# Silicon-on-Insulator Based Nanoresonators for Mechanical Mixing at Radio Frequencies

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*Abstract*—**Nanomechanical resonators now allow operating frequencies approaching the range of several 100 MHz. Thus, nanomechanical devices become interesting for applications in signal processing. The main advantage of these devices is their high robustness against thermal and electrical shocks. Therefore, they can be used as very sensitive detectors or frequency selective components in communication electronics. Driving the resonators into nonlinear response increases the sensitivities further. Most importantly, such resonators can be used for a novel kind of mechanical mixing. Here, the mechanical oscillations of tiny bridges and oscillators can be used to realize such novel devices for high-frequency signal processing. We will present measurements on mechanical mixing in a nanomechanical resonator operated at 100 MHz.**

## I. Introduction

Simple beams on the nanometer scale are perfect model systems for studying the mechanical behavior of small mechanical systems. However, these systems can be used as sensitive charge or displacement detectors. In this paper, we want to concentrate on a high-speed property of these resonators, nanomechanical mixing at radio frequencies due to nonlinear response. We present the fabrication technique of nanomechanical devices in semiconductor crystals with eigenfrequencies of the order of several 100 MHz. In early work by Rugar and Grütter [1], and Greywall *et al.* [2], the importance for applications in scanning probe microscopy with mechanical cantilevers was demonstrated and noise evasion techniques for frequency sources and clocks were investigated. We want to discuss how to machine such nanomechanical resonators out of Silicon-on-Insulator wafers [3]–[5] and how to operate them in the nonlinear regime at 100 MHz [6] in order to investigate higher-order mechanical mixing at radio frequencies [7]. These mixing properties are of great importance for signal processing and exemplify nonlinear dynamics on the nanometer scale.

## II. Methods and Results

The starting materials are commercially available Silicon-on-insulator (SOI) substrates with a thickness of the silicon layer and the $SiO_2$ sacrificial layer of 205 nm and 400 nm, respectively (Smart-Cut wafers [8]). The gate leads connecting the resonator to the chip carrier are defined using optical lithography. The nanomechanical resonator is defined by electron beam lithography. The sample is dry-etched in a reactive-ion etcher (RIE) in order to obtain a mesa structure with clear-cut walls. We then perform a hydrofluoric (HF) wet-etch step in order to remove the sacrificial layer below the resonators and the metallic etch mask (Al). The last step of processing is critical point drying, in order to avoid surface tension by the solvents. The suspended resonator is shown in a scanning electron beam micrograph in Fig. 1; the inset shows a close-up of the suspended beam. The restoring force of this Au/Si-hybrid beam is dominated by the stiffer Si supporting membrane. The selection of the appropriate HF etch allows for attacking only the Si, and thus the minute determination of the beam's flexibility and, in turn, the strength of the nonlinear response.

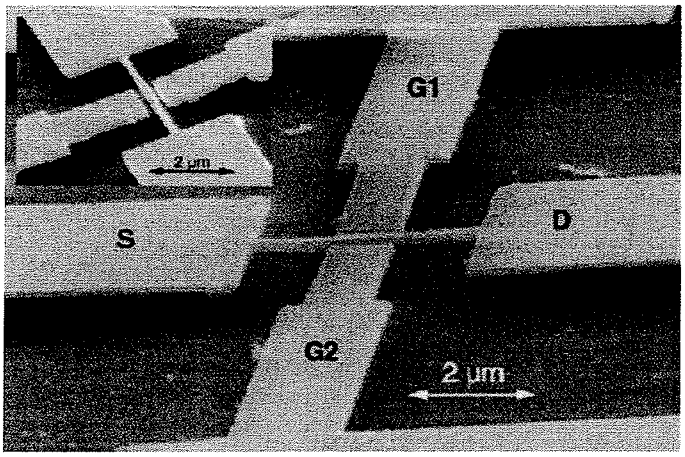


Fig. 1. Scanning electron beam micrograph of the electromechanical resonator with a length $l = 3$ $\mu$m, width $w = 200$ nm, and height $h = 250$ nm. The silicon supporting structure is covered by a thin Au sheet (50 nm thick). The electrodes on the left and right allow tuning of the elastic properties. Inset shows a magnification of the beam.

