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Suspending highly doped silicon-on-insulator wires for applications in nanomechanics

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Abstract. We report on a new method to build suspended silicon nanowires in highly doped silicon films in silicon-on-insulator substrates. The beams are defined by high-resolution, low-energy electron-beam lithography using a two-layer positive electron resist. Micromachining techniques including dry and wet etching are applied to pattern the structures. We show first low-temperature measurements of these novel devices indicating electron–phonon interaction.

Suspended nanostructured semiconductor devices in combination with single-electron detection have recently attracted considerable interest. Cleland *et al* [1] first demonstrated the usability of suspended silicon bridges formed in bulk silicon crystals as nanometre-scale mechanical resonators. Krömmer *et al* [2] used the silicon-on-insulator (SOI) as a starting material to build mechanical resonators with suspended in-plane gates operating as charge sensors in the nonlinear regime. Moreover, nanometre-scale electrometers in a torsional resonator on suspended SOI films allow a charge detection sensitivity of $0.1e/\sqrt{\mathrm{Hz}}$, comparable to that of cryogenic single-electron devices [3]. Erbe *et al* [4] used a suspended nanometre-scale silicon clapper setup as a mechanically flexible tunnelling contact, transferring electrons by mechanical motion with a resolution down to seven electrons per cycle.

Apart from applications as nanomechanical resonators, the disconnection from the bulk material offers the possibility to study thermal transport and the influence of phonons on the electronic properties of suspended low-dimensional semiconductor structures, as was investigated in early work by Kelly [5]. Since the structure is thermally decoupled from the environment, the influence of thermally activated phonons is minimized [6, 7]. Therefore, the application for sensitive cryogenic bolometers is especially obvious [8]. The first structures for examining phonon transport in nanometre-scale free-standing wires were reported by Lee *et al* [9] and Smith *et al* [10]. By cooling suspended wires on the nanometre scale down to temperatures of about 20 mK, the dominant phonon wavelength λ_{ph} is of the order of 5 μm and thus easily exceeds the nanostructure's dimensions. Since the phonon spectrum exhibits distinct modes in two dimensions, inelastic electron–phonon scattering is restricted to distinct values of the phonon momentum change. Therefore, the dissipative electron–phonon scattering is assumed to be strongly reduced, allowing the application as high-current nanodevices. Moreover, in cryogenic experiments it should be possible to measure the quantization of thermal conductivity in units of $(\pi^2 k_B{}^2 T)/3h$ [11–13]. Nevertheless, in thin suspended metallic CuCr films no effect of phonon quantization on the temperature dependence of the electron-phonon scattering rate has yet been found [14]. On the other hand, theoretical results obtained for suspended quantum wires indicate a possible enhancement of acoustic-phonon scattering in some nanoscale structures [15]. Other theoretical results for suspended quantum dot structures suggest that acoustic-phonon-assisted transport processes should obey selection rules sensitive to the wire's geometry and may influence phonon bottleneck effects in nanoscale quantum dot structures [16]. In general, it has to be noted that the disconnection from the bulk material might also be important for electronic devices on the nanometre scale, since the restriction of the phononic relaxation pathways effectively reduces the heat load of the nanostructures.

Whereas most devices realized up to now either use the mechanical motion or the electric properties of an evaporated metallic film on top of the suspended semiconductor structure, only little effort has been made to fabricate suspended doped semiconductor structures. These devices combine the thermal decoupling with effects occurring in low-dimensional semiconductor devices. In particular, by measuring single-electron tunnelling in suspended nanostructures one would gain insight into electron–phonon interaction [16]. To our knowledge, in this context up

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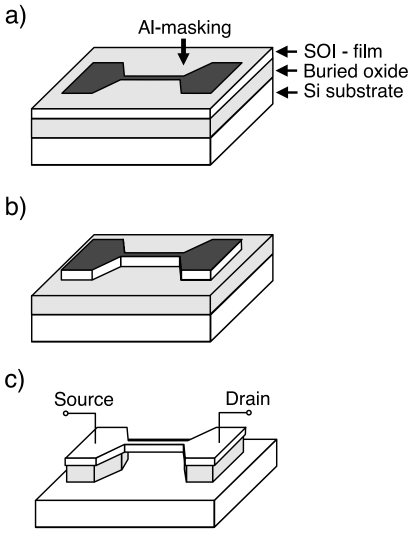

Figure 1. Fabrication of suspended silicon nanowires: (*a*) electron-beam lithography defines an aluminium etch mask on an SOI wafer with a thin, protecting silicon-oxide film on top, (*b*) RIE etching of the mesoscopic structure using CF_4, (*c*) underetching of the buried oxide in HF and drying of the sample in a critical point dryer using liquid CO_2.

