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Integrated Nanoscale Mechanics and Electronics

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1. Introduction

The continuing miniaturization of electronic devices has had two complementary benefits: firstly, individual transistors can have improved performance while secondly more can be integrated in a small chip. Physicists have exploited these techniques to their own ends – exploiting the quantum nature of electrons confined to small volumes at low temperature. The quantum Hall effect, universal conductance fluctuations and, most relevant to this paper, Coulomb blockade are all evidence of the utility and interest of this subject.

The field of microelectromechanical systems (MEMS) is in a much earlier stage of development, however miniaturization of mechanical devices is continuing as well, spawning the field of nanoelectromechanical systems, or NEMS. Whether this miniaturization will lead to improved individual device performance or improved systems integration is still an open question. In recent years, proposals and experiments have begun to explore the regime of NEMS at low temperatures, attempting to demonstrate the quantum regime for mechanical structures[1].

The simplest NEMS device is a vibrating beam, forming the heart of force sensors and many scanned probe microscopes. Such a vibrating beam can be described as a simple harmonic oscillator with resonant frequency $f_0 = \omega_0/2\pi$, mid-point displacement x, and effective mass m. The position of the oscillator fluctuates continuously at a temperature T, with root mean square displacement amplitude

$$\delta x = \sqrt{k_B T / m\omega_0^2} \ . \qquad (1)$$

One implication of quantum mechanics, however, is that the quantized nature of the oscillator energy yields an intrinsic fluctuation amplitude, the 'zero-point' motion

$$\delta x_{ZP} = \sqrt{\hbar / 2m\omega_0} \ , \qquad (2)$$

that is achieved for temperatures T well below the energy quantum,

$$T << T_Q \equiv \hbar\omega_0 / k_B \ . \qquad (3)$$

This zero point motion, or in fact any deviation from classical behaviour, has not yet been observed in a macroscopic mechanical object[2]. The ability to measure such deviation is important both for the development of new transducers as well as for its implications in the field of quantum measurement. With the growing interest in quantum computation in solid-state systems, the measurement of a coherent quantum state is becoming more important[3].

In order to measure the approach to the zero-point motion for NEMS resonator, stringent conditions must be achieved. Firstly, the temperature must be reduced such that $T \approx T_Q$, which for a 100 MHz resonator is ~30 mK. Secondly, the nearly vanishing displacement must be measured, without overly perturbing or heating the resonator.

The use of nanoscale electronics, particularly the single electron transistor (SET) is well suited for this task. SETs are the most sensitive electrometers, measuring small fractions of an electronic charge at sub-Kelvin temperatures, dissipating very little power[4].

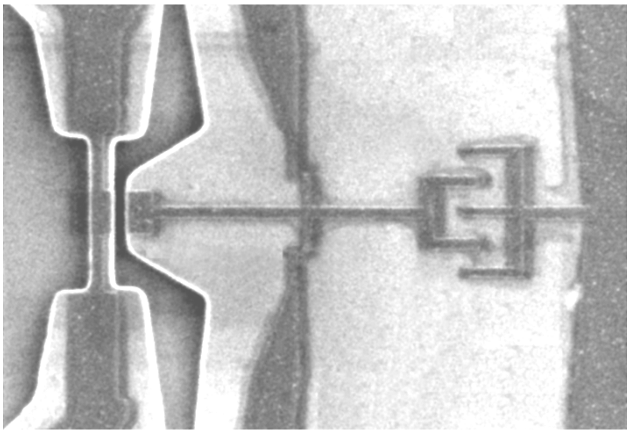

Fig. 1 Top view electron microscope image of an integrated NEMS/SET device. The vibrating beam on the left is 3 by 0.25 μm in size, and 200 nm thick. The SET tunnel junctions are at the center of the image.

2. Experiment

We fabricated a doubly clamped beam of single-crystal GaAs using successive steps of electron-beam lithography and etching from a GaAs/AlGaAs/GaAs heterostructure. A SET was defined next to the vibrating beam, using electron beam lithography and standard Al/AlO_x/Al shadow evaporated tunnel junctions[5] (see Fig. 1). The mechanical beam could be driven by applying a radio-frequency current along the electrode on its top, using the Lorentz force developed in an 8T magnetic field perpendicular to the plane of the device. The induced EMF across the device may be measured, enabling a determination of the resonant frequency f_0 =

