Quantized Conductance in Quantum Point Contacts

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The quantized conductance in quantum point contacts (QPC) was observed in 0.05mm Gold, 0.1mm Steel, and 0.025mm Aluminum wires. Steps occurred at the integer multiples of $2e^2/h$, usually at the time intervals of around 1ms. QPCs happened at a very slight contact, as the strings of atoms were forming bridges between the vibrating wires. These connections were comparable in dimensions to the wavelength of an electron. The experiment was based on the earlier work by E.L. Foley *et al* (American Journal of Physics, 67, 389(1999)).

I. Introduction

Since the invention of the first transistor electronic devices kept decreasing in size to improve performance and power consumption. If the technology will continue to progress at the present pace, the devices will become so small that they will no longer be governed by diffusive conduction model used today. Instead, nano-machines will obey quantum laws of nature, which are quite foreign to modern industry. Therefore, it is becoming increasingly important to investigate quantized conductance and behavior of matter at atomic scale in order to build reliable circuitry. Usually quantum contacts are made using sophisticated techniques and state-of-the art equipment. However, recently it was shown that quantum contacts can also be shown by gently vibrating two thin wires. This simple experiment, based on earlier work by E.L. Foley *et al* (American Journal of Physics, 67, 389(1999)), will demonstrate how conductance across quantum point contacts between the wires of gold, steel and aluminum varies as more atoms come in contact with each other. It will also illustrate which of the metals is more suitable for this experiment. In addition, we will try to determine whether quantized conductance is affected by changes in current.

II. Background Information

It is still a question whether conductance steps, which occur in metals with Fermi wavelength λ_F close in value to atomic spacing, correspond to the actual conductance quantization, rather than to a simple rearrangement of atoms[2-7]. However, it is clear that as the Fermi wavelength λ_F becomes much larger the conductance steps will become less dependent on atomic rearrangements. For instance, the experiment involving nanocontacts in bismuth undoubtedly shows that the conductance steps, along with resultant histograms correspond to the number of allowed conduction modes. [1,7] Unfortunately, this experiment is only available at low temperature. For the purpose of our experiment we are using metals (Au, Al, Fe) at room temperature, with Fermi wavelength close to the atomic spacing, therefore the pattern of conductance steps may be affected accordingly.

In order to understand what the conductance steps actually are and why they occur at the integer multiples of $2e^2/h$ we need to refer to a simplified explanation of this complicated phenomena[1]:

1. $I = Q/t = Ne/t = Nev/L$

Current is defined as the flow of charge, thus it is $I = Q/t$. Net charge Q, is the number of electrons N times the charge e of every contributing electron. In addition, time can be through of as velocity of an electron v, over the distance L that it travels.

2. $G = I/V = Nev/LV$

Conductance G is a reciprocal of resistance.

3. $\Delta U = eV$

Drop in potential energy for every electron involved is simply its charge multiplied by the voltage across the sample. Thus, $V = \Delta U/e$.

4. $G = Ne^2v/L\Delta U$

From 2 and 3, we can infer that the conductance G is dependent on the number of electrons, their charge, velocity and drop in potential energy, as well as the length of the wire. However, the key to this problem lies in finding the number of electrons N, which contribute to the conductance.

5. $\lambda = L/n$

According to quantum mechanics for a particle in a box, in a box of length L, de Broglie wavelength of an electron can only take distinct values: $\lambda = L/n$, where n=1,2,3...

6. $v = h/\lambda m$

In addition, it can be inferred from the Heisenberg Uncertainty Principle as well as from Quantum Mechanics for a particle in a box that $v = h/\lambda m$, where h is Planck's constant, m is mass, and λ is the wavelength of the electron.

7. $v = nh/Lm$

But because we know that the wavelength can only take discrete values we can infer that the velocity will also be distinct. Thus $n = vLm/h$.

