

Quantized Conductance II: Detecting Atomic Wires

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I. Introduction

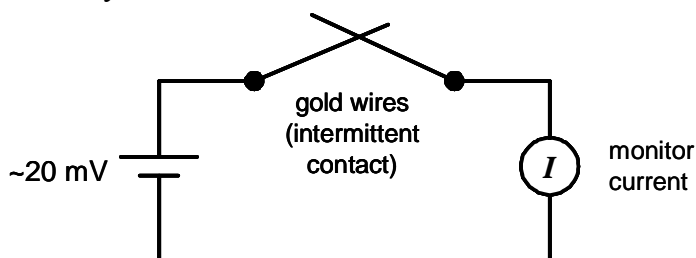
When two wires of pure gold are brought in and out of contact with each other, a narrow bridge only a few atoms wide sometimes forms, joining the two macroscopic wires. Due to the affinity of gold atoms for each other, when two pieces of gold touch, they bond where they are in intimate contact, assuming the surfaces are clean. When the macroscopic pieces of gold are separated, the malleability of pure gold allows the contact to stretch into a thin wire before it finally breaks. Atomic wires that form in such a “mechanical break junction” cannot be seen with the human eye or an optical microscope. They can only be imaged with a microscope that has atomic or near-atomic resolution, such as a transmission electron microscope (see references below for images). Such images show that just before an atomic bridge breaks, it often narrows to only one atom in width, forming the ultimate nanowire.

You do not have to use a multimillion dollar electron microscope to see whether a single bridge of atoms has formed. It turns out that a conductance measurement can be just as illuminating. (Recall that conductance G is the ratio of current I to voltage V , and is the inverse of resistance: $G = I/V$.) The conductance of a single-atom wire is determined by quantum mechanical effects. Theoretically, the conductance is:

$$G_0 = 2e^2/h = 7.75 \times 10^{-5} \Omega^{-1}$$

This implies a resistance of $h/2e^2 = 12900\Omega$ for an atomic wire. Widening the nanowire to two atoms wide provides another conductance channel for electrons, so in theory the conductance would increase to $2G_0$. For an N atom wide wire, the conductance is predicted to be NG_0 . Thus, conductance can be used to probe the atomic structure of the gold nanowire.

In the last lab, you built a circuit that will enable you to measure the conductance of the gold nanowire that forms at the contact between two macroscopic gold wires. A simplified version of your circuit is shown below:



A constant voltage of ~ 20 mV is applied across the contact between two pieces of gold wire while the current is monitored. Recall that the current is not measured directly; rather, it is amplified and converted to a voltage so that it can be read by an oscilloscope.

The amplification factor is 100 mV for every 1 μA of current or 10^5 V/A. The digital oscilloscope reads and displays the changing signal as a function of time.

Gold bridges tend to last for ~ 1 ms, and changes in width tend to be relatively sudden. For example, if a bridge suddenly narrows from 3 atoms wide down to 2, from 2 to 1, and then breaks completely, the current vs. time graph will look like a staircase (see, for example, E.L. Foley). The sudden decreases in current correspond to the conformational changes of the gold atoms. Each plateau indicates the presence of a nanowire that is stable for the duration of the plateau. The current through the nanowire can be divided by the ~ 20 mV applied across it to give the conductance of the nanowire, which gives information about the atomic structure of the gold nanowire.

Microscopic Origins of Resistance

To better understand quantum resistance, it is important to review conduction of electrical current in macroscopic wires. Recall that resistance of an object depends on its cross-sectional area, A , its length, L , and the resistivity of the material ρ :

$$R = \frac{\rho L}{A}$$

For gold at room temperature the resistivity is $\rho = 2.2 \times 10^{-8} \Omega\text{m}$; for copper at room temperature $\rho = 1.7 \times 10^{-8} \Omega\text{m}$. Gold has a greater resistivity than copper because electrons scatter somewhat more when they pass through gold. Scattering slows the progress of an electron through a conductor. The electric field established by the applied voltage causes an electron to accelerate in the direction opposite the field; the acceleration continues until the electron scatters. According to the Drude model, scattering randomizes the direction of the electron so that on average it has zero velocity along the direction of the field. The field then acts to once again accelerate the electron. The more an electron scatters, the lower its average velocity in the direction opposite the field, and the slower the current for a given voltage.

