

Fabricating and Measuring an Atomic Point Contact

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Abstract

This paper describes a method for fabricating and measuring an atomic point contact. An atomic point contact is defined, and the requirements for making and studying one are described. The mechanical break junction which is the method for creating the contact is described, as well as the methods for mechanically isolating the contact from the outside environment. Also, the methods of measuring the electrical properties of the point contact are included.

Introduction

Lately, there has been much interest in creating atomic point contacts and studying their properties. Some of the properties which have been studied include formations of atomic chains before breaking, integer multiples of conductance being present[3] and shot noise suppression at those integer multiples of the quantum of conductance.[5] It is hoped that if a very stable atomic point contact can be created in this lab, then additional properties of the atomic point contact can be investigated. Some examples include a test of the reproducibility of shot noise suppression at multiples of conductance with possible applications in the engineering of integrated circuits[1]and a study of the possibility that shot noise is suppressed not only at integer multiples of conductance, but also because of electron correlations, as has been theorized.[7]

Atomic Point Contact

What is an Atomic Point Contact?

An atomic point contact is a special electrical device, which consists of two atomically sharp electrodes which are held close enough to each other in space for electrons to tunnel from one electrode to the other. This arrangement has many special properties which one may want to study, which will be discussed later, but before these properties can be studied, some requirements must be met that make it possible to study the atomic point contact.

Requirements for Studying the Atomic Point Contact

First, the electrodes must be in an ultra high vacuum. Because of the nature of the point contact, if it is not in a vacuum, it is possible that a molecule of some gas could get stuck between the electrodes. That might provide an excellent experiment, studying how electrons travel through a single molecule, but, as the properties of the point contact to be investigated here are based on electrons tunneling in vacuum, that would be detrimental. In addition to being in an ultra high vacuum, an apparatus is necessary for creating the atomically sharp electrodes in the vacuum, and, that mechanical arrangement must make the electrodes stable for lengths of time longer than the length of time that measurements will take. Also, to make the aforementioned measurements will require some electrical circuitry designed to capture the appropriate data.

Ultra High Vacuum via Low Temperature

There are a plethora of experiments that must be performed in ultra high vacuum, so one might ask why this is a point of enough interest to be discussed in this paper. The reason, is that the ultra high vacuum for this experiment is not achieved in a common way. Many high vacuum systems require a

rough pumping to drop the pressure of the system from room temperature to a few millibar and then a turbo pump to drop the pressure down to high vacuum levels. These first two steps are relatively simple, but to achieve the ultra high vacuum is somewhat more annoying. All of the components in the system have some amount of gas in them that they absorbed while at a higher pressure, and as the pressure of the system drops, these objects outgas, causing a perpetual low pressure that takes long periods of time with the turbo pump to drop to ultra high vacuum levels. Sometimes this process is expedited by baking, heating the system so that any of the gases escape more quickly, but this is still a time consuming and less than exciting process. We use an approach that is much faster, and in my opinion, much easier. Table 1 shows the freezing points of some gases commonly found in the atmosphere. We achieve an ultra high vacuum by submerging the experiment in liquid helium, which is much colder than any of the freezing points of these gases, at a temperature of about 4.2 K. This means that as soon as the casing in which the experiments is contained reaches thermal equilibrium with the helium, any gas in that container will freeze solid when it makes contact with the wall. So what we do is pump the experiment down with a roughing pump to just a few millibar and then cool it down, and all of the gases that remain in the container freeze to the walls where they cannot interfere with the experiment.

