Silicon nanopillars for mechanical single-electron transport

Dominik V. Scheible[a]
Center for NanoScience and Fakultät für Physik der Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, 80539 München, Germany

Robert H. Blick
Department of Electrical and Computer Engineering, University of Wisconsin–Madison, 1415 Engineering Drive, Madison, Wisconsin 53706

(Received 24 November 2003; accepted 8 April 2004; published online 19 May 2004)

Nanomechanical systems have been shown to accurately regulate the flow of electric current. We present the concept and demonstrate experimental operation of a vertical electromechanical single-electron transistor. The device is fabricated from silicon forming a nanopillar situated between source and drain contacts. The advantage of this concept is its straightforward manufacturing, which only includes two processing steps: Electron-beam lithography and reactive ion etching. The device operates at room temperature and at frequencies in the range of 350–400 MHz. A theoretical model of the operation of this device is given, explaining qualitatively the obtained experimental data. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1759371]

Mechanical resonators manufactured at the nanometer scale operate at frequencies in the high-frequency/very high-frequency range[1] and, more recently, in the GHz domain.[2] Apart from realizing nonlinear dynamics[3] and chaotic response[4] in this radio-frequency regime, these so-called nanoelectromechanical systems (NEMS) not only promise experimental insight into quantum aspects of mechanical systems,[5] but are also lending themselves to applications in communication and information technology.[6,7] In this letter, we focus on the electrical current achieved by such NEMS, as demonstrated by Erbe *et al.*[8] Charge transport by mechanical means is intrinsically coupled to the dynamic properties of the mechanical system, i.e., to its resonant response. This concept consequently allows mechanical clocking of electron tunneling in nanoelectronic devices and lets mechanical resonators act as low-loss filters for ac signals.[6] Here, we present a mechanical transistor machined as a silicon nanopillar shuttling single electrons at 0.4 GHz.

A mechanical degree of freedom in nanostructures is usually obtained via the sacrificial layer process. This process includes a combination of anisotropic dry etching and isotropic selective wet etching, involving hydrofluoric acid and high-pressure liquid carbon-dioxide drying.[9] The present device is manufactured in a two-step process: First, nanoscale lithography using a scanning electron microscope (SEM), and, second, dry etching in a fluorine reactive ion etcher (RIE). The lithographically defined gold structure acts as both electrical current leads and etch mask for the RIE. A simple geometry defined by the SEM consequently results in the free-standing isolating nanopillar of intrinsic silicon with a conducting metal (Au) island at its top [see Fig. 1(a)]. This island serves as the charge *shuttle*.

The metal island and the nanopillar are placed in the center of two facing electrodes, denoted by source *S* and drain *D*. For excitation, we employ an ac voltage at source, rather than a sole dc bias, since the large mechanical stiffness present in NEMS inhibits the dc-self excitation as proposed by Gorelik *et al.*[10] Moreover, application of an ac-signal allows excitation of the nanopillar resonantly in one of its eigenmodes. The device itself is mounted in a probe station, providing vacuum condition for a reproducible and controlled environment of the pillar. This also removes water and solvents which may have condensed at the surface of the NEMS.

The basic concept underlying the device is its excitation via the excess charge present on the shuttle. This charge results in a resonant Coulomb force (RCF) within the ac source-drain field, which, in turn, causes mechanical oscillation if the ac frequency matches the frequency of a mechanical eigenmode. Hitherto employed excitation mechanisms, such as magnetomotive driving, are not applicable for mass-production devices due to the high magnetic field density

