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Observing Conductance Quantization by a Novel Magnetic Control System

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Highlights

- A low-cost system was designed for investigating conductance quantization.
- This study includes quantized conductance experiment by using a relatively simple magnetic system.
- It is shown that it is possible to move an object on a bending beam in the nanometer range.

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Abstract

In this study, a novel magnetic system that allows observing quantized conductance for undergraduate and graduate laboratories is presented. Bending of a magnetic cylindrical beam, like a cantilever, is controlled by an electromagnet to provide contact between needle type electrode and a plane of conductor. It is shown that by using the beam bending, it is possible to displace an object on the beam in nanometer and micrometer scale. The measured quantized conductance results prove that the designed system can be used for demonstration of the quantized conductance.

1. INTRODUCTION

Nanotechnology and nanoscience have attracted the interest of both researchers and the public as they are used in various fields such as technology, energy, and medicine [1-5]. One of the important effects, when the size of the materials is reduced to the nanometer range, is conductance quantization due to the limitation of the movement of electrons [4-6]. The limiting effect is observed when the material size is smaller compared to the mean free path or wavelength of electrons. With this interest, there is a need for researchers and students to understand and develop new methods of nanoscale research.

One of these methods, conductance quantization, was first observed in experiments measuring the properties of a two-dimensional electron gas and GaAs-AlGaAs heterojunction in 1988 [7, 8]. After the first discovery, experimental techniques have progressed significantly towards measuring the electrical and mechanical properties of nanoscale contacts [9, 10, 11]. As examples, conductance quantization was observed in molecular electronics [12] and was used to find contaminants in materials [13]. Interesting results were obtained with magnetic nanocontacts in various studies. Conductance quantization in nickel nanowires [14], magnetostriction with magnetoresistance control [15], and remote control of electrical conductivity with magnetic field instead of mechanical control for Terfenol-D which shows high magnetostriction properties at room temperature are some of these studies [16]. The quantized step structure of conductance was observed by the mechanically controlled break junction (MCBJ) technique for various systems including metals of Al, Cu, and Pt in liquid helium and room temperature [17, 18]. Further studies

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have shown that MCBJ like quantized conductance may also occur in less complex situations. For example, they can occur between two vibrating wires (Au, Cu, Pt and metallic glass) and relay contacts [19, 20]. Recently, also many relatively low-cost MCBJ based setups have been introduced for laboratory experiments [21-24]. The mechanism of this method mainly depends on breaking or forming metallic contacts of a micro diameter wire by applying a force to bend a structure where the wire is attached. As an example of precise measurement methods, conductance quantization experiments for gold nanocontacts was conducted by scanning tunneling microscopy (STM) at room temperature and low temperatures [25]. The STM is used to examine the contact and breakpoints formed between the tip and the sample metal surface. As there is still a need for improvement of the presented systems our work, merges the working principle of STM with magnetic control and break junction method, has the potential to contribute to the studies on the electrical conductivity of nanoscale systems with the advantage of its simplicity.

For this purpose, a simple and low-cost conductance quantization experiment that can be used for undergraduate and graduate laboratories that will be easily replicable due to its simplicity, is designed and implemented. The system, inspired by the STM based setups, consists of a cantilever beam that bends with the electromagnetic force applied by an electromagnet. Electromagnet is controlled by an applied current, resulting in nanocontacts between a sharp pointed edge of a needle on the beam and a metal plate. It is shown that it is possible to create and break nanocontacts and observe the quantized conduction phenomenon with this setup.

2. MATERIALS and METHOD

In quantized conduction experiments, one of the challenging parts is the control of contacts to form nano-dimensional channels between conductors. An alternative solution is proposed in this paper to form these nanocontacts in measurable time ranges, such as several milliseconds to seconds. As shown in Figure 1, the aim of the designed experiment is to control the distance between a conduction plate and a sharp pointed edge (a needle) placed on a beam (solid metal cylinder) by bending the beam with an electromagnet. With this setup, it will be possible to create or break nanoscale electrical channels between the needle and conducting plate by controlling the micro/nanoscale movement of the needle on the beam. The designed system has four main subsystems, electromagnetic control, mechanical control, quantization measurement, and optical bending measurement.

