Nanomechanical Resonator Shuttling Single Electrons at Radio Frequencies

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(Received 8 November 2000; published 13 August 2001)

We observe transport of electrons through a metallic island on the tip of a nanomechanical pendulum. The resulting tunneling current shows distinct features corresponding to the discrete mechanical eigenfrequencies of the pendulum. We report on measurements covering the temperature range from 300 down to 4.2 K. We explain the I-V curve, which unexpectedly differs from previous theoretical predictions, with model calculations based on a master equation approach.

DOI: 10.1103/PhysRevLett.87.096106 PACS numbers: 68.60.Bs, 73.23.–b, 87.80.Mj

One of the traditional experiments in the electrodynamics class is set up by two large capacitor plates and a metallized ball suspended in between the plates. Applying a constant voltage of several hundred volts across the plates leads to the onset of periodic charge transfer by the ball bouncing back and forth, similar to a classical bell [1]. The number of electrons transferred by the metallized ball in each revolution naturally depends on the volume of the metal, but can be estimated to be of the order of 10^{10}. At an oscillation frequency of some 10 Hz up into the audible kHz range, this gives a typical current of 1–10 μA.

The question arising is whether such an experiment can be performed on the microscopic level in order to obtain a transfer not of a multitude but of only one electron per cycle of operation at frequencies of some 100 MHz. Indeed this can be achieved by simply scaling down the setup and applying a nanomechanical resonator. In recent experiments [2] the importance of the excitation of mechanical modes for electronic transport through single fullerenes was discussed.

Here we present our results on shrinking the mechanical electron shuttle to submicron dimensions by integration of an electron island into a nanomechanical resonator functioning as an electromechanical transistor. Mechanical stability requires that the resonator is made relatively stiff. Thus an external ac voltage is added to the setup in order to drive the resonator into resonance. The clear advantages are the increased speed of operation and the reduction of the transfer rate, allowing us to count electrons one by one. A similar combination was proposed theoretically by Gorelik *et al.* [3] for metallic particles, which are connected to the reservoirs by elastically deformable organic molecular links. The main difference to common single electron transistor devices is the fact that only one tunneling barrier is open at a certain time. This leads to an exponential suppression of cotunneling effects and thus increases the accuracy of current transport. Detailed calculations for theoretical limits of the accuracy have been presented elsewhere [4]. In the present work we report on measurements of transport of electrons through a nanomechanical electron shuttle. The I-V characteristics which unexpectedly differ from theoretical predictions [4] can be explained by taking into account the driving voltage.

An important feature of the device is the effective modulation of the tunneling rates onto and off the electron island given by the mechanical motion at a large speed of operation ($f \sim 100$ MHz). This basically enables the device to mechanically filter and select electrons passing through the electromechanical circuit by simply adjusting the tunneling rate Γ. Additionally, the device is a tool to regularize the stochastic tunneling process through a well-defined geometry. Another advantage of nanomechanical resonators machined out of silicon-on-insulator (SOI) material is their insensitivity to thermal and electrical shocks as has been shown in their application for electrometry [5,6]. This and the high speed of operation enable direct integration in filter applications [7]. We have already demonstrated that a nanomechanical tunneling contact, which operates at radio frequencies, can be built out of SOI substrates [8].

The nanoelectromechanical electron shuttle is machined out of SOI material. In order to avoid mechanical defects in the structure, so-called "Smart Cut" [9] is used rather than SIMOX [10]. The fabrication process is divided into two steps: First the metallic leads (made out of Au) and the etch mask (made out of Al) are defined by optical and electron beam lithography. Then the mechanical pendulum is etched in a combination of dry and wet etch steps. Alignment of the etch mask with respect to the metallic leads has to be accurate down to 10 nm in order to provide well-defined tunneling contacts. In an earlier work we ensured that the processing steps, which are also used in our present work, provide clean and tunable tunneling contacts [8]. An electron micrograph and a schematic circuit diagram of the measurement setup are shown in Fig. 1.

