Investigation of nano-electromechanical-systems using surface acoustic waves

F.W. Beil *, A. Wixforth, R.H. Blick

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

Abstract

This study presents measurements on nanomechanical resonators implemented on a GaAs substrate. We observed several eigenmodes with eigenfrequencies up to 115 MHz and quality factors of about 200. Using finite element methods we were able to match the resonances to the surface acoustic waves excitation within a few MHz. We report on investigations regarding the coupling of surface acoustic waves to the nanoresonators.

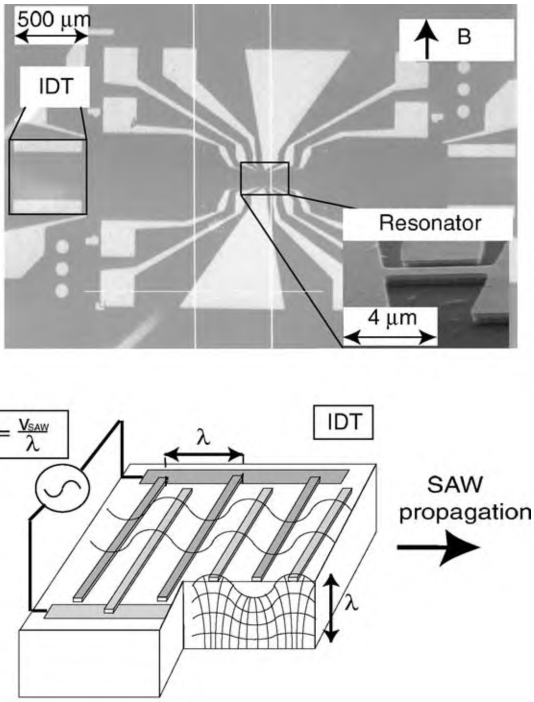
Nano-electromechanical-systems (NEMS) are mechanical devices like beam resonators with dimensions in the nanometer range. Due to the dimensions of such NEMS structures, eigenfrequencies up to several 100 MHz with high-quality factors can be reached, the basis for possible applications in sensor and telecommunication technology [1]. Moreover, when reaching resonance frequencies in the GHz range, the energy quantum $h\nu$ of such a classical resonator becomes comparable to the thermal energy kT in the mK range. Such a resonator is then expected to exhibit inherent quantum mechanical behavior at low temperatures and thus opening a novel experimental field in quantum physics. Quantum squeezing [2] is only one example of this kind.

Up to now there are basically two established ways to drive such nanoresonators: when covered by a conducting layer to support an AC current of the appropriate frequency, the induced Lorentz force in an external strong magnetic field can cause the structure to resonate. Another way is the direct excitation by side-gate electrodes, used to capacitively couple to the resonator oscillation [3]. The oscillations of the NEMS oscillator are then observed by measuring the frequency-dependent change of its impedance or the voltage drop across the side gate. However, these driving mechanisms suffer from severe Ohmic losses, which make it difficult to reach high-quality factors. Thus alternative excitation and detection schemes have to be explored.

The very high eigenfrequencies of our NEMS resonators offer a possibility for the first time to investigate the coupling to acoustic modes like surface acoustic waves (SAW) (see Fig. 1). SAWs are harmonic acoustic modes which are bound to the surface of a crystal within approximately one wavelength and propagate at a velocity v_{SAW} of 2865 m/s on (1 0 0)

* Corresponding author. Tel.: +49-(0)89/2180-3586; fax: +49-(0)89/2180-3182.

E-mail address: beil@informatik.uni-muenchen.de (F.W. Beil).



(a)

(b)

Fig. 1. (a) SEM micrograph of the sample design: On both sides of the structure one IDT is placed allowing SAW transmission experiments. The mechanical resonator is placed in the center, consisting of a GaAs beam of 4 μm length, width of 500 nm, and height of 200 nm, covered by a 50 nm-thick Au layer. The magnetic field is oriented perpendicular to the sample surface. (b) SAW generation by IDTs: The applied AC voltage produces stresses due to the inverse piezoeffect, which generate an acoustic beam at the resonance frequency $f = v_{SAW}\lambda$.

