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Addressing Dissipation Phenomena in Silicon Quantum Dots

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1. Introduction

Already in 1961 Rolf Landauer pointed out the importance of dissipation for computing processes [1]. He calculated that the energy necessary to change the state of a single bit is of the order of only $k_B T \ln 2$. Naturally, this concept of information processing seemed to be quite out of reach in these days.

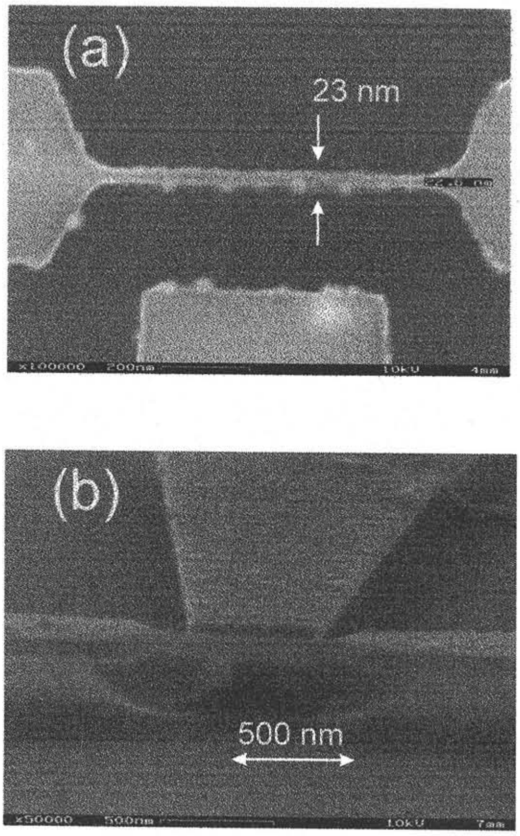

Fig. 1(a) Shown is a top view and in (b) a side view of the suspended silicon nanowire used here. The strongly doped wire is clearly underetched, the gate allows to tune the carrier density in the wire. The dimensions are: 700 x 24 x 80 nm^3 (length x width x thickness).

Nowadays, however, basic research on semiconductor nanostructures is aiming at single electron transistors like quantum dots. So far only Coulomb charging effects are considered and the overall target is the steady increase of the charging energy $E_C = e^2/C_{total}$ [2], which finally should lead to room temperature operation. Recently indications were given that discrete phonon modes in quantum dots could cause inelastic transitions [3]. First structures have now been build in AlGaAs heterostructures to address this effect [4].

Here, we want to present some of our most recent results on investigations of electron-phonon interaction in silicon quantum dots, i.e. dissipation in single electron circuits. In order to study these phenomena we machined free standing silicon nanowires as seen in the scanning electron beam micrographs in Fig. 1. Incorporated in these are electron islands leading to Coulomb blockade. By using the Coulomb islands as thermometers within the wires we are able to determine the electron temperature locally. Thus a comparison of free standing and non-free standing wires reveals directly the influence of phonon quantization for low temperature transport which represents the fundamental limit of heat transfer [5].

2. Processing

Processing of samples started by highly phosphorus doped SIMOX-wafers with a silicon film thickness of 190 nm and a 360 nm buried oxide (BOX) as well as arsenic doped 100 nm thick Smart-cut films on 400 nm BOX. In order to build suspended silicon nanowires we employ low-energy electron beam lithography with a two-layer PMMA-electron resist in combination with a lift-off of a 50 nm thick evaporated Al-film to create a hard-masking for the subsequent dry-etching of the silicon film.

Minimum feature sizes achieved with this technique is in the range of about 20 nm. The masked silicon film is subsequently etched by a CF_4 reactive ion etch (RIE) step. Underetching of the BOX in buffered HF allows to suspend the silicon nanobeams. Fig. 1(a) shows the top-view of our smallest structure with a wire width of only 23 nm. The thickness of the wire is only 70 nm, since the HF wet etch tends to attack the doped silicon slightly. Fig.1(b) shows the suspended nanostructure in a side-view. The fabrication method used is described in detail by Pescini *et al.* [6].

