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A mechanically flexible tunneling contact operating at radio frequencies

A. Erbe, R. H. Blick,[a] A. Tilke, A. Kriele, and J. P. Kotthaus
Center for NanoScience and Sektion Physik, Ludwig-Maximilians-Universität, 80539 München, Germany

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We report on a nanomachined electromechanical resonator applied as a mechanically flexible tunneling contact. The resonator was machined out of a single-crystal silicon-on-insulator substrate and operates at room temperature with frequencies up to some 73 MHz, transferring electrons by mechanical motion. © *1998 American Institute of Physics.* [S0003-6951(98)03651-1]

Old fashioned doorbells apply simple electromechanical resonators to generate sound. A common design for such a bell is to integrate a clapper in between two electrodes, where one is then charged by a current. At a certain voltage the mechanical clapper is pulled towards one of the electrodes and charge can flow onto the metallic link. The clapper itself is then pulled back by the mechanical restoring force and delivers the acquired charge to the grounded electrode. Naturally, many different realizations of bells exist, but basically we can note that the combination of electrostatic and mechanical forces in such a bell lead to a resonant transport of electrons. Since the electron's charge is quantized a bell can in principle be used to count single electrons, much in the same way as in Millikan's famous experiment with oil drops[1] or by using single electron transistors.[2–5] Here, we demonstrate a new technique for counting electrons with a mechanical resonator, which is based on a mechanically flexible tunneling contact.

In the case of macroscopic bells the granularity of the charge carriers is not observed, because of the large currents used. In our case the underlying idea is to scale down a classical bell—the electromechanical resonator—in order to build a ''quantum bell'' with which single electrons can be transferred. Naturally, there are basic differences between a classical bell and our resonator: we rely on radio frequency (rf) electrostatic excitation of the clapper and not on a small magnet. Moreover, the clapper shown in the scanning electron microscope (SEM) micrograph of Fig. 1 has a size of only $1000\ \text{nm}\times150\ \text{nm}\times190\ \text{nm}$ (length×width ×thickness), leading to eigenfrequencies up to 400 MHz. However, regarding the fundamental similarities we find that electrons are transferred by a mechanically flexible contact. Besides reducing the size of the resonator, a quantum bell requires tunneling contacts in order to achieve tunneling of only a few electrons in each cycle of motion onto and off the clapper.

In these first measurements we want to focus on the demonstration of electron tunneling through the contacts at different resonance frequencies. Hence, the clapper is fully metallized and we operate the bell as a mechanical switch, where we drive the clapper at radio frequencies up to 100 MHz and measure the dc current of only a few electrons tunneling each cycle through the clapper/drain contact.

The sample was machined out of a single-crystal silicon-on-insulator (SOI) substrate by a combined dry- and wet-etch process. The SOI substrate consists of a 190 nm thick silicon layer, a 390 nm SiO_2 sacrificial layer, and the semi-insulating Si wafer material. In a first step, optical lithography was performed defining metallic gates and pads capable of supporting radio and microwave frequencies. In a second step we used electron-beam lithography to define the metallic nanostructure (displayed in Fig. 1). The metal layers deposited on Si during lithography are a thin adhesion layer of NiCr (1.5 nm), a covering Au layer (50 nm), and an Al-etch mask (30 nm). A reactive-ion etch was then applied to mill down by 600 nm the silicon not covered by the metal. Finally, the sample was etched in diluted HF, defining the suspended silicon layer with a thickness of 190 nm. The suspended quantum bell can be seen in Fig. 1: drain (D) and source (S) tips function as tunneling contacts for the metallized Si clapper (C) in the center. The two additional gate contacts (G1) and (G2) allow effective capacitive rf coupling, lead to an in-plane motion of the clapper between drain and source.

In the present measurements the rf modulation is applied to gate 1 and 2, while the source contact is grounded—the signal on gate 1 is phase shifted by $\phi=\pi$. We operate at frequencies up to some 100 MHz across the clapper electrode. Current then flows from the clapper to the drain contact and the dc current is finally amplified, as indicated in the circuit diagram of the inset in Fig. 1. The sample is mounted in a standard sample holder allowing measurements in vacuum and at low temperatures. The obtained dc-IV characteristic is shown in Fig. 2: at 300 K we find an exponential increase of the current with $V_{\text{clapper/drain}}$ when the clapper is pulled towards the drain contact around $V_{\text{clapper/drain}} \cong -1$ V. Electrons are then tunneling across the gap, as indicated in the left inset. Further biasing of the clapper finally leads to a metallic contact. The upper right inset shows the same characteristic measured at 4.2 K: clearly the onset of the tunneling current occurs at larger bias voltage. The temperature dependence of the IV characteristics can be explained by the enhanced Brownian motion and the reduced stiffness of the clapper at room temperature (no hysteresis is observed at 300 K). Moreover, we find a hysteresis at low temperatures from which we estimate the contact force to be on the order of ~330 nN (here we calibrated the displacement of the clapper with respect to drain voltage applied and used the spring constant for Si). The dc-IV response is not