GaAs. Wavelengths λ of several μm are common, so that via

$$f = \frac{v_{SAW}}{\lambda} \tag{1}$$

frequencies in the MHz range are achieved. As both the NEMS resonator and the SAW frequency are governed by the same elastic properties of the substrate, the coincidence of their eigenfrequencies for given length scales is not surprising. Moreover, on piezoelectric materials, SAWs are easily excited by simple planar structures, the so-called interdigital transducers (IDT) (see Fig. 1). Hence, coupling of SAWs to mechanical oscillations of our NEMS resonators opens a possibility of excitation and detection of GHz resonances.

Our beam resonators are prepared out of GaAs heterostructures [4–6,3]. By subsequent steps of electron-beam lithography, anisotropic dry-etching, and selective wet under-etching a freely suspended beam covered by a 50 nm-thick Au layer is created as shown in Fig. 1(a). On each side of the resonator a comb-like IDT is placed, generating a SAW by converting an AC voltage of the right frequency into a strain and stress field close to the crystal surface. The resonance condition for the coherent generation of a SAW is given by Eq. (1). The SAW wavelength λ is only determined by the finger separation of the IDT, as shown in Fig. 1(b).

To characterize the beam resonators in the first place, they are driven by Lorentz force (magnetomotive excitation) as mentioned above. It has to be noted that in all experiments, the magnetic field was oriented parallel to the sample surface yet perpendicular to the beam, so that modes with an out of plane displacement are excited.

The resonances of the beam can be observed in two different ways. Conventionally, the displacement of the oscillating motion is observed by monitoring the amplitude-dependent impedance of the resonator. For this purpose, a specially equipped network analyzer is used which scans the reflected power over the range of interest (see Fig. 2(a)). The shift of the resonance frequency with increasing magnetic field is assigned to nonlinear elastic effects due to a stronger driving force. Due to the shape of the excited mode, a double-peak structure of the resonance can be observed. In another set of experiments, the beam displacement can directly be detected via the aforementioned side gates. A displacement of the beam results in a change of the capacitance between the side gate and the beam itself. We have shown that this detection method is more sensitive compared to the first one [7]. The form of the resonance peak is in both cases Lorentzian:

$$A(\omega) = \frac{1}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4\mu^2\omega^2}}, \tag{2}$$

where A is the amplitude of the oscillation, μ the damping constant, ω_0 the eigenfrequency of the beam, and ω the frequency. When evaluating the induced voltage in the conducting layer due to motion in a magnetic field, it is found that $V_{ind} \simeq A(\omega)$. In order to derive an analog dependence for the capacitive detection it is advantageous to use an expansion to the second order of

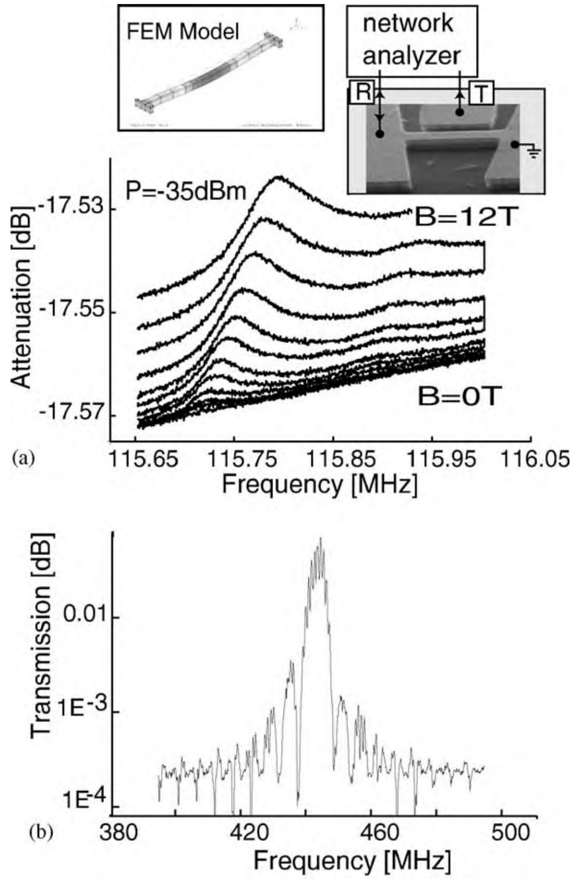


Fig. 2. (a) Measured 115.7 MHz resonance of one of the nano-resonators. The right inset shows the set-up, consisting of a network analyzer which scans the reflected power in the range of interest. The left inset shows a numerical simulation of this beam. The eigenfrequencies can be reproduced fairly well allowing frequency matching with the SAW. (b) Transmitted acoustic power over the delay line consisting of two IDTs depicted in Fig 1(a). The frequency of maximum power transfer is about 4 times the mechanical resonance frequency of the resonator.

