

# E.K.A. ADVANCED PHYSICS LABORATORY

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## GETTING STARTED ON THE QUANTIZED CONDUCTANCE EXPERIMENT

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### 1. SUMMARY OF PROCEDURE

In this experiment, you will create and destroy thousands of gold nanowires and study their properties statistically. The wires are created at the point of contact between a wafer of ultrapure gold (which you will make) and a gold wire (which you will arrange carefully in the existing needle). The bulk of your work will be spent mastering how to get this contact suitably arranged. The data taking consists of repeatedly touching these two pieces together and pulling them apart, and is automated by the program *Igor* (take a look at the *Igor* manual written for this lab before you begin). The data analysis, also in *Igor*, will provide the results you need to write a lab report.

### 2. SETTING UP THE EQUIPMENT

The equipment should be already hooked up and working. The aluminum housing for the wafer and wire rests on a vibration isolation table that should be pressurized to 60 psi. The deflated inner tube is to further damp low-frequency vibrations. Check that the main housing is connected to ground through the shield of one of the wires. The three boxes sitting on the table are:

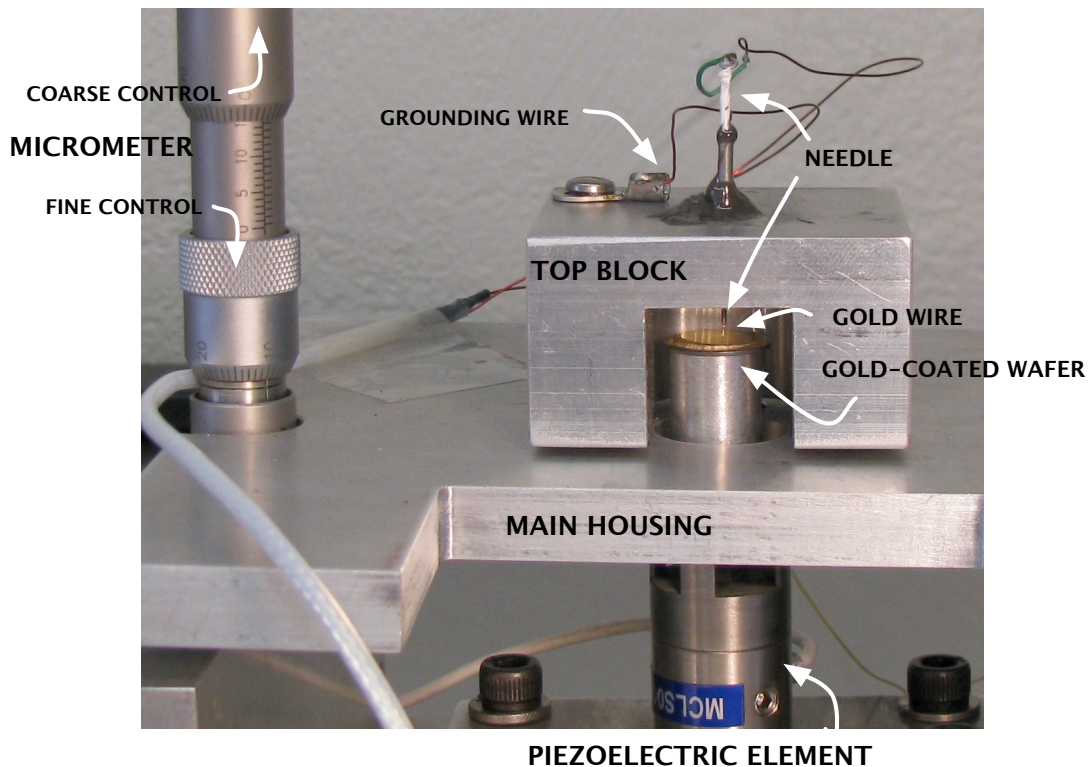
- (1) the PXI chassis and cards (which applies a constant voltage across the contact),
- (2) the Keithley current amplifier (which detects the tiny current across the contact), and
- (3) the MCL controller for the piezoelectric element (which controls the touching by raising and lowering the gold wafer under your wire).