Mechanical Apparatus

Mechanical Break Junction

The most difficult aspect of the entire experiment is the question of how to break a wire and then bring it back together within the width of an atom. This task is accomplished with the mechanical break junction in this experiment. The design of the mechanical break junction described here is a variation of the improved break junctions used by many groups[8][9][3] from the original design of Moreland and Ekin[2]. This mechanical break junction consists of a flexible substrate to which a thin gold wire is attached, some counter supports, a driving rod for wire breaking and a piezoelectric stack for fine control of the atomic point. The driving rod is just a screw that drives the flexible substrate as it is turned. The motion of the screw is reduced by the arching of the substrate so that the range of the screw is just enough to break the wire. In our experiment, the screw is connected to a long rod and a knob which sits outside of the helium dewar and can be turned by the experimenter. When the screw has been turned enough that the wire is broken, the piezo stack is used to control the motion of the two broken points on a very fine scale. A piezoelectric crystal is a device which transforms electrical energy into precisely controlled mechanical displacements[4]. The crystal has some structure that when an electric field is applied across it, the structure changes by stretching or squeezing a small amount. So we control the motion of the atomic point contact by applying a voltage to the piezo until we know we are in a regime where electrons tunnel. The piezo we use has a maximum displacement of $11.6 \pm 2.0 \mu m$ when 100 volts are applied. These micrometer displacements are much larger than the displacements we need, but thankfully, the displacement of the piezo is reduced by a factor of about 10 in the low temperature environment, and, there is also motion reduction caused by the flexing of the substrate.

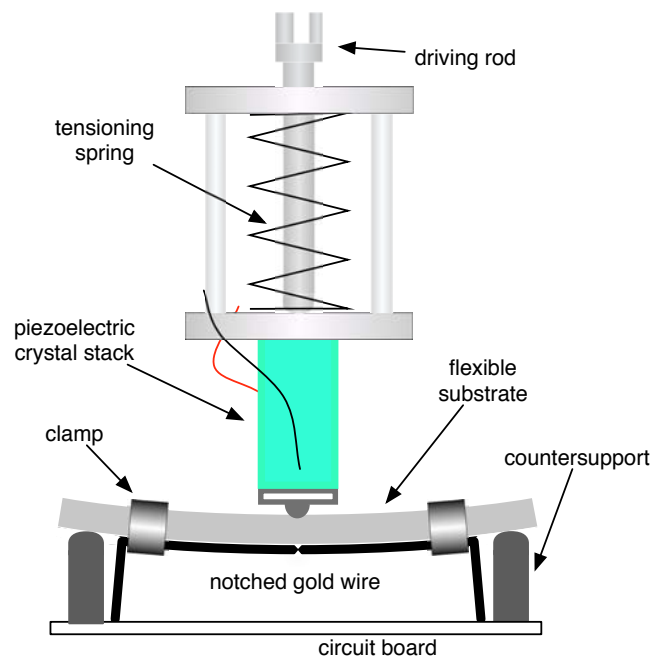


Figure 1: A diagram of the mechanical break junction

Gross Vibration Isolation

Since the atomic point contact is a device with two electrodes with sizes measured by angstroms, separated by length scales measured by angstroms, any vibrations that cause relative motions between the two sides of that size could be devastating to an experiment that requires the contact to be stable for more than a few seconds. The experiment rests at the bottom of a large dewar, and if this dewar sits on the floor on its wheels, as it is usually stored, all of the vibrations in the floor couple to the experiment through that physical connection. The first step to removing vibration is to lift the dewar away from the ground. We hang the dewar from the ceiling with a chain hoist, but now, since each chain link is connected to each other link in a rigid fashion, and there are just as many vibrations in the ceiling as in the floor, something else is needed. We add a non rigid element, a bungee, between the chain hoist and dewar which provides a passive method of isolating from vibration. The bungee is a low pass filter for mechanical vibrations with a cutoff frequency of $\omega = \sqrt{g/L}$ where g is the usual $9.8m/s^2$ and L is the length of the stretch of the bungee. There is no need to be concerned about vibrations of such a low frequency for the following reason: the wavelength of the vibration is much larger than the length scale of the experiment. Since the wavelength is much longer than any of the length scales in the experiment, all of the parts ride the wave together, as opposed to a very high frequency vibration where the parts are at different heights of the wave, moving relative to each other in a ruinous way.