the capacitance between gate and beam:

$$C(A) = C(0) + \frac{\partial C(A)}{\partial a}|_0 A + \frac{1}{2}\frac{\partial^2 C(A)}{\partial A^2}|_0 A^2 + \dots \quad (3)$$

Since from symmetry $(\partial C(A)/\partial A)|_0 = 0$ it is found that $V_{\mathrm{cap}} = Q_C/C(A) \simeq A(\omega)^2$, where Q_C is the accumulated charge on C when a potential is applied. The dependence on $A(\omega)^2$ results in a narrowing of the peak. This observed reduction of the line width can be used to increase the achievable sensitivity for sensor applications.

For an optimized coupling between the SAW and the resonator, it is first of all crucial to match both frequencies within the bandwidth of the mechanical resonator (a few kHz) or higher harmonics thereof. To derive this eigenfrequency, it is usually assumed for the eigenfrequency:

$$\omega_i = \frac{i^2\pi^2}{L^2}\sqrt{\frac{EI_z}{\rho B}}. \quad (4)$$

Here, i numbers the harmonic resonances, L denotes the length of the beam, I_z is the moment of inertia, E is the modulus of elasticity, ρ the density and B the cross section of the beam. However, it turns out that the frequencies computed from this formula cannot reproduce the eigenfrequencies of the investigated beams. Much better results are achieved by numerical methods like FEM [8]. Fig. 2(a) shows the mechanical resonance of the resonator depicted in Fig. 1(a) together with a numerical model in the upper-left inset. The eigenfrequency is reproduced to within a few MHz without any fit parameter. In Fig. 2(b) we depict for comparison the transmission of acoustic power between the two IDTs (Fig. 1(a)) as a function of the applied frequency. The SAW transducers have been designed such that the SAW frequency matches the forth harmonic of the beam resonance. This harmonic coupling has been used, as the lateral dimensions of the IDT increase with decreasing frequency, and space limitations on the sample do not allow such low-frequency transducers.

As can be seen from Fig. 3(a), we indeed observe a transmitted acoustic signal at $f = 112$ MHz, which is close to the eigenfrequency of the beam. In the lower panel of Fig. 3(a), we depict this resonance as obtained by Lorentz force impedance spectroscopy. In Fig. 3(b), the response of the beam impedance to acoustic excitation is shown. At high acoustic input powers a resonance peak in beam impedance can be observed which becomes less pronounced with decreasing field and eventually vanishes at zero field. This behavior is interpreted as direct evidence of the mechanical origin of the observed resonance. A mechanical motion of the beam in the magnetic field results in an induced voltage which changes the impedance and so the reflected power. In the present case, our set-up already realizes a very sensitive frequency-dependent sensor element. Depending on the applied detection scheme, displacements of the resonator down to a few μÅ are detectable, which can be used for ultra-sensitive detection of electromagnetic waves.

To date, it has not been feasible to design and process a NEMS resonator which results in an exactly determined eigenfrequency. The problem of nonsufficient frequency matching, however, can be overcome by the so-called chirped IDTs, where the finger spacing is linearly varied over the width of the IDT. Such IDTs act as broadband SAW generators with bandwidths up to several tens of MHz. To further increase the SAW coupling, the fingers of the IDTs can be bend to focus the produced SAW on the mechanical resonator [9].

To conclude, we have shown how to build nanoresonators on GaAs with eigenfrequencies up to 115 MHz. These can be used as sensors or electrometers while the achievable sensitivity depends on the detection mechanism applied. Capacitive detection is favorable due to a reduced width of the resonance peak. We demonstrated that our resonators are able to detect the electromagnetic SAW excitations while direct coupling to SAWs is still weak due to frequency mismatch. Matching will be improved by using broadband SAW generation, thus we expect an optimized SAW–resonator coupling.