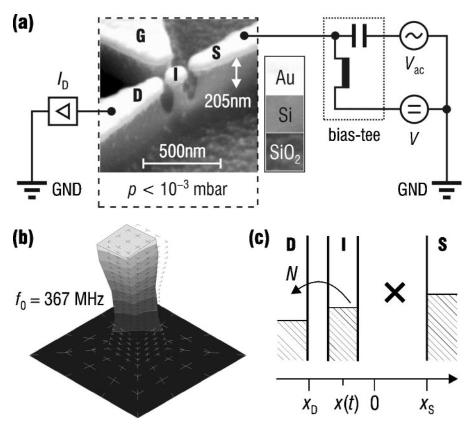

FIG. 1. (a) SEM micrograph and experimental circuitry of the silicon nanopillar: At source *S*, we apply an ac signal V_{ac} with a superimposed dc bias *V* and detect the net current I_D at drain *D* with a current amplifier. The third electrode *G* is floating. (b) Finite element simulation of the base oscillation mode which compiles for the nanopillar to $f_0 = 367$ MHz. (c) When the island is deflected toward one electrode, the instantaneous voltage bias determines the preferred tunneling direction. Cotunneling is absent in this case, due to an increased distance to the opposite electrode (×).

[a]Author to whom correspondence should be addressed; electronic mail: dominik.scheible@lmu.de

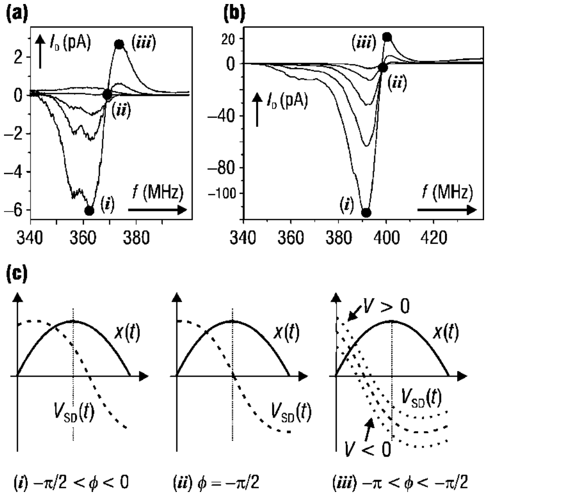

FIG. 2. (a) and (b) Measured spectral drain current I_D vs source frequency f for two nanopillar devices. In (a), power P ranges from 0 to $+10$ dBm and in (b) from $+2$ to $+8$ dBm. The resonance frequencies are $f_0^{(a)}=369$ MHz and $f_0^{(b)}=399$ MHz. (c) Phase relations of pillar deflection and source–drain bias. For a driven harmonic oscillator the phase lag ϕ varies from 0 to $-\pi$ and assumes $-\pi/2$ for resonance ($f=f_h$). In this case (*ii*), maximum island deflection occurs at the moment when the voltage bias vanishes, and hence no net current flows. (*i*) and (*iii*) show the cases $f<f_h$ and $f>f_h$ respectively. In (*iii*), a small superimposed dc bias reduces ($V>0$) or increases ($V<0$) the phase shift (dotted lines).

required (~12 teslas). In addition to this, our device needs no cryogenic cooling and operates at room temperature.

When the shuttle is deflected to one electrode it exchanges electrons across the tunneling barrier between island and the respective electrode. As the deflection toward one electrode causes the distance between the island and the other electrode to increase, only one tunneling barrier has to be considered at a time and no cotunneling occurs.[11] During this deflection, the shuttle exchanges charge carriers with the electrode: N electrons tunnel off the island and M electrons tunnel onto the shuttle. The respective amounts N and M are determined by the instantaneous electrical bias [see Fig. 2(c)]. The detected current I_D is given by the net number of transferred electrons times the shuttle frequency f:

$$I_D=gef(N-M)\equiv gefn, \tag{1}$$

where e is the electronic charge and g accounts for a statistical limitation for the case that deflection does not suffice for charge transport each cycle.