[a]Author to whom correspondence should be addressed; electronic mail: robert.blick@physik.uni-muenchen.de

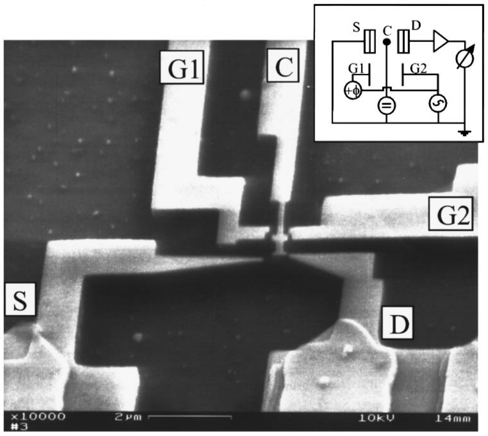

FIG. 1. The quantum bell: shown is a scanning electron beam micrograph of the suspended silicon structure, having a thickness of 190 nm, covered by an evaporated metallic layer of 50 nm. The clapper in the center is under etched up to the second joint. The inset shows an electrical circuit diagram of the bell with drain (D), source (S), clapper (C), and gate contacts (1 and 2). Here, the clapper is biased and current flows through the drain contact and is finally amplified. Radio frequencies are applied at gate contacts 1 and 2, while the source contact is grounded. The signal on gate 1 is phase shifted by $\phi=\pi$ to gate 2.

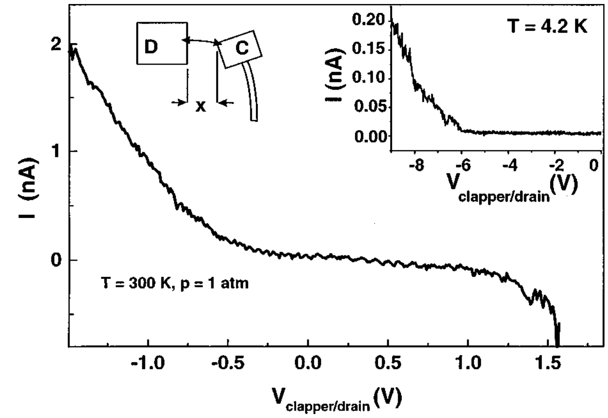

FIG. 2. Static *IV* characteristic of the mechanical clapper without radio frequency applied. Plotted is the dc current as a function of bias voltage across the clapper/drain contact at $T=300$ K. Inset shows the *IV* characteristic at 4 K.

symmetrical when the current preamplifier is connected to the source contact. This is due to the off-center position of the clapper which can be seen in Fig. 1. The measurements at low temperatures were performed after the sample holder was evacuated and a small amount of ^{4}He gas was admitted in order to enhance cooling.

We have seen that the resistance of the contact (clapper/drain) depends exponentially on the tip displacement and hence on the distance to drain/source by $R[x(t)] = R_0 \exp(x(t)/\lambda)$. This can be adjusted by electrostatic tuning; λ is a material constant of the metallic electrodes defined by $\lambda^{-1}=\sqrt{(2m_e\Phi)}/\hbar$, with Φ being the work function and m_e the electron mass. This allows a mechanical variation of the *RC* constant and hence the tunneling characteristics of the junction, which is not possible for common single electron transistor (SET) devices. By applying radio frequencies up to 100 MHz across gate 1 and the source contact, we finally realize the nanomechanical resonator. In order to verify appropriate rf coupling we used a commercially available program (Sonnet Software, ver. 5.1, Liverpool, NY, 1998). We find very effective coupling, which is only slightly attenuated towards 100 MHz. We estimate the capacitance of the clapper tip to drain contact to be on the order of $C\approx 25$ aF. This estimation is based on a method proposed by de Vries *et al.*[6] and on calculations with electromagnetic problem solvers (MAFIA, ver. 3.20, 1993). Combining the capacitance and the tunneling resistance found in dc measurements, we obtain a *RC* constant of $\tau\sim 25\,\mathrm{aF}\times 1\,\mathrm{G}\Omega=25$ ns. Hence, the electrons are transferred one by one with a rate which can be approximated by the *RC* constant. The values of 25 ns correspond to 40 MHz, which is the range of operation of our mechanical resonator. Hence, the mechanical motion leads to a modulation or ''chopping'' of the electron tunneling rate. Electron tunneling is a discrete process, as exemplified by shot noise.[7–9] Since we are able to modulate the resonator at this rate, we transfer only a small discrete number of electrons in each cycle of operation. In other words, the average current is given by $\langle I\rangle=\langle q\rangle f=\langle n\rangle ef$, where $\langle n\rangle$ is the average number of electrons being transferred at frequency f in each cycle.

