Single-electron devices with a mechanical degree of freedom

Yu A Pashkin¹, J P Pekola², D A Knyazev³, T F Li⁴, S Kafanov¹, O Astafiev¹ and J S Tsai¹

¹ NEC Green Innovation Research Laboratories and RIKEN Advanced Science Institute, Tsukuba, Ibaraki 305-8501, Japan
² Low Temperature Laboratory, Aalto University, P.O. Box 13500, 00076 AALTO Finland
³ Lebedev Physical Institute, Russian Academy of Sciences, Moscow 119991, Russia
⁴ Institute of Microelectronics, Tsinghua University and Tsinghua National Laboratory for Information Science and Technology, Beijing 100084, China

E-mail: pashkin@zp.jp.nec.com

Abstract. We have succeeded in integrating a single-electron transistor (SET) and a nanomechanical resonator into one device by suspending the SET island. In this case the island has flexural modes whose resonance frequencies depend on the material parameters and the island dimensions. The device is made of Al and can be studied in both the normal and superconducting states allowing observation of various physical phenomena. By driving the resonator with an external force at a frequency close to the resonance frequency of the fundamental flexural mode, we observe a characteristic feature in the dc SET transport, which is due to the mechanical resonance of the island. The resonance frequency as high as 0.5 GHz was detected. The observed response is reproduced in the simulations based on the semiclassical model of single-electron tunneling with the mechanical degree of freedom taken into account. Besides the studies of charge transport in single-electron circuits, the device can also be used for investigation of quantum effects in the charge qubits with a mechanical degree of freedom.

1. Introduction

Progress in the fabrication technology allows creation of mechanical resonators and electronic circuits with the dimensions in the nanometer range. Miniaturization of the resonators as well as the use of light materials with a high Young’s modulus result in a smaller mass and higher resonance frequency of the resonators. This is beneficial for various applications, such as, for example, mass and force sensing. Even more intriguing, a truly quantum regime becomes accessible for a mechanical system represented by a high-frequency resonator, which offers a possibility to study quantum-mechanical effects in a macroscopic mechanical system [1].

Nanoelectromechanical systems (NEMS) consist of two basic parts: a nanomechanical resonator and a transducer – detector transforming mechanical vibrations into an electrical signal. Principal requirements for the transducer are: (i) high sensitivity to mechanical displacement and (ii) low back action on the resonator. The single-electron transistor (SET) [2] capacitively coupled to a nanomechanical resonator satisfies both requirements. In particular, its extremely high charge sensitivity and low back action makes it possible to measure motion of the resonator in the quantum regime [3]. The first successful realization of the SET as a detector...
of mechanical motion was reported in [4]. Using a rf version of the SET, a position resolution only a factor of 4.3 above the quantum limit was achieved [5].

Until now, nanomechanical resonators, usually beams clamped on both sides, have been made of single-crystal semiconducting or insulating materials, such as Si [6], AlN [7], SiC [8], SiN [9], GaAs [10], etc. Characterization of such resonators at low temperatures requires their metallization, which affects the resonators’ performance. Furthermore, coupling of such resonators to the transducer implies that two separate processing steps are used for the fabrication of the resonator and transducer on the same chip, which imposes some constraints on the alignment of both devices. We have developed a fabrication method for metallic resonators [11] with the possibility of their integration into various electronic devices such as SET, SQUID, charge and flux qubits, etc. In this case the whole fabrication process is carried out in one technological cycle and is fully compatible with the process for the nanoscale electronic devices. Despite the polycrystalline nature of the metallic resonators, their performance at low temperatures is as good as that of single crystal structures.

In this work we present a conventional aluminum SET with a suspended island doubly clamped from both sides by the source and drain electrodes [12]. This is a two-in-one device that includes both the nanomechanical resonator and displacement sensor. The SET operates in the dc regime and reacts to the mechanical motion due to the rectification of the ac signal on the nonlinearity of the SET transport characteristics. Aluminum being a light material allows for appropriate dimensions of the resonator to achieve resonant frequencies up to several GHz. With proper cooling it can thus be operated in quantum regime. Mechanical motion of the resonator is detected as modulation of the SET current due to variation of the electric charge on the SET island when it oscillates about the equilibrium position. The estimated displacement sensitivity is about $3 \times 10^{-13}$ m/Hz$^{1/2}$. A similar SET based on a carbon nanotube was reported in [13, 14].