Fine Vibration Isolation

Even though the experiment hangs from the ceiling on a spring (bungee) it could still happen that acoustic vibration in the air could vibrate the walls of the dewar and thus the experiment. Another layer of isolation was added to prevent this kind of vibration from disrupting the experiment. There are rods that

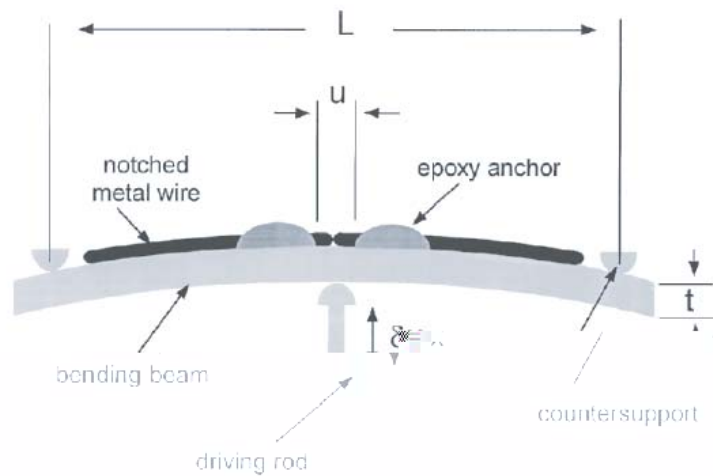


Figure 2: A diagram substrate in the break junction. The flexing of the substrate reduces the motion of the atomic points in relation to the displacement applied to the substrate by a factor of $6tu/L^2$ [8]

support the experiment which attach to the body of the probe which in turn is rigidly connected to the body of the dewar. So, to eliminate the possibility of this vibration finding its way to the experiment, instead of connecting the rods directly to the experiment, the rods connect via springs, which isolate the system in the same manner as the rough vibration isolation. There are also connections with the various wires to make the electrical measurement so it is a requirement that the spring constant of the wiring be less than that of the spring, or else the vibrations travel through the wiring. There is one last connection through which vibrations can pass. The driving rod that runs from the outside of the dewar all the way down to the back of the beryllium copper substrate. To break this connection, the driving rod is not actually solid, but has a fork coupling to the screw that actually drives into the back of the device. The fork allows the driving rod to be engaged until the wire is broken, and then turned back a quarter of a turn so that the driving rod and all of its vibrations have no actual contact with the experiment.

Electrical Arrangement

Conductance Measurement

One of the properties of the atomic point contact which is necessary to measure is the conductance. Conductance is the reciprocal of resistance, so instead of $V=IR$ as is usually seen, $I=GV$ where G is conductance. It can be seen from the equation that to know G , it is necessary to know the current through the atomic point contact and the voltage across it. We make these measurements with the circuit in figure 1. There is a voltmeter that is used to measure the potential difference across the contact and there is another volt meter used to measure the potential difference across a bias resistor. If the value of this bias resistor is known, the ratio of the voltage across the resistor to the value of the resistor gives the current through it ($V=IR$). Also, Kirchoff's current law states that all current entering a junction must leave it, so this means that the current through the bias resistor must be equal to the current through the atomic point contact. In this way, we measure both V and I , and thus, can calculate the conductance.

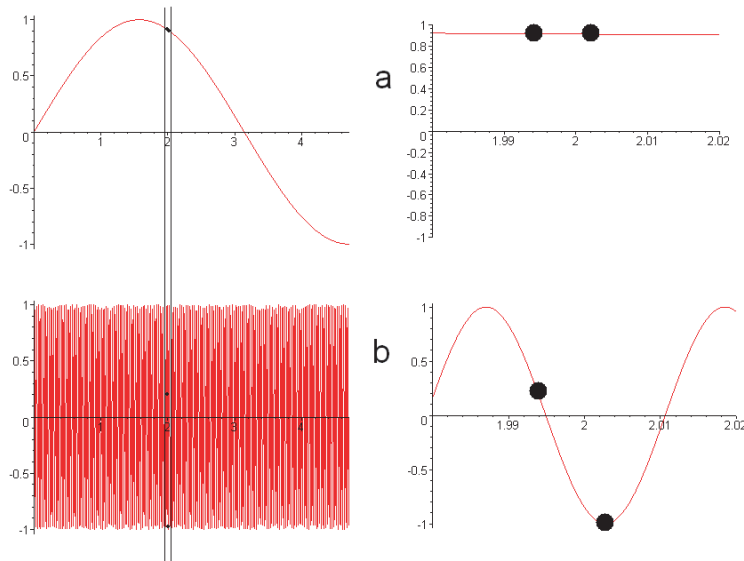


Figure 3: A diagram of two cases of vibration making its way into the experiment. a) a low frequency wave and b) a high frequency wave. The left side shows a full wavelength of the low frequency wave in arbitrary magnitude versus arbitrary position and the left hand side shows a view of a length scale of the experiment for the two waves (as indicated by vertical lines on the left) with the black dots representing the electrodes of the atomic point contact

