Superlattices and Microstructures, Vol. 27, No. 5/6, 2000
doi:10.1006/spmi.2000.0873

Silicon-based nanoelectronics and nanoelectromechanics

A. TILKE, A. ERBE, L. PESCINI, H. KRÖMMER, R. H. BLICK, H. LORENZ, J. P. KOTTHAUS†

Center for NanoScience and Sektion Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1,
80539 Munich, Germany

(Received 28 February 2000)

We demonstrate Coulomb blockade oscillations in different single-electron devices in Silicon-On-Insulator (SOI) films up to temperatures of 300 K. The layer sequence in SOI allows the underetching of these devices in order to realize suspended, highly doped silicon nanostructures. Similar suspended silicon beams are fabricated to form novel nanomechanical resonators that can be excited at radio frequencies up to about 300 MHz. Controlling the vibration frequency by a side-gate voltage, these resonators allow charge detection with a sensitivity of 0.1 $e/\sqrt{\mathrm{Hz}}$, comparable to that of cryogenic single-electron devices.

Key words: single-electron devices, nanomechanics.

1. Introduction

High-resolution low-energy electron-beam lithography using the negative electron resist calixarene gives us the definition of device dimensions down to 10 nm for the fabrication of nanostructures in thin Silicon on Insulator (SOI) films [1]. We realize both highly doped nanowires [2] to study Coulomb blockade (CB) in the classical metallic regime as well as quantum dots defined in inversion layers of metal-oxide field effect transistors (MOSFETs) [3] to observe non-periodic CB oscillations strongly affected by spatial quantization. Underetching of these nanostructures in the SOI-system allows to realize suspended single electron transistors (SuSETs) [4] and, by metallization of these suspended beams, also a novel kind of nanomechanical resonators [5].

2. Quasi-metallic Coulomb blockade oscillations

We combine the well-established SOI-technology with the fabrication of quasi-metallic narrow Si-wires by an extremely high doping of our SOI-films [2]. In many cases these act as metallic single-electron transistors (SETs) and offer many similar charging states and hence a broad range of operating points. Our samples have a nominal doping level of 10^{21} cm^{-3} realized by ion-implantation of arsenic. This leads to a mean distance of only 1 nm between the dopants. Figure 1 depicts the conductance of a 50 nm wide nanowire at a temperature of 4.2 K as a function of the applied topgate-voltage. CB oscillations with a clear periodicity are observed, indicating the metallic nature of the SET. From the slope of the CB diamond we determine the

---

†E-mail: `jorg.kotthaus@physik.uni-muenchen.de`

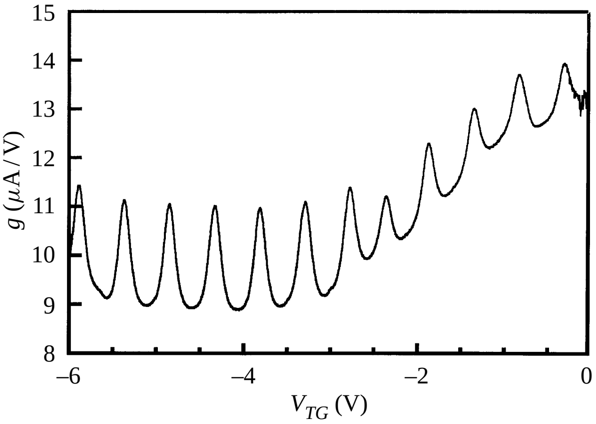

Fig. 1. Coulomb blockade oscillations in a quasi-metallic nanowire showing almost perfect periodicity.

charging energy in the dot presented to be $E_C = 17.5$ meV. Presumably, in this quasi-metallic nanostructure, the pattern-dependent two-dimensional oxidation of narrow wires in combination with edge roughness and the pile-up effect of As-dopants during dry oxidation [6] lead to the observed SET-behavior.

3. Coulomb blockade in inversion-channel quantum dots

In contrast to the use of highly doped SOI-films, embedding lithographically defined SET-structures into the inversion channel of SOI-field effect transistors allows us to observe CB oscillations up to very high temperatures [2, 7]. Since the tunneling barriers are defined by geometry, the controllability of these devices is greatly enhanced in comparison with random effects found in highly doped nanowires. We prepared geometrically defined quantum dot structures embedded in SOI-MOSFETs with lateral dimensions below 20 nm [3]. In Fig. 2A the CB oscillations in a dot with an estimated lithographical diameter of 15 nm are presented. A strong influence of spatial quantization inside the dot leads to a deviation of the classical periodicity of the CB oscillations. From the slope of the CB diamond and the mean spacing between two adjacent conductance oscillations one can deduce the charging energy to $E_C = 56$ meV. In Fig. 2B the source–drain I–V characteristics are shown for various temperatures. Figure 2B also shows the I–V characteristics as well as the source–drain conductance at 300 K. Clear CB operation at room temperature is reflected in the minimum of the conductance g around zero bias.