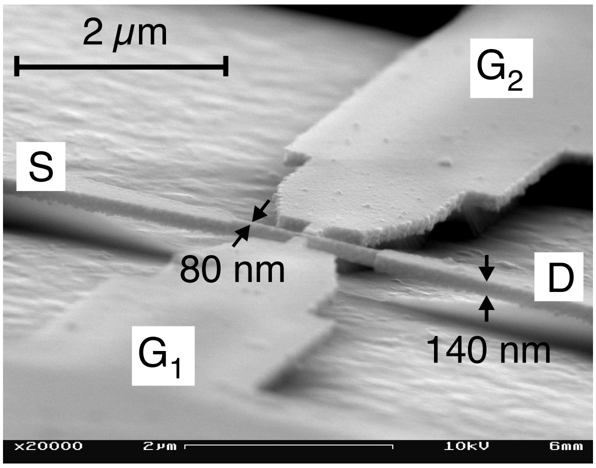

Figure 2. Suspended silicon quantum wire in a highly n-doped SOI film. As the n-silicon etches slowly during the underetching in HF, the starting film thickness of 190 nm is reduced to about 140 nm. The wire width is 80 nm and the length 1.5 μm. The suspended lateral sidegates were not biased in the current experiments.

to now only Blick *et al* have demonstrated the possibility of preparing suspended GaAs/AlGaAs heterostructures containing a two-dimensional electron system (2DES) [17]. Here, we present the realization of suspended nanowires in highly doped SOI films. In contrast to 2DES realized in GaAs/AlGaAs heterostructures, where the depletion length of 2DES at the edges of the structure only allows lateral dimensions down to about 250 nm, the SOI materials enable us to prepare suspended devices with lateral sizes down to about 50 nm and a length of the suspended part of 1–2 μm. Moreover, we show first low-temperature transport measurements on such suspended wires.

The SOI wafers containing a silicon film of 190 nm thickness and a buried oxide (BOX) with a thickness of

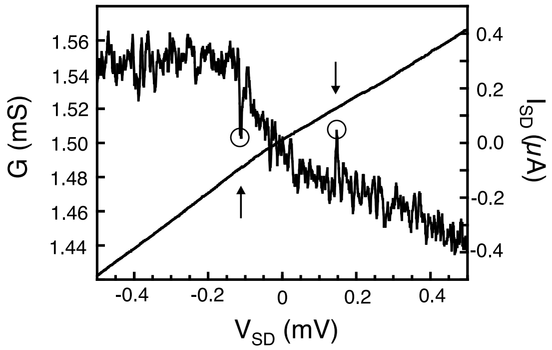

Figure 3. Conductivity and dc current of a suspended silicon wire at a temperature of 2 K. According to the longitudinal sound velocity given in [23], we find $\lambda_{ph} \simeq 110$ nm, which roughly corresponds to the wire's width and thickness.

360 nm were highly n-doped by phosphorus diffusion at a temperature of 950 °C for 60 min in a tube furnace using solid phosphorus diffusion sources consisting of silicon pyrophosphate. The doping level of about 5×10^{19} cm^{-3} is far above the metal–insulator transition for phosphorus in silicon of 3.74×10^{18} cm^{-3}. The wire and dot structures were defined by high-resolution low-energy electron-beam lithography using a scanning electron microscope with a thermally assisted field emission source and a commercial beam and stage control system. For the electron-beam lithography a two-layer PMMA electron resist was chosen and an Al film of about 30 nm thickness was subsequently evaporated producing a thin, structured etch mask after lift-off (figure 1(*a*)). In order to separate the underlying silicon from the Al and prevent Al diffusion into the SOI film during the dry etching process, a 50 nm SiO_2 film was deposited before electron-beam lithography by sputtering [18]. Another photolithographic step after the electron-beam lithography is required to obtain a photoresist etch mask for the larger bond-pad regions. We subsequently etched the silicon film by reactive-ion etching using CF_4 (figure 1(*b*)). Underetching of these structures by removing the BOX in 2% HF (etching rate about 10 nm min^{-1}) forms suspended silicon wires (figure 1(*c*)). Since the HF also attacks the highly doped silicon film with an etch rate of about 1.8 nm min^{-1}, the underetching additionally leads to a lateral and vertical shrinking of the defined device structure and therefore to minimum lateral sizes of about 50 nm, where the residual film thickness is in the range of 140 nm. After underetching, the sample was rinsed in deionized water and then immersed in several propanol beakers, exchanging water by alcohol. In order to avoid damaging the suspended structures by the high surface tension of the propanol, we dried the sample in a critical point dryer using liquid CO_2. Figure 2 shows a suspended silicon wire with a width of 80 nm and a film thickness of 140 nm, while the length is 1.5 μm.