8. $N = 2Lm\Delta v/h$

According to Pauli Exclusion Principle no two electrons in a solid can have identical quantum states, thus there can only be n energy states that fill up the wire to a certain level (Fermi energy). Since the current flows between the two terminals of the wire, one terminal has to be higher than the other by ΔU. Therefore, the electrons below the Fermi energy of one terminal can flow into the unoccupied states of the other terminal. Because of the electron degeneracy, the actual number of electrons N, contributing to conductance, will be twice the number of energy states n. This will result in $N = 2Lm\Delta v/h$, for a specific range of energy ΔU.

9. $K = mv^2/2$
   $\Delta K = mv\Delta v$

Kinetic energy for an electron of mass m and velocity v is $K = mv^2/2$. However, we are interested specifically in electrons that attribute to conduction G,

which will exist at the specific range of energy ΔE and speed Δv. Thus change in kinetic energy ΔK becomes mvΔv.

$$10.\ G = (2Lm\Delta v/h)e^2 v/L\Delta U$$
$$G = 2Lm\Delta v e^2 v/hL\Delta K$$

From 8 and 2 we can derive that $G = 2Lm\Delta v e^2 v/hL\Delta U$. The change in potential energy of an electron will correspond to the change in kinetic energy of the electron, therefore $\Delta U = \Delta K$.

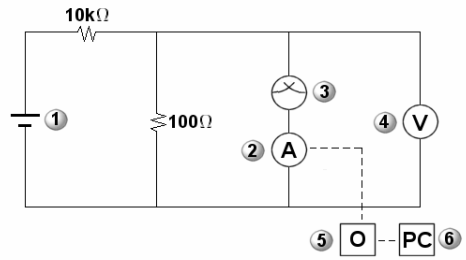
$$11.\ G = 2Lmv\Delta v e^2/hL(mv\Delta v)$$

From 10 and 9, we can infer that $G\ G = 2e^2/h$. Thus the quantized conductance steps in our experiment will occur at the integer multiples of $2e^2/h$. These steps will be flat plateaus that will jump rapidly from one integer value to the next. Remarkably, the quantized conductance steps, as well as the integers where they occur, allow us to "see" the surface of the material.[9] This property of quantized conductance can potentially facilitate many current applications.

III. Experimental Setup

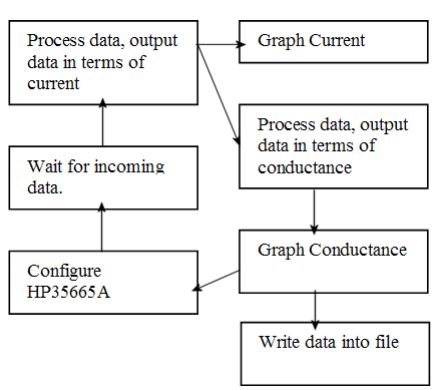
The circuit used for our experiment consists of HP34401A Multi-meter, HP3325B Function Generator, ITHACO 1211 Current Preamplifier, HP35665A Dynamic Signal Analyzer and locally assembled 10kΩ-100Ω voltage divider (Figure 1). We found the adjustable voltage feature on HP3325B particularly useful because it allowed us to easily change voltage across the sample, without replacing the voltage divider. HP34401A was used in the beginning of the experiment to make sure that the voltage across the sample is of the right magnitude. Its use during the experiment is optional. ITHACO 1211 Current Preamplifier was set to the sensitivity of 10^{-3}A, with the constant multiplier of 10. Thus the voltage on the output terminal was 100 times larger than the current on the input terminal. HP35665 Dynamic Signal Analyzer was used to capture the incoming voltage on the interval of 4000 ns and transfer the resulting data to the computer via GPIB interface. We found HP35665 to be slow for this experiment, because it could only take 256 points of data every 1000 ns, which is the necessary timeframe. Although the performance of HP35665 was satisfactory, we recommend using cheaper storage oscilloscopes[1] that take data at a higher

Figure 1. Experimental Setup



1. HP3325B Synthesizer/Function Generator. Adjustable voltage 0-10V. Output resistance 50Ω.
2. ITHACO 1211 Current Preamplifier. Represents current in terms of voltage.
3. Sample.
4. HP34401A Multimeter
5. HP 35665A Dynamic Signal Analyzer
6. Dell Dimension 8300 PC equipped with GPIB Interface Board and Labview 6.1

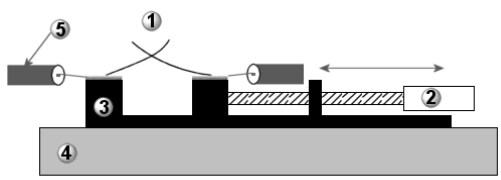
Figure 2. Computer Software



frequency. In addition, we found it particularly helpful to use Labview 6.1 to communicate with HP35665 through the GPIB interface as well as process and output data. Software for Labview 6.1 was written using HP35670A driver (Figure 2).

