Quantum Point Contact Switches

D. P. E. Smith

Switching behavior between electron tunneling and ballistic transport states was induced by repeatedly bringing a sharpened nickel wire into contact with a gold surface. The high-conductivity ballistic state had a quantized conductance of 0.977 ± 0.015 ($2e^2/h$). Switching was accomplished by moving the electrodes with a piezoelectric actuator over a distance of 2 angstroms. The two electrodes and the actuator form a three-terminal device that is demonstrated to be a reliable digital and analog switch; it shows good discrimination between high and low states and possesses the important property of power gain. The conductance channel is most likely only one atom wide and possibly consists of a single atom.

The miniaturization of electronics has reached the stage where the discussion of devices with atomic-scale dimensions is becoming technologically relevant. One important question is how the behavior of existing electronic devices is altered as their size shrinks. A second question is how the quantum behavior of ultrasmall structures might form the basis for new devices. Here, we present relevant experiments based on a very easily realized geometry, the quantum point contact (QPC). The experiments show that atom-sized metallic constrictions can be easily fabricated with conductivity quantized in units of $2e^2/h$, where e is the charge on the electron and h is Planck's constant. The QPC is shown to make a very reliable digital switch with a stable high-conductance state of $2e^2/h$. The quantum bistability is also demonstrated to be useful for applications such as analog switching. The QPC switch is an active device that demonstrates the important property of power gain. It most likely operates by opening a conductance channel only one atom wide, and very possibly the channel consists of a single atom. The behavior of the QPC switch is in this respect similar to the single-atom tunneling switch demonstrated by Eigler *et al.* (*1*).

Theoretical work has suggested that quantum interference effects cause metallic constrictions to show step-like oscillations in conductance when their widths are varied on the order of λ_F, the fermi wavelength of the electrons (*2*). The sharpness of the quantization depends on constriction length, temperature, applied bias, impurities, and nonuniformities in geometry and potential. The first experimental observations of quantized conductance in metallic point contacts were those of Gimzewski and Möller (*3*) and Dürig *et al.* (*4*). They observed an abrupt jump to contact as the tip of a scanning tunneling microscope (STM) was brought close to a surface. The residual contact resistance was found to be approximately 10 kilohms in both cases, slightly lower than the quantized resistance $h/2e^2 = 12.906$ kilohms. More recent experiments (*5–9*) have shown that quantized resistance steps can be observed but that the exactness of the quantization depends on the metals used and the experimental conditions. The most convincing evidence comes from measurements by Agraït *et al.* (*6*) and Krans *et al.* (*7*) that were performed at a temperature of 4.2 K. At low temperatures the thermally excited motion of the metallic atoms is very low, leading to more reproducible results. For Au-Au junctions (*6*) and Cu-Cu (*7*) junctions, the quantization of the first conductance channel was very close to $2e^2/h$. This may have to do with the fact that atoms of Au and Cu can be assumed to be fairly accurately represented by simple spherical wave functions, as many theoretical QPC calculations assume.

In our experiments, an electropolished nickel tip is positioned close to a ball of gold, with electrical connections made as shown in Fig. 1A. The nickel tip can be translated in three dimensions with a single-tube piezoelectric transducer (PZT), as is done in STM use. The measurements were made in helium gas at temperatures of 4.6 to 8.6 K. The Ni-Au system was chosen because of the theoretical and experimental results of Landman *et al.* (*10*). They found that after the initial approach, the nickel tip becomes wetted by several monolayers of gold; further tip-sample approaches then make Au-Au point-contact junctions. The cold helium gas provides a very clean environment; contamination of the junctions over time was not observed. In the tunneling regime, the work function between the two electrodes was found to be between 3.0 and 4.0 eV after initial contact (*11*); these values are characteristic of clean metal surfaces. In the point-contact regime, a quantized conductance of 0.977 ± 0.015 ($2e^2/h$) was measured (Fig. 2). This value could be stably measured over one position for a period greater than 24 hours and is in good agreement with detailed simulations that find a stable single-atom contact with a quantized conductance of 0.93 ± 0.05 ($2e^2/h$) (*12*). Quantized conductance was not found over all the sample surface, which suggested that contamination and geometry are important in observations of QPC behavior. The observed deviation from the exact quantum value may have a variety of geometric and material causes (*2, 12*).