The first measurements were performed at room temperature. The sample was mounted in an evacuated sample holder with a small amount of helium gas added to ensure thermal coupling. During evacuation the sample holder was heated. The 300 K trace shows a variety of resonances, where the source-drain current is increased due

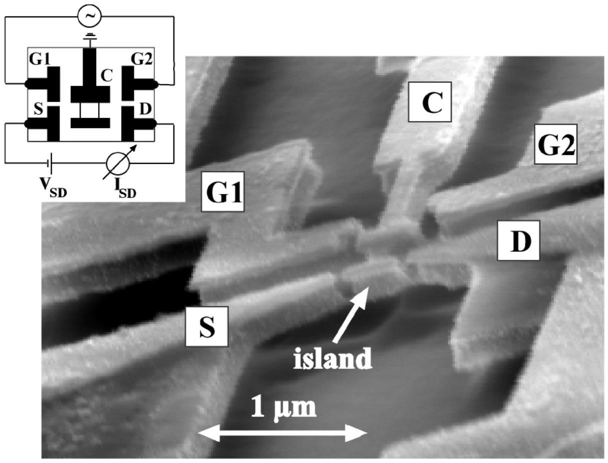

FIG. 1. Electron micrograph of the quantum bell: The pendulum is clamped on the upper side of the structure. It can be set into motion by ac power, which is applied to the gates on the left- and right-hand sides (G1 and G2) of the clapper (C). Electron transport is then observed from source (S) to drain (D) through the island on top of the clapper. The island is electrically isolated from the rest of the clapper which is grounded. The inset shows a simplified circuit diagram indicating the dc source-drain voltage and the driving voltage.

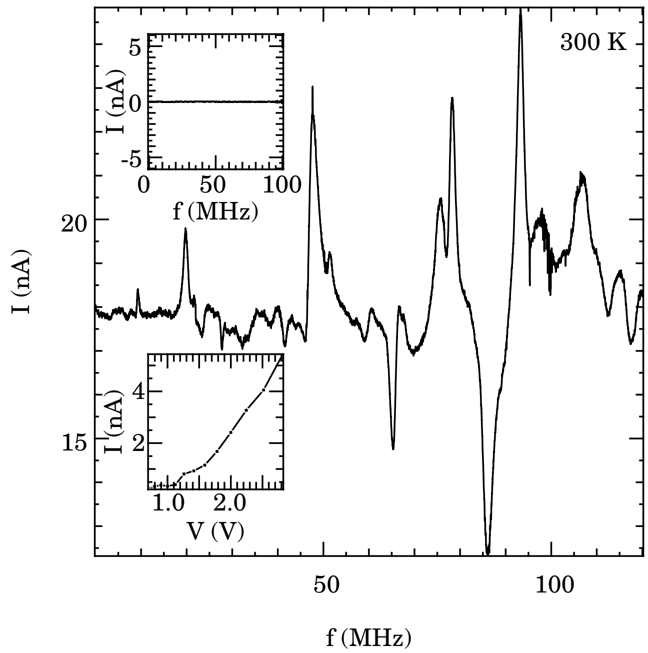

FIG. 2. Measurement of the tunnel current from source (S) to drain (D) at room temperature (driving ac voltage ± 3 V). The complex spectrum is similar to measurements on a single mechanically moving tunnel contact [8]. Finite element simulations show a complex spectrum of mechanical resonances [11]. The upper inset shows a measurement on a sample with identical layout, where the pendulum was prevented from moving by small silicon connections to the bulk material. No capacitive cross talk or conduction through the substrate could be observed. In the lower inset the current in one of the peaks is shown as a function of the driving voltage V.

to the motion of the clapper (see Fig. 2). This behavior is well known from the measurements performed on the single tunneling barrier [8]. It can be understood by taking the complex shape and mass distribution of the clapper into account. This leads to a large variety of modes including pure flexural, torsional, and combinations of both kinds. The mode spectrum can be simulated by finite element calculations [11]. The peaks are superimposed on a background, which depends linearly on the source-drain bias. This background is due to the thermal motion of the clapper, since it disappears at lower temperatures.

The clapper is set into motion by an ac voltage (± 3 V) applied to the two driving gates at frequency f_0. This leads to an alternating force acting on the grounded lower part (see C in Fig. 1) of the pendulum. Additionally, the driving voltage also acts as a gate voltage. In order to calculate the influence of this gate voltage on the number of electrons transferred we estimate the capacitance between the closest driving electrode and the island at positions of the island where tunneling occurs. This electrode as seen by the island has a radius of roughly 215 nm. With a distance of 300 nm between the driving gate and the island, the resulting gate capacitance is

$$C \simeq 4\pi\varepsilon_0 \left(\frac{1}{215 \text{ nm}} - \frac{1}{300 \text{ nm}} \right)^{-1} \approx 84 \text{ aF}$$

which corresponds to gate charges of up to $\pm 527e$ if voltages of up to $\pm 1V$ are applied. Because of this large number of electrons the applied voltages lead to an electrostatic force on the island.

