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F. W. Beill, R. H. Blick, Achim Wixforth

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Acoustically driven NEMS resonators

Florian W. Beil1*
Center for NanoScience & Sektion Physik, LMU München, München, DE 80539 Germany
Robert H. Blick
Department of Elect. and Comp. Eng., University of Wisconsin-Madison, Madison, WI 53706 U.S.A
and Achim Wixforth
Lehrstuhl für Experimentalphysik I, Universität Augsburg, Augsburg, DE 86135 Germany

Abstract — Mechanical systems scaled down to the nanometer range promise to offer novel devices for information processing and sensor applications. As the dimensions of these systems lie well below 100 nm the eigenfrequencies recently crossed the 1 GHz barrier. For a further increase of the eigenfrequencies an appropriate driving mechanism, able to excite this systems far into the GHz regime, is needed. Conventional techniques rely on electrostatic or magnetic forces, which are getting weak compared to e.g. surface tension on the nanometer scale. Here we want to investigate the possibility to use a mechanical excitation scheme, namely surface acoustic waves (SAW), for these small devices. We discuss different approaches to drive nanomechanical systems (NEMS) by resonant acoustic excitation.

I. INTRODUCTION

IN recent years mechanical systems were scaled down from macroscopic devices towards the nanometer range [1]. Nowadays, it is possible to produce e.g. double clamped beam resonators with dimensions well below 100 nm, which show increased eigenfrequencies up to 1 GHz [2]. In this frequency range NEMS could serve as filters for information processing applications. Another range of applications emerges from the sensitivity these devices could reach in sensor applications. Using sophisticated detection schemes this might even lead to the quantum limit where e.g. the uncertainty principle might be observed in the motion of a mechanical resonator [3]. Although great progress had been made in miniaturizing mechanical systems one fundamental problem of these devices still has to be solved. Scaling down mechanical systems not only improves device characteristics like increased eigenfrequencies or reduced power consumption, but also is accompanied by some undesirable effects. As the dimension L of any mechanical system gets smaller, the forces used for driving and detection purposes scale down. In conventional electromechanical systems electrostatic F_{el} or magnetic forces F_{mag} are used to drive NEMS resonators. Under reasonable conditions [4] it follows that this forces both scale with the square of the system dimension, so $F_{el} \sim F_{mag} \sim L^2$. In contrast to these experimentally accessible forces, e.g. the surface tension scales as L, so that for NEMS the surface tension becomes the dominant force. On the other hand electric as well as magnetomotive excitation suffers from the drawback of a necessary integration of conducting metal layers into the moving parts. These metal layers decrease the achievable eigenfrequencies due to the mass loading of the mechanical parts and additionally contribute to internal dissipation [5].

In this sense a excitation mechanism, better suited for NEMS, not relying on conduction layers and applicable at room temperatures without any magnetic fields would allow the further development of NEMS towards standard applications.

II. INTERACTION OF SAW WITH NEMS

Surface acoustic waves are a promising candidate for a direct mechanical excitation scheme applicable to NEMS. The frequencies, wavelengths and amplitudes of a Rayleigh wave propagating in the [110] direction on GaAs are on the same order of magnitude as the according quantities of NEMS. Furthermore SAW are easily generated using simple, planar structures called interdigital transducers (IDTs), and are well applicable at room temperature. The achieved coupling of the SAW to the NEMS depends on some design characteristics that could be properly chosen. The forces a SAW in principal exerts on a NEMS system, and how they could be used for resonant excitation will be discussed in the following.