For the excitation via RCF, it is necessary that the shuttle sustains a certain excess charge during oscillation. This is ensured by a mechanical asymmetry that strongly favors one tunneling barrier at which the shuttle can be reset to the same charge state each cycle. If we assume m electrons present on the shuttle for the time period when both tunneling barriers are closed, the RCF calculates as

$$F_{\mathrm{RCF}}(t)=me\frac{\widetilde{V}_{\mathrm{ac}}\sin(2\pi ft)}{d_{SD}}, \tag{2}$$

with the ac amplitude $\widetilde{V}_{\mathrm{ac}}$ and the source–drain distance d_{SD}. For stable operation, the relation $(N-M)=n<m$ must hold. Via a finite element simulation,[12] we can estimate the electrode-island capacitance to be $C_{SI}\approx 10$ aF. This results in a maximum excess charge $m\approx 24$ electrons, causing a force of 7 pN at an incident ac power of $P=+5$ dBm.

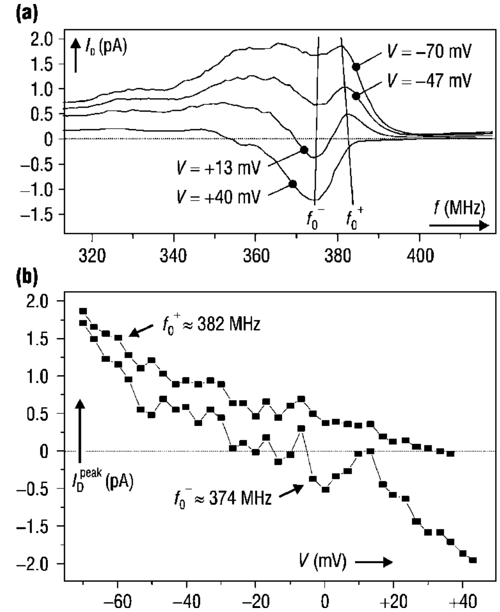

FIG. 3. (a) Tuning of the current resonance by a superimposed dc bias V. Both negative and positive current response are entirely detuned by the respective bias. This is a further test of the excitation of the shuttle via the RCF. (b) Negative (lower trace) and positive (upper trace) peak currents I_D^{peak} vs dc bias V. The traces represent a section of the entire set of current spectra at frequencies $f_0^-\approx 374$ MHz and $f_0^+\approx 382$ MHz.

The current frequency behavior is strongly influenced by the phase relation between the mechanical motion and the electrical ac bias. In the case of a harmonic oscillator (HO), the driven entity follows the applied force with a phase lag of

$$\phi_h(f)=\arctan\left(\frac{\Gamma f}{f_h^2-f^2}\right), \tag{3}$$

with the dynamic damping Γ and the resonance frequency f_h of the HO when no damping is present.[13] For excitation of a mechanical eigenmode h of the nanopillar, the phase lag equals $\phi=-\pi/2$, i.e., maximum deflection occurs when the ac bias vanishes [see Fig. 2(c)]. For an ideal system, we accordingly expect a zero net current $I_D=0$ for $f=f_h$. Above and below the resonance frequency f_h, the phase lag approaches $-\pi$ and zero, respectively. Depending on the sign of the excess charge m, we find either a positive current for $f>f_h$ and a negative current for lower frequencies, or vice versa.

We have carried out the basic measurement of the current–frequency response for a couple of devices showing similar behavior at slightly different eigenfrequencies f_0. This variation is explained by the different height and waistline of the pillars. Via a finite element simulation,[14] both the absolute resonance frequencies and variations were reproduced [see Fig. 1(c)]. The current traces I_D for a set of ac powers P are plotted in Figs. 2(a) and 2(b). Highest current amplitudes correspond to a transported net amount of electrons $n<2$ after Eq. (1), which well satisfies $n<m$. For the two samples, the negative and positive peak current differ by a factor of 2 and 5, respectively. Mechanical asymmetry and inhomogeneity of the effective electric field destroy the phase relation of an ideal HO, and hence cause the asymmetry of the peaks. Furthermore, maximum deflection occurs at a frequency $f_h^*<f_h$ when a finite damping is present.