A characteristic drawback of the mechanical resonator is the discrete set of eigenfrequencies, which are determined by its overall geometry. Accordingly, only a limited number of frequencies are available for electron transfer. On the other hand, this gives the flexibility to design a resonator with a specific mode spectrum in the radio frequency range only, which in turn minimizes ''leakage'' currents in the low-frequency regime and the influence of $1/f$ noise. A simulation of the mechanical properties of our resonator is performed with a software package (MCS PATRAN, ver. 6.2), allowing us to test the influence of shape and clamping points on the eigenmodes of the device. Since the Au layer has almost the same thickness as the silicon supporting structure, it is necessary to model a hybrid Au/Si system. This is done by simply assuming two rigidly coupled bars with different spring constants ($\kappa_{\mathrm{Au}}=0.38$ N/m, $\kappa_{\mathrm{Si}}=46$ N/m—these values include geometrical factors). The resulting eigenfrequency spectrum shows a strong resonant response between $f=10$ and 100 MHz. The specific shape of the resonator produces different eigenmodes, as will be shown in the measurements.

The rf response of the resonator is presented in Fig. 3—it is obtained at 300 K under He^4 gas pressure of 1 bar: in Fig. 3(a) the current through the clapper-drain contact is plotted versus radio frequency applied ($V_{\mathrm{rf}}^{\mathrm{pp}}=\pm 5$ V) at a small bias value. The different traces in Fig. 3(b) correspond to various dc-bias voltages on the clapper. As seen, we find a number of mechanical resonances with a small quality factor Q of $\eta_1\cong 100$, $\eta_2\cong 30$, and $\eta_3\cong 15$ where the complex resonance structure is a result of the geometry of the clapper. Here we assume that the mechanical resonator is not experiencing a back action by the tunneling electrons. Applying the relation for the average dc current $\langle I\rangle=\langle n\rangle ef$, we obtain the logarithmic plot given in the inset of Fig. 3(a). In the low-frequency resonances, up to 10^4 electrons are transferred in each cycle, while at 73 MHz we find a transfer rate of $\sim$130 electrons at this amplitude of the driving voltage. The peak currents and the noise increase at larger bias voltages (0.1 V–0.5 V). It can also be seen that the background conduc-

