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Tunable coupled nanomechanical resonators for single-electron transport

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Abstract. Nano-electromechanical systems (NEMS) are ideal for sensor applications and ultra-sensitive force detection, since their mechanical degree of freedom at the nanometre scale can be combined with semiconductor nanoelectronics. We present a system of coupled nanomechanical beam resonators in silicon which is mechanically fully Q-tunable $\sim$700–6000. This kind of resonator can also be employed as a mechanical charge shuttle via an insulated metallic island at the tip of an oscillating cantilever. Application of our NEMS as an electromechanical single-electron transistor (emSET) is introduced and experimental results are discussed. Three animation clips demonstrate the manufacturing process of the NEMS, the Q-tuning experiment and the concept of the emSET.

1. Introduction

With the advent of three-dimensional nanostructuring of semiconducting materials, nanoelectromechanical systems (NEMS) came into the focus of mesoscopic physics. Apart from the increasing demand for highly sensitive sensor devices [1], NEMS operating in the GHz range will allow quantum limited displacement sensing [2]. Most promising is the realization of controllable mechanical single-electron transistors, which have been treated theoretically (e.g. see [3]). The accuracy of such electromechanical single-electron transistors (emSETs) can be enhanced substantially [4], since the tunnelling barriers can now be modulated mechanically at several hundred megahertz [5].

Here we present a system of coupled nanomechanical resonators, consisting of driven and balancing beams. A doubly clamped central beam and two singly clamped cantilevers at both

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ends of the central beam were fabricated in Si, see figure 1(a). Partial metallization provides conductance for actuation and signal detection. Coupling between the two parts of the system allows us to tune the mechanical properties of the complete system and the non-direct driving of the cantilevers. Mechanical coupling is facilitated via the clamping points. This concept is feasible up to the non-linear regime of large deflection amplitudes and even chaotic response has been observed [6].

In order to ensure reproducibility, we fabricated a series of resonator systems with equivalent layout, revealing similar spectra of mechanical excitation as shown for a single structure in figure 1(b). Each peak in this spectrum corresponds to one eigenmode of the entire system, denoted as M_1, M_2 and M_3. This demonstrates that manufacturing of our system of coupled nanomechanical resonators is very reproducible, cf figure 1(c). In numerical studies by finite-element methods, the different modes M_i were reproduced.

The structuring process is shown in the animation clip of figure 2: the resonator system was processed from a silicon-on-insulator (SOI) wafer, incorporating a 400 nm sacrificial layer of SiO_2 beneath the single-crystal Si surface layer with a thickness of 200 nm [7, 8]. The structured top coating (evaporated Au and Al) serves as an etch mask as well as an electrically conducting layer. The Al is finally removed during the wet etch.

2. Mechanical properties

A crucial figure of merit for mechanical resonators is the quality factor Q, defined as the ratio of the oscillation energy $\epsilon_{\rm osc}$ and the amount of energy $\epsilon_{\rm dis}$ which is dissipated during one period, i.e. $Q = \epsilon_{\rm osc}/\epsilon_{\rm dis}$. The latter is obviously proportional to the oscillator's attenuation Γ. For $Q \gg 1$ the approximation

$$Q = f_0/\Delta f_0 \tag{1}$$

holds, where f_0 is the eigenfrequency, and Δf_0 the full width at half maximum of the resonance peak. The present nanomechanical resonator is designed in order to minimize energy loss: in addition to preceding work of ours [5, 9] this is achieved by adopting the layout of classical tuning forks and adding electrodes gating the mechanical resonator (see figure 1(a)). Here, the entire so-called Q-tips are coated with Au and compensate as *counterweights* for the central resonator's motion during oscillation. As a consequence, the centre of mass is fixed at all times, and hence we expect a decreased attenuation and an enhanced quality factor Q. This is an equivalent concept to that of a tuning fork, in which two resonators oscillating in plane ensure large Q. Figure 3 demonstrates this behaviour by holding the centre of mass $\boldsymbol{R}$ fixed in the case of Q-tuning.

Due to the rigid clamping points, the total resonator can be treated as consisting of three separate parts. The energy transfer from the central resonator to the Q-tips is suppressed at the lowest resonance (M_1). This is due to the fact that the frequency related to the first order eigenmode of the Q-tips is higher than the frequency of M_1. As a result, we observe virtually no displacement of the outer Q-tips when the driven oscillator is in its lowest mode (verified via capacitive detection [6]).

From this, we deduce the mode shape M_1 to be as shown in figure 3(b), with an eigenfrequency of $f_{M_1} = 40.79$ MHz. Once excitation frequencies reach the first eigenfrequency of the Q-tips, displacement is indeed observed. The resulting mode M_2 corresponds to the second harmonic mode of the central system with $f_{M_2} = 61.24$ MHz.