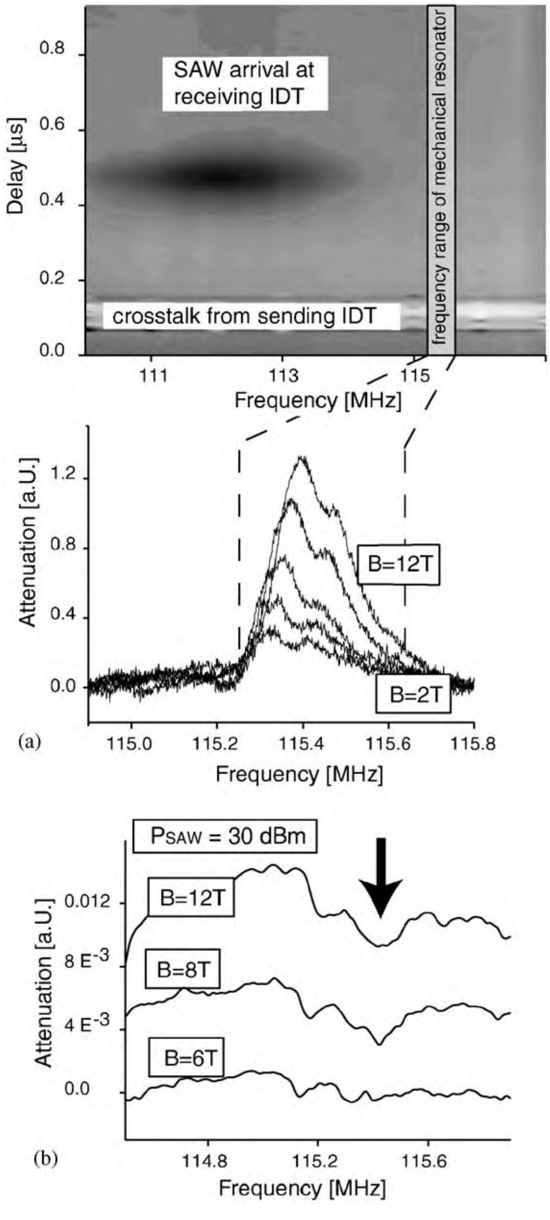


Fig. 3. (a) Comparison of the mechanical resonance frequency (lower part) and the subharmonic generated SAW (grayscale plot). The 80 ns SAW-pulse is produced by the emitting IDT with a delay of 100 ns. After 350 ns the acoustic power is received at the second IDT of the delayline, which corresponds to a mid-to-mid distance of the IDTs of 1000 μm. The gray area indicates the frequency range of the mechanical resonator. The frequency range of SAW transmission is slightly off the mechanical resonance of the resonator depicted in the lower view graph, which decreases the coupling of the SAW to the resonator. (b) Induced mechanical resonance at the resonator when a power of 30 dBm is applied to the IDT. The arrow indicates a peak at the mechanical resonance frequency. On decreasing the magnetic field, the signal disappears, proving its mechanical origin.

References

[1] C.T.-C. Nguyen, Proceedings of the 1998 IEEE Aerospace Conference, Vol. 1, 1998, pp. 445–460.

[2] D. Rugar, P. Grütter, Phys. Rev. Lett. 67 (1991) 699.

[3] A. Kraus, A. Erbe, R.H. Blick, Nanotechnology 11 (2000) 165.

[4] D.W. Carr, S. Evoy, L. Sekaric, H.G. Craighead, J.M. Parpia, Appl. Phys. Lett. 75 (1999) 920.

[5] H. Krömmer, A. Erbe, A. Tilke, S.M. Manus, R.H. Blick, Europhys. Lett. 50 (2000) 101.

[6] L. Pescini, A. Tilke, R.H. Blick, H. Lorenz, J.P. Kotthaus, W. Eberhardt, D. Kern, Nanotechnology 10 (1999) 418.

[7] Florian W. Beil, IEEE (2002), submitted for publication.

[8] SOLVIA, ver. 95.0, 1997.

[9] W. Sauer, M. Streibl, T.H. Metzger, A.G.C. Haubrich, S. Manus, A. Wixforth, J. Peisl, A. Mazuelas, J. Härtig, J. Baruchel, Appl. Phys. Lett. 75 (1999) 1705.