Transport through the island on the clapper can be described by a simple master equation [4]

$$\frac{d}{dt} p(m,t) = -[\Gamma_{\mathrm{L}}^{(+)}(m,t) + \Gamma_{\mathrm{R}}^{(+)}(m,t)]p(m,t) - [\Gamma_{\mathrm{L}}^{(-)}(m,t) + \Gamma_{\mathrm{R}}^{(-)}(m,t)]p(m,t) + [\Gamma_{\mathrm{L}}^{(+)}(m-1,t) + \Gamma_{\mathrm{R}}^{(+)}(m-1,t)]p(m-1,t) + [\Gamma_{\mathrm{L}}^{(-)}(m+1,t) + \Gamma_{\mathrm{R}}^{(-)}(m+1,t)]p(m+1,t), \tag{1}$$

where Γ are the transition rates and p the probability to find m additional electrons on the island at time t. In a golden rule approach the tunneling rates are of the form [12]

$$\Gamma = \frac{1}{e^2 R} \frac{\Delta E}{1 - \exp(-\frac{\Delta E}{k_{\mathrm{B}} T})}. \tag{2}$$

Taking into account that the energy changes ΔE are time dependent due to the periodic motion of the shuttle [4] one obtains

$$\Gamma_{\mathrm{R},m}^{(\mp)}(t) = \frac{1}{\tau} \frac{\pm(m + \frac{C_G V_G}{e} + \frac{C_L(t)V}{e}) - \frac{1}{2}}{1 - \exp\{-[\pm(m + \frac{C_G V_G}{e} + \frac{C_L(t)V}{e}) - \frac{1}{2}] \frac{e^2}{C_\Sigma(t) k_B T}\}}, \tag{3}$$

where $\tau = R_R(t_{\max})C_R(t_{\max})$, $t_{\max}$ is the time, where the island is at its closest point to the right electrode, and $C_\Sigma(t) = C_R(t) + C_L(t) + C_G(t)$. For the left electrode the indices R and L have to be interchanged, V has to be replaced by $-V$, and $x(t)$ by $-x(t)$.

The numerical solution of Eq. (1) results in the height of the peaks being determined by the applied gate voltage V_G. If the frequency f_0 of the driving force coincides with the eigenfrequency of the clapper, resonant motion is excited. In our simulations this kind of motion shows a large number of electrons transferred at a high signal to noise ratio during each cycle. This creates the large peaks seen in the measurements. In agreement with this simulation we observe a linear increase of the number of transferred electrons at high voltages (lower inset of Fig. 2). If the shuttle moves with frequencies different from f_0 (e.g., excited thermally), the resulting current has a much smaller signal to noise ratio. Both the amplitude and direction of the current peaks depend on the phase relation between the applied driving voltage and the mechanical movement of the clapper. Different modes exhibit widely different phases with respect to the driving voltage which is also seen in finite element calculations [11]. This explains the fact that dips in the current can be seen as well as peaks. The number of electrons transferred hardly depends on source-drain bias, since the voltages applied on the driving gates are a factor 10^3 larger than the source-drain bias which agrees with the experimental result as shown in the inset of Fig. 3.

The displacement noise of a cantilever can be calculated in analogy to an electrical circuit [13]. The mean square displacement is given by the fluctuation-dissipation theorem $\langle u^2 \rangle = k_B T \chi_T$, where $\chi_T = \int d\omega \, \mathrm{Im}\chi/\omega$ can be approximated by $\Delta f \, \mathrm{Im}\chi/f$ for a peak at frequency f of width Δf. Thus the formula for Johnson noise derived by Nyquist [14] can be transformed for the mechanical case yielding

$$\langle u^2 \rangle = 4 k_B T \Delta f \, \mathrm{Im}\left\{-\frac{1}{\omega} \frac{u_k}{F_i}\right\}, \tag{4}$$

where u_k are the displacements due to applied forces F_i. This explains the amplitude of the thermal background. A contribution to the current by the substrate can be excluded as well as a displacement current by direct capacitive coupling of the ac power by measuring a sample with identical layout, where the pendulum was prevented from moving by small silicon connections to the bulk material (shown in the upper inset of Fig. 2).