All of these boxes are connected to the computer, and are operated within an existing *Igor* procedure that you will run. If there are any problems with the setup, have an instructor consult Appendix B below.

### 3. PREPARING THE GOLD CONTACT

The first thing you will want to do is prepare the contact using someone's old wafer and some scrap gold wire, and take some data with it, just to see what it's like. The goal of this section is to prepare the apparatus to look like Figure 1.

FIGURE 1. A Close-Up View of the Apparatus



Pick up the top block from the main housing and set it on its side. The block contains a needle into which you will slide a gold wire such that it protrudes several millimeters from the needle tip. The wire should initially slide in easily, but you will want it to stick very firmly in the needle; one way to accomplish this is to bend it back and forth at one spot, until this “kinking” produces a bulge that will stick. *Be careful not to break the wire too close to the needle that you can't pull it out again!* If this happens, the needle will have to be remade; have an instructor consult Appendix A below.

Once the wire is firmly in place, take the specially-marked gold scissors and cut the very tip of the wire at a steep angle. This will ensure the smallest, sharpest, and cleanest contact between the wafer and the tip. After this point, be sure nothing touches the tip of the wire.

Find an old wafer and set it gently on the magnetic wafer platform, which is connected to the piezoelectric element below. **Be careful not to put any forces or torques on the wafer platform, as this could permanently damage the piezo!**

When you set the top block back onto the main housing, be sure the tip and wafer don't touch immediately, as this will bend the tip. The top plate of the housing can be raised and lowered with the micrometer. Then, using the microscope and a table lamp, watch the tip as you use the micrometer to bring the tip toward the wafer. Watch for the tip's reflection in the wafer below; just as they are about to meet, stop and set up the computer. You'll return to this point when the controller program is armed.

#### 4. SETTING UP THE COMPUTER

As the *Igor* manual explains, there are two types of *Igor* files, Experiments (.pxp) and Procedures (.ipf), in addition to data files. An Experiment file incorporates Procedure files into a single, user-friendly interface. A Procedure file is a routine that controls a specific process or piece of equipment. In our setup, you will ALWAYS create a new Experiment file out of the existing Procedure files each time you attempt to collect new data, to ensure no faulty parameters have been set. (The data you collect is safely written to disk elsewhere, so you won't lose it.) To load the Procedure files correctly, use the following commands.

- (1) Open *Igor* to generate a blank Experiment
- (2) Choose File → Open File → Procedure
- (3) Navigate to the folder C:\Experiments and open Current\_Spectroscopy\_2007.ipf
- (4) Choose Macros → Compile, and then Macros → StartupDAQ to open the panel
- (5) Click the large green **Start** button
- (6) Check the **RiseTime**, **SuppressI**, **On**, and **Beep** buttons.
- (7) If the computer has just been restarted, click inside each of the text boxes on the panel, and press return to re-enter each parameter