The samples are then bonded and brought into a variable

(see the other side)

temperature insert (VTI) mounted in a helium bath cryostate allowing a temperature variation from 1.5 K up to 200 K. The measurement setup consists of a low-noise current preamplifier and a standard lock-in amplifier operated at a frequency of 130 Hz, applying a low ac voltage of V_{sd} = 100 µV. Measurements at higher drain/source voltages are performed by superimposing a dc offset to the ac sensing signal.

3. Results

Fig. 2(a) shows the non-linear *IV*-characteristic of a suspended nanowire as a function of temperature. A clear minimum of the conductance around zero bias V_{sd} = 0 V can be observed up to temperatures of about T = 20 K. This conductance resonance arises from the Coulomb blockade mechanism of the MTJs [7]. As seen the resonance is not extending towards $G = 0$, i.e. the MTJ's not completely suppress transport, but only block several transport channels. This is of advantage, since it allows to consider the MTJ conductance resonance as a local thermometer, which does not alter the physical properties of the nanowire. In the following we will evaluate the temperature dependence of the full-width-at-half maximum (FWHM) of these conductance resonances.

In contrast to non-suspended highly doped SOI-nanostructures where the conductance can be tuned to zero by depletion with a metallic top-gate, in the suspended nanostructures reported here, the carrier density can be controlled by a suspended sidegate machined out of the same highly doped SOI-film. This sidegate depletes the wire by about 40%, but cannot suppress the conductance completey. Therefore, the tunnel junctions formed by random dopant distribution still provide a relatively strong coupling of the individual electron islands.

In Fig. 2(b) a comparison between the FWHM of the suspended and non-suspended quantum wires is depicted. As seen a saturation of the FWHM is found around 10 K, which roughly corresponds to the crossover temperature $T_{co} = (h\ v)/\ (2\pi\ k_B w) \sim 8$ K for the phonon quantization regime [5]. Here, w is the wire width of 20 nm and v the velocity of sound in silicon ~ 6000 m/sec. The picture we consider is the following: Electrons flowing through the doped wire, dissipate energy due to scattering in the MTJs, and thus heat the lattice of this nanocrystalline wire. The heat is commonly radiated by phonons into the clamping points of the wire. By reducing the temperature below T_{co} only the thermal quantum of heat can be funneled through the waveguide. A more detailed description of the processes is given elsewhere [8].

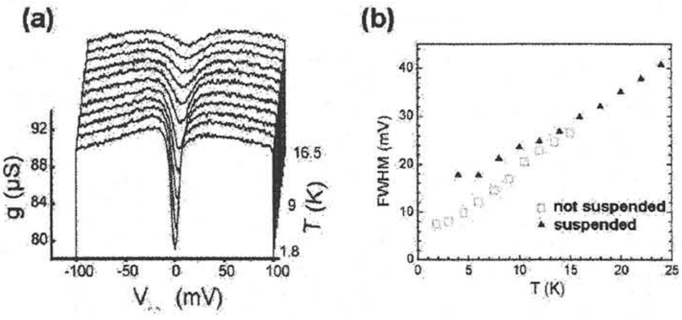

Fig. 2(a) Conductance of the nanowire under large bias V_{sd}. (b) Comparison of the temperature dependence for the suspended and the non-suspended wires. As seen we find a saturation below 10 K, indicating phonon quantization in the suspended nanowire.

4. Conclusions

In summary we have investigated and compared the electrical properties of highly doped suspended and non-suspended silicon nanowires in the sub-100 nm regime. We found single electron effects due to the random dopant distribution and a strong conductance modulation at high source-drain currents when the wires are suspended. We interpret this observation as a direct influence of the reduced phonon density of states of the suspended wires, indicating the importance of the electron/phonon interaction. Good agreement with the recently reported phonon quantization of heat transport is found.

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