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Mechanical properties of suspended structures at radio frequencies

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Abstract

We report on our work on nanomechanical resonators. The resonators are machined out of commercial silicon-on-insulator (SOI) material with a covering metal layer having eigenfrequencies in the radio frequency (RF) regime. At higher oscillating amplitudes they are driven into nonlinear response. The properties of the nonlinear resonators can be used for charge detection. Furthermore, we report on first experiments on using these resonators for exciting phonon and roton modes in ^{4}He. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Micromechanical devices; Electromechanical resonance; Vibrations

Nonlinear micromechanical resonators have been shown to be very efficient tools for charge detection [1]. Scaling down these resonators leads to even higher accuracies [2]. Additionally, the frequencies are increased to the RF-regime, enhancing the speed of charge detection significantly.

Our resonators are machined out of silicon on insulator (SOI) material applying either SIMOX or smart cut. The buried oxide of the materials is used as a sacrificial layer which is removed in a wet etch step using hydrofluoric acid. The lateral structuring of the resonator is performed by electron beam lithography followed by etching in a reactive ion etcher (RIE) using CF_4. A SEM-micrograph of the final structure is shown in Fig. 1. The resonator has a length of almost 3 μm, width and height 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 side of the beam are biased for detuning the resonators eigenfrequency capacitively. They can also be used to drive the resonator by applying an RF-voltage. The beam is situated in a magnetic field perpendicular to the beam's direction. If a current is driven through the beam, the magnetic field induces a Lorentz force, which in turn sets the resonator into motion at resonance.

If the resonator is driven by a small AC-current, the resulting resonance curve is fully symmetrical. When increasing the incident power, 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 [3]. If one of the gates is charged by applying voltage V, an additional term proportional to V^2 appears in the Duffing equation. Thus the eigenfrequency changes quadratically with V. This change can be seen best, 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 depending on the gate's charge.

Driving the beam into nonlinear response allows us to maintain the motion in liquid ^{4}He as well. The motion of a suspended beam in a normal fluid creates phononic excitations. A superfluid cannot be excited till a certain velocity is exceeded. In ^{4}He this velocity corresponds to the creation of vortex states at zero pressure and to the excitation of rotons at higher pressures. The velocities are 25 and 60 m/s, respectively. In our first experiments we have driven the resonator in liquid but not superfluid ^{4}He in order to show the possibility of detecting vortex states and rotons.

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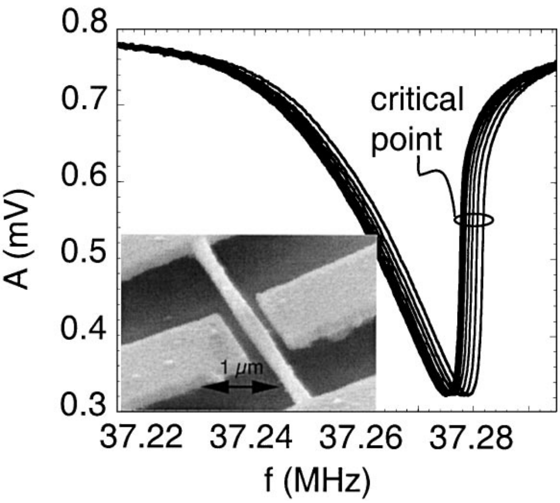

Fig. 1. Resonance curves taken at different voltages applied at the gate. The resonator is driven in the transition between the linear and nonlinear case. The resonance position shifts quadratically with the applied voltage. Inset: Micrograph of a nanomechanical resonator, machined out of Si with a 100 nm evaporated Au-layer. The center gates couple capacitively to the resonator.

We have performed measurements during filling the sample holder with ^{4}He. The resonance was shifted to lower frequencies and broadened, both due to viscous damping in the liquid.

The fact, that we were not able to suppress the mechanical motion completely shows our ability to drive the beam into resonance in the superfluid ^{4}He as well. Until the beam reaches the velocity, which is needed to create vortex states, no damping should be present, because the fluid is not excited by the motion of the beam [4]. Further acceleration leads to the excitation of vortex states in the fluid resulting in an increased energy consumption. This can be seen in a flattening of the resonance curves.

In order to verify, that we are able to reach the range of the critical velocities, we monitored the velocities of the beam depending on the input power and the amount of ^{4}He in the sample holder. We begin at a velocity of 20 m/s, which is then reduced to 5 m/s in the liquid. The decrease of the velocity is mainly due to the deterioration of the quality factor. To reach the critical velocities in ^{4}He we have to increase the velocity by a factor of 5. However, it should be noted that a much better quality factor is expected in superfluid ^{4}He due to the reduced attenuation. If the quality factor is comparable to the one in vacuum, the range of vortex state creation is already reached. Since a frequency range of 1 GHz seems to be a realistic goal with the current lithography, velocities up to 10 times larger than what we have achieved are possible to achieve. Thus even the regime of roton excitation might be accessible.

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