Typical QPC measurements are shown in Fig. 3A. The middle trace is V_Z, the voltage on the z electrode of the PZT. From the manufacturer's specifications, the transducer is calculated to give a displacement of 1.1 nm/V at liquid helium temperatures. The ramp in Fig. 3A therefore corresponds to a peak-to-peak displacement of 0.24 nm and a tip velocity of 280 nm/s. This displacement is smaller than the electronic diameter of a gold atom (0.32 nm). A feedback loop with a time constant of several seconds was set to maintain an average constant current corresponding to a gap resistance of 0.1 to 1 megohm. V_Z was

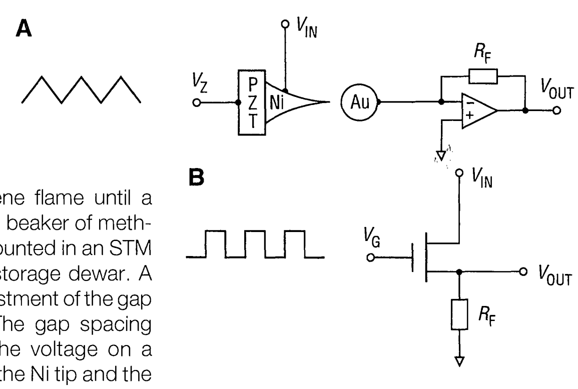

Fig. 1. (**A**) Experimental setup for measuring QPCs. The Ni tip was formed by electrochemically etching a nickel wire (diameter 0.5 mm) in concentrated HCl and rinsing in deionized water. The Au ball was prepared by heating a gold wire (diameter 0.5 mm) in an oxygen-acetylene flame until a molten ball dropped off and landed in a beaker of methanol. The two metal electrodes were mounted in an STM that was inserted into a liquid helium storage dewar. A mechanical screw provided coarse adjustment of the gap between the Ni and Au electrodes. The gap spacing could be finely adjusted by varying the voltage on a PZT. A bias voltage V_{IN} was applied to the Ni tip and the current was sensed at the Au ball by means of a FET-input, room-temperature current amplifier. The resistance of resistor R_F was 986.7 kilohms for the measurements shown in Figs. 3, A and C, and 4; it was reduced to 99.90 kilohms to increase the precision of the bias voltage measurement in Fig. 2 and to increase the measurement bandwidth in Fig. 3B. (**B**) FET analogy for the electrical operation of the QPC switch.

IBM Research Division, Schellingstrasse 4, 80799 Munich, Germany.

Present address: Massachusetts Institute of Technology, E52-126, 50 Memorial Drive, Cambridge, MA 02142–1347, USA. E-mail: dpesmith@aol.com

modulated with a triangular signal such that it caused the tip to vary between the tunneling (high electrical impedance or low current) and point-contact (low impedance or high current) regimes. The two states of the QPC switch correspond to the highest possible tunneling transport conductance and the lowest possible ballistic transport conductance. QPC switching behavior was observed over most areas of the sample. The ratio between the high and low values of current was typically about 20. The good discrimination between high and low states is the result of the extreme displacement sensitivity of the tunnel gap (*13*). The duty cycle (the ratio of the time spent in the high versus the low state) could be varied by changing the current set point of the feedback loop, as shown in the top and bottom traces of Fig. 3A.

A higher resolution view of QPC switching is given in Fig. 3B, where the tip is ramped 0.22 nm at a velocity of 650 nm/s. The overshoot on the rising and trailing edges is due to stray capacitance. The difference in the z position between where the switch turns on and where it turns off is on average 30 pm, or about one-tenth the diameter of a gold atom. It is unclear whether this difference originates from elastic deformation of the junction or piezoelectric hysteresis. Due to mechanical resonances in the experimental apparatus, the fastest triangular signal that could be applied to the PZT was about 2 kHz. To achieve a higher time resolution of the QPC switching behavior, we turned off the triangular signal and set the feedback set point to maintain an average junction resistance of slightly more than $h/2e^2$. The junction atoms were observed to fluctuate between two well-defined values corresponding to a high conductance of 13 kilohms and a low conductance of approximately 200 kilohms (Fig. 3C). Similar fluctuations have been previously observed (*5, 6*). The diameter of a gold atom is about 1.4 times the size of the piezoelectric displacement in Fig. 3B, so it is not unreasonable to expect that the fluctuation of a single atom causes the observed switching behavior in Fig. 3C. Switching speeds as fast as 10 μs (limited by the input capacitance to the current amplifier) could be resolved. It should be possible to achieve very high active switching speeds, in the megahertz range, by replacing the PZT with a micromachined electrostatic transducer. Molecular dynamic simulations have shown that the fastest possible switching time for single atoms in the point-contact configuration is on the order of 1 ps (*10*).

