# Nano-Electromechanical Transistor operated as a Bi-Polar Current Switch

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***Abstract* — We report on nanomechanical transistors operating in the radio frequency range. Fabrication of the devices is compatible with semiconductor processing techniques of Silicon-on-Insultaor subtrates. Device operation is demonstrated at room temperature. For achieving maximal dissipation control of the mechanical quality factor *Q* a *tuning fork* resonator design has been adapted. Adjusting gate voltage parameters allows application of the transistor as a phase sensitive bi-polar current switch.**

***Index Terms* — Nanotechnology, nano-electromechanical systems, semiconductor devices.**

## I. INTRODUCTION

Incorporating a mechanical degree of freedom on the micro- and nano-scale enables the fabrication of electromechanical transistors [Erb1,Shb2a]. Based on standard silicon processing techniques such transistors enable direct integration of sensor and signal processing elements into standard circuitry. Especially, since the operating frequency of nano-mechanical devices is now crossing 1 GHz [Hug3], application for signal processing is possible [Ngy1]. Nano-electromechanical transistors will prove to be of importance, e.g. when applied as sensor elements for gas sampling through field effect ionization [Shb3a], as a diode operated as a ultra-sensitive fuse [Shb3b], or as a switch as discussed here. An important precondition for this is the ability to control the mechanical properties of the nano-resonator completely. This we achieved recently when we demonstrated tuning of the mechanical quality factor *Q* [Shb02b]. In the following we will first discuss layout and fabrication of the electro-mechanical transistors and then focus on the experiments performed with respect to the current switching.

## II. MEASUREMENT SETUP AND FABRICATION

Operation of nano-electromechanical systmes (NEMS) in the radio-frequency range and GHz-domain is well established. Mostly these nano-scale mechanical systems are driven by the Lorentz force which, in turn, is caused by an AC current in a perpendicular magnetic field. Hence, these devices require high magnetic field densities (up to 20 teslas), and consequently elaborated cryogenic cooling. In contrast, the concept of the single electron transistor relies on capacitive excitation of the nano-mechanical resonator [Erb1]. This ensures room temperature operation and large bandwidth of operation. Charge transport is then achieved across the mechanically ondulated tunneling barriers between the gates and the island, which occurs at a sufficiently low voltage bias. Our device consists of a nano-machined cantilever made from silicon-on-insulator material (see Fig. 1). At the tip of a freely suspended cantilever of about 1 micron length we deposited a gold island with dimensions 80x80x50 nm$^3$. Two gates A and B face the grounded cantilever C, and the island I oscillates between source S and drain D. AC excitation is applied to gate A, whereas an additional DC bias is imposed via source S. The resulting net current $I_D$ is detected at drain D, and recorded versus AC

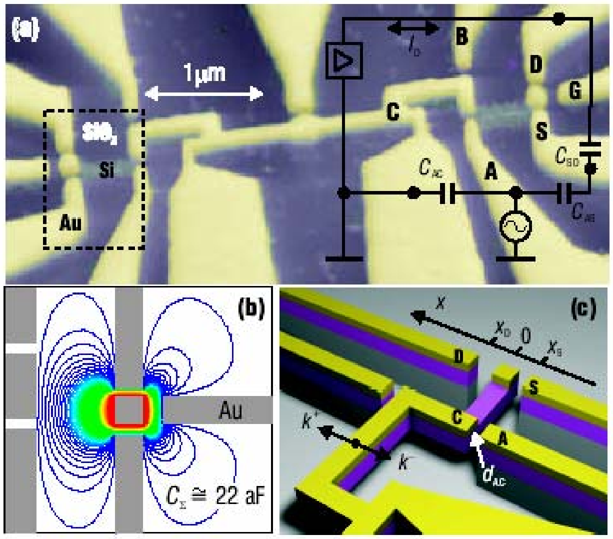

Fig. 1: (a) Tuning fork resonator with two electromechanical transistors on the outer tips of the nano-resonator, i.e. boxed region on the left. Circuit diagram with the voltages on gates A and B, mechanically controlling the clapper C, which oscillates the island between source (S) and drain (D). The gating contact G is mechanically fixed. (b) Electromagnetic field distribution around the electron island and source/drain contacts. The total capacitance of the island is determined to be 22 aF. (c) Sketch of the transistor: evaporated gold contacts on single crytalline silicon (purple) with spring constants $k^{+/-}$.

excitation frequency $f$ for the DC bias $V$ as the parameter. We have shown the manufacturing process and detailed operation of the device elsewhere [Shb2a,Shb2b]. Using an electro-magnetic problem solver (see Fig. 1(b)) we find an island capacitance of roughly 22 aF, which allows to estimate the electrostatic forces involved. These are balanced by the mechanical stiffness of the cantilever, where we use a spring constant $k$ assuming bulk values for the materials (silicon and evaporated gold).