The sample was assembled using a piece of wood and horizontally adjustable lever. Copper contacts were placed opposite to each other, while gold, steel, and aluminum wires were soldered on top of the contacts. The contacts were then mounted on the lever and soldered to BNC cables to enable easier connection to the instruments (Figure 3). The wires were then vibrated by gently tapping the table or horizontally adjusting the lever.

Figure 3. Sample



1. Gold, Steel, Aluminum wires
2. Horizontally adjustable lever handle
3. Lever
4. Wood (vibration isolation)
5. BNC cables

IV. Results

The primary focus of this experiment is to observe the quantized conductance steps in the 0.05mm gold wires. The best results were achieved at 2V (20mV across the sample) (Figure 5). Histogram (Figure 6) shows clear peaks at 1, 2, 4, 7, and 9. Histograms of other staircase functions looked similar, but unfortunately lacked high resolution, due to inability of HP35665 to measure more than 256 points per 1ms. Measurements were also taken at 10mV, 50mV, 75mV and 100mV. Data above 20mV proved to be inconsistent, especially at 75mV and 100mV where steps practically vanished. This can be attributed to the electron heating effects[1]. Although quantized conductance at higher currents was less common, gold is still a great metal to use in the experiment. Overall data of $1x10^6$ points gathered at 20mV, shows a clear peak at $2e^2/h$ (1). Perhaps decreasing the wire diameter, as well as setting up the sample under a microscope can improve the results. While using larger wires, 0.1mm Steel, quantized conductance became less evident (Figure 7). Lower conductance steps were infrequent and isolated, while the majority was seen around $20e^2/h$ (10). Staircase functions became narrower and contained less steps. We attribute it to the diameter of the wire, which could make the material more resistant towards vibrations that are crucial for the formation of the quantum point contacts. In addition, the atomic structure of the steel can be the cause of the appearance of the steps at the higher conductance. Overall, conductance was measured at 20mV, 50mV and 100mV, yielding the best results at 20mV. Similarly, quantized conductance was seen in aluminum at 20mV (Figure 8). However, the results were rare, proving that aluminum is not suitable for this kind of an experiment. Even at higher voltages (75mV) creating a contact between two aluminum wires was problematic, primarily because of the oxidation. The only results were obtained by twisting the wires together and gradually tearing them apart. Furthermore, because of the awkwardness of the method and rarity of the contact between the aluminum wires, it is unclear whether the staircase

function (Figure 8) is at all a representation of quantized conductance. Unlike gold and steel, which easily exhibit staircase functions, a more sophisticated setup is required to determine if quantized conductance exists in aluminum wires. Oxidation is possibly a factor, since atomic bridges that cause quantum point contacts might be unable to exist altogether.

In addition, we found it necessary to adjust conductance, as described in E.L.Foley, by including the output resistance of the voltage source as well as residual resistance.

$$G_c=(G^{-1}-(R_{res}+ R_{out}))^{-1}$$

We found residual resistance to vary for every metal and voltage used. R_{res} helped us to shift the histograms peaks to the right spots.

Overall, the experiment demonstrated that it can easily be set up in a lab and can be used to explore the properties of quantum point contacts, especially in gold and steel wires. While the experiment requires originality, especially in sample setup and data acquisition, we find these challenges to be a great learning tool for college students, that sheds the light on many aspects of modern physics lab.

V. Acknowledgments

This research was made possible by National Science Foundation and National High Magnetic Field Laboratories. Special thanks to Dr. Jan Jaroszynski, Dr. Dragana Popovic and Dr. Sergey Vitkalov for scientific expertise and the valuable advices.