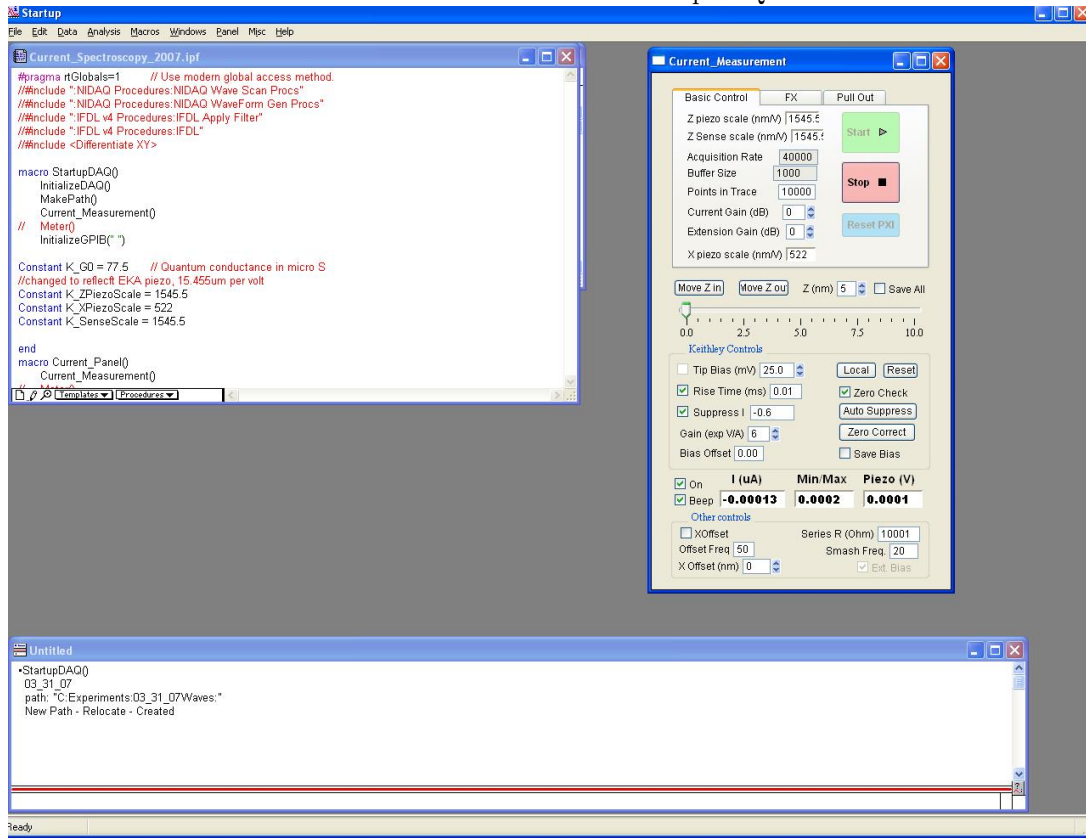
Your screen should look like the snapshot in Figure 2.

Now that the program is ready and armed, you are almost ready to collect data. The **ZeroCheck** button prevents the extremely sensitive components inside the Keithley box from being terminally zapped by static electricity. You'll need to un-check it in order for the experiment to work – but, from now on, you must be careful not to introduce any sources of static (like your body) into the circuit! So, either don't touch any wires that belong to the circuit (ONLY touch grounded stuff like the micrometer and/or the main housing), or ground yourself using the tethered wrist straps hanging from the ceiling, or both.

Once the zero check is disabled, the system will beep any time the gold pieces are touched together. Go to the table and bring the wire down to the wafer very slowly (you may wish to use the fine control on the micrometer, which is the lower dial). As soon as you hear beeping, raise it back up a tiny amount. Cover the apparatus with the acoustic shield and set the stainless steel slug on top. Any stray wires should be tucked under the shield, to minimize the electrical interference in the signal path.

From now on, all the controlling will be done from the computer. In the DAQ panel, slowly move the slider to the right until you hear beeping; you have just used the piezoelectric element to

FIGURE 2. Screenshot of the StartupDAQ Panel



raise the wafer up to the wire. Again, move the slider out a tiny bit until the beeping stops. (If the beeping doesn't stop until well past the point where it started, it probably means the wire is slipping and will have to be re-set and the tip re-cut. *Don't forget to enable the zero check before you correct this.*)

## 5. DATA ACQUISITION

Now that all the hardware is in position, you want to instruct the computer to perform a trace. The essence of the routine is that the computer will bring the wafer up until contact is made, and then pull it out a small, fixed distance. You hope that over the course of this distance (we usually set it to 5 nanometers), a good, solid gold contact will be made, stretched into a nanowire, and broken. The computer will measure the conductance (current divided by voltage) during this trace.

First, make sure the **Z piezo scale** and **Z sense scale** boxes read 1545.5, corresponding to our piezo's calibration (15.455 microns per 10.0 kilovolts). Then click the **Pull Out** tab on the top of the DAQ panel. The settings that load automatically should give reasonable traces, but feel free to play with them if not (**PullRate** controls the speed of the pullout, **Excursion** sets how far to pull out, and **Conductance** sets the minimum amount of contact to be made when the pieces are

brought together before the pullout begins, in units of  $G_0$ ). Remember to press return after you enter a new parameter - simply entering a new value in the box isn't recognized by the program!

