

# Public exhibit for demonstrating the quantum of electrical conductance

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We present a robust setup that demonstrates the quantum of electrical conductance for a general audience. The setup is continuously available in a public space and allows users to manually thin a gold wire of several atoms in diameter while monitoring its conductance in real time. During the experiment, a characteristic step-like decrease in the conductance due to rearrangements of atoms in the cross-section of the wire is observed. Just before the wire breaks, a contact consisting of a single atom with a characteristic conductance close to the quantum of conductance can be maintained for up to several seconds. The setup is permanently available, needs little maintenance and can be used on different educational levels. © 2011 American Association of Physics Teachers. [DOI: 10.1119/1.3593276]

## I. INTRODUCTION

Reducing the size of electronic components has been a main ingredient for innovation in the electronics industry for over the last half century. By reducing the size of electronic structures, the physics needed to describe the electron's motion changes. A characteristic length scale marking the transition between two different physical regimes is the average distance over which an electron travels before it is scattered, that is, the electron's mean-free path  $L_e$ . For example, in copper  $L_e = 39$  nm at room temperature.<sup>1</sup> This length is comparable to the size of today's smallest electronic components.<sup>2</sup> Hence, we might wonder what happens to the electrical conductance of a conductor when its size is less than  $L_e$ . This question was answered in 1988 when improvements in semiconductor technology allowed the fabrication of nanoscale devices with precisely controllable dimensions.<sup>3,4</sup> If  $L \ll L_e$ , the system is in the ballistic regime. In this regime, electrons still collide with the walls of the conductor, but hardly scatter off each other. The experiments showed that for a ballistic conductor, although hardly any electron-electron scattering is expected, a finite electrical conductance  $G = 1/R = I/V$  is measured. The conductance decreases in a step-like fashion as the conductor's cross-section is continuously decreased. This behavior differs from macroscopic conductors, whose conductance decreases continuously with its cross-sectional area (Ohm's law). Intriguingly, the magnitude  $G_0$  of each conductance step is material independent. It is an universal constant, called the quantum of conductance  $G_0 = 2e^2/h = (12.9 \text{ k}\Omega)^{-1}$ , where  $e$  is the electron's charge and  $h$  is Planck's constant.

The area of condensed matter physics that studies the behavior of systems at these nanoscales is called mesoscopic physics. Concepts developed in this area during the 1980s have greatly shaped our present understanding of electron transport in small electronic devices.

In this paper, we present a demonstration apparatus in which users explore one of the central concepts of mesoscopic physics, the quantum of conductance. The apparatus illustrates that the physics of quantum nanosystems differs qualitatively from the physics that governs our macroscopic world. As a consequence, it is suited for provoking fascination and enthusiasm for nanoscale physics.

## II. THE PHYSICS OF QUANTIZED CONDUCTANCE

The physics that underlies the quantization of conductance results from the quantum confinement of electrons. To see how quantum confinement applies to a nanoscale conductor, we consider a two-dimensional conductor of width  $W$  and length  $L$  connected to two bulk conductors [see Fig. 1(a)]. In the ballistic regime, the electrons can be regarded as freely moving. In the transverse direction, the electrons interfere between the walls of the constriction and form discrete quantum states at energies  $E_n$ . Here,  $n = 1, 2, 3, 4, \dots$  is the index for each wave harmonic [see Fig. 1(b)]. In other words, standing waves between the walls of the conductor are formed similar to a particle in a box, demonstrating the wave-like nature of electrons. The conductance is determined by electrons that propagate along the constriction. In this direction, the electrons are still free to propagate. The 1988 experiments show that the conductance decreases in a step-like fashion as the width  $W$  of the constriction is decreased continuously. This decrease can be understood by realizing that the only discrete states that are actually occupied by electrons are those that lie below the Fermi energy of the conduction electrons in the bulk conductors. The conduction electrons in the metal are characterized by the Fermi wavelength  $\lambda_F$ . Therefore, the index  $n$  of the highest occupied electron state is given by  $n_{\max} \approx 2W/\lambda_F$ . Hence, the number of occupied states can be controlled by changing the width of the channel. Each time the channel width is reduced by  $\lambda_F/2$ ,  $n_{\max}$  is reduced by one. Thus, as the channel becomes narrower, the number of occupied levels drops in a step-like fashion.