4. Suspended single-electron structures

Underetching the SiO_2-spacer of the lithographically defined SOI-nanostructures leads to a suspension of the single-electron devices and therefore to a thermal decoupling from the silicon substrate. The buried oxide is removed locally in buffered hydrofluoric acid and the sample subsequently rinsed in water and isopropanol [4]. Due to random dopant fluctuations, single-electron effects become visible in these wires at low temperatures.

5. Nanoresonators

Nonlinear micromechanical resonators have been shown to be very efficient tools for charge detection [8]. Scaling down these resonators to dimensions in the 100 nm range leads to even higher accuracies [5]. Cor-

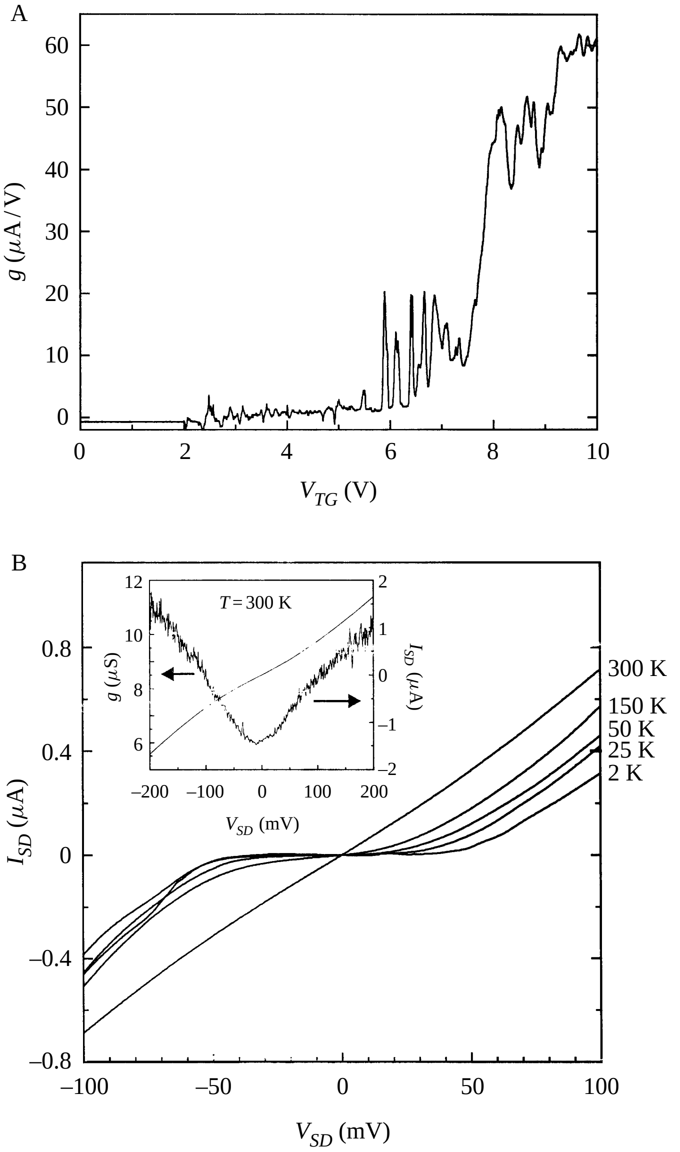

Fig. 2. A, Dependence of the conductance g of an inversion quantum dot on gate voltage V_{TG}. Coulomb blockade is observed near threshold voltage. B, Temperature dependence of the I_{SD}–V_{SD} trace of the dot at a top gate voltage of $V_{TG} = 4.5$ V. At 300 K clear single-electron effects remain visible.

respondingly, the frequencies are increased to the rf-regime, enhancing the speed of charge detection significantly. Our resonators are machined out of SOI material similar to the doped suspended structures. A SEM-micrograph of a final structure is shown in the inset of Fig. 3. This resonator has a length of almost 3 μm, width and thickness being 200 nm. This particular resonator is a straight beam of silicon covered with a thin layer of gold (50 nm). The two gates on the left and right sides of the beam can be biased capacitively to detune the resonators eigenfrequency. They can also be used to drive the resonator by applying an rf-voltage. The beam is cooled down to 4.2 K and placed in a magnetic field perpendicular to the beam's