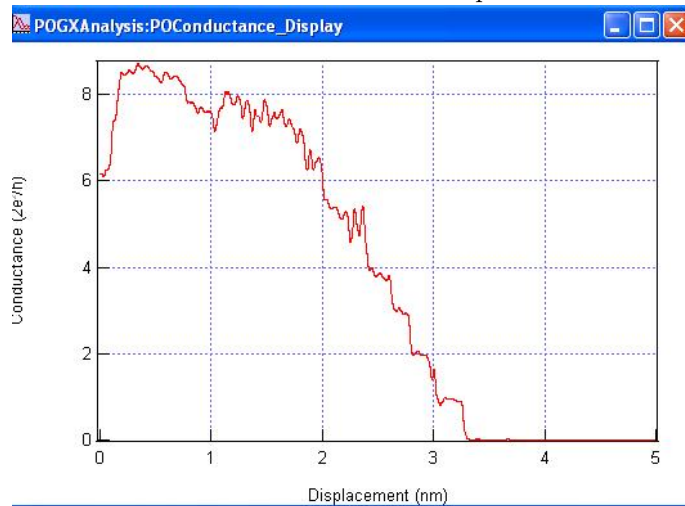
Click the PullOut button to attempt a trace. This process will take a few seconds, and, if successful, will bring up three new windows, from top to bottom:

- (1) the vertical position of the piezo over the course of the trace,
- (2) the conductance of the contact in units of  $G_0$ , plotted on a linear scale, and
- (3) the conductance of the contact in units of  $G_0$ , plotted on a log scale.

If the windows don't pop up, you may not have brought the wafer close enough to begin with. (You can check: the command window, at the bottom of the screen, records the average conductance of each trace in real time; if it reads 0.0, you haven't made any contact.) You can move the slider around some more, or for finer control, try the buttons marked **Move Z in** and **Move Z out**.

Once you acquire a successful trace, several things could be going right or wrong. If the traces look like the beautiful stepladder in Figure 3, you're ready to go. Chances are it won't look this good yet, but it's a nice goal to work toward. If the plots are extremely noisy, you should make sure nothing is touching both the vibration table and its housing - if so, there may be vibrations coupled to the table. To further eliminate noise, kick out extraneous people from the room, close the door, turn off the air conditioning, place acoustic shielding around the noisy PXI box, etc. You could also try replacing the aluminum foil on the acoustic shield to limit electrical noise. Dust on the wafer or tiny gold shards bridging the contact can also be problematic; eliminate these with a blast of compressed air. A bent tip is a likely source of problems; if it's not a severe deformation, you can move the slider far past the point of contact and back, thereby smashing the tip and re-stretching it into a point. If the data looks completely berserk, there might be a problem with your setup, so check manually to see if the gold is making contact and staying in place, or consult an instructor.

FIGURE 3. A Beautiful Stepladder



Once your plateaus look good, you are ready to begin collecting and saving data. Pick the number of traces you would like to collect and enter it in the box labeled **Stop**. Then click **GoPullOut**. This routine will automatically perform that number of traces and save them (as *Igor* wave files) to the

folder created, and echoed in the command box, when you compiled the DAQ routine. You can see how many have been recorded in real time in the box labeled **#saved**.

The GoPullOut routine is a little smarter than the simple PullOut button - it will even smash the tip for you if it deems it necessary! However, there can still be times when the routine hangs, or doesn't save waves, and if so, you need to click **Abort** in the bottom left corner and restart *Igor*. Don't save your Experiment file - it's useless, since you'll be re-creating everything from the Procedure files as before.