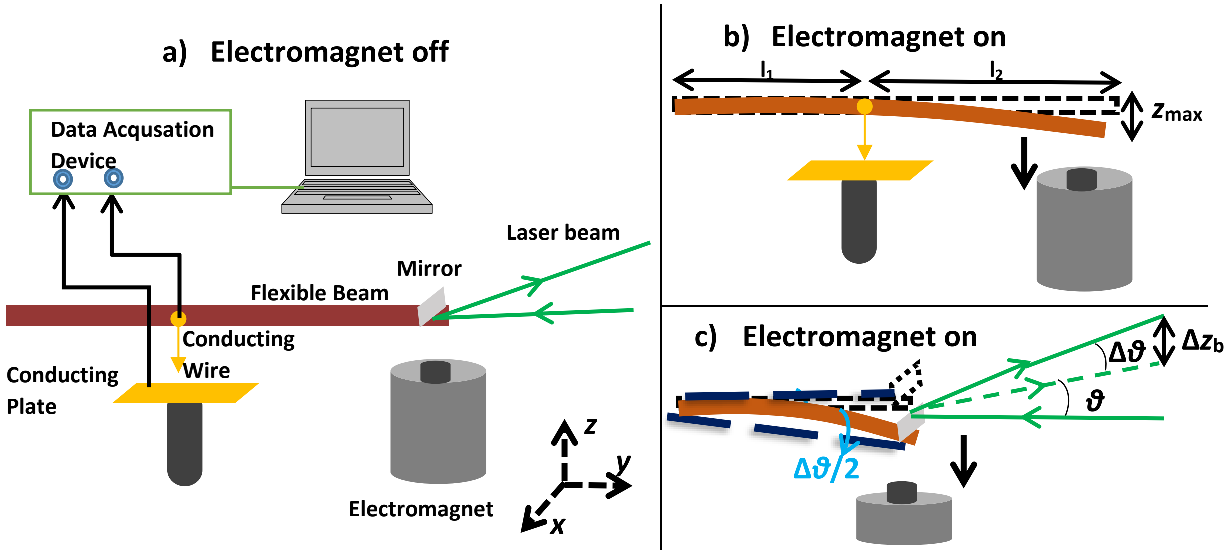

__Figure 1.__ a. Schematics of the setup (electromagnet off), b. bending of the beam (electromagnet on) c. optical measurement of bending (electromagnet on)

2.1. The Electromagnetic Control Part

An electromagnet was designed using 250 turns Leybold solenoid (562 13 Model, L=0.0027 H, 0.6 Ω) with Leybold 560 31 pole piece as the core. The bored pole piece was used with its soft-iron insert. The electromagnet was placed under the end of the magnetic flexible thick beam to apply attractive force. The sharp pointed end of the core is aligned with the beam to create a magnetic field gradient and force. The electromagnet is driven by GW Instek GPS-3030DD model laboratory type DC power supply. The power supply was operated in constant current mode, and it has line/load regulation of 0.2% + 3 mA, and less than ± 4.24 mA ripple current specifications.

In this operation, the sum of gravitational force and magnetic attractive force between the electromagnet and the magnetic beam are the effective forces to bend the beam. Since the weight of the flexible beam wire is negligible, gravitation force for bending can be ignored. The bending of the wire will be mainly due to the magnetic force between the electromagnet and the beam. The beam magnetic susceptibility and the magnetic field magnitude and gradient are important factors of this nonlinear force. It is clear that the magnitude of the applied field, and thus the magnetic force can be controlled by electromagnet current. The distance between the electromagnet and the flexible beam is also an important parameter for the force to control current sensitivity of the system. Detailed information can be obtained from the studies examining the forces between two magnetic systems [26].