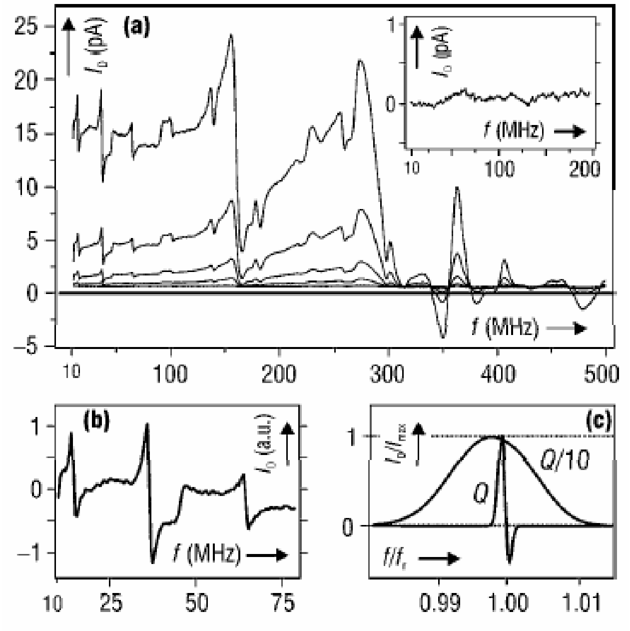

Fig. 2: (a) Current vs. frequency sweep: the different mechanical modes of the electromechanical transistors can be clearly distinguished. Inset gives a measurement after the transistor has been burnt out. (b) Magnification of the low frequency end with the typical resonance feature around 36 GHz. (c) Calculation of the resonance trace for two different $Q$-values. At high $Q$ the resonance feature measured is reproduced.

## III. EXPERIMENT

In the experiment we measured the current vs. frequency relation at room temperature, as shown in Fig. 2. The different modes are related to the discrete modal spectrum of the clapper resonator. The AC excitation power $P$ has to be increased. In the case of the present device reasonably low powers of $P = -30$ – $-10$ dBm suffice for stable operation at room temperature. At 77 K however, a substantially higher power of $P = +8$ dBm was required in order to produce a comparable DC current of the nanomechanical diode. This increase of the AC power $P$ by two orders of magnitude allowed the device to establish the transition. The inset shows a measurement after the island was destroyed by a large voltage pulse. In Fig. 2(b) a magnification of the low frequency end of the spectrum is shown at low bias. As seen the sign of the current can be switched by a slight shift in frequency. This can also be achieved by $Q$-tuning through the center contact as a simple model calculation indicates (Fig. 2(b)). For higher $Q$-values the resonance shape changes as found in the experiment. The underlying mechanism is given by the fact that the clapper reveals a phase lag of $\pi/2$ to the excitation voltage. Accordingly, the electromechancial transistor can be biased to operate as a bilpolar switch at radio frequencies.

## IV. CONCLUSION

We introduced a tuning fork resonator as a $Q$-tunable nano-electromechanical structure. Under appropriate gating the device can be operated as a bio-polar current switch. Layout and fabrication are compatible with standard silicon processing techniques, which lends the device for straight forward integration in on-chip sensing and communication components.

## ACKNOWLEDGEMENT

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## REFERENCES

[Erb1] A. Erbe, C. Weiss, W. Zwerger, and R. H. Blick, ‘Nanomechanical Resonator Shuttling Single Electrons at Radio Frequencies", *Phys. Rev. Lett.* **87**, 096106 (2001).

[Ngy1] C. T.-C. Nguyen, ‘Vibrating RF MEMS for low power wireless communications (invited)’, *Proceedings; 2000 Int. MEMS Workshop (iMEMES'01)* Singapore, July 4-6, 21, 2001.

[Hug3] X.M.H. Huang, C.A. Zorman, M. Mehregany, M.L. Roukes, ‘Nanodevice motion at microwave frequencies’, *Nature* **421**, 496 (2003).

[Shb2a] D.V. Scheible, A. Erbe, and R.H. Blick, ‘The mechanically tunable single electron transistor’, *New J. Phys.* **4**, 86 (2002).

[Shb2b] D.V. Scheible, A. Erbe, and R.H. Blick, ‘Dynamic $Q$-control of coupled nanomechanical resonators’, *Appl. Phys. Lett.* **82**, 3333 (2003).

[Shb3a] D.V. Scheible, Ch. Weiss, J.P. Kotthaus, and R.H. Blick, ‘Periodic field emission from an oscillating nano-scale electron island’, submitted to *Phys. Rev. Lett.* (2003).

[Shb3b] D.V. Scheible, D.R. Koenig, and R.H. Blick, ‘Coulomb driven shuttling of single electrons in a nanomechanical diode’, submitted to *Phys. Rev. Lett.* (2003).