Scattering occurs when there are imperfections in the crystalline arrangement of atoms. These imperfections can take the form of a missing atom (vacancy), an atom of a different type (substitution or impurity), a boundary between two adjacent crystalline regions with different orientations (grain boundary), or one of several other classes of defects. The thermal motion of atoms also causes deviation from perfect crystalline order and leads to scattering (collections of thermally excited atoms are called phonons). At room temperature scattering by phonons is the dominant cause of scattering and hence electrical resistance. Thermal motion is much reduced at low temperature, so cold metals have much less resistance. For example, gold at 1K has a resistivity $\rho = 0.02 \times 10^{-8} \Omega\text{m}$.

When electrons cross a one-atom-wide wire, they essentially are forced to go single file. The current is limited by this single-file process, and this leads to “quantum resistance.” Notice that quantum resistance is independent of nanowire length and material. The only thing that matters is the number of “conductance channels” available to electrons. The full derivation of the conductance quantum requires quantum mechanics, and is beyond

the scope of this course. See E.L. Foley for a discussion of the quantum mechanics involved (listed in *References* section below).

Scattering is negligible in atomic wires unless the wire has a defect. Phonons no longer play a significant role (except for very long nanowires) since they tend to scatter electrons at shallow angles, not an option in a one-dimensional conductor. If a wire does have a defect, some of the electrons will be scattered back in the direction they came from. This will lower the current through the nanowire for a given voltage, and such a wire will have a lower conductance than a perfect one.

References

J.L. Costa-Kramer, et. al. "Nanowire formation in macroscopic metallic contacts: quantum mechanical conductance tapping a table top," *Surface Science* **342** L1144 (1995).

H. Yasuda, A. Sakai, "Conductance of atomic-scale gold contacts under high-bias voltages," *Physical Review B*, **56**, 1069 (1997).

E.L. Foley, et. al. "An undergraduate laboratory experiment on quantized conductance in nanocontacts," *American Journal of Physics*, **67** (5) 389 (1999).

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II. Procedure

A. Prelab

1. Turn on the power to the box containing the measurement circuit. Test that the voltage at the BNC labelled “V” is ~ 20 mV. If not, check the batteries and replace if necessary. Record this voltage.
2. Work through questions 1 and 2 of the Analysis section.

B. Set up the equipment

1. On the metal box containing your measurement circuit, Use a coaxial cable to connect the BNC connector labeled “out” to the channel 1 input on the digital oscilloscope.
2. Attach the two coaxial cables that terminate in banana plugs to the BNC connectors labeled “gold wires.” Put the banana plug connected to the central wire of the coaxial cable (not the banana plug labeled “GND”) into the socket on the brass wire holder.
3. KEEP THE GOLD CLEAN, DO NOT TOUCH IT! Only touch the copper wires soldered to the gold, not the gold itself.
4. Unscrew the posts on the brass wire holders and insert the copper ends of the wires into the holes. Tighten the post tops on the ends of the copper wires.
5. Turn on the power switch on the back of the metal box with the measurement circuit.

C. Set up the digital oscilloscope

1. Plug in the digital oscilloscope power cord. Make sure the USB connector is plugged into the back of the computer.
2. Turn on your computer. Double-click on the desktop icon labeled *DSO2102* to start the digital oscilloscope software.
3. Click on the *Go* button for the oscilloscope and touch the gold wires together briefly. You should see a trace recorded on the screen. If not, ask your TA for help.
4. Some useful initial settings are: for channel A1, set V/div to 200 mV; set *Trig ch* to *A1*, *Trig mode* to *Normal*, *Rate* to 2 MSa, *Zoom* to $10:1$. Discuss with your lab partner what these settings mean. Try playing with them if you are not sure.
5. The green and blue dashed horizontal and vertical lines are cursors that are useful for measurement (the red dashed lines set trigger levels). Drag them around with the mouse while watching the digital readouts at the top change to get a feel for it.
6. Set the horizontal cursors at the voltages you would expect for one-atom and two-atom wide bridges. This will help you spot the formation of such bridges.
7. Make sure the vertical trigger (dashed red line) is approximately in the middle of the window. This is where the trace will transition from low to high (or high to low).
8. Check the horizontal trigger (dashed red line) is substantially above 100 mV to avoid triggering on noise.