VI. References

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Figure 5. Quantized Conductance Steps in gold wires. (0.05mm 20mV)

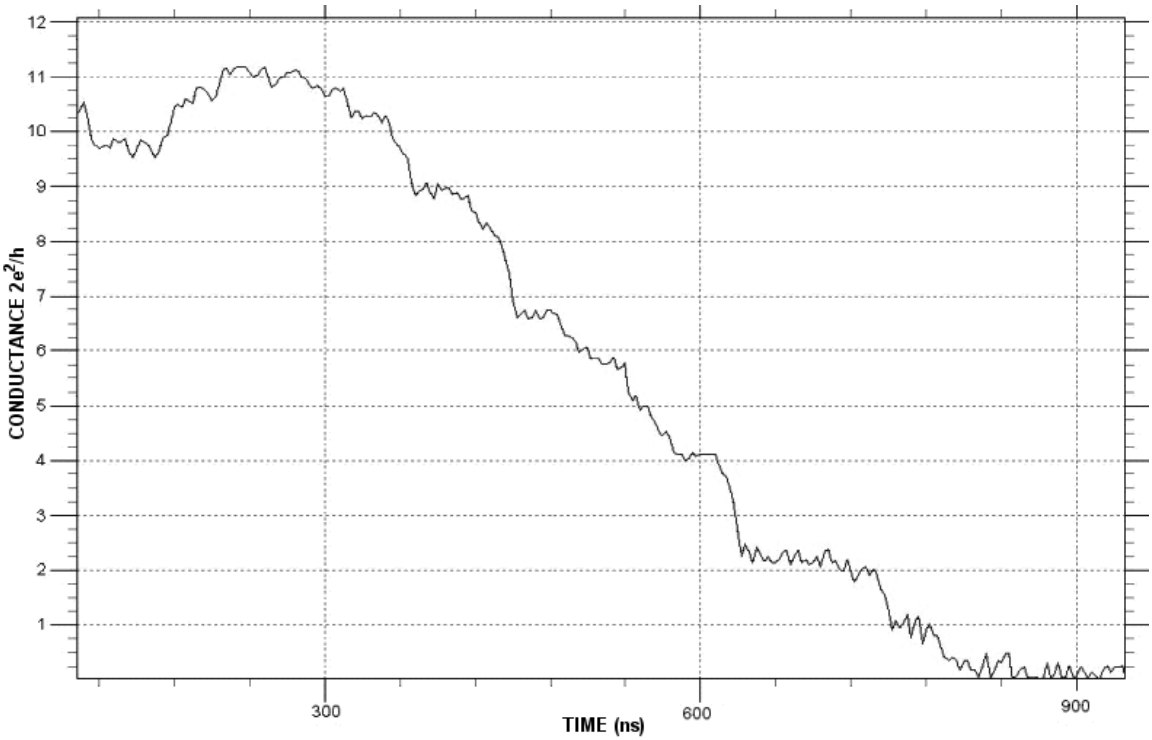

Figure 6. Histogram of Quantized Conductance Steps in gold wires (0.05mm 20mV)