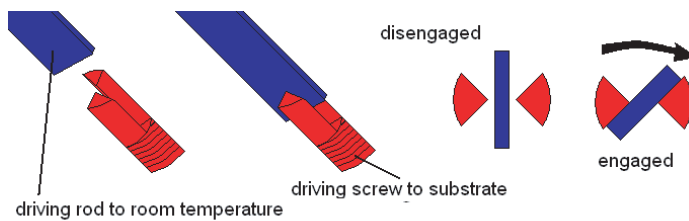


Figure 4: A diagram of the fork coupling. The first frame shows the separated components, and the second shows how they align in the system. The third and fourth frames are a cross sectional view of the state where the driving rod has been pulled back a quarter turn so that it does not make contact with the experiment, and a view

Shot Noise Measurements

What is Noise

Noise means random fluctuations about an average signal. and noise is a very important part of the measurements made on the atomic point contact. Unfortunately, or fortunately, depending on who you ask, it is not completely true that $V=IR$, or in the notation preferred here, that $I=GV$. It turns out that this is a statement of averages. If one assumes that the conductance of the device is fixed, which it should be, and a constant voltage is applied, then, for some time average of the current, $\langle I \rangle = GV$. But at any instant in time $I \neq GV$. The actual values for I can be high or low, as they fluctuate about the average current as shown in figure 2. This fluctuation is called current noise, and it turns out that the atomic point contact has some interesting current noise. But to measure noise, we need a way to characterize it, some nice number that says something about the fluctuations without listing all of the measured data. The number used to describe the magnitude of these fluctuations is the spectral density. The spectral density is found by taking the magnitude squared of the fourier transform of the time varying fluctuations in the current

and it is denoted S_I .

How to Measure Noise

If we want to have a reliable measurement of S_I , it can be seen that many measurements are necessary. Suppose that we want to know the value of S_I to 1/1000 and we measure the value of the current once per second. We can use the equation $\Delta S_I/S_I = 1/\sqrt{\beta\tau}$ [6], where β is the bandwidth and τ is the integration time and $\Delta S_I/S_I$ is the fractional uncertainty in S_I , to calculate how long we would have to wait, it turns out that we would need to wait 1 million seconds which is about 11 days and annoyingly long. If however, we measure the fluctuations at a higher frequency, say 1 MHz, the length of time that must be waited for such a measurement of S_I can be greatly reduced. However, we cannot use the same circuit to measure the high frequency fluctuations that we used to measure conductance, which is a DC measurement. Because we have the experiment at a low temperature, in a helium dewar, there is a long coaxial cable that must carry the signals from the experiment to the measurement equipment. This cable has capacitance between the inner and outer conductors, and the impedance a signal feels due to a capacitor is inversely proportional to the frequency of that signal, high frequency signals would rather jump across the cable and thus bounce around down in the bottom of the dewar than make it up to the measurement equipment. However, using the appropriate arrangement of electronics, that signal can be convinced to find its way to the measurement equipment. We use an LC resonance circuit to transform the signal down in voltage but up in current. So now, if we think of the cable as an impedance that is variable depending on frequency and the measurement device as a resistor that is fixed for all frequencies, then the measurement is a divider; as the current is stepped up by the LC transformer, more and more signal is dissipated in the measurement device, and for the appropriate values of L and C, the signal is indeed large enough to be measured reliably.

Shot Noise

Now we know we can measure noise, but one of the special properties of the atomic point contact is that it has a specific kind of noise called shot noise. Shot noise is present here because shot noise is caused by electrons tunneling, and as the atomic point contact is defined as two atomically sharp electrodes between which electrons tunnel, it is obvious that once we have successfully made the atomic point contact, there is shot noise. Shot noise was first predicted in 1918 by Walter Schottky[10] and the spectral density of this shot noise goes as $S_I = 2e\bar{I}$ where e is the electrons charge and \bar{I} is the average current.