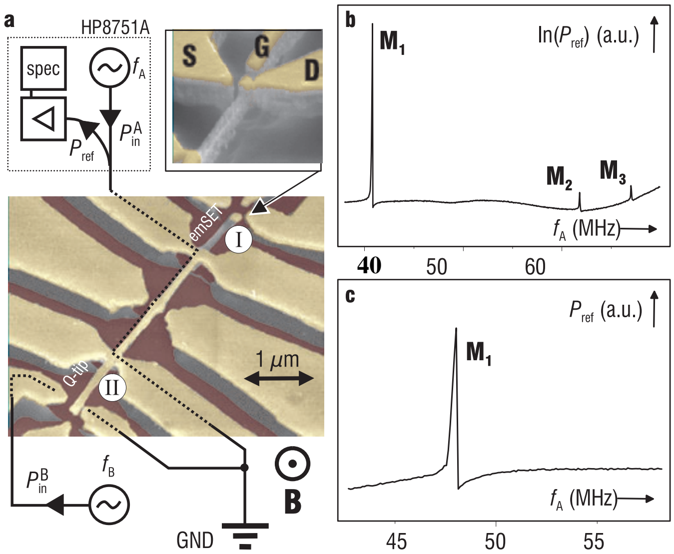

Figure 1. (a) SEM micrograph of the resonator system and experimental setup: the network analyser (HP8751A) provides the ac signal $P_{\rm in}^{\rm A}$ for excitation in a perpendicular magnetic field **B** and measures the reflected signal $P_{\rm ref}$. The latter is achieved by a built-in S-parameter test set. (I) and inset, the electrically isolated configuration as an emSET; (II) the capacitve drive $P_{\rm in}^{\rm B}$ for Q-tuning. The actual sample is symmetric. (b) Spectrum of mechanical excitation $P_{\rm ref}$ versus frequency $f_{\rm A}$, featuring the three main modes $\rm M_1$, $\rm M_2$ and $\rm M_3$. (c) The first mode $\rm M_1$ for a second representative sample.

A qualitative model of beam resonators can be obtained by using the Duffing equation, modelling the displacement $y(t)$, where the restoring force of a driven and damped harmonic oscillator is expanded in a Taylor series:

$$\partial_t^2 y(t) + 2\Gamma\omega_0\partial_t y(t) + \omega_0^2 y(t) + k_3 y^3(t) = K\cos(\omega t), \tag{2}$$

Γ denotes the attenuation, ω_0 the (circular) eigenfrequency, ω the frequency of the driving force and K its amplitude. In (2) we truncated the series expansion after the first additional k_3-term, i.e. we neglect asymmetric potential components so far. Classical non-linear beam mechanics still applies to our NEMS, as treated in concise detail in [11].

As mentioned above, clamping prevents the Q-tips from oscillating at base frequency. In this mode, the desired compensation of the central resonator's motion is therefore suppressed, hence the relatively poor $Q \sim 700$. By ac driving the gates, however, it is possible to prepare the desired mode shape. The Q-tips are excited capacitively by applying a large ac signal $P_{\rm in}^{\rm B}$ at the outer gate pairs (see figure 1(a)(II)). At the same time the magnetomotive excitation of the central beam is performed. When both frequencies match in such a way that the entire resonator moves in phase, the resonator's centre of mass is spatially fixed. Dissipation is reduced and according to equation (1) the quality factor Q is strongly increased, see figures 3(c) and (d).

We have to point out that the resonance shape in the case of maximized Q clearly deviates from the usual Lorentzian. We explain this with an increased non-linear behaviour due to the excitation by two sources. However, the crucial ingredients of increasing Q—enhanced mechanical response close to the resonance and suppressed response elsewhere—is featured