2.2. Beam Bending and Optical Bending Measurement

When a current passes through the electromagnet, the flexible beam will bend toward the electromagnet. The bending of the beam when a force of net F (along z direction) is applied from the endpoint can be written as:

$$z = \frac{Fy^2(3\mathrm{L}-y)}{6\mathrm{EI_y}} \tag{1}$$

where y is the distance from the fixed point of the beam, E is the modulus of elasticity (Young's modulus), $\mathrm{I_y}$ is the moment of inertia with respect to the y axis, and L (14.5 mm) is the length of the flexible beam. By using Equation (1), the maximum deflection at the endpoint y = L can be written as:

$$z_{\max} = \frac{F\mathrm{L}^3}{3\mathrm{EI_y}}. \tag{2}$$

Deflection at any y point can be calculated by measuring $\mathrm{z_{max}}$

$$z = \frac{z_{\max} y^2(3\mathrm{L}-y)}{2\mathrm{L}^3}. \tag{3}$$

To measure the z_{max} value, the optic system shown in Figure 1.c is designed. The displacement $\Delta \mathrm{z_b}$ on the wall was found by placing a mirror on the endpoint of the beam, and was used for reflecting a laser on a wall that is $\mathrm{l_d}$=14.5 m from the beam. Along with the displacement Δz_b, cosine theorem ($\cos(\Delta\theta) = 1 - \Delta z_\mathrm{b}{}^2/2\mathrm{l_d}{}^2$) was used to find the $\Delta\theta$ angle. Then, $z_{\max}$ is found using the $\Delta\theta/2$ angle. Electromagnet current I vs z_{max} measurements were taken for different distances between the electromagnet and the beam.

2.3. Mechanical Control

Mechanical control was achieved by placing a micrometer under the conducting plate. The function of this control is to provide a short mechanical contact between the conducting wire and the plate in the first stage, and then to set the smallest step that will disrupt this contact. Therefore, the distance between the conductive wire and the plate can be reduced to the micrometer level. Instead of the micrometer, a fine pitch screw can be inserted here and this distance can be adjusted in millimeter-micrometer range. Keeping this distance short will bring advantages such as keeping the force value dependent on the current lower in magnetic control and increasing the sensitivity by keeping the distance between the magnet and the electromagnet larger.

2.4. Electrical Setup

Resistance changes of the contact between plate and the wire were measured via the circuit presented in Figure 2. A 1.5 V battery (V_0) was utilized to drive the circuit and a resistor of 10 kΩ (R_S) was connected in series to wire and plate junction. Potential difference between the wire and plate was measured with data acquisition card DAQ, LabJack U3-LV unit connected to a computer.

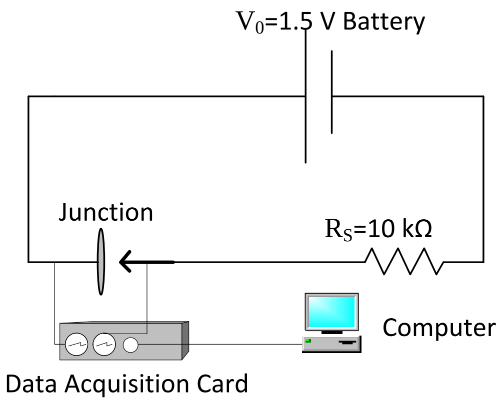

Figure 2. *The schematics of the electrical measurement setup*

When the plate and the wire have no contact the measured potential difference will be equal to the voltage of the battery. When the contact occurs it is expected to have a short circuit and the measured voltage is 0 V. But between these processes it is possible to observe the effect of nanocontacts and so the quantized conduction mechanism can be observed.