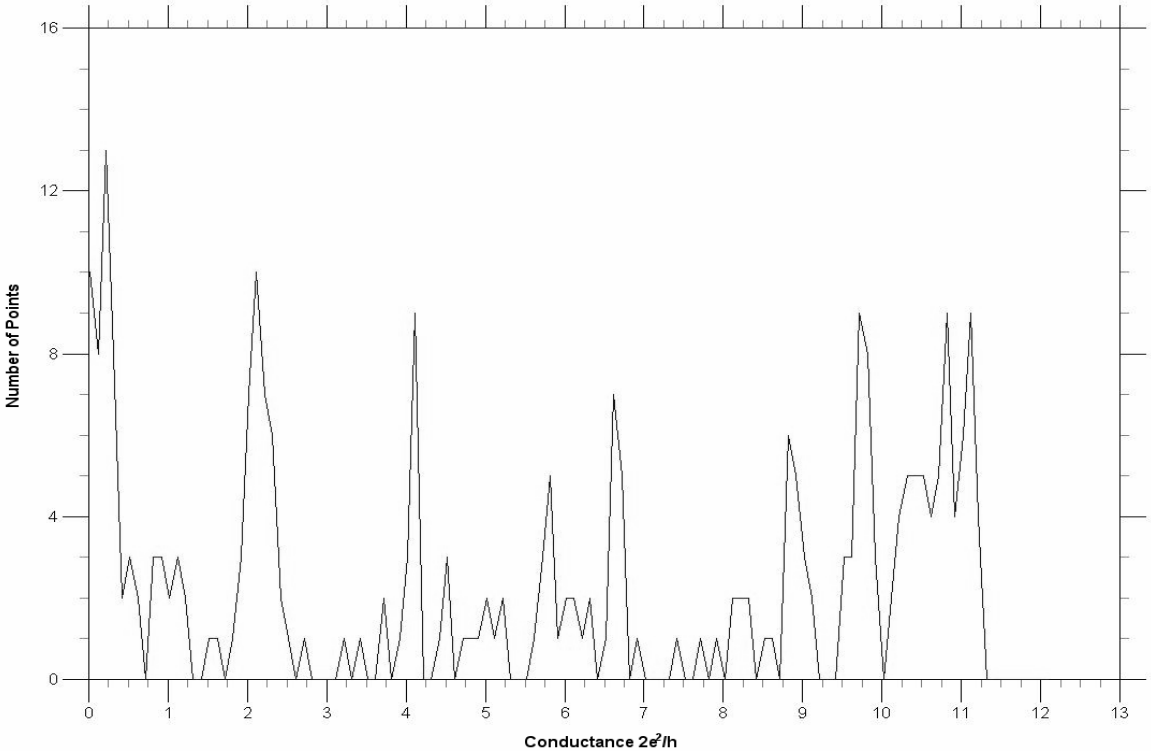

Figure 7. Quantized Conductance Steps (.1mm Steel wires at 10mv,)