The chip is mounted in a sample holder and a small amount of $^4$He exchange gas is added (10 mbar) to ensure thermal coupling. The sample is placed at 4.2 K in a magnetic field, directed in parallel to the sample surface but perpendicular to the beam. When an alternating current is applied to the beam, a Lorentz force arises perpendicular to the sample surface and sets the beam into mechanical motion. For characterization we used a spectrum analyzer (Hewlett Packard 8594A, Palo Alto, CA). The output fre-

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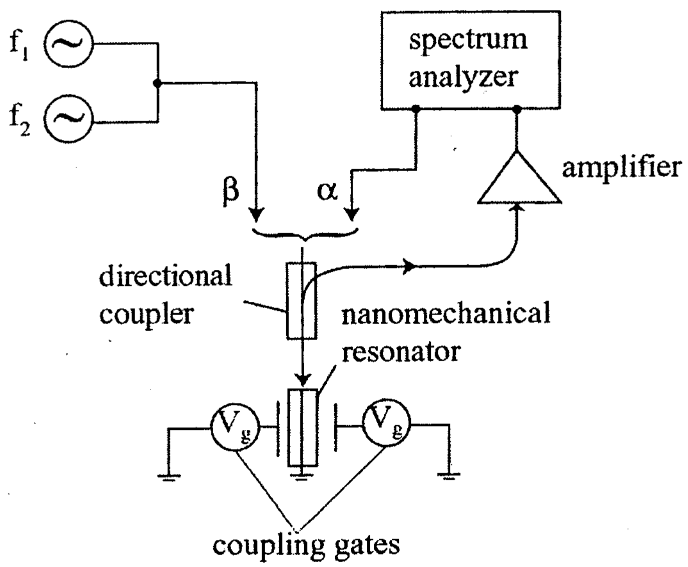


Fig. 2. Experimental setup for sampling the mechanical properties of the suspended beam. For characterization we used a spectrum analyzer scanning the frequency range of interest ($\alpha$). Mechanical mixing is analyzed by combining two synthesizers ($f_1$, $f_2$) and detecting the reflected power ($\beta$).

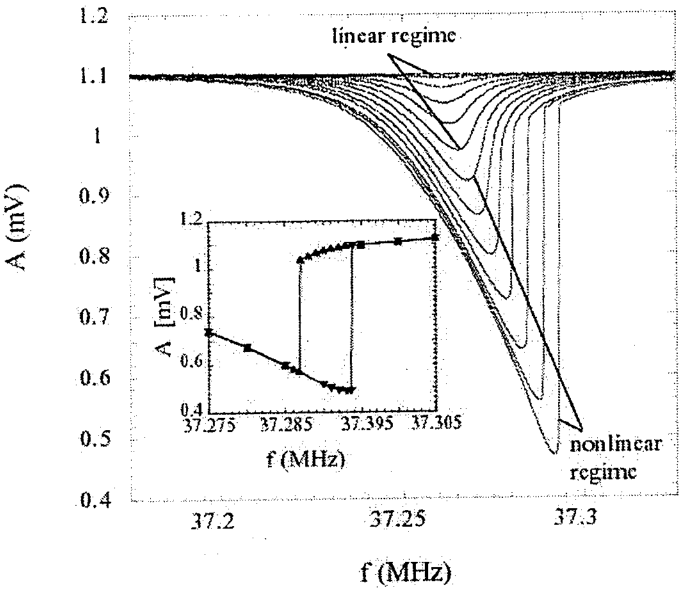


Fig. 3. Characterization of the nonlinear response of the suspended beam by ramping the magnetic field from 0 T up to 12 T, obtained with the spectrum analyzer operated with output power level of 50 dBm (setup $\alpha$). Inset shows the measured hysteresis: $\vee$ corresponds to an increase in frequency and $\wedge$ represents the lowering branch.

quency is scanning the frequency range of interest, the reflected signal is tracked then amplified (setup $\alpha$ in Fig. 2, reflectance measured in millivolts). The reflected power changes when the resonance condition is met, which can be tuned by the gate voltages $V_g$ applied at the coupling gates in a range of several 10 kHz. The mixing properties of the suspended nanoresonators are probed with a different setup comprising two synthesizers (we used Marconi 2032, London, UK and Wavetek 3010, Everet, WA) emitting excitations at constant, but different, frequencies (setup $\beta$ in Fig. 2). Here, the reflectance is measured in decibel-meters for better comparison of the driving amplitudes and the mixing products. The reflected power is amplified and detected by the spectrum analyzer.