Each of the  $n_{\max}$  states in the constriction contributes one quantum of conductance to the channel's total conductance. To probe the junction's conductance  $G = I/V$ , an energy offset between electrons in the two bulk conductors at each side of the constriction is created by applying a small bias voltage  $V$  while measuring the resulting current  $I$ . The current carried by each state can be determined by counting the number of particles carrying a charge  $e$  over the energy interval given by the applied bias  $eV$ :<sup>5</sup>

$$I_n = 2e \int_0^{eV} \rho_n(E) v_n(E) dE. \quad (1)$$

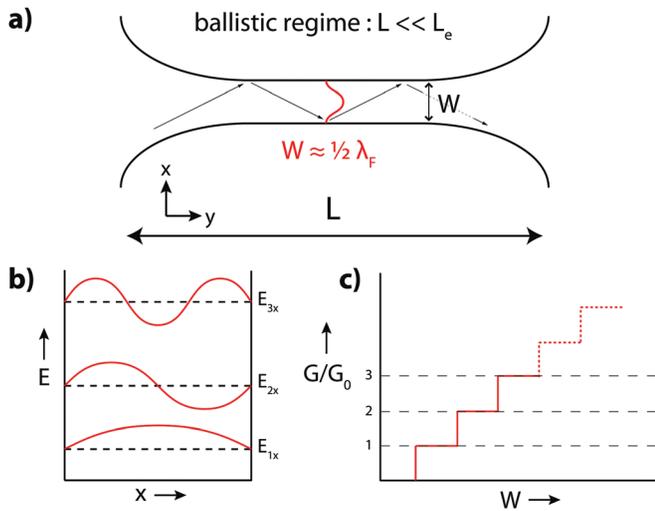


Fig. 1. (Color online) (a) Schematic representation of a two-dimensional ballistic piece of conductor of length  $L$  and width  $W$ . In the ballistic regime,  $L$  is much smaller than the mean-free path of the electrons  $L_e$ . The arrows depict a classical presentation of a trajectory of an incoming electron. However, at these length scales electron propagation must be described as waves. These waves interfere between the walls of the constriction, and standing wave patterns develop in the transverse direction  $x$ . The confinement gives rise to a discrete set of energy states  $E_n$ , depicted in (b). The index  $n$  indicates the number of “half” electron waves ( $1/2$  times the Fermi wavelength,  $\lambda_F$ ) that can fit in  $W$ . Within each transversally confined level, the electrons propagate freely along the direction of the wire. (c) Each state  $n$  contributes one quantum of conductance to the total conductance of the wire. Each time  $W$  is reduced by  $\lambda_F/2$ , the conductance drops by one quantum of conductance.

Here,  $\rho_n(E)$  is the one-dimensional density of states for electrons moving in state  $n$  in the forward direction, and  $v_n(E)$  is the group velocity of an electron in state  $n$  at energy  $E$ . The factor of 2 is due to the spin degeneracy—each state can carry an electron with spin up and spin down. In one dimension, the product of  $\rho_n(E)v_n(E) = 1/h$  (see Ref. 5), where  $h$  is Planck’s constant. Therefore,  $I_n = (2e^2/h)V$  and the conductance of each state equals  $G_0 = 2e^2/h$  independent of  $E$ ,  $V$ , and  $n$ . Hence, by continuously decreasing the width  $W$  of the conductor, a step-like decrease in the conductance is observed at equidistant intervals  $G_0$  [see Fig. 1(c)]. For a more complete derivation of the quantum of conductance, we refer to Refs. 6 and 7.

The initial observation of conductance quantization was made at temperatures of about 1 K in a material consisting of epitaxial layers of semiconductors, grown in ultra-high vacuum. Both  $L_e = 8.5 \mu\text{m}$  and  $\lambda_F = 42 \text{ nm}$  are relatively long in this material.<sup>3</sup> To create the constriction, an advanced patterning technique called electron-beam lithography was used. These conditions are expensive to establish and are not suitable for a permanent public exhibit. In the 1990s, it was found that atomically sized metal wires with a diameter of a few atoms often have conductance values which are near integer values of  $G_0$ .<sup>8</sup> The archetypical example is gold. By applying stress in the longitudinal direction of a gold wire, its atoms rearrange to form a longer and thinner wire. This thinning can be continued up to the point where the thinnest part spans only one atom. Although steps occur at almost all conductance values, conductance values near integer multiples of  $G_0$  appear more frequently. Most notably, just before the wire breaks, a plateau very close to  $G_0$  is observed. Conductance measurements of gold atomic contacts in a high resolution transmission electron microscope confirm that wires with a