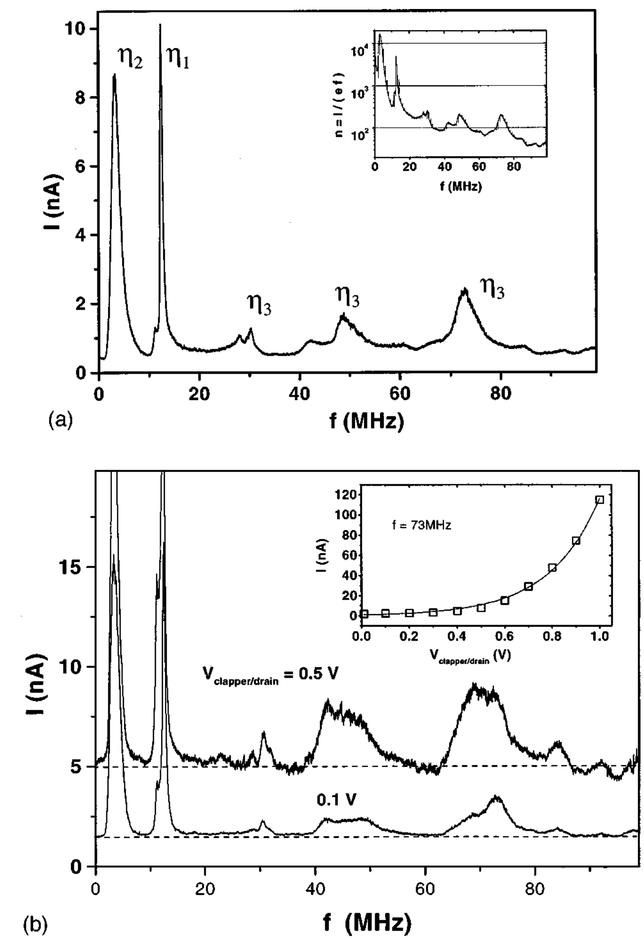

FIG. 3. (a) Tunneling current through the clapper/drain contact against applied frequency (applied at gate contacts 1 and 2). Several mechanical resonances up to 73 MHz with a quality factor of $Q \sim \eta_1 \cong 100$, $\eta_2 \cong 30$, and $\eta_3 \cong 15$ are found (see indices in the plot). Inset: log plot of electron number vs frequency—in the high-frequency peaks about 130 electrons are transferred in each cycle. (b) Resonance curves at different values of the dc-voltage bias across clapper/drain contact. The variation of the voltage bias results in an exponential increase of peak and background current. Inset: exponential behavior of peak current at 30.5 MHz—the solid line is an exponential fit to the data points (open boxes).

tance increases. The peak values themselves show an exponential increase of the current with $V_{\mathrm{clapper/drain}}$, which is shown in detail in the inset for the peak at $f = 73$ MHz. Here the solid line is an exponential fit to the data points. From this exponential behavior of the peak current at 73 MHz shown in the inset of Fig. 3(b), we can estimate x, which gives a value for the distance between clapper and drain contacts at the maximum applied dc voltage—we obtain $x_{\max} \approx 5$ nm.

Reducing the amplitude $V_{\mathrm{rf}}^{\mathrm{pp}}$ of the driving electric field leads to a reduced value of the number of electrons transferred in each cycle. An example is presented in Fig. 4: we chose a sufficient signal-to-noise ratio of the tunneling current $S/N \approx 3$ for the mechanical resonance at 30.5 MHz. In this representation the current is normalized to the average number of electrons transferred in each cycle of the frequency $f[\langle n \rangle = \langle I \rangle/(ef)]$. We achieve with a sufficient attenuation of the rf amplitude an average transfer rate of (7 ± 2) electrons at the maximum peak value. The inset gives the averaged number of electrons/cycle in time, showing a maximum variation of ± 2 electrons. This variation is limited by shot noise or Johnson (Nyquist) noise, depending on the parameters of eV_{DS} and $k_B T$.

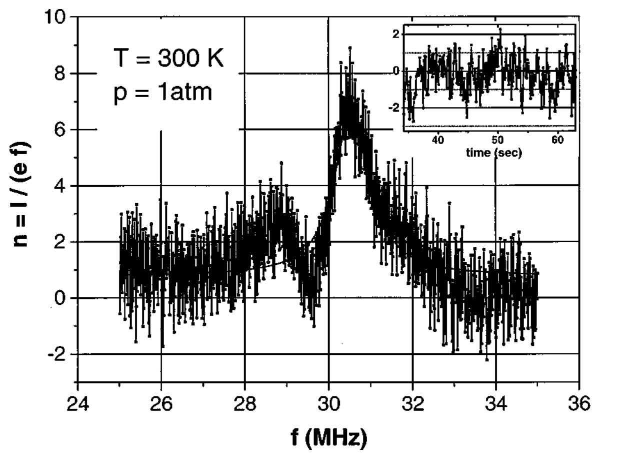

FIG. 4. Tunneling current through clapper/drain contact as a function of radio frequency applied to gate 1 and 2—the current is normalized to the average number of electrons tunneling in one cycle $[n = I/(ef)]$. At high frequencies, $f = 30.5$ MHz, and small excitation amplitude the number of electrons is reduced to only 7—the current shows a variation of $\pm 2e$. A Lorentz fit in the resonator maximum is shown as well. The inset shows the fluctuations in time of ± 2 electrons at maximum current.

To conclude, by scaling down a classical bell in size we have shown that a quantum bell can be built which rings in the ultrasonic frequency range. The essential requirement is a nanometer scale clapper resonating at radio frequencies and the ability to tune the *RC* constant of the tunneling contact. So far, we have obtained an accuracy of about ± 2 electrons, which can be transferred in a single revolution of the clapper. In a future setup of the experiment we will include a metallic island at the tip of the clapper, forming a metallic SET, in order to realize an electron shuttle mechanism, as proposed by Gorelik *et al.*[10]

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