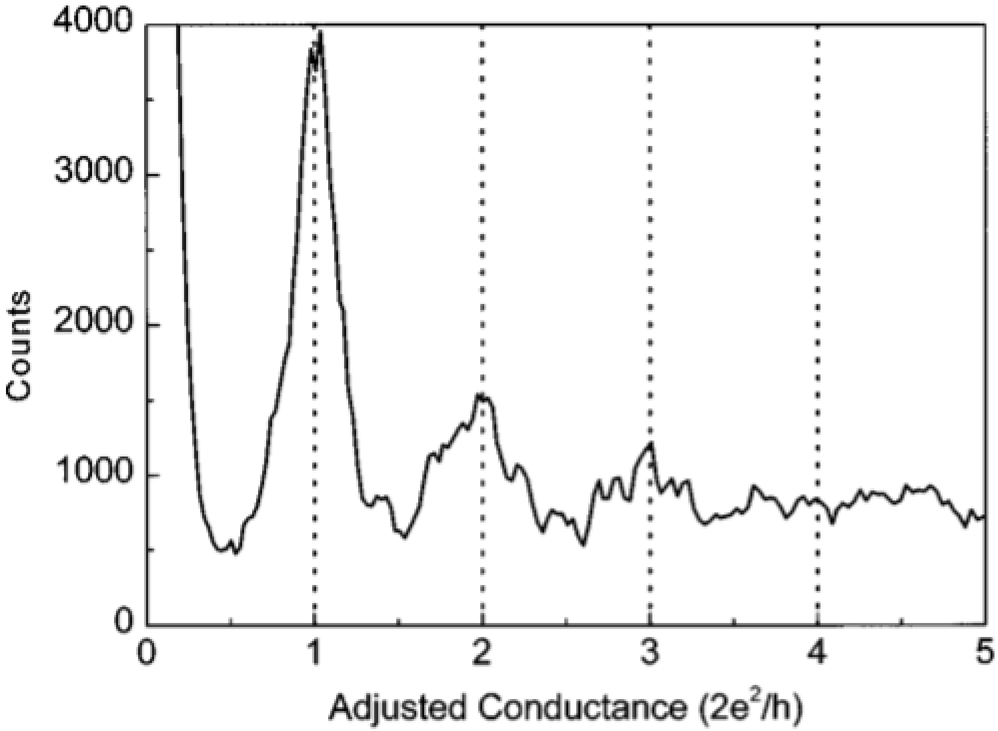


Fig. 3, adapted from E. L. Foley, D. Candela, K. M. Martini, and M. T. Tuominen.