In Fig. 3 the radio-frequency (rf) response of the beam near resonance is shown for increasing magnetic field strength $B = 0, 1, 2, \ldots, 12$ T with the excitation power of the spectrum analyzer fixed at $-50$ dBm. The mechanical quality factor, $Q = f/\Delta f$, of the particular resonator under test in the linear regime is $Q = 2330$. As seen, the profile of the resonance curve changes from a symmetric shape at moderate fields to an asymmetric, sawtooth shape at large field values, characteristic of an oscillator operated in the nonlinear regime. This behavior can be described by the Duffing equation [9]:

$$y''(t) + \mu y'(t) + \omega_0^2 y(t) + \kappa y^3(t) = F(t), \qquad (1)$$

with a positive prefactor $\kappa$ of the cubic term being the parameter of the strength of the nonlinearity. In (1) $\mu$ is the damping coefficient of the mechanical system, $\omega_0 = 2f_0$, where $f_0$ is the mechanical eigenfrequency of the beam, and $y(t)$ its displacement. In our case, the external driving $F(t)$ is given by the Lorentz force:

$$F(t) = \frac{lB}{m_{\text{eff}}} I(t) = \frac{lB}{m_{\text{eff}}} I_0 \cos[2f(t)], \qquad (2)$$

where $l = 1.9$ $\mu$m is the effective length and $m_{\text{eff}} = 4.3 \times 10^{-16}$ kg is the effective mass of the resonator; $B$ is the magnetic field, and $I_0$ is the input current. Solving (1) and computing the amplitude of the oscillation as a function of the driving frequency $f$ for several excitation strengths reproduces the measured curves shown in Fig. 3. The solutions at large power exhibit a region in which three different amplitude values coexist at a single frequency. This behavior leads to a hysteretic response in the measurements at high powers, as shown in the inset of Fig. 3, in which we used an external source (Marconi) to sweep the frequencies in both directions. If the frequency is increased (inverted triangles ($\bigtriangledown$) in the inset), the resonance first follows the lower branch, then suddenly jumps to the upper branch. When sweeping downward from higher to lower frequencies ($\triangle$), the jump in resonance occurs at a different frequency.

We turn now to the unique properties of the nonlinear nanomechanical system: By applying two separate frequency sources as shown in Fig. 2 (setup $\beta$), it is possible to demonstrate mechanical mixing, as shown in Fig. 4. The two sources are tuned to $f_1 = 37.28$ MHz and $f_2 = 37.29$ MHz with constant offset and equal output power of $-48$ dBm, well in the nonlinear regime. Without applying a magnetic field, the two input signals are simply reflected (upper left panel). Crossing a critical field of $B \approx 8$ T higher order harmonics appear. In-