For characterization we measured the conductivity of the suspended structures using a standard lock-in technique as well as a dc current measurement setup. All measurements were performed in a ^{4}He bath cryostat with a variable-temperature insert allowing temperatures in the range of 1.5–300 K. The sample itself was immersed in the gas flow of the cooling ^{4}He. Figure 3 shows both the differential conductivity and the current through a suspended wire similar to that shown in figure 2 (but with a width of 150 nm), at a temperature of 2 K. In both measurements we obtain a wire resistance of about 1 kΩ. In four-terminal measurements, the conductivity of the highly doped SOI film at a temperature of 2 K evaluates to 7 mΩ cm. Calculating the total resistance of the wire, we find a value of about 5 kΩ. Therefore, we can conclude that the conductivity of this silicon nanowire is not lowered by our preparation method. On the other hand, especially for the smallest structures with lateral dimensions down to about 50 nm, the measured conductivity was found to be much lower than expected from the four-terminal measurements. For these, the ratio between the surface and volume of the suspended wire becomes extremely large. Therefore, possible surface effects such as irradiation damage induced during dry etching, surface traps and electron scattering due to surface roughness become important and have to be taken into account [7].

In the measurement shown in figure 3, a deviation from the ordinary ohmic behaviour near zero bias is found. We believe that this effect is due to the existence of random potential fluctuations in the highly doped silicon nanostructure. This is investigated in detail in the case of non-suspended silicon nanowires [19]. A random donor distribution, that cannot be assumed to be isotropic for device dimensions in the few tens of nanometres regime leads to the formation of small conducting puddles, separated by low-conducting barriers. The nanowire is therefore electrically separated into a series of multiple quantum dots, where the conductivity at zero bias is suppressed by Coulomb blockade. Using this effect, simple silicon single-electron transistor (SET) structures can be realized [20]. Since the curve in figure 3 does not display the expected Coulomb blockade effect for SET devices with respect to zero bias, we assume that the formation of separated conducting islands is not well achieved. On the other hand, changing both the doping level and the geometry of the suspended devices should lead to single-electron effects in our novel suspended structures. The peaks marked with a circle seen in the dc current measurement in figure 3 are also interesting when considering discrete phonon modes in this floating wire. An estimation of the dominant phonon wavelength given by [21], $\lambda_{ph} \simeq V_s h/2k_B T$, at $T = 2$ K and assuming a longitudinal sound velocity V_s for bulk silicon on the order of 4500 m s^{-1} [22]†, yields $\lambda_{ph} \simeq 54$ nm. Nevertheless, according to [23], the longitudinal sound velocity is about 9000 m s^{-1} and yields $\lambda_{ph} \simeq 110$ nm which fits the sample's thickness and width much better. Therefore, the observed features could be a consequence of thermal-phonon finite-size effects [24]. Another indication is given by estimating the temperature equivalent to the source/drain voltage $V_{SD} = k_B T/e \simeq 0.17$ mV with $T = 2$ K. This value coincides with the values at which the peaks in figure 3 occur. An electron tunnelling through different discrete electronic states might emit acoustical phonons corresponding to the energy given by the voltage bias of the wire.

† For the surface acoustic wave velocity on silicon single crystals this reference quotes a value of $v = 4545$ m s^{-1} along [110]. This is a justified assumption, since our beam has a thickness of only 140 nm, hence only surface acoustic waves, i.e. Rayleigh modes, might be excited.

The application of these suspended, highly doped nanowires as nanomechanical resonators is currently being investigated. With setup of [2] we have not so far succeeded in observing mechanical oscillations of the wires because of the relatively large dc resistance of the doped silicon beam. Nevertheless, with an improved measurement setup in comparison with the metal–silicon hybrid used in [2], we expect to be able to detect higher resonance frequencies and a higher mechanical Q-factor due to the absence of a metallic top-layer. Better impedance matching by lowering the dc resistance and therefore a higher detectable signal should be achievable with an even higher doping of the wire using ion-implantation. Further measurements are required to give conclusive evidence for single electron–phonon interaction.

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