The quantized conduction equation will determine the expected value of junction voltage:

$$G(n) = \frac{2e^2}{h} n = G_0 n \; ; n=1, 2, 3\ldots \tag{4}$$

will determine the expected value of the junction voltage measured by data acquisition card. In Equation (4), e is the charge of an electron, h is the Plank constant, *n* is the quantization term. This equation is derived from the quantum mechanical behavior of electrons in a narrow conducting wire or channel. The electrons can only occupy certain energy levels, or "modes," in the channel when the any dimension of the channel is much smaller than the electron wavelength or electron mean free path [27]. These modes are quantized, meaning they can only take on certain discrete values. As a result, the conductance of the channel is also quantized, and can only take on certain discrete values determined by the number of convenient modes, or conducting channels, in the channel. The conductance quantum G_0, shows the smallest possible conductance that can be achieved in a conducting channel. The quantized conduction equation reveals the conductance of the channel to the number of conducting channels in the channel, with the conductance increasing linearly with the number of channels. This relationship has been experimentally documented and is widely used and has great significance in the fields of electronics such as nanoelectronics and biomolecular electronics [4, 27]. G_0 is around 1/(13 kΩ). So the junction resistance is expected to be around 13 kΩ for *n*=1 and decrease as *n* increases. The resistance of the junction (R_j) and the potential difference between the ends of the conducting wire and the plate (Vj) was formulated as

$$R_j = \left\{ \begin{matrix} Open\ circuit \leftarrow No\ contact \\ 1/G(n) \leftarrow Atomic\ contact \\ Short\ circuit \leftarrow Contact \end{matrix} \right\} ; Junction\ Voltage = \left\{ \begin{matrix} V_0 \leftarrow Broken(open\ circuit) \\ V_0 \frac{R_j}{R_j + R_s} \quad \leftarrow Atomic\ contact \\ 0\ V \quad \leftarrow Intact(short\ circuit) \end{matrix} \right\}. \tag{5}$$

3. THE RESEARCH FINDINGS AND DISCUSSION

The beam and the electromagnet distance z_{max} was measured using the optical system shown in Figure 1 to calculate the needle tip to conducting plate distance. The current applied to the electromagnet was started from 3 A and decreased to 0 A and increased from 0 A to 3 A with 0.5 A steps. The electromagnet current I vs z_{max} measurements are presented in Figure 3 for different distances between the electromagnet and the beam.

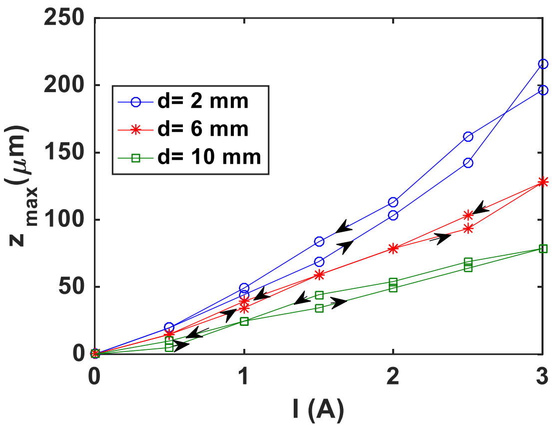

Figure 3. *Maximum beam deflection versus electromagnet current (I) for different electromagnet to beam distances (d)*

Hysteresis like curves were obtained for z_{max} with respect to I. The cause of this can be explained by the change of the magnetic field and its gradient during the bending of the beam. In addition, the nature of the nonlinearities in the susceptibilities of both the beam and the core of electromagnet also contributes. Maximum bending was observed for the minimum distance of d=2 mm as expected and vice versa. Since z_{max} has less nonlinear dependence to the current I at this distance, the value of d=6 mm was selected for further quantized conduction experiments. The approximate position of the needle with respect to its initial position z=0, shown in Figure 4, was calculated by using Equation (3) for the z_{max} value of 127.80 µm when I=3 A and d=6 mm. As seen from Figure 4, it is possible to control the position of the needle tip micrometer range to nanometer range by choosing the needle position on the bending beam.