The mechanism of RCF can be tested in the present setup via a superposition of a dc bias V onto the ac voltage $V_{ac}(t)$. This is accomplished by a bias-tee which is placed in between the device and the signal generator. The dc bias shifts the voltage sine of $V_{ac}(t)$ up and down relative to the zero base line [see Fig. 2(c)]. As long as this bias is small compared to the ac amplitude $\tilde{V}_{ac}$, the main influence is a mere shift of phase between deflection and the effective source–drain bias. As a result, we are able to tune the negative and positive current peaks (*i*) and (*iii*) as well as the zero-current (*ii*). In Fig. 3(a), we show the spectral current for a set of selected values of the dc bias V ranging from -70 mV to $+40$ mV. It is important to note, that the observed behavior not only supports the concept of RCF, but also demonstrates the tuneability of this mechanical rectifier via a simple dc bias.

A section of all current traces at the lower and upper peak-frequencies $f_0^{\pm}$ reveals that the peaks are not only detuned, but also can give reverse current response. As Fig. 3(b) shows, this is achieved for a high dc bias exceeding 40 mV of magnitude. In addition to the detuning, a regular steplike structure is observed in both peaks when the dc bias V is ramped. We attribute this to a gradual change of the oscillatory mode rather than Coulomb blockade effects. Although the distance of the steps ($\sim$23 mV) would correspond to the island–electrode capacitance, its overall capacitance is larger than the required $e^2/2k_BT \approx 3$ aF for 300 K. Nevertheless, operation of nanomechanical electron shuttles in the regime of Coulomb blockade, even at room temperature, appears within reach for a smaller pillar.

The authors would like to thank C. Weiss for useful discussions, and J. P. Kotthaus and D. W. van der Weide for their support. One of the authors (D.V.S.) gratefully acknowledges financial support by the Deutsche Forschungsgemeinschaft (DFG) under Grant No. Bl-487/1-3.

[1] R. H. Blick, A. Erbe, L. Pescini, A. Kraus, D. V. Scheible, F. W. Beil, E. Höhberger, A. Hörner, J. Kirschbaum, H. Lorenz, and J. P. Kotthaus, J. Phys.: Condens. Matter **14**, R905 (2002).
[2] X. M. H. Huang, C. A. Zorman, M. Mehregany, and M. L. Roukes, Nature (London) **421**, 496 (2003).
[3] D. V. Scheible, A. Erbe, and R. H. Blick, Appl. Phys. Lett. **82**, 3333 (2003).
[4] D. V. Scheible, A. Erbe, G. Corso, and R. H. Blick, Appl. Phys. Lett. **81**, 1884 (2002).
[5] M. L. Roukes, Phys. World **14**, 25 (2001).
[6] C. T.-C. Nguyen, IEEE Trans. Microwave Theory Tech. **47**, 1486 (1999).
[7] N. Maluf, *An Introduction to Microelectromechanical Systems Engineering* (Artech House, Norwood, MA, 2000).
[8] A. Erbe, C. Weiss, W. Zwerger, and R. H. Blick, Phys. Rev. Lett. **87**, 096106 (2001).
[9] D. V. Scheible, A. Erbe, and R. H. Blick, New J. Phys. **4**, 86.1 (2002).
[10] L. Y. Gorelik, A. Isacsson, M. V. Voinova, B. Kasemo, R. I. Shekhter, and M. Jonson, Phys. Rev. Lett. **80**, 4526 (1998).
[11] C. Weiss and W. Zwerger, Europhys. Lett. **47**, 97 (1999).
[12] MAFIA finite element system for Maxwell equations (v. 3.20).
[13] F. K. Kneubühl, *Oscillations and Waves* (Springer, Berlin, 1997).
[14] SOLVIA finite element system for mechanical eigenmodes (v. 99.0).