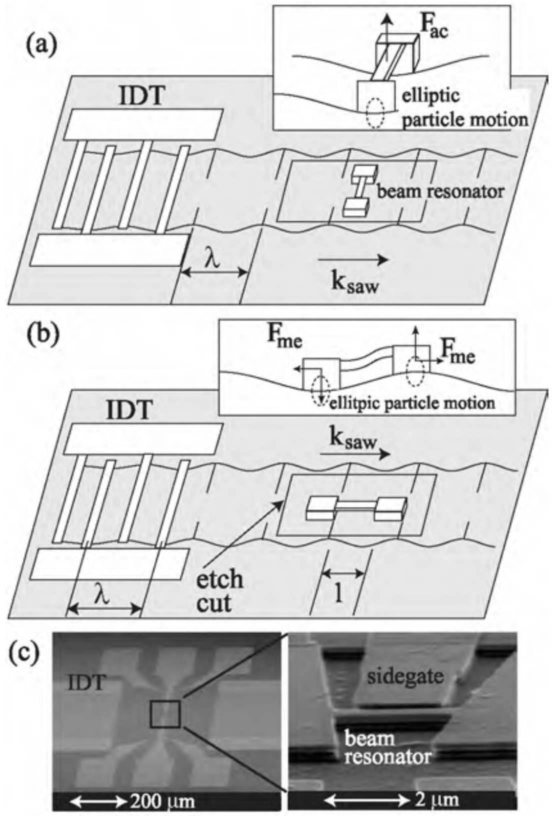

Figure 1: (a) The beam is oriented parallel to the SAW wave vector. Due to the SAW induced movement of the beam's suspensions the beam is stressed, and the mechanical deformation forces F_{me} act on the beam. (b) If the beam is oriented perpendicular to the SAW wave vector, the only forces acting on the beam are the acceleration forces F_{ac}. (c) Implementation of a model system. The electron micrographs show in the overview on the left side two IDTs for SAW generation, while the zoomed image on the right shows the freely suspended beam resonator. With this setup it was possible to investigate non-resonant interaction of SAW with NEMS beam resonators [5,6].

For further considerations we restrict ourselves to a simple mechanical system, namely a double clamped beam resonator. This structure is widely used in recent research due to the higher eigenfrequencies and improved quality factors compared to other resonant structures like cantilever beams. The beam resonator is produced on the surface of a piezoelectric material like GaAs, by successive steps of electron beam lithography, anisotropic RIE etching and selective isotropic wet etching (for further details on production of NEMS refer to [6]). To interact with the SAW a beam resonator is placed in the line of fire of IDTs, which effectively convert an applied RF signal with frequency f_{saw} into acoustic waves. The mid frequency of the IDT is given by $f_{saw} = v_{saw}/\lambda$, where v_{saw} is the SAW velocity and λ is the lithographically defined wavelength of the SAW (see Fig. 1). A SAW propagating along the crystal's surface now will interact with the suspended beam resonator via the induced motion of the beam's suspensions. As the wavelength λ usually is large compared to the vertical dimension h of the beam (h is determined by the heterostructure, the sample is made of) it is not possible to feed acoustic power directly into the suspended resonator.

Two limits for the SAW-beam interaction are possible. In the first setup the beam is oriented perpendicular to the SAW wave vector [see Fig. 1(a)]. In this configuration the SAW will move both suspensions of the beam in phase, and the only force that acts on the resonator is the acceleration force F_{ac}. This force is given by

$$F_{ac} = m \cdot a = \rho \cdot L^3 \cdot A_{saw} \cdot \Omega_{saw}^2 \approx \rho \cdot A_{saw} \cdot L \tag{1}$$

where m is the mass of the beam, ρ its density, A_{saw} the amplitude of the SAW and Ω_{saw} the frequency of the SAW. Assuming that the SAW is frequency matched to the beam's eigenfrequency Ω_{saw} scales as the inverse of the beam's dimension L^{-1} [4], and the total force scales as L. Although this is a better scaling than magnetic or electrostatic forces, the prefactor, due to an typical SAW amplitude of A_{saw}=1 Å, is small. Stronger forces can be exerted on the beam when orienting it parallel to the SAW wave vector, and matching its length l to λ/2 [see Fig. 1(b)]. In this case the suspension points of the beam will be moved out of phase an the mechanical force F_{me}, acting on the beam will be given by

$$F_{me} = c \cdot S_{11} \cdot a_{beam} \approx c \cdot \frac{\Delta l}{l} \cdot a_{beam} \approx c \cdot A_{saw} \cdot L \tag{2}$$

where c is the elastic constant, S_{11} is the longitudinal strain in the beam, a_{beam} is the beam's cross section, Δl is the elongation of the beam due to the action of the SAW, and A_{saw} is the longitudinal SAW amplitude. Due to the typical size of $c=10^{11}$ N m^{-2}, this force component will be orders of magnitude larger than F_{ac}.

Although the mechanical deformation forces are strong compared to the accelerative forces, the SAW induced strain in the beam does not favor direct excitation of eigenmodes (in contrast to F_{ac}, as this force component acts in transversal direction on the beam, similar to mangetomotive or electrostatic actuation). On the other hand the periodic stresses induced in the beam by the SAW could readily be used to excite parametric resonances, when the SAW is frequency matched to a beam's eigenmode. The SAW induced longitudinal strain periodically modulates the eigenfrequencies of the beam, so that the beam's motion x_i due to its i-th eigenmode can be described by

$$\frac{\partial^2 x_i}{\partial t^2} + (\omega_i + \Delta\omega_i \cdot \cos(\Omega_{saw} \cdot t))^2 \cdot x_i = 0 \qquad (3)$$