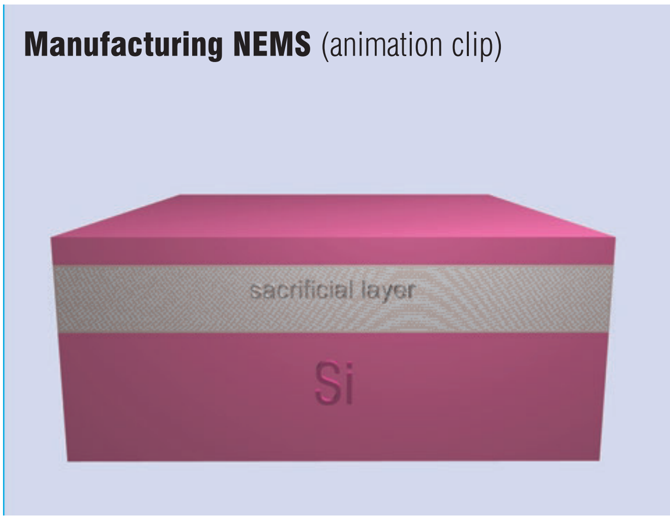

Figure 2. (Animation clip DivX encoded [10]: nems.DivX.avi; Cinepak encoded: nems.CPK.avi). Manufacturing process. (a) The SOI-chip is coated with PMMA (b) as a resist for electron-beam lithography and the NEMS layout is transferred by electron-beam writing (c). After resolving the exposed acrylate (d) the bare silicon is coated (e) first with a layer of NiCr, a Au metal layer and an Al protection layer (shown as only one). Subsequent lift-off of the metal film (f) prepares the sample for dry etching (g), which defines the nanostructure. The SiO_2 is removed selectively in a buffered oxide etchant (h) and dried using critical point drying (not shown).

by this experiment. Using approximation (1), we calculate a maximum value of $Q \sim 6000$. Although $Q \sim 10^4$ appears poor for macroscopic oscillators, it still represents a very high value for NEMS.

3. Mechanical single-electron transistors

So far it has been shown that coupled nanomechanical systems can be used to tune the properties of a resonator. Additionally these measurements show that mechanical motion can be transferred from the Q-tips to the central resonator and vice versa. Taking advantage of this coupling leads to the concept of a controllable mechanical single-electron transistor (cf figure 1(a)(II)).

The SET is based on the so-called Coulomb blockade: due to a very small island capacitance $C_\Sigma = C_S + C_G + C_D$ its charging energy $E_{n\to n+1}$ for a single electron can be substantially higher than the thermal energy E_T of the electrons (cf figures 4(b)–(g)). Once the condition

$$\frac{e^2}{2C_\Sigma k_B} \gg T \qquad (3)$$

is satisfied, further transfer of electrons onto the island is blocked. SETs allow a charge detection sensitivity down to fractions of the elementary charge e [12]. Nanomechanical systems enable a single-electron transistor to be mechanically shuttled between the source and the drain contacts, i.e. only one tunnel barrier can be surmounted by a single electron at a time, and co-tunnelling is strongly suppressed [4].

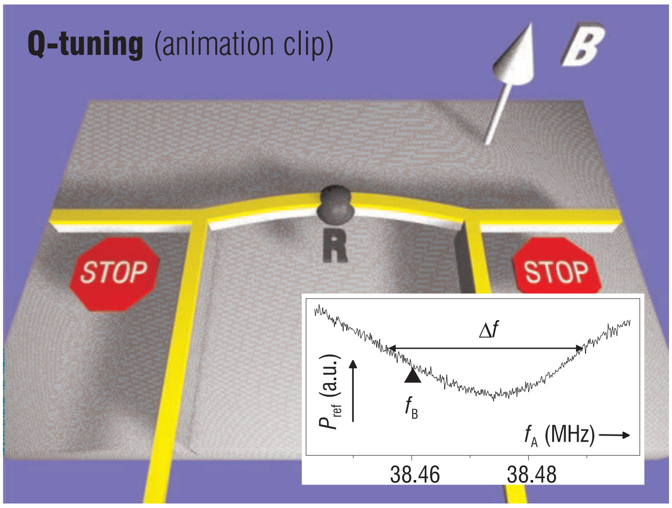

Figure 3. (Animation clip DivX encoded [10]: Qtuning.DivX.avi; Cinepak encoded: Qtuning.CPK.avi). The Q-tuning experiment. (a) Resonance frequencies do not match for the base mode M_1 and only the central beam is excited mechanically. (b) The centre of mass is not fixed in space and hence the structure possesses a poor Q. (c) Additional driving of the outer cantilevers with a resonance-matched frequency close to f_1 renders the system's centre of mass fixed in space, and consequently enhances the Q-factor (d). Insets show experimental data (mechanical response P_{ref} versus frequency f) for each situation.

In preceding work of ours [5], the approach of employing a single nanomachined cantilever with an isolated conducting island at its tip has been shown to draw a current across source and drain. Coupled nanomechanical systems allow us to provide sufficient mechanical tunability in terms of deflection amplitude and general dynamics, to shuttle single electrons in a well defined manner each cycle: firstly, because displacement does not need to be generated via close driving gates that inescapably interfere with the SET; secondly, dynamic stability is crucial for current standard applications of such systems.