2. Device fabrication and layout

Fabrication process of a suspended SET is depicted in Fig. 1. We have utilized the fabrication method described in detail in [15] but with one important modification: besides the regular side gate we have an additional bottom gate beneath the SET island. The idea of suspension of the

![Figure 1. Fabrication flowchart for the suspended SET. The thickness of the various layers is not to scale.](#)

![Figure 2. Scanning electron micrograph of the suspended SET.](#)
SET is to fabricate it on a pedestal made of organic polymer which can be easily ashed away in a mild oxygen plasma after the SET fabrication is completed. Our choice for an organic polymer is calixarene, a negative tone electron-beam (EB) resist, because: (i) it is chemically compatible with the subsequent fabrication process and (ii) use of low-energy oxygen plasma for removing it leads to almost no change in sample resistance in the ashing process.

The device fabrication process consists of one photolithography step followed by three EB lithography steps with a proper layer alignment. After the formation of gold pads and coplanar waveguides on an oxidized silicon wafer, a gold bottom gate was patterned by EB lithography. Then, an about 50 nm-thick calixarene pedestal covering the bottom gate was formed. The height of the pedestal determines the gap between the SET and the bottom gate in the final structure (after removing calixarene). Next, a tri-layer resist structure LOR3A/Ge/poly-methyl-methacrylate (PMMA) with the corresponding thicknesses 400 nm/20 nm/50 nm was built, where the bottom lift-off resist LOR3A is a polymer providing large undercut profiles regardless of the EB exposure dose. The desired pattern for Ge mask was drawn in the top PMMA layer and then transferred into the Ge layer by reactive ion etching in CF₄. The remaining PMMA on top of Ge was removed by oxygen plasma. The undercut in LOR3A was created by submerging the chip in remover PG and rinsing it in water. At this stage, the suspended Ge mask supported by the LOR3A layer is ready.

The SET was fabricated by a conventional two-angle deposition of Al through a Ge mask with an oxidation step after the first deposition. The suspension of the SET island was performed byashing the calixarene pedestal in a mild oxygen plasma.

There are two reasons for having the bottom gate in addition to the usual side gate of the SET: (i) the capacitance between the bottom gate and the SET island can be easily made larger than the capacitance between the side gate and SET island, which makes the coupling of the SET with the resonator stronger; (ii) control of the SET current and coupling of the SET with the resonator can be made independently by applying corresponding voltages to different gates, which simplifies the measurement process.

Scanning electron micrograph of one of our samples (SET1 in Table 1) is depicted in Fig. 2. The SET was fabricated such that after ashing the calixarene only the island and the very tips of the source and drain electrodes became suspended. The island was connected in series through the tunnel junctions Al/AlOₓ/Al to and clamped by the source and drain electrodes. The clamps were about two times thicker than the island. The area of each junction was defined by the overlap of the bottom and top electrodes and it was designed to be about 3000 nm², which should give the SET charging energy of about 100 µeV. The island length of the suspended SET shown in Fig. 2 was \( L = 1.5 \mu m \). The other two SETs studied in this work (SET2 and SET3 in Table 1) had 1 µm and 0.67 µm long suspension. For all our samples the width and thickness of

### Table 1

|     | \( L \) (µm) | \( R \) (kΩ) | \( E_c \) (µeV) | \( f_0 \) | \( f_{exp} \) | \( C_{tot} \) | \( C_{gs} \) | \( C_{gb} \) |
|-----|--------------|--------------|----------------|--------|-------------|-------------|-------------|-------------|
| SET1| 1.5          | 142          | 141            | 88     | 95          | 567         | 1.22        | 54.2        |
| SET2| 1            | 281          | 117            | 199    | 206         | 684         | 0.97        | 29.9        |
| SET3| 0.67         | 150          | 121            | 443    | 492         | 661         | 0.75        | 27.5        |
the SET island were \( w = 70 \text{ nm} \) and \( t = 40 \text{ nm} \), respectively.