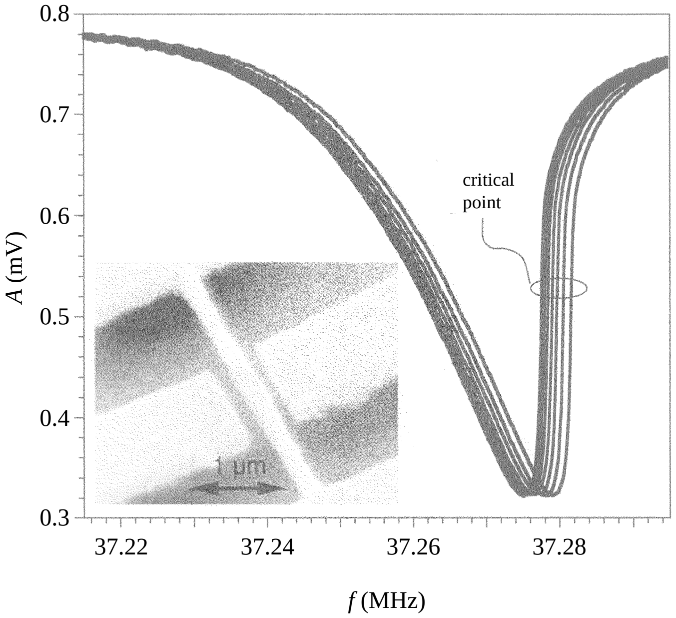

Fig. 3. Resonance curves of the reflected rf power of the suspended wire shown in the inset. The resonator is driven into the nonlinear regime by the Lorentz force in a B-field of 12 T applied perpendicularly to the rf current. Different curves are measured at different values of the voltage on one of the sidegates. Inset: SEM micrograph of the structure.

direction. If a current is driven through the beam, the magnetic field induces a Lorentz force, which in turn sets the resonator into motion.

If the resonator is driven by a small ac-current, the resulting resonance curve is fully symmetrical. When increasing the ac current, the resonator is driven into nonlinear response. The motion of the center of mass is then properly described by the well-known Duffing equation, i.e. the eigenfrequency shifts and the resonance curve becomes asymmetrical [9]. If one of the gates is charged by applying a voltage V with respect to the wire, the eigenfrequency changes quadratically with V and hence an additional term proportional to V^2 appears in the Duffing equation. This change can best be seen, if the resonator is driven in the transition regime between linear and nonlinear behaviour. Then the resonance curve exhibits a region of infinite derivative (critical point). The variation of the position of this region can be monitored in dependence of the gate's potential.

This behavior is demonstrated in Fig. 3. The shift in the resonance frequency can be best resolved at the point of large derivative, which is indicated as critical point. Due to the quadratic dependence of the resonance frequency on the applied voltage the charge resolution is increased when increasing the gate voltage. At a gate voltage of 4 V, we find a resolution of $0.1\ e/\sqrt{\text{Hz}}$. The resolution is thus comparable to common SET charge detectors working at much lower temperatures.

References

[1] A. Tilke, M. Vogel, F. Simmel, A. Kriele, R. H. Blick, H. Lorenz, D. A. Wharam, and J. P. Kotthaus, J. Vac. Sci. Technol. B **17**, 1594 (1999).
[2] A. Tilke, R. H. Blick, H. Lorenz, J. P. Kotthaus, and D. A. Wharam, Appl. Phys. Lett. **75**, 3704 (1999).
[3] A. Tilke, L. Pescini, R. H. Blick, H. Lorenz, and J. P. Kotthaus, submitted to Appl. Phys. A, (1999).
[4] L. Pescini, A. Tilke, R. H. Blick, H. Lorenz, J. P. Kotthaus, W. Eberhardt, and D. Kern, Nanotechnology **10**, 418 (1999).

[5] H. Krömmer, A. Erbe, A. Tilke, S. Manus, and R. H. Blick, Europhys. Lett. **50**, 10 (1999).
[6] A. S. Grove, O. Leistiko Jr., and C. T. Sah, J. Appl. Phys. **35**, 2695 (1964).
[7] E. Leobandung, L. Guo, Y. Wang, and S. Y. Chou, Appl. Phys. Lett. **67**, 938 (1995).
[8] A. N. Cleland and M. L. Roukes, Nature **392**, 160 (1998).
[9] U. Parlitz and W. Lauterborn, Phys. Lett. **107A**, 351 (1985).