conductance of  $2 G_0$  and  $G_0$  correspond to a configuration with two and one atom in the smallest part of the wire, respectively.<sup>9</sup> The diameter of a gold atom in a lattice ( $2.5 \text{ \AA}$ ) is about half of the Fermi wavelength ( $\lambda_F = 0.52 \text{ nm}$ ). Therefore, a single atom forms a constriction as described in Fig. 1 with  $n_{\text{max}} = 1$ . It is less clear how atomic contacts make a constriction with  $n_{\text{max}} > 1$ . When thinning an atomic gold wire, the diameter of the wire decreases in a step-wise fashion, atom by atom. Therefore, the preferred conductance values at multiple integers of  $G_0$  can be explained as arising from the discrete number of atoms in the wire (each contributing  $G_0$ ) instead of transversal quantum confinement in a constriction of varying width. For gold, it turns out both explanations are correct, as discussed in the following.

Studies on atomically sized contacts made from different metals showed interesting nuances. For example, not all metals form single atom contacts with a conductance close to  $G_0$ . In contrast to gold, transition metals often show a plateau before breaking around non-integer values much greater than  $G_0$ .<sup>8</sup> This difference seems to be correlated with both the shape and occupancy of the outer valence orbitals of the atom. A gold atom has a spherically symmetrical outer valence orbital ( $6s$ ) with only one electron in it. This orbital dominates charge transport near the Fermi energy. In contrast, a transition metal can have multiple electrons in strongly directional outer orbitals. Also, not all metals form single atom contacts with a conductance near  $G_0$  carried by a single quantum state. Non-integer conductance values can be understood by realizing that a state as depicted in Fig. 1 does not have to be fully transparent and might contribute only a fraction of  $G_0$  in systems where back-reflection of electron waves in the channel can occur.<sup>10</sup> For example, for aluminum, a contact with a conductance close to  $0.8 G_0$  frequently appears just before breaking. This conductance is carried by three partly transmissive states.<sup>8</sup> For gold, electrical (shot) noise measurements confirm that the current in a single atom contact is carried by an almost fully transparent single quantum state.<sup>11</sup> Therefore, the  $G_0$  plateau is an elegant demonstration of the quantization of conductance, because a gold atom acts as a single fully transparent waveguide for electron waves. It directly demonstrates what conductance value occurs in ultimately thin and clean nanowires.

### III. DESCRIPTION OF THE PUBLIC EXHIBIT

Simple experimental realizations of the gold wire experiments have been proposed. One can even observe the quantization of conductance by disrupting two gold wires attached to a table by tapping the table top<sup>12,13</sup> or by opening an electromagnetic relay.<sup>14</sup> These experiments need to be supervised when performed by a lay person in a short time span. This supervision is expensive and limits the accessibility of these experiments to a general audience. Also, the time span over which the quantization is observed is on the order of milliseconds or less. This time span requires detection with a fast oscilloscope and does not allow observation at the time scale of a human observer.

We report a robust, low maintenance setup that allows users to perform the gold wire experiment in real time. The setup is permanently accessible in a public space where users can operate it without supervision. The cost of setting it up was about \$13,000. In the following, we describe the technique used to make atomic gold contacts and the design of the setup.

To create atomic contacts, we used the mechanical break junction technique. Figure 2(a) shows a schematic drawing of this technique. A gold wire is created on top of a flexible, insulating substrate and is designed to be notched in the center to create a weak point. The sample bends by moving the central pushing rod up while holding the outer ends of the sample using counter supports. The pushing rod's motion results in a shear force on the wire, thereby elongating the wire and reducing its diameter. This thinning can be continued until a single atom contact is formed. Pushing further breaks the gold wire in two separate atomically sharp electrodes. By reversing the pushing rod's motion after breaking, the sample bends back such that the two electrodes will touch and "self-heal" into a single gold wire again. This procedure can be repeated thousands of times.

Mechanical break junctions feature an impressive subatomic resolution and mechanical stability in distance control. These features result from the bending geometry, which results in a strongly attenuated change in the gap size between the electrodes  $\Delta d$  when moving the pushing rod over a distance  $\Delta Z$ .<sup>15</sup> For our junctions, we found that  $\Delta d : \Delta Z \approx 1:5000$ . In other words, a displacement of the pushing rod of 1  $\mu\text{m}$  results in a change in gap size of approximately 0.2 nm; the size of atoms. Furthermore, due to this attenuation, the lifetime of the single atom contact is usually not limited by vibrations and allows the user to observe the formation of a single atom contact while breaking a thin gold wire in about 1 min.