In the absence of mechanical stress the resonance frequency \( f_0 \) of the fundamental bending mode of such a doubly clamped beam for out-of-plane vibrations is given by \( f_0 \approx 1.03 \times \sqrt{E/\rho \times (t/L^2)} \) [16], where \( E \) and \( \rho \) are Young’s modulus and mass density of the resonator material, respectively. Inserting island dimensions and aluminum parameters \((E = 69 \text{ GPa} \) and \( \rho = 2700 \text{ kg/m}^3 \)) into the above formula we obtain an estimate for \( f_0 \) values for all three SETs. Due to mechanical stress caused by the difference in the thermal contraction coefficients of aluminum (the island material) and silicon (the substrate material) one should expect an increase of the resonance frequency by a few percent, which is observed in the experiment (Table 1).

3. Experimental setup
The device under study and measurement setup (the wiring of the device and voltage sources used in the experiment) are presented in Fig. 3. To drive the beam we applied to the bottom gate a small (rms value up to \( 1 \text{ mV} \)) rf voltage \( V_{\text{rf}} \). Mechanical vibrations of the island are converted to the change of its electric charge when constant voltage is applied to the bottom gate. Therefore, to increase the coupling of the SET to the mechanical oscillations, we simultaneously applied to the same gate a high (up to \( \pm 4 \text{ V} \)) constant voltage \( V_{\text{dc}} \). To control the state of the SET, side gate of the structure was connected to constant voltage source \( V_{g} \). The measurements of the SET behavior both in superconducting and normal state were carried out in a dilution refrigerator (DR) with a base temperature of about \( 25 \text{ mK} \). To transfer the SET into the normal state, a magnetic field of \( 1 \text{ T} \) was applied perpendicular to the sample chip plane. All dc voltages were supplied to the sample through filtered dc wires. The rf signal was delivered to the bottom gate through a coaxial line with a 20 dB attenuator at the \( 4 \text{ K} \) stage of the DR. In order to apply a dc voltage to the same gate, we also inserted a DC block in the rf line.

4. Results and discussion
First, we characterized all SETs both in superconducting and normal state. Namely, we measured SET current \( I \) as a function of bias voltage \( V \) and two gate voltages: side gate voltage \( V_{g} \) and bottom gate voltage \( V_{\text{dc}} \). All the measured SETs exhibited very good stability and demonstrated typical traits predicted by the orthodox theory [17]: Coulomb blockade of charge tunneling controlled by the gate voltage. From these measurements we extracted basic SET parameters (total tunnel resistance \( R \), charging energy \( E_c \), total island capacitance \( C_{\text{tot}} \), side gate capacitance \( C_{gs} \) and bottom gate capacitance \( C_{gb} \)) that are listed in Table 1.

Then, in order to detect mechanical resonance of the suspended SET island, we applied two voltages, \( V_{\text{dc}} \) and \( V_{\text{rf}} \), to the bottom gate. At fixed values of \( V, V_{\text{dc}}, \) rf power and frequency we...
measured current $I$ though the SET as a function of side gate voltage $V_g$. Since the dependence $I(V_g)$ is periodic, the range of $V_g$ was chosen to be equal to one period of side gate modulation of the SET current, so the measured $I(V_g)$ curve had a maximum at $C_{gb}V_g/e = 0.5$. Then this measurement was repeated at different frequencies of the driving signal $V_{rf}$. The frequency was increased by an increment smaller than the expected resonance width $f_0/Q$, where $Q$ is the resonator quality factor.

Even away from the resonance $I(V_g)$ peak gets suppressed and broadened by the rf signal. This effect does not depend on the frequency and leads only to the splitting of $I(V_g)$ peak at high enough rf power. Once the driving frequency gets close to the resonance frequency, there is an additional effect on the $I(V_g)$ peak, which strongly depends on the frequency. The intensity plot revealing the measured resonance is depicted in Fig. 4a. The resonance manifests itself as a characteristic feature in $I(f)$ dependence. This resonance feature is seen at any $V_g$, but most pronounced at $C_{gs}V_g/e = 0.5$ (Fig. 4b). Our observations are in good agreement with the predictions of the orthodox theory [17] with the mechanical degree of freedom of SET island taken into account. In simulations we took the SET parameters from the experiment and used $Q = 10^4$. An example of the stimulated $I(f)$ dependence at $C_{gs}V_g/e = 0.5$ is shown in Fig. 4c.