By increasing the size of the triangular ramp, it is possible to open a second quantized channel, as shown in Fig. 4A for a ramp of 0.35 nm. The second conductance channels are far noisier than the first conductance channels, which suggests that their geometry is less stable. The conductance was found to be twice that of the first channel to an average accuracy of 5%. Figure 4B shows the opening of a third conductance channel in the absence of any quantized conduction plateau. Distinct plateaus were never observed beyond the opening of the second channel, although an irregular and unreproducible staircase structure was usually seen. These findings agree with previous experimental evidence (*6, 7, 9*) as well as the model calculations that

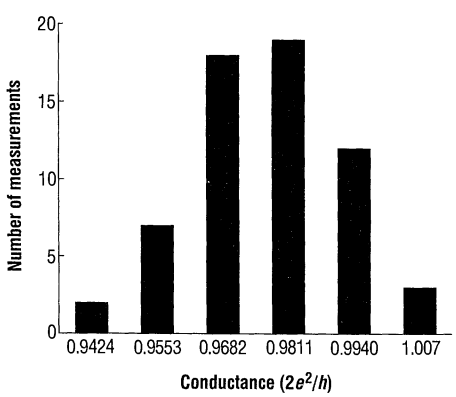

Fig. 2. Distribution of 61 conductance measurements for the Ni-Au QPC taken at T = 7.2 K with an applied bias V_{IN} of 400.3 mV. The measured quantized conductance value, 0.977 ± 0.015 (mean ± SD), is in good agreement with the molecular dynamics simulations of Todorov and Sutton (*12*), who found that the quantized conductance settles at a value of 0.93 ± 0.05 for a single-atom contact.

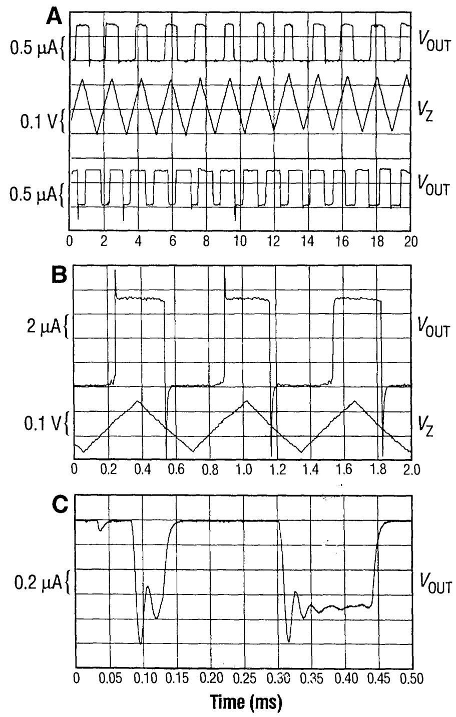

Fig. 3. (**A**) Ramping the voltage V_Z on the PZT (middle trace), corresponding to a peak-to-peak displacement of 0.24 nm, causes the junction resistance to switch between 13 and ~200 kilohms (top trace) with an applied bias V_{IN} of 10.0 mV. A feedback loop with a time constant of several seconds keeps the average current within the required levels. The duty cycle of the high-conductance state could be increased by increasing the average current set point (bottom trace; ramp voltage not shown). The temperature for all traces was T = 6.0 K. (**B**) Higher resolution time and voltage measurement of the QPC switch at T = 8.6 K. Bottom trace: ramp voltage on the PZT corresponding to a peak-to-peak displacement of 0.22 nm. Top trace: junction current with a bias V_{IN} of 100.0 mV. The overshoots are due to stray capacitance. (**C**) Spontaneous resistance fluctuations with no PZT ramp when the current set point was slightly below I = 10.0 mV/13 kilohms = 0.77 μA. The high state corresponds to a resistance of 13 kilohms and the low state to ~200 kilohms. The oscillations are due to the settling time of the electronics, which is dominated by the capacitance of a coaxial cable (length 1 m) used for input to the current amplifier. The quantized fluctuations, probably caused by the motion of single atoms, can be resolved to within about 10 μs. These fluctuations suggest that the $1/f$ noise observed in vacuum tunnel junctions may originate from the rearrangement of atoms at the electrodes.