Results

Is this setup adequate?

The purpose of this mechanical and electrical arrangement was to produce a stable atomic point contact so that shot noise and conductance could be measured. The following two plots show that for a measurement of noise and conductance, the atomic point was stable. If it had not been stable, the IV curve would

Microwave Noise Measurement Circuit

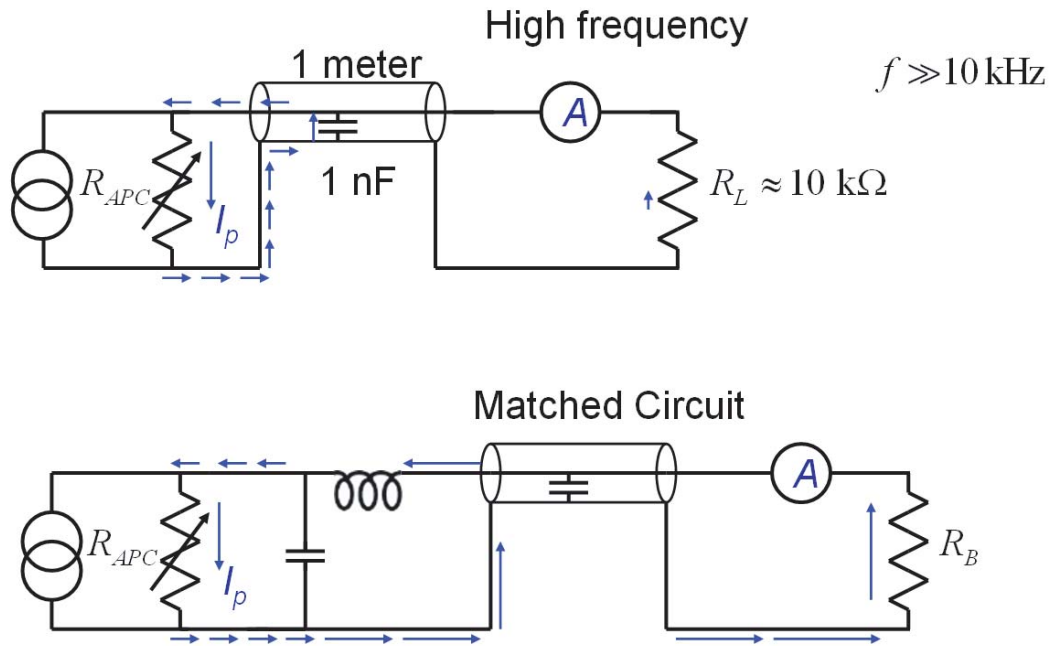


Figure 5: A diagram of the difference between attempting to measure noise at high frequency without and with matching

not be a straight line, curvature or bumps would indicate that the conductance changed over the time the measurement was conducted. Such curvature could come from a change in the relative position of the atomically sharp electrodes, or perhaps some molecule of gas being stuck between them. Also, the noise curve makes a nice V, where each arm has a slope of $2e\bar{I}$, which is exactly what we would expect to see from a shot noise measurement with a stable conductance.

Conclusion

The plots presented in the results were taken over a two minute time period, so the point contact was stable for at least that length of time. These measurements were in some cases repeated consistently for hours, while other times they lasted only a few minutes. This indicates that the structure used to correct them works reasonably well, it would be nice to have stable points that lasted for hours more often, but it could be that every time a new gold wire is used, the geometry of the breaking when the wire is pulled apart has some influence on stability and that cannot be controlled. It is also possible that some improvements could yet be made to the apparatus such as a feedback loop to control possible hysteresis of the piezo crystal. Overall, the ability to repeatedly make atomic point contacts for study has been demonstrated, and now the special properties can be studied.