We initially fabricated junctions using phosphor bronze substrates and electron-beam lithography.<sup>16</sup> To fabricate samples more cheaply and efficiently, we developed a simpler fabrication method on Cirlex substrates<sup>17</sup> using optical lift-off based lithography. We use a deep-UV mask aligner and vacuum evaporation to pattern gold break junctions of 120 nm thickness. Four junctions are simultaneously placed on

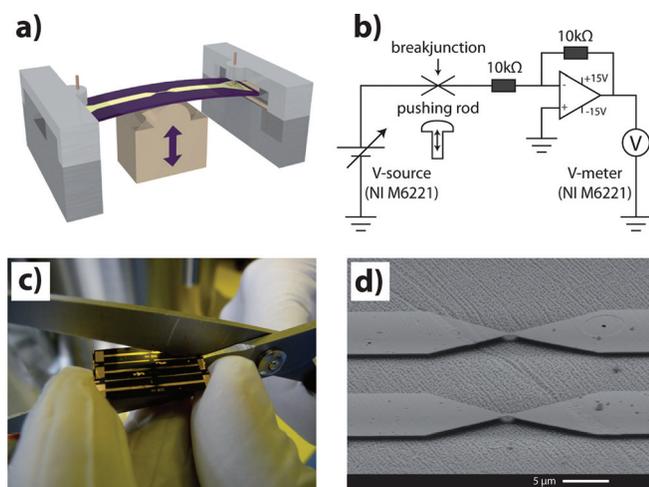


Fig. 2. (Color online) (a) Schematic representation showing the mechanical break junction clamped in a three-point configuration. The pushing rod's motion results in a lateral stress on the lithographically patterned gold wire, thereby thinning and eventually breaking it. (b) Simplified electronic scheme of the setup. The voltage ( $V$ -source) is applied by a computer via a data acquisition card. This card also reads the output of the current meter (a voltmeter which probes the output of a trans-impedance amplifier). The pushing rod is manually controlled using a turning handle. The computer is connected to a touch screen. (c) Four junctions are simultaneously fabricated on a Cirlex substrate using lift-off based photo lithography. Individual samples can be isolated using scissors. (d) Scanning electron micrograph of two suspended mechanical break junctions after device fabrication.

top of a polished Cirlex substrate of 22 mm  $\times$  20 mm  $\times$  0.51 mm (length  $\times$  width  $\times$  thickness). The patterns include contact pads for the spring-loaded pins depicted in Fig. 2(a). To obtain a suspended central constriction of the junctions, the samples are exposed to an oxygen plasma that etches away a small amount of substrate material. Finally, the four junctions are separated using regular scissors [see Fig. 2(c)]. Figure 2(d) displays a scanning electron micrograph of a finished junction. A junction needs to be replaced after 3–6 months of full-time operation. Many samples can be made in less than a day in a facility equipped for microelectronic device fabrication. An exhibit at a site without its own device fabrication facilities can be supplied with a multi-year stock of samples (say 20 samples) for less than \$1000.

Figure 3 shows a photograph and close-ups of the setup in the entrance hall of our Science Faculty building. The setup is controlled via a touch screen and a turning handle. The break junction, spring contacts, bending bench, and the mechanical transmission are displayed in a transparent case so that while operating the setup, the motion of the mechanical parts and, in particular, the bending of the break junction are clearly visible to users. Users directly control the pushing rod using a turning handle. The handle's rotation is converted into a linear motion of the pushing rod via a precision micrometer (50  $\mu\text{m}$  translation per rotation). A low gear-ratio worm drive (1:20) between the micrometer and the turning handle further attenuates the relation between user motion and inter electrode displacement. As a consequence,  $\Delta d$  can be controlled with impressive precision: A full turn of the handle results in a 2.5  $\mu\text{m}$  translation of the pushing rod. This translation results in a gap size displacement  $\Delta d$  of roughly 0.5 nm, the equivalent of two gold atoms, while users can easily control a small fraction of a full turn.