We extracted one peak of the complex spectrum by subtracting the thermal background and overlapping neighboring peaks. The peak height does not depend on the dc source-drain bias. This can be explained by the large gate voltage. In the inset of Fig. 4 the electric field distribution around the clapper is shown in a top view by assuming a potential $V_G = 1$ V at one of the driving gates. The calculation was performed by using a finite element program [15]. This simulation shows that a large portion of the driving voltage also acts on the island. The number of transferred electrons in this peak is approximately 1000 which agrees with our theoretical estimate based on Eq. (1). These results show that the electron transfer works well at room temperature.

Measurements at lower temperatures show a complete suppression of the background and thus indicate its thermal nature. At temperatures of about 12 K a pronounced peak at 120 MHz is found. The oscillation amplitude of the motion at the peak position is strongly attenuated towards lower temperatures of 4.2 K due to the increased stiffness of the clapper. The rest of the complex spectrum is completely suppressed at 4.2 K also because of the increased

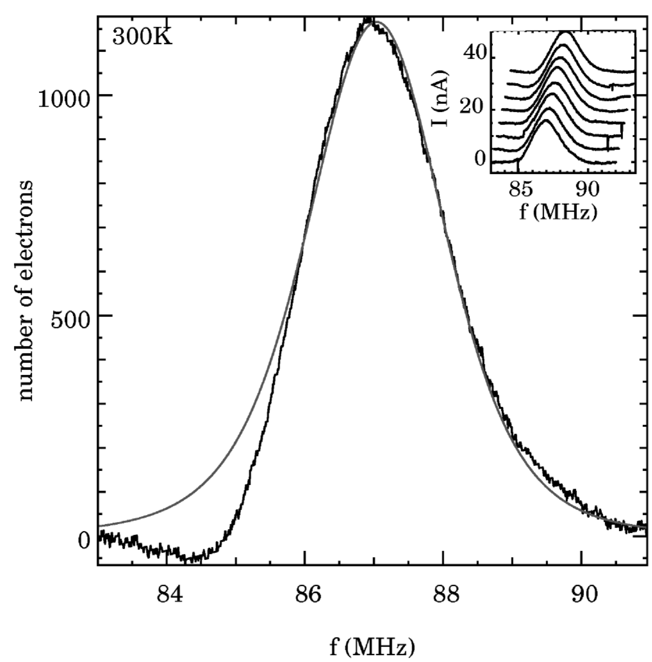

FIG. 3. Transport through the island is characterized at a frequency of 87 MHz. A fit to the peak according to Eq. (5) shows differences to the peak shape found in measurements on the single nanomechanical tunneling contact [8]. The peak was extracted from the complete spectrum (shown in Fig. 2) by subtracting the thermal background and overlapping neighboring peaks. The inset shows the peak at source-drain voltages from 0 mV (lowest curve) to 10 mV (top curve).

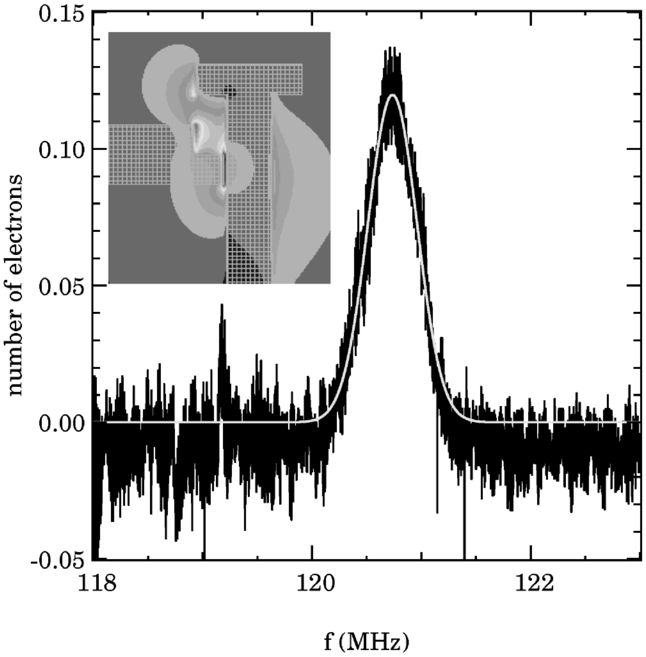

FIG. 4. At low temperatures only one peak remains, which can be fitted by the model given in Eq. (5). Inset: Capacitive cross coupling between the driving gates and the island calculated by a finite element program [15]. The electric field distribution around the clapper is shown in a top view by assuming a potential $V_G = 1$ V at one of the driving gates.