Figure 4 shows the concept of a mechanical single-electron transistor, in which the driving mechanism is represented as a black box. In the actual experiment excitation of the cantilever can be achieved either by mechanical coupling to a magnetomotively driven beam resonator or via capacitive driving similar to Q-tuning with the single-electron island at the end of an extended cantilever.

The chip is mounted in a cryostat, providing up to 12 T and temperatures of 1.5–300 K. In addition to the resonator beams we introduced a set of tuning/signal gates to the system. These gates, denoted here by the letters S (source), G (gate) and D (drain), enabled us to apply a bias V and detect a current I at gating electrodes. Tuning excitation frequency to match mechanical eigenmodes and hence induce displacement of the respective parts of the system is crucial in this experiment. The signal is amplified by a current/voltage converter.

The observed current of the charge shuttle is calculated as

$$I = gnef, \tag{4}$$

with $g \cdot n$ the average number of charges e transferred each cycle. Here, we separate two main

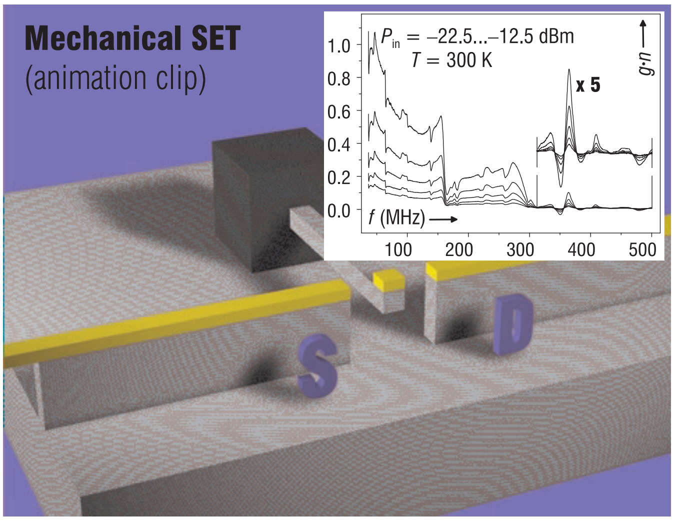

Figure 4. (Animation clip DivX encoded [10]: mset.DivX.avi; Cinepak encoded: mset.CPK.avi). concept of a mechanical single-electron transistor, illustrated for $g \cdot n = 1$. (a) A tiny island of gold (size $100\,\mathrm{nm} \times 100\,\mathrm{nm} \times 100\,\mathrm{nm}$) is shuttled back and forth between source and drain contact. Excitation is achieved via mechanical coupling. (b) Crucial for Coulomb blockade are the two capacitances C_{S} and C_{D} (the gate has been left out for clarity). Once the source contact is biased at a voltage V (c) a fractional voltage V_{I} is applied to the island (d). Deflection of the cantilever toward the source gate (e) causes the left tunnel barrier to become surmountable, and an electron tunnels (f). When the bias, capacitances and temperature satisfy the Coulomb-blockade condition (3) further electron tunnelling is blocked (g), and the NEMS shuttle transports a single electron each cycle (h). The inset of the initial frame and (h) shows number of transferred electrons $g \cdot n$ versus excitation frequency f for a set of input (driving) powers P_{in}, as calculated via (4) from actual experimental data.

limiting mechanisms. As described above, Coulomb blockade constitutes the maximum number n of electrons the island can hold. A *transport factor* g accounts for mechanical limitations, such as the deflection-dependent tunnelling rate. In the case of ideal self-excitation we have simply $g = 2$, as discussed by Gorelik *et al* [3]. For an external shuttle drive though, determination of $g \cdot n$ is somewhat more difficult [5].

Measurements show that a current can be drawn across the mechanically oscillating structure, with strong frequency dependence, as expected (figure 4 inset). The modal spectrum ranges up to 0.5 GHz (in good accordance with simulation [13]), and shows exponential dependence on applied power P_{in}. The animation clip of figure 4 demonstrates the ideal situation in which one electron is transferred each cycle, i.e. $g \cdot n = 1$. Data reveal an even lower value $g \cdot n < 1$ throughout the modal spectrum, which indicates a statistically dominated limitation mechanism. This can be mainly ascribed to an insufficient deflection amplitude.

4. Conclusion

In conclusion, we are able to fully control the dynamic response of a coupled nanomechanical resonator by featuring a design similar to a classical tuning fork. Q-tuning in a wide range is achieved by a combination of capacitive and magnetomotive excitation. Furthermore, current transport across a mechanically displaceable system has been discussed and shown. Improvement in bias and temperature promise full display of Coulomb-blockade physics in a nanomechanical device and hence allows application as a displacement sensor with ultra-high sensitivity and precision.

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