The conductance of a break junction is determined by applying a constant bias voltage  $V$  and measuring the current  $I$  through the junction using a hand-made trans-impedance amplifier [see Fig. 2(b)]. A central component in the setup is a personal computer equipped with a National Instruments data acquisition board (M6221). The acquisition board applies the bias voltage  $V$  and records the output of the current meter at 100,000 samples per second. It also actively protects the junction and the rest of the setup against damage that might occur if a user rotates the handle outside the designed operation range. To this end, it reads out a motion (Hall) sensor installed on the handle, which detects the direction of handle rotation. We use this signal together with the measured conductance values as inputs to a feedback mechanism which controls a coaxial magnetic coupler between the handle and the worm drive. If the user is turning in the undesired direction (closing when opening is required and vice versa) for a considerable time, the computer will decouple the handle from the central axis. Also, two switches are installed just before an upper and lower limit for the micrometer. When a switch is hit by the micrometer, the handle is automatically decoupled.

A software interface consisting of a PowerPoint presentation embedded in a LABVIEW program guides the user through the experiment. The interface has three parts. During the first part, a slide show introduces the context of nano-electronics and the relevant physical concepts. In the second part, the experiment is performed, and the computer presents a graph of conductance versus time [see Fig. 3(a)] while the user turns the handle. After breaking, the user needs to close the junction. By closing the junction, the two electrodes "self-repair"

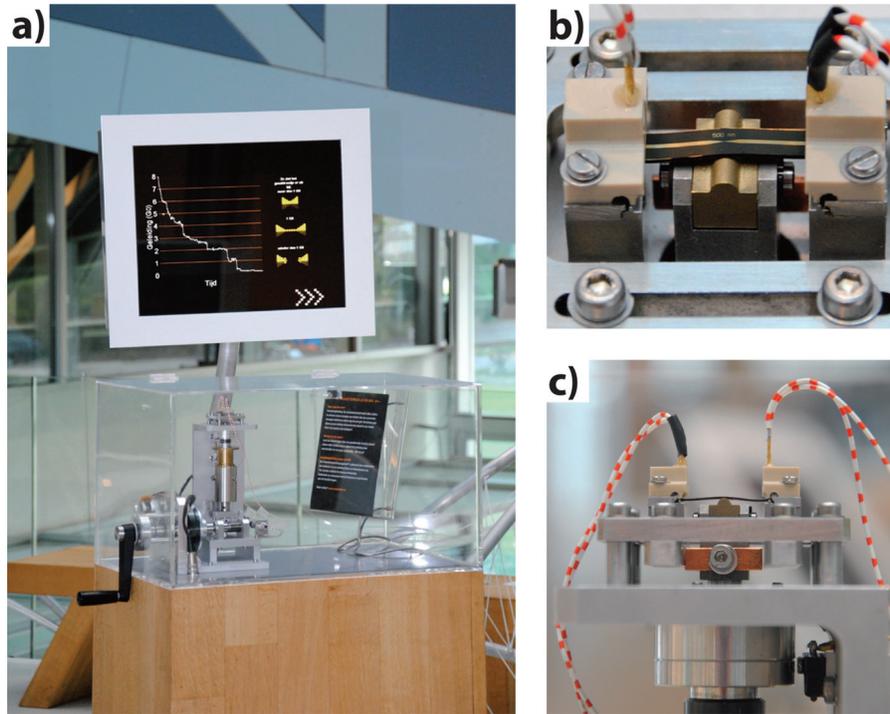


Fig. 3. (Color online) (a) Photograph of the setup in the entrance hall of our faculty building. The user can operate the setup using a turning handle and a touch screen. (b)–(c) Close-up of the mechanical part of the setup showing a top and side view of the three-point bending bench with a break junction. The distance between the wire connections on the left and right side is  $\approx 2.5$  cm.

into a single gold wire,<sup>16</sup> and users can choose whether they wish to redo the experiment. For a single junction, this opening and closing cycle can be repeated more than about 1000 times. When proceeding to the third part, a slide show further explains the observations. Several parts of this setup (the mechanics, electronics, and software) were created by undergraduate students in projects that were part of their curriculum, with graduate students having a primary role in supervision and project management.

#### IV. RESULTS AND DISCUSSION

Figure 4(a) shows five typical curves obtained in an experiment by rotating the handle at a constant speed of approximately one turn per second ( $\Delta d \approx 0.5$  nm/s). The conductance  $G$  of the wire is expressed in units of  $G_0 = 2e^2/h = (12.9 \text{ k}\Omega)^{-1}$ . For each trace, approximately 10 turns ( $\approx 5$  nm) are needed to break the junction. While the junction is stressed in a continuous fashion, the conductance drops in a step-like fashion due to rearrangements of the atoms in the junction. Plateaus occur at almost any conductance value greater than  $G_0$ . However, plateaus appear more frequently for  $G$  near  $G_0$ , indicating that a relatively stable configuration, that is, a single atom contact, is formed. The breaking of the single atom contact is observed as an abrupt jump in  $G$  at the end of the one  $G_0$  plateau. If the user starts to close the junction again, the wires' ends only make contact after going back a few turns, thus revealing a hysteresis in the dependence of  $G$  on  $\Delta Z$ .<sup>16</sup> As soon as the wire ends touch each other again, we typically observe a very rapid increase in  $G$  to a value of several  $G_0$  (data not shown).