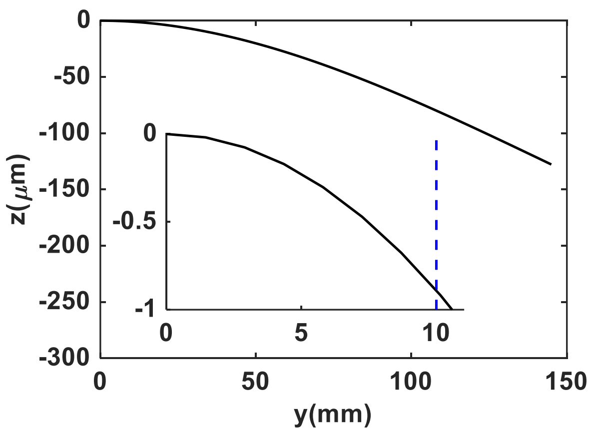

Figure 4. *Theoretical position of the deflected wire with respect to z-y coordinates. Inset: Theoretical position of the deflected wire with respect to z-y coordinates y=0-10 mm (Dashed line: conductive wire position)*

For ideal case, when nanocontacts start, the junction voltage can be calculated using the Equation (5). The junction is initially an open circuit and the junction resistance is expected to start with 1/Go≈13 kΩ and decrease with increasing n and eventually became short circuit. The calculated values of the junction voltage are shown in Figure 5. In Figure 5, time is given in arbitrary units. In this kind of experiments time is usually in milliseconds or seconds. Of course, if the system is stable the states of quantized conduction can be kept for a longer time.

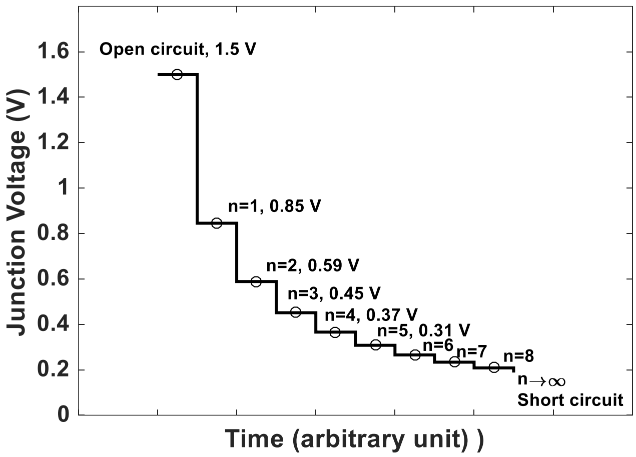

Figure 5. *The calculated voltage values of junction for different n values*

An acupuncture needle was placed at the position of l_1=5 mm (Figure 1.b) on the beam and a coin was selected as a conducting plate. The material of the acupuncture needle is medical stainless steel. The coin is an alloy and made of metals of 75% Cu, 10% Zn, and 15% Ni. First the needle and plate were connected mechanically and after they were separated with a small adjustment. The electromagnet to beam distance was aligned to d=6 mm and experiments started with I=0 A. Afterwards, the current applied to the electromagnet was changed until the start of the quantized conductance observation and the junction voltage was recorded during all operations. As a result of several experiments, the voltage-time curves were obtained. The selected part of the measured junction voltage results are presented in Figure 6a and their histogram is given in Figure 6b. These values were obtained at different current values applied to the electromagnet in the range of 0-3 A. The current values are not given because the values of current were different for the repeated experiments when quantized conductance is observed. In the observed results there are non-integer *n* values, and fast transitions between short circuit and open circuit.