where x_i is the amplitude of the i-th beam's eigenmode, ω_i is the eigenfrequency of the i-th mode, Ω_{saw} is the SAW frequency and $\Delta\omega_i$ is the modulation of the eigenfrequency of mode i, due to the SAW induced stress. Equation (3) has the form of a parametric differential equation. The solutions of this equation show stable or unstable behavior, dependent on the position in the parameter space $\Delta\omega_i \times \Omega_{saw}$ [8]. If the SAW frequency is matched to an eigenfrequency ω_i of the beam, the corresponding eigenmode will be parametrically excited by the SAW. Crucial for this concept of acoustic excitation is the achievable size of the parameter $\Delta\omega$. Assuming a SAW amplitude of 1 Å, together with a beam length of l=1µm, results in a longitudinal strain in the beam of $S_{11}=10^{-4}$ [5]. Due to this strain the frequency ω_i of eingenmode i will shift following [9]

$$\omega_i = \omega_i^0 \sqrt{1 + \frac{F_{me}}{F_i}} = \omega_i^0 \sqrt{1 + \frac{c \cdot S_{11} \cdot a_{beam} \cdot l^2}{(i \cdot \pi)^2 \cdot c \cdot I}} = \\ = \omega_i^0 \sqrt{1 + \frac{24 \cdot l \cdot A_{saw}}{h^2 \cdot (i \cdot \pi)^2}} \qquad (4)$$

where ω_i^0 is the unstressed eigenfrequency of mode i, F_i is the critical load for the Euler instability, and I is the beam's momentum. In Eq. (4) a matching of l to λ/2 was assumed, so that $\Delta l=2A_{saw}$. Assuming a height h=200 nm, the relative modulation of e.g. the third eigenfrequency $\Delta\omega_3/\omega_3$ will be on the order of several 0.1%. Figure 2 shows the calculated amplified and unamplified regions for an assumed third harmonic ω_3 of around 100 MHz. From this it is clear that parametric resonances in NEMS beam resonators, driven by SAW should be observable, assumed the SAW is frequency matched to an eigenmode of the beam resonator. This matching can be achieved by use of broadband IDTs together with finite element simulations of double clamped beam resonators [10].

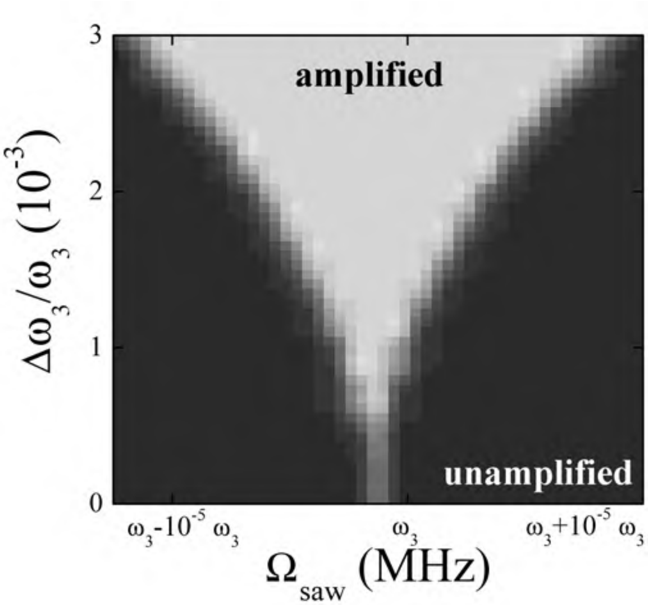

Figure 2: The time development of the solution of Eq. (3) depends on the parameters Ω_{saw} and $\Delta\omega_3$. If Ω_{saw} is close to the eigenfrequency ω_3, this eigenmode gets amplified. The figure shows the calculated region of amplification for a relative shift in eigenfrequency of the third eigenmode $\Delta\omega_3/\omega_3$ up to $3 \cdot 10^{-3}$, whereas the third eigenfrequency was assumed to be around 100 MHz. The simulated data was smoothed to give a more realistic picture of the results expected in measurements.

III. Conclusion

We have shown by theoretical considerations that it is feasible to use SAW as a high frequency, room temperature excitation mechanism for nanomechanical beam resonators. The SAW can in principle exert acceleration as well as mechanical deformation forces on the beam. The exerted stress forces are orders of magnitude larger than the achievable acceleration forces, which predestine them as a parametric excitation scheme. The change in eigenfrequencies due to the stress exerted by the SAW is large enough to observe parametric amplification of a frequency-matched eigenmode.

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* e-mail: florian.beil@physik.uni-muenchen.de