stiffness of the structure. The maximum current amplitude of the peak is (2.3 ± 0.02) pA, which corresponds to a transfer of 0.11 electrons on average per cycle of motion of the clapper. Peaks in the classical experiment [8] show Lorentzian line shape. In order to obtain a formula for the peak form in the present experiment we use the simple expression

$$\langle N \rangle \propto \frac{t_0}{RC}$$

for the average number of electrons transferred derived in [4] in the limit of small contact times $t_0 \propto 1/(f\sqrt{x_{\max}})$. The cantilever behaves like a damped harmonic oscillator with amplitude x, bare frequency f_0, and damping constant $2\pi k$ driven by an oscillating force at frequency f. Because of the strong dependence of R on the tunneling distance the peak shape can be modeled by the following approximation:

$$N = \frac{A}{f}\sqrt{\frac{x_{\max}(f_{\mathrm{r}})}{x_{\max}(f)}}\exp[-B\{1 - x_{\max}(f)/x_{\max}(f_{\mathrm{r}})\}], \tag{5}$$

where $x_{\max}(f) \propto 1/\sqrt{(f^2 - f_0^2)^2 + k^2 f^2}$ is the amplitude of the oscillation in resonance and $f_r = \frac{f_0}{2}\sqrt{4 - 2k}$ is the shifted frequency of the damped oscillator, respectively. As shown in Fig. 4 this describes the observed peak form very well, with a quality factor $Q = f_0/k$ of the order of 10. Small Qs are essential for operation as a switch where the oscillating force is replaced by a step function. For small quality factors the oscillatory solution of the differential equation vanishes on a short time scale.

In summary we have demonstrated a new way of transferring electrons at radio frequencies by using a combination of nanomechanics and single electron devices. At 4.2 K we measured an average of 0.11 ± 0.001 transferred electrons which shows that the resolution of current transport through the shuttle should also resolve Coulomb blockade after minimizing the effects of the driving voltage. We estimate the temperature at which Coulomb blockade should be observable to be 600 mK. Scaling down the island size will increase this temperature. In future work, forming superconducting and magnetic islands will be of interest for the understanding of the tunneling process itself.

We thank U. Sivan for discussion. Special thanks to J. P. Kotthaus for his support. This work was financially supported by the Deutsche Forschungsgemeinschaft (DFG Bl-487/1-1). C. W. acknowledges support by the SFB 348.

[1] M. T. Tuominen, R. V. Krotkov, and M. L. Breuer, Phys. Rev. Lett. **83**, 3025 (1999); P. Benjamin, *The Intellectual Rise in Electricity* (Appleton, New York, 1895), p. 507.
[2] H. Park, J. Park, A. K. Lim, E. H. Anderson, A. P. Alivisatos, and P. L. McEuen, Nature (London) **407**, 57 (2000).
[3] L. Y. Gorelik, A. Isacsson, M. V. Voinova, R. I. Shekter, and M. Jonson, Phys. Rev. Lett. **80**, 4526 (1998).
[4] C. Weiss and W. Zwerger, Europhys. Lett. **47**, 97 (1999).
[5] A. N. Cleland and M. L. Roukes, Appl. Phys. Lett. **69**, 2653 (1996).
[6] H. Kroemmer, A. Erbe, A. Tilke, S. M. Manus, and R. H. Blick, Europhys. Lett. **50**, 101 (2000).
[7] N. M. Nguyen and R. G. Meyer, IEEE J. Solid-State Circuits **25**, No. 4, 1028 (1990).
[8] A. Erbe, R. H. Blick, A. Tilke, A. Kriele, and J. P. Kotthaus, Appl. Phys. Lett. **73**, 3751 (1998).
[9] M. Bruel, FR Patent No. 2 681 472 (1993); U.S. Patent No. 5 374 564 (1994).
[10] J.-P. Colinge, *Silicon-on-Insulator Technology: Materials to VLSI* (Kluwer Academic Publishers, Boston, 1991).
[11] solvia, v. 95.2 (a finite element system).
[12] *Single Charge Tunneling,* edited by H. Grabert and M. H. Devoret, NATO ASI Ser. B, Vol. 294 (Plenum, New York, 1992).
[13] G. G. Yaralioglu and A. Atalar, Rev. Sci. Instrum. **70**, 2379 (1999).
[14] H. Nyquist, Phys. Rev. **32**, 110 (1928).
[15] MAFIA, electromagnetic finite element program, v. 3.20.