As the GoPullOut routine collects traces, you should begin to see a histogram of the traces appear on the screen, with the x axis labeled in units of  $G_0$ . Almost right away, peaks should appear at integer multiples of  $G_0$ . This histogram is just a preview of what you'll do in the analysis section of this lab; you'll generate it again with a different Procedure file when you want to perform the analysis. First, you should go back and make your own pristine gold wafers, set and cut your best gold tip, wait until the traffic dies down on 120th street, and collect a beautiful set of data.

## 6. SAMPLE PREPARATION

See the document on Sample Preparation to prepare your own gold-coated wafers.

## 7. DATA ANALYSIS

Once you have collected a reasonable number of traces using the GoPullOut routine, you are ready to perform some analyses. The analysis is broken into two parts; first, you will fit the histogram of your data and find the quantum of conductance,  $G_0$ ; then, you will create a histogram of the lengths of the  $1 G_0$  plateaus and investigate chain length.

**7.1. Fitting to find  $G_0$ .** This section of the analysis utilizes the Procedure `PullOutAnalysis.ipf`, also inside `C:\Experiments`. First, you *must* open and compile the DAQ panel, as it contains some global parameters that are used in the analysis code. Once both procedures are open and compiled, start the Macro `PullOutAnalysis` to bring up the analysis panel.

In the box on the lower left, enter only the date of the folder where your data is stored. (The folders are created when you compiled the DAQ code on the date you collected your data. If your folder is called `03_09_07Waves`, enter `03_09_07` in the analysis panel.) Make sure the `Drive` directive is `C`.

As you click the increase arrow next the box labeled `start#`, you should see the trace with that index reappear on your screen. Take a look at a bunch of your data and make sure all the runs look reasonable - if there is a stretch of data that is extremely noisy, you may wish to use a part of your dataset that doesn't include this batch.

Try smoothing out some of the noise by enabling the `Smooth Cond.?` feature. You can perform the same smoothing algorithm multiple times on the same trace by increasing the `Repeat` index. Once you choose a smoothing depth, it will be applied to all traces before they are added to the histogram you are about to create.

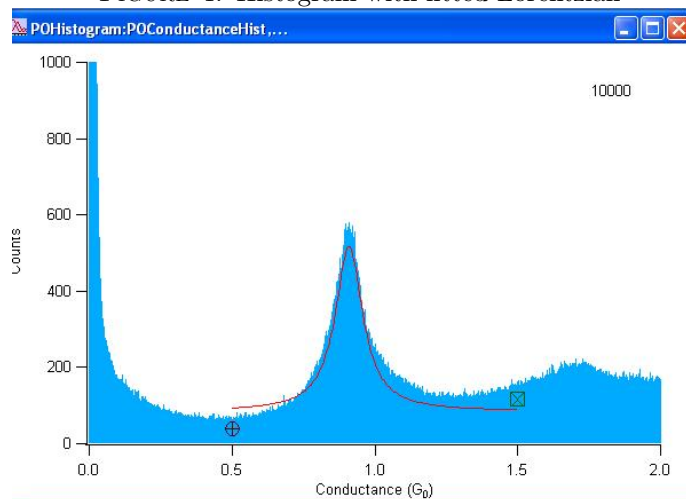
First, try generating a histogram of some small part of your dataset, so you can get a feel for the right smoothing parameters. Enter the range of trace numbers you wish to histogram in the boxes marked `Start` and `Stop` (usually the traces start from 0); the total number to be included will appear in `#Inc.`. You may also play around with the bin size by altering the number in `Bin`. (And if you want to histogram values greater than  $2 G_0$ , change the number in the `Max` box.)

When you finally click the blue button `HIST`, traces are added one at a time to a new window containing your histogram, which should begin to look roughly like Figure 4. When it finishes,

re-scale the graph until you can see its features. The red curve over the 1.0  $G_0$  area is *Igor's* best attempt at a Lorentzian fit; the fit parameters, which are critical to your lab report, are echoed in the command window. You can look up their meaning by searching for the Lor function in *Igor's* help browser.