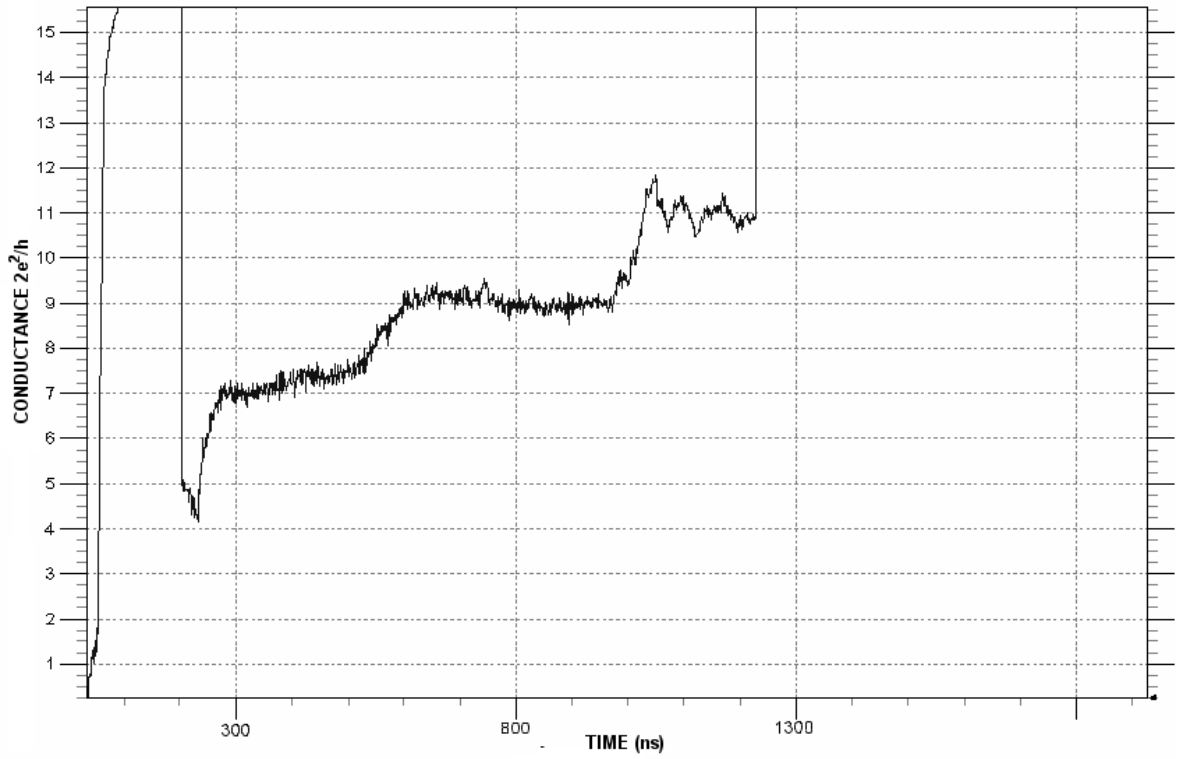
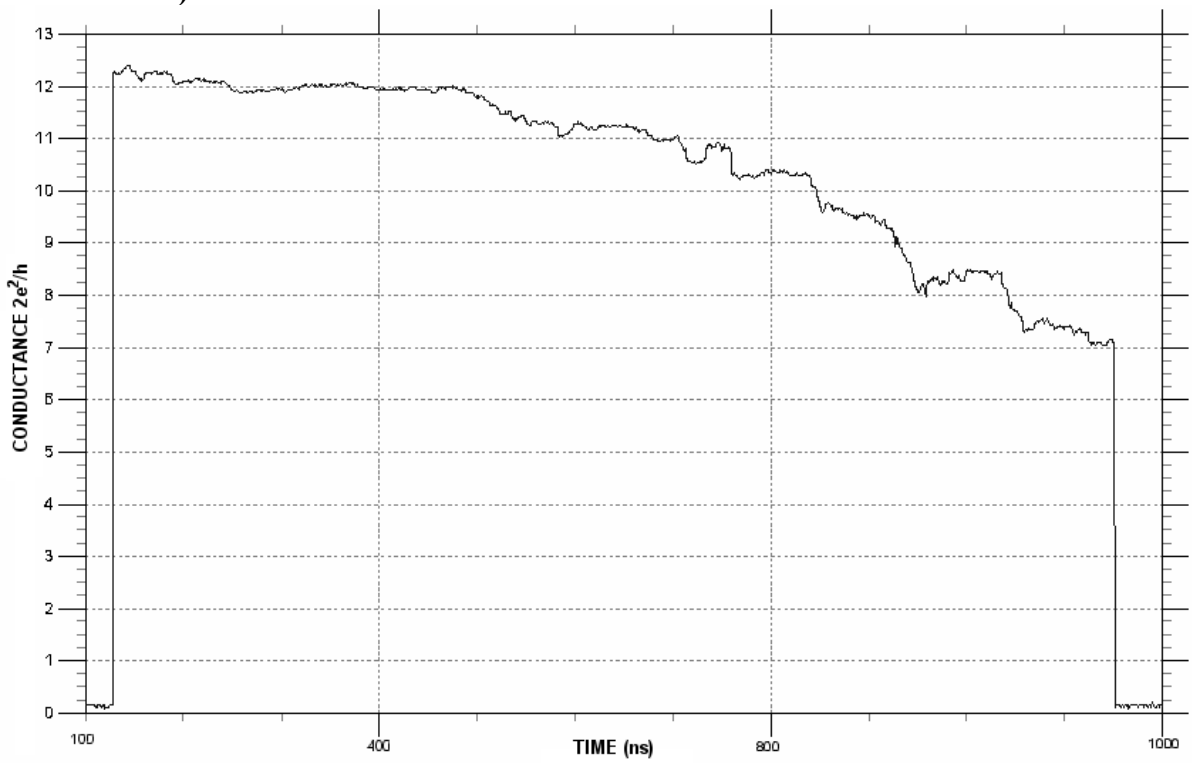
Figure 8. Quantized Conductance Steps (.025mm Aluminum wires at 20mv, RRES=450Ω)