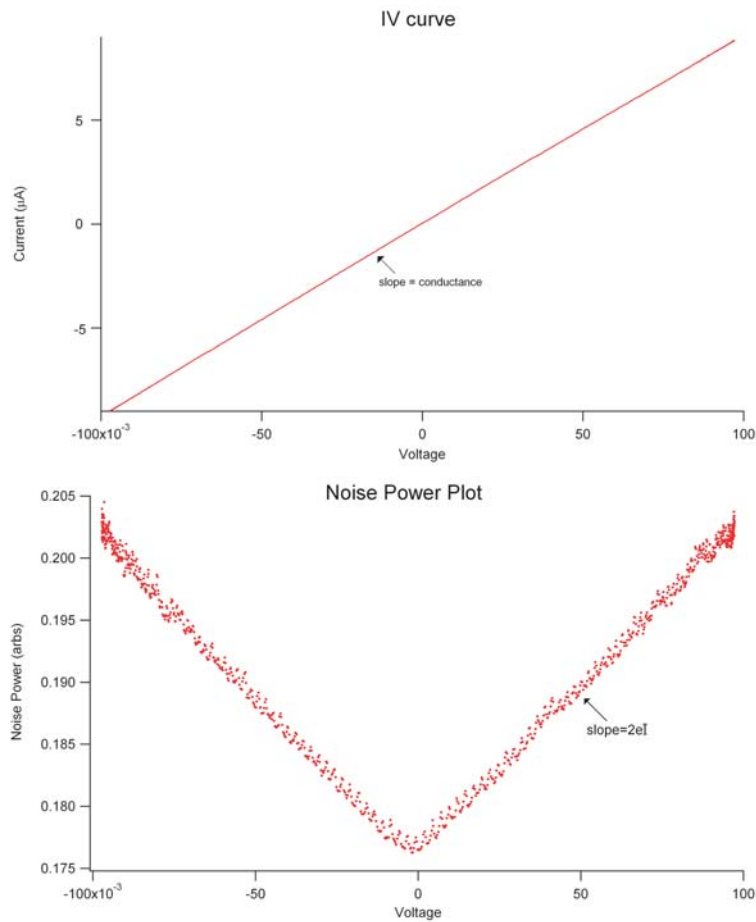


Figure 6: *top: A plot of an IV curve taken from an atomic point contact bottom: A plot of a noise curve taken from the same atomic point contact*

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I also thank my advisor Konrad Lehnert for providing us with such an interesting experiment from which interesting data could be acquired in a 10 week period. The most interesting part of all of this was actually trying to understand and analyze the data.

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References

- [1] B. Zimmerman. *A New Resistance Standard - Microwave Measurements of Shot Noise Suppression in an atomic point contact* University of Colorado JILA, August 2006.
- [2] J. Moreland and J. W. Ekin. Electron Tunneling Experiments Using Nb-Sn "Break" Junctions. *Journal of Applied Physics* **58** 10, 3888 (November 1985).
- [3] A. I. Yanson. *Atomic Chains and Electronic Shells: Quantum Mechanisms for the Formation of Nanowires*. PhD thesis, Universiteit Leiden, February 2001.
- [4] W.P. Mason. *Piezoelectric Crystals and their Application to Ultrasonics*. Van Nostrand, 1950.
- [5] H.E. van den Brom, J.M. van Ruitenbeek. Quantum Suppression of Shot Noise in Atom-Size Metallic Contacts. *Physical Review Letters* **82**, 1526, (February 1999).
- [6] D.M. Pozar. *Microwave Engineering*. John Wiley and Sons Inc., second edition, 1998.
- [7] C. Sloggett, A. I. Milstein, O.P. Sushkov. Correlated electron current and temperature dependence of the conductance of a quantum point contact. arXiv:cond-mat/0606649 v2 (2006)
- [8] J. M. van Ruitenbeek, A. Alvarez, I. Pineyro, C. Grahmann, P. Joyez, M. H. Devoret, D. Esteve, and C. Urbina. Adjustable Nanofabricated Atomic Size Contacts, *Review of Scientific Instruments* **67**(1), 108 (Jan 1996).
- [9] C. Zhou, J. Muller, M. R. Deshpande, J. W. Sleight, and M. A. Reed, Microfabrication of a Mechanically Controlled Break Junction in Silicon, *Applied Physics Letters* **67**(8), 1160 (Aug 1995).
- [10] W. Schottky, *Ann. Phys. (Leipzig)* **57**, 16432 (1918)