When you histogram the entire dataset (or your chosen subset of “good” traces), you may wish to save the histogram to save yourself the time needed to re-generate it; do this by checking **Save Hist?** *before* you start making it. You may also want to export it for use in your report; see the *Igor* manual section on saving graphics.

FIGURE 4. Histogram with fitted Lorentzian



**7.2. Investigating the chain length.** This part of the analysis is still under construction. Consult an instructor.

## 8. ADDITIONAL EXPERIMENTATION

Consider using a different, highly conductive and highly malleable metal to collect traces. Consult an instructor.

## 9. APPENDICES

**9.1. Appendix A: Remaking the Needle.** To re-make the needle that holds the gold wire, you will need two sizes of hypodermic needle tips (0.067” and 0.010” inner diameter), teflon tape, a small wooden stick, stainless steel solder and flux, a soldering iron, and some cheap 5-minute epoxy. All of these supplies are kept in the plastic drawers in the QC room.

De-solder the existing inner needle from the wire and unscrew the grounding wire from the top block for an easier job. Use pliers, cutters, or a knife to remove both existing needles, leaving only a clean hole in the top block.

Cut the plastic heads off the new needles, and cut the larger needle a shorter length than the smaller one. Wrap the entire length of the smaller needle in teflon tape and ensure it will slide all the way through the outer needle (if not, wrap the tape more thinly). Make a quarter-sized

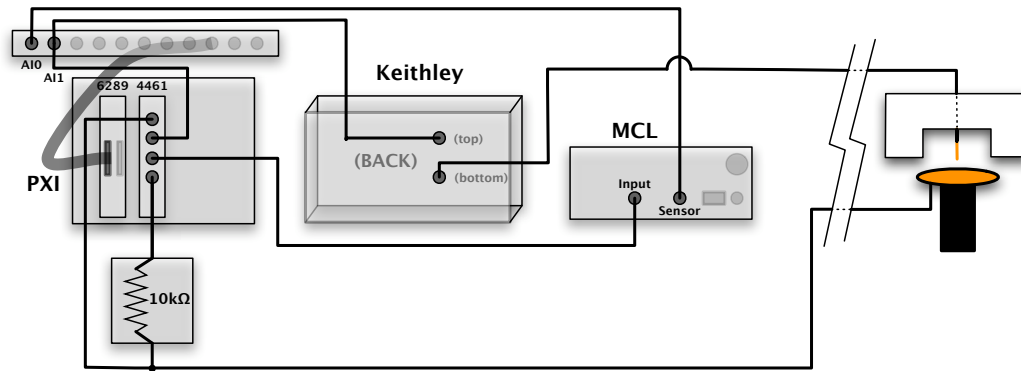
amount of epoxy and try to insert it as much as possible into the region between the inner and outer needles.

Insert the needle combination into the top block. Make sure the smaller needle is oriented with the side you didn't cut down, or the gold wire won't fit!. Use the rest of the epoxy to secure the outer needle to the top block.

The top of the inner needle will need to be fluxed in order to attach the wire. First, melt a dab of stainless steel solder onto the iron's hot tip. Dip a wooden stick in the flux and touch it and the iron to the needle simultaneously. Solder should adhere to the needle, which will then attach to the wire via normal soldering procedures. *DO NOT TOUCH THE FLUX OR BREATHE ITS FUMES, AS IT IS EXTREMELY HARMFUL.* Do not forget to also attach the grounding wire.

**9.2. Appendix B: Connections.** Figure 5 depicts the exact wiring diagram. All wired connections are shielded coaxial cables with BNC connectors, except at the actual device itself. The main housing should be grounded to the shield of one of the wires. The equipment should be turned off before any connections are changed.

FIGURE 5. The wiring diagram for this experiment



**9.3. Appendix C: Acknowledgements.** This lab was made possible by the generous guidance of Professor Latha Venkataraman and her graduate students, particularly Masha Kamenetska, who operate almost identical equipment in a research lab in the Department of Applied Physics and who donated their software for use in this lab. Professor Morgan May oversaw the development. Kiyoo Igaya, Ori Druks, and Jeremy Carlo were also of assistance.