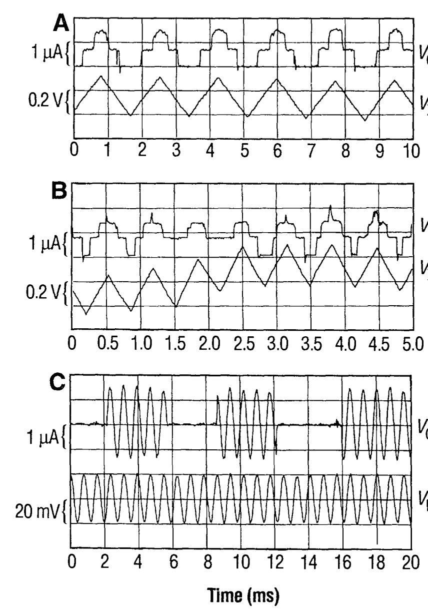

Fig. 4. (**A**) Increasing the PZT ramp to 0.35 nm peak-to-peak opens a second quantized channel for a combined parallel resistance of 6.5 kilohms (V_{IN} = 9.96 mV; T = 6.0 K). (**B**) The third and higher conductance channels do not form quantized resistance plateaus and are not stable or reversible. Because of a mechanical vibration during the ramp (as shown by the low frequency displacement of V_Z), the single channel failed to open twice. (**C**) A sine-wave voltage (bottom trace) is applied to V_{IN} and the current is monitored at V_{OUT} (top trace) while a 0.24-nm triangular signal (not shown) is applied to V_Z with a period of 7 ms (T = 6.4 K). The circuit functions in analogy to an analog FET switch (Fig. 1B) or, more precisely, as a electromechanical relay whose active element is of atomic dimension.

take into account the finite length of the one-dimensional channel and the finite temperature (2). The stability and reproducibility of the single channel is qualitatively different from the higher order conductance channels, most likely because of the increased disorder and fluctuations that can occur as the number of atoms making up the channel increases.

What is the size of the QPC junctions studied here? Comparison of the experimental behavior with the model of Tekman and Ciraci (2) shows that the width of the single conductance channel is less than λ_F (0.52 nm for Au). Wider channels correspond to higher order channels. The Tekman and Ciraci model also suggests that the length of the QPC junctions measured here is less than λ_F; if the constriction were longer, the higher order conductance plateaus would be much more distinct than are observed experimentally [see figure 2 of (2)]. We therefore conclude that for the single quantized channel, which corresponds to the high-conductance state of the QPC switch, the width is less than λ_F and the length is probably also less than λ_F. Because the electronic diameter of a metallic atom is $0.611\lambda_F$, the single-channel constriction probably corresponds to a single atom.

The application of the QPC for use as an analog signal switch is demonstrated in Fig. 4C. A sine-wave voltage with no dc component is applied to V_{IN} and the current is monitored at V_{OUT} while a 0.24-nm ramp (not shown) is applied to V_Z (see Fig. 1A). This analog switch is functionally analogous to the field effect transistor (FET) switch shown in Fig. 1B, where the gate voltage is used to modulate the drain-source channel between high- and low-conductance states. The width of the conductance channel of the FET is controlled by an electric field, whereas the width of the conductance channel of the QPC is controlled by mechanical displacement of atoms in the junction. The QPC switch functions more precisely as an electromechanical relay. The interesting features are that on-off switching is accomplished by displacing the electrodes by only 2 Å and that the contact region is extremely small, perhaps only one atom in size.

Eigler *et al.* have shown that the motion of a single atom of Xe between a tungsten tip and a nickel surface can cause the tunneling conductance between the electrodes to change by a factor of between one and seven (1). The maximum high-conductance state corresponded to a resistance of 220 kilohms, and the device could only operate at very low temperatures because of the mobility of Xe. By comparison, the QPC switch demonstrated here has a conductance ratio of about 20 and a high-conductance state with an impedance of 13 kilohms. Another important distinction is that the Xe switch is a two-terminal device that is toggled by applying a current pulse between the electrodes. In contrast, the QPC switch is a three-terminal device with an independent control input. An important disadvantage of a two-terminal device is the impossibility of power gain, that is, a large current is required to switch a smaller current. The QPC switch displays power gain and can be used to make an oscillator (by feeding the output signal back into the control input) or to drive a series of other QPC switches. Finally, QPC behavior has been observed at room temperature (8, 9). The angstrom size of the QPC conductance channel suggests that the QPC may be useful in exploring the physical and engineering issues surrounding atomic-scale electron devices.