D. Get the gold wires in contact

This part requires some practice and patience. If you persist you will get beautiful data! Here are a few tips on how to set up the gold wires so they form nanowires:

1. Start with the copper wires horizontal. Slight bend one copper wire so that it angles downward a few degrees.
2. Begin with the wires out of contact. Rotate one brass wire holder slowly until the gold wires overlap and just barely touch.
3. The wires should be touching softly enough that when you tap the table lightly with your fist they bounce in and out of contact for a few seconds.
4. On the oscilloscope trace, a plateau (i.e. constant current) indicates the presence of a stable nanowire for the duration of the plateau.
5. If you don't see any evidence of nanowires after five or ten table taps, reposition the wires to a new, hopefully cleaner, location and try again. The gold tends to be cleanest near the solder joint, so try to form your nanowires there.

E. Data logging and Browsing Files

Record all of your data using the data log feature. If you see a nice trace you would like to go back to later, remember the filename (it will appear in the top line of the window) so that you know which file to open.

1. Under the *File* menu choose *Data log settings*. In the window where it says *File name* enter "XXX" where "XXX" stands for a few letters such as your initials. Every data file will start with these letters.
2. Choose *All* where it says *Save every N captures*.
3. Select *.DSO* format for saving files.
4. To start saving data, go under the *File* menu and click on *Data log*. If you look at the *File* menu again, there should be a check mark in front of this option.
5. To browse files, first press the *Stop* button. Then choose *Data log load...* in the *File* menu. Choose *Browse* to select the first file you want to look at and *Previous file* or *Next file* to step to the next file.

G. Recording and Analyzing Data

You can stop recording data when you have at least five files that show nanowires.

1. Measure the height of all plateaus in the five files you saved, using the cursors in the digital oscilloscope software, and record this information.
2. With a gradually varying trace, it can be difficult to tell one plateau from another or to determine the end-points of a plateau. In this case, place a horizontal cursor on a plateau. As long as the trace touches the cursor, it is part of the same plateau. Where the cursor and trace diverge, this marks the end of the plateau.
3. Print a copy of the file that shows your longest-lasting nanowire for your lab report. Mark the height and duration of the plateaus on your printout.

III. Analysis

1. For a single-atom bridge, calculate the theoretical current that will pass through at the voltage measured from the voltage divider in your circuit.
2. The measurement circuit has a current-to-voltage amplifier with a gain of 10^5 V/A. Calculate the theoretical voltage output for a single-atom wide bridge. Also, calculate the output for a two-atom wide bridge.
3. Using the formula for resistance of macroscopic objects, compute the resistance of a gold bridge 4 atoms long and one atom wide, assuming the diameter of a gold atom is 0.2 nm and given that the room temperature resistivity of gold is $\rho = 2.2 \times 10^{-8}$ Ωm . Repeat your calculation for a gold bridge that is one atom wide and 100 atoms long. How do these values compare to the quantum mechanical resistance value?
4. A metallic carbon nanotube behaves as a “two-channel” conductor, i.e. its conductance is twice the fundamental conductance quantum. What is the minimum resistance of a carbon nanotube?
5. Do nanowire bridges form when the gold wires are brought together, separated, or both? Explain your answer based on your observations.
6. Make a table with columns for your nanowire data “ V_{out} (mV),” “ I (A),” “ G (Ω^{-1})” and “ G/G_0 .” In the first column, record the plateau heights as measured on the oscilloscope. Use this to find the current through each nanowire I , its conductance G , and finally its conductance as a fraction of the theoretical conductance quantum G/G_0 .
7. Make a histogram using your data G/G_0 from question 6. From your data, what size nanowire occurred most frequently?
8. Is there evidence of defects in the nanowires you made? Explain your answer.
9. Do your data provide evidence for the existence of a conductance quantum of value G_0 as predicted by theory? Explain your answer.
10. Attach the labeled printout showing your longest-lasting nanowire. How long did your most stable nanowire last? Is the break junction method you used to form nanowires practical for building circuits?