116.7 MHz, Q = 1800 and effective spring constant k_{eff} = 0.9 N/m for the device.

The SET was operated with the electrode on the beam acting as a capacitively coupled gate[6]. A dc voltage V_{beam} was applied to this electrode. The capacitance C between the SET and the beam then has a coupled charge $q = V_{beam}C$. As the beam vibrates in the x direction, in the plane of the device, the resulting variation in capacitance ΔC will modulate the charge induced on the SET, $\Delta q = V_{beam}\,\Delta C$, changing the SET source–drain current. As the voltage V_{beam} is increased, the charge modulation Δq and the sensitivity to the resonator motion will increase. However, the source-drain current is due to the stochastic flow of electrons through the SET, so the centre island's voltage fluctuates randomly. This causes a fluctuating 'back-action' force on the beam. This force increases as V_{beam} increases, resulting in a voltage for which the total noise is minimized. The displacement sensitivity at this optimal voltage is calculated to be $S_x \sim 10^{-16}$ m/Hz$^{1/2}$, approaching the sensitivity needed to measure quantum effects.

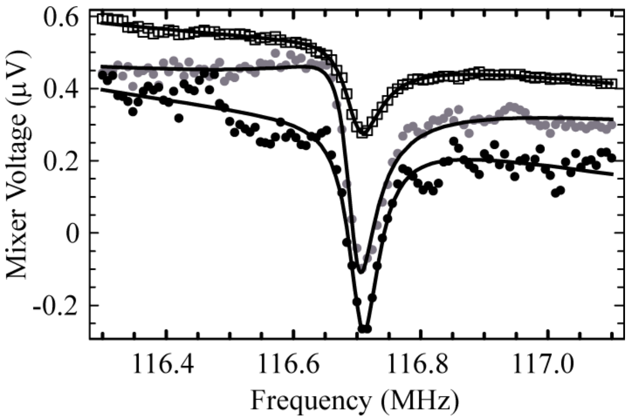

Fig. 2 Raw data, and fit, to SET response to beam motion for -105 dBm, -115 dBm and -125 dBm drive powers (bottom to top). For the -125 dBm curve, the response is 9.9 V/µm corresponding to a sensitivity of 2.0×10^{-15} m/Hz$^{1/2}$, limited by noise in the room temperature electronics.

In order to operate the SET at the resonant frequency of the beam, the SET was used as a mixer[7]. The SET was biased to give maximum curvature in the gate-dependence of the current-voltage characteristic. A second gate (left side of Fig. 1) was used to couple in a local oscillator, offset in frequency from the signal frequency by a fixed value of 151 Hz. The non-linearity introduced the sum and difference frequency components, and the low-pass nature of the wiring allowed clear measurement of the difference signal, without complicated frequency matching or cryogenic preamplification.

3. Results

Raw data, and fits to the resonance as measured using the SET at 30 mK in an 8T magnetic field are shown in Fig. 2. The measured EMF for higher powers enables a calibration of the displacement of the beam midpoint versus drive power. A drive power of -125 dBm on resonance corresponds to a displacement of 2.35×10^{-14} m. Noise in the room temperature conventional electronics limits the sensitivity to the midpoint displacement on resonance to $S_x \approx 2.0\times10^{-15}\,\mathrm{m/Hz^{1/2}}$. This sensitivity is a factor of ~100 away from the thermal noise in the resonator at 30 mK, and represented (at the time) the closest approach to the zero point motion ever achieved in a macroscopic mechanical object[8]. Subsequent measurements in a similar system have improved on these limits, and bring to the fore the question of how to prepare, measure a mechanical object in a coherent quantum state[9]. The back-action of the SET on the beam has not yet been measured, however back-action is the unavoidable ultimate limitation on the direct measurement of position of an object.

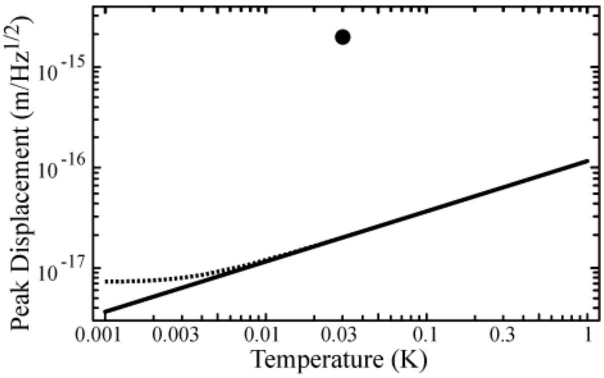

Fig. 3 Demonstrated sensitivity of SET displacement measurement (point) compared with expected thermal (solid line) and quantum-limited (dotted line) displacement of the beam on resonance.

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