To illustrate the stability of the setup, we measured the lifetime of 108 single atom contacts while slowly turning the pushing rod ( $\approx 2$  rpm) and stopping further turning as soon

as a one  $G_0$  plateau was observed. Figure 4(b) shows a lifetime histogram of all contacts. The lifetime of the contact varies over 3 to 4 orders of magnitude and is centered around 1 s. By using similar junctions of a similar geometry at low temperatures, single atom contacts can be maintained for hours.<sup>8,16</sup> This difference in lifetime indicates that the enhanced thermal mobility of the gold atoms at room temperature limits the lifetime of a single atom contact using the mechanical break junction technique.

Our setup has been part of a permanent exhibition in the entrance hall of the faculty building of Natural Sciences of our university since September 2008. The goal of the exhibition is to display current research of the faculty to a broad audience. The setup is used as a stand-alone exhibit where students, faculty, staff, and visitors can measure the conductance of a single gold atom in a few minutes without any supervision. Users perform the break junction experiment and, most importantly, become familiar with the quantization of conductance. Small groups (2–5 people) of high school or undergraduate students and a supervisor (often a graduate student) perform the experiment and go through the steps of sample preparation in the cleanroom to illustrate nano-fabrication. Sample inspection using a scanning electron microscope is used to visualize a break junction. By zooming in on the sample using this microscope, we can illustrate the “powers of ten” to be overcome to engineer at the nanometer scale.

Future plans for the setup include implementing an internet interface to the setup. Users can then send the results of an experiment to a personal e-mail address. This implementation will add a third way of doing the experiment while visiting the exhibit. Users can work out and analyze the results on a computer, either during the visit to our facility, or later at home or at school. Analysis can be supported by material

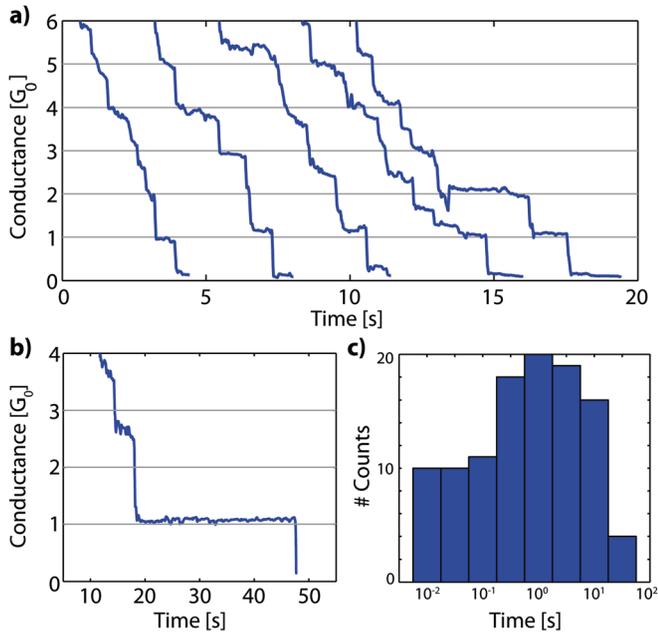


Fig. 4. (Color online) (a) Five typical conductance versus time traces when turning the handle at 1 turn per second. The applied voltage is 100 mV. (b)–(c) The stability of the mechanically controllable break junction technique is illustrated when turning the handle at low speeds ( $\approx 2$  rpm) and holding the handle once a conductance of one  $G_0$  is reached. In (b) a trace featuring a relatively long one  $G_0$  plateau is plotted. When repeating the experiment 108 times, the single atom contact holding time (the time the conductance remains between 1.5 and 0.5  $G_0$ ) has a wide distribution centered around 1 s. At room temperature, the lifetime of a single atom contact is limited by the diffusion of gold atoms.

on the exhibit website.<sup>18</sup> We plan to monitor the results of the setup and to collect statistics of the conductance values that occur so that we can investigate the long-term behavior and aging effects of these junctions. We estimate that fabrication costs of future setups can be reduced to approximately \$7,000.

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