It is clearly seen (Fig. 4b) that the measured $I(f)$ dependence has a dispersive-like shape instead of Lorentzian that one expects for a driven harmonic oscillator with small dissipation in the linear regime. This is because the capacitance change due to mechanical displacement changes its phase by $\pi$ with respect to the drive when passing through the resonance.

When the sum of voltages $V_{dc} + V_{rf}$ is applied to the bottom gate, displacement $x$ of the island center from its equilibrium position results in the change of the bottom gate capacitance $\Delta C_{gb} = C_{gb}x/d$, where $C_{gb}$ and $d$ are the bottom gate capacitance and island clearance in equilibrium. Comparing the induced island charge $\Delta q = V_{dc}\Delta C_{gb} = V_{dc}C_{gb}x/d$ to the SET charge noise $\delta q$ we obtain the device sensitivity to mechanical displacement $\delta x = d\delta q/(V_{dc}C_{gb})$. For the SET working in the dc regime the charge noise $\delta q$ is dominated by $1/f$ fluctuations of the background charge and can be conservatively set to $10^{-3}e/\text{Hz}^{1/2}$, where $e$ is the electron charge. Then for $d = 50\text{nm}$ and $C_{gb} = 30\text{aF}$ (see Table 1), the estimated sensitivity is $\delta x \approx 3 \times 10^{-13}\text{m/Hz}^{1/2}$ per volt of $V_{dc}$.

In accordance with the equipartition theorem, the rms displacement of the island due to thermal fluctuations is $\langle x_T^2 \rangle = k_B T/(4m_{\text{eff}}\pi^2f_0^2)$, where $k_B$ is the Boltzmann constant and $m_{\text{eff}}$ is the effective island mass. For $T = 25\text{mK}$, a typical value of $\langle x_T^2 \rangle$ is $3 \times 10^{-13}\text{m}$ that is comparable to $\delta x$. Hence, the sensitivity of our devices to mechanical displacement is sufficient to detect the thermal motion of the nanomechanical resonator at mK temperatures. For the rf

![Figure 4](image-url)

**Figure 4.** (a) Intensity plot of SET1 current as a function of side gate voltage and frequency at $V = 0.12\text{mV}$, $V_{dc} = -2.5\text{V}$ and rf power $P_{rf} = -60\text{dBm}$. The resonance is seen as a distinctive feature at about 95 MHz. (b) Measured $I(f)$ curve at $C_{gs}V_g/e = 0.5$. (c) Simulated $I(f)$ dependence at $C_{gs}V_g/e = 0.5$. 


version of the SET operating in the MHz frequency range, the charge noise is about two orders of magnitude lower [18]. Therefore, the suspended rf SET is capable of resolving its own quantum zero-point motion.

The experiment described above opens a possibility for studies of a charge qubit (Cooper pair box) with a mechanical degree of freedom. The charge qubit with a probe junction used for readout [19] is basically an asymmetric superconducting SET, and the suspension of its island is rather straightforward. According to the analysis of the charge qubit electrostatically coupled to a nanomechanical resonator that was performed in Ref. [20, 21], the qubit energy spectrum becomes modified and depends on the Fock state of the resonator. Away from the qubit degeneracy point, the qubit-resonator energy levels form a manifold with the separation of $hf_0$ between the neighboring levels, where $h$ is the Planck’s constant. In the spectroscopy measurements, these extra energy levels may be revealed as additional peaks in the probe current. Observation of these current peaks would yield a direct evidence of the quantum regime of the nanomechanical resonator.

In conclusion, the suspended SET in the dc regime is capable of detecting its own high-frequency mechanical oscillations. The described device also allows studies of quantum mechanical effects in macroscopic mechanical objects at mK temperatures.

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