In some quantized conduction studies, voltage values corresponding to non-integer n values have been observed [19, 20, 23, 27]. The non-integer n values were observed even in STM experiments [19, 27, 28]. STM is a mechanically and electronically well-established versatile device with high vibration isolation and generally operated in an ultra-high vacuum. STM tip position is generally controlled by using piezoelectric systems which makes sub-nm scale control over the tip displacement possible. Due to these reasons stable molecular contacts for measurement of the electrical properties are possible. One of the STM based experimental conductance for gold atomic contacts theoretically investigated and non-integer values of the conductance are explained by formation of the diatomic chains [28]. Non-integer values of gold contacts were also observed in both STM and magnetically controlled break junction setups and it is explained by the presence of contaminations and adsorbates at the contacts [23]. They also pointed out that the electrical and mechanical noise has an influence on the histogram [23]. Well controlled impurity, contamination and mechanical instability free experiments with the STM shows clear integer values for gold contacts [29]. In the presented setup, there are no vacuum which makes electrodes open to the contaminations, no special vibration isolation, and the power supply used for driving the electromagnet has a maximum 4.24 mA ripple current, it causes current fluctuations and obviously has influence on the mechanical stability of measurements. In spite of these, as can be seen from the both Figure 6.a and Figure 6.b several quantized conductance levels were observed successfully. Obtained results are found to be consistent with the studies on this subject [19, 20, 22, 23].

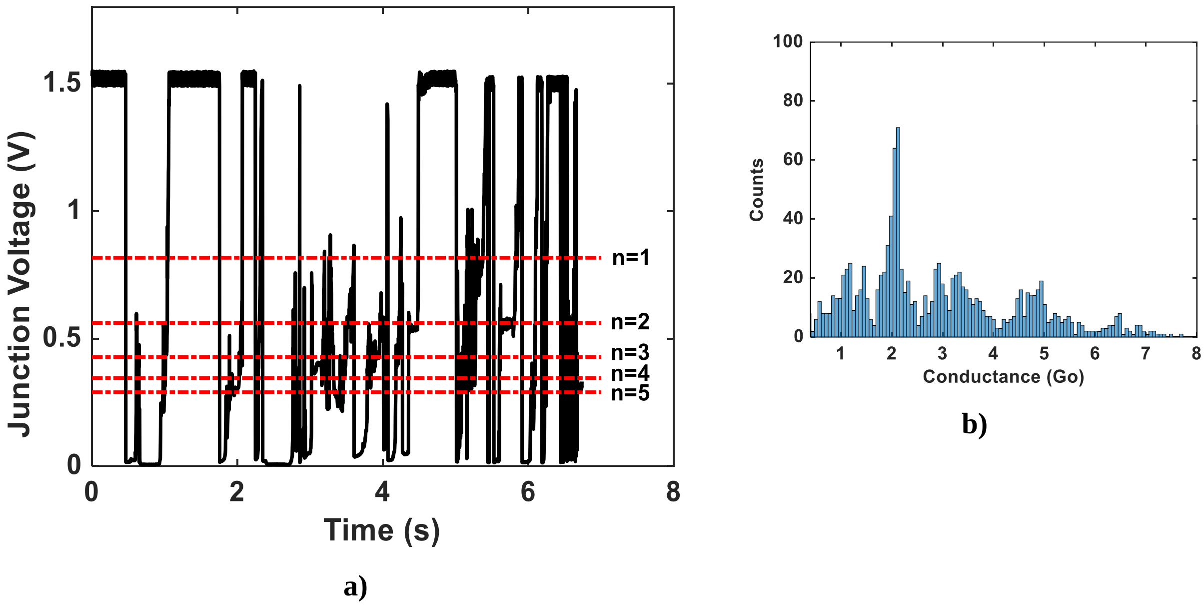

Figure 6. *Measured voltage values (a), their histogram (b)*

4. CONCLUSION

In our study, a quantized conductance experiment was conducted using a relatively simple magnetic system. Bending a magnetic beam is realized using an electromagnet and the maximum bending of the beam is measured by an optical system. It is theoretically shown that it is possible to move a tip, attached to the beam, from nm to µm range by changing its position. Quantized conduction results were obtained by controlling the junction between a simple needle and a coin. The system can be used as an undergraduate or a graduate quantized conductance experiment and also has the potential to improve and helps students to understand the mechanisms of STM-like structures where the precise control of a tip to the material distance is crucial.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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