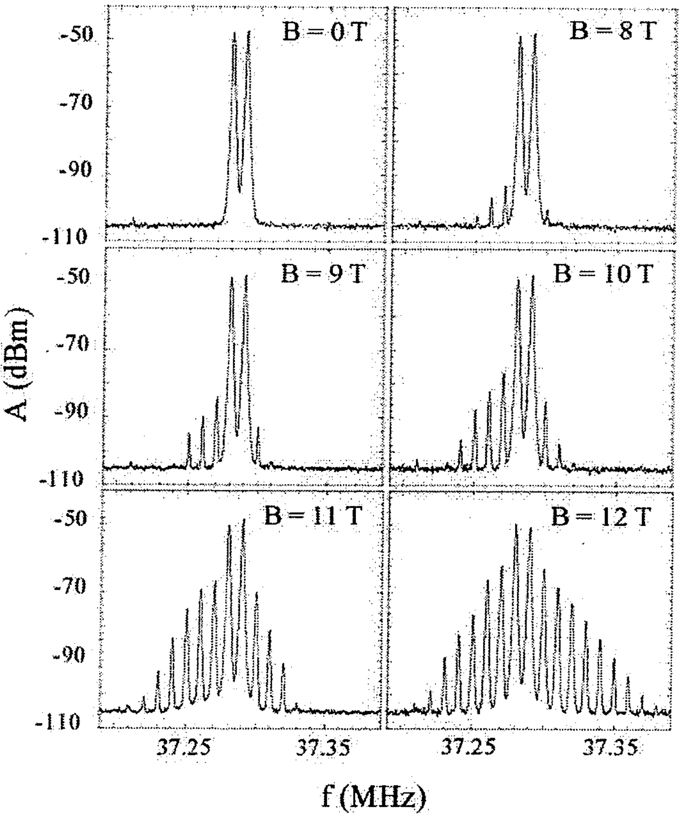


Fig. 4. Two synthesizers (setup $\beta$ in Fig. 4) operated at frequencies of $f_1 = 37.28$ MHz and $f_2 = 37.29$ MHz with constant offset (output power −48 dBm) induce higher order harmonics as a result of mechanical mixing by the nanoresonator in the nonlinear regime ($B > 8$ T).

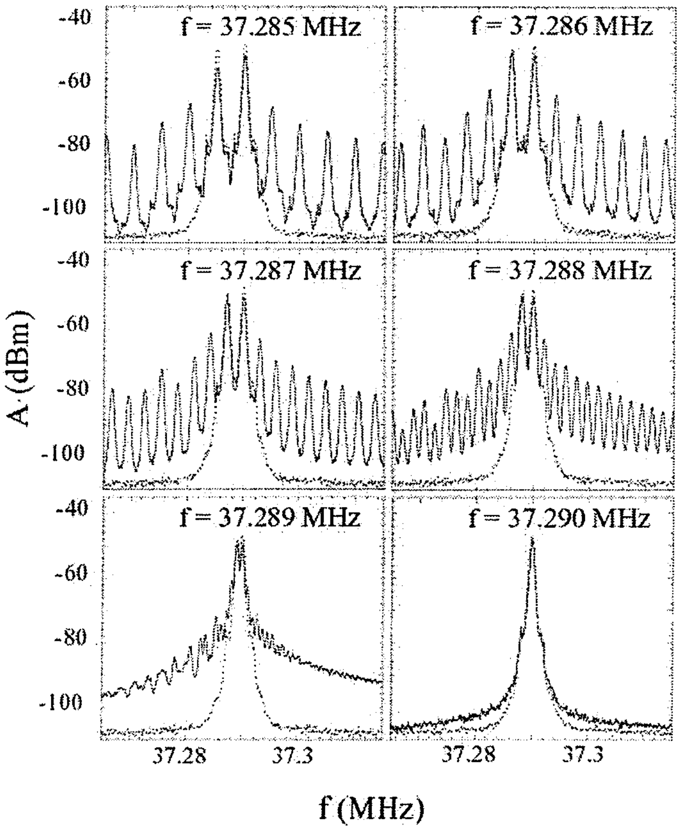


Fig. 5. Excitation with two frequencies at 48 dBm and $B = 12$ T: Base frequency is $f_1 = 37.290$ Mhz; the sampling frequency is varied in 1 kHz steps from $f = 37.285$ to 37.290 MHz. The spacing of the harmonics follows the offset frequency $\delta f = (f_1 - f_2)$.

creasing the field strength further, a multitude of satellite peaks evolves. The limited bandwidth of this mechanical mixer allows effective signal filtering. Variation of the offset frequencies leads to the data presented in Fig. 5: Excitation at 48 dBm and $B = 12$ T with the base frequency fixed at $f_1 = 37.290$ MHz and varying the sampling frequency in 1 kHz steps from $f_2 = 37.285$ MHz to 37.290 MHz yields satellites at the offset frequencies $f_{1,2} \pm n\Delta f$, $\Delta f = (f_1 - f_2)$. The dotted line is taken at zero field for comparison, showing only the reflected power when the beam is not set into mechanical