REFERENCES AND NOTES

1. D. M. Eigler, C. P. Lutz, W. E. Rudge, *Nature* **352**, 600 (1991).
2. E. Tekman and S. Ciraci, *Phys. Rev. B* **43**, 7145 (1991).
3. J. K. Gimzewski and R. Möller, *ibid.* **36**, 1284 (1987).
4. U. Dürig, O. Züger, D. W. Pohl, *Phys. Rev. Lett.* **65**, 349 (1990).
5. C. J. Muller, J. M. van Ruitenbeek, L. J. de Jongh, *ibid.* **69**, 140 (1992).
6. N. Agraït, J. G. Rodrigo, S. Vieira, *Phys. Rev. B* **47**, 12345 (1993).
7. J. M. Krans *et al.*, *ibid.* **48**, 14721 (1993).
8. J. I. Pascual *et al.*, *Phys. Rev. Lett.* **71**, 1852 (1993); L. Olesen *et al.*, *ibid.* **72**, 2251 (1994).
9. J. I. Pascual *et al.*, *Science* **267**, 1793 (1995).
10. U. Landman, W. D. Luedtke, N. A. Burnham, R. J. Colton, *ibid.* **248**, 454 (1990). In particular, the final sentence is relevant for the experiments presented here: "Our studies suggest a method for preparation of atomic size contacts and atomically thin wires (by the process of contact formation between a metallic tip and a soft metal substrate, followed by gentle separation) which could be used to study conductance (and quantum effects) in narrow constrictions."

11. The work function was measured by addition of a z-modulation (Δz = 40 pm) to the piezoelectric transducer and detection of the modulation ΔI in the tunneling current. Assuming $I \propto \exp(-2\kappa z)$, where κ is the electron wave number, then $\Delta I/I = 2\kappa\Delta z$; the value of κ thus derived enables calculation of the work function $\varphi = (\hbar\kappa)^2/2m_e$, where $\hbar = h/2\pi$ and m_e is the electron mass. Ratios of $\Delta I/I$ between 0.75 and 0.9 were measured, which implied values of φ between 3.0 and 4.0 eV.

12. T. N. Todorov and A. P. Sutton, *Phys. Rev. Lett.* **70**, 2138 (1993).

13. It is possible to estimate the change in resistance in the tunnel regime as $\rho = R_1/R_2 = \exp[2(\kappa_1 z_1 - \kappa_2 z_2)]$. Assume that the tunnel barrier maintains a constant value of $\kappa = 10\ \text{nm}^{-1}$, corresponding to φ = 4 eV, until contact occurs (3, 4) and that Δz = 0.15 nm, the approximate portion of the ramp in the tunnel regime. Then $\rho = \exp(2\kappa\Delta z) = 20$, in agreement with the observed switching behavior.

14. W. Häberle assisted in the construction of the experimental apparatus and G. Binnig provided helpful criticism of the manuscript.

22 February 1995; accepted 17 May 1995

Ferroelectric Field Effect in Epitaxial Thin Film Oxide $SrCuO_2/Pb(Zr_{0.52}Ti_{0.48})O_3$ Heterostructures

C. H. Ahn,* J.-M. Triscone, N. Archibald, M. Decroux, R. H. Hammond, T. H. Geballe, Ø. Fischer, M. R. Beasley

A ferroelectric field effect in epitaxial thin film $SrCuO_2/Pb(Zr_{0.52}Ti_{0.48})O_3$ heterostructures was observed. A 3.5 percent change in the resistance of a 40 angstrom $SrCuO_2$ layer (a parent high-temperature superconducting compound) was measured when the polarization field of the $Pb(Zr_{0.52}Ti_{0.48})O_3$ layer was reversed by the application of a pulse of small voltage (<5 volts). This effect, both reversible and nonvolatile, is attributed to the electric field–induced charge at the interface of $SrCuO_2$ and $Pb(Zr_{0.52}Ti_{0.48})O_3$. This completely epitaxial thin film approach shows the possibility of making nonvolatile, low-voltage ferroelectric field effect devices for both applications and fundamental studies of field-induced doping in novel compounds like $SrCuO_2$.

Recent developments in the physical vapor deposition of complex oxides, notably advances in magnetron sputtering, laser ablation, and reactive molecular beam epitaxy (MBE), have permitted the growth of very high quality epitaxial oxide thin film structures, as demonstrated, for example, by the fabrication of thin film superlattices of the copper oxide superconductors (1, 2). Although in large part developed for the growth of high transition temperature (high-T_c) superconductors, these techniques have now been applied to other oxide materials, including ferromagnetic and ferroelectric perovskites (3, 4). These advances offer the possibility of growing

C. H. Ahn, R. H. Hammond, T. H. Geballe, M. R. Beasley, Department of Applied Physics, Stanford University, Stanford, CA 94305, USA.
J.-M. Triscone, M. Decroux, Ø. Fischer, Département de Physique de la Matière Condensée, University of Geneva, 24 Quai E.-Ansermet, 1211 Geneva 4, Switzerland.
N. Archibald, Department of Physics, Stanford University, Stanford, CA 94305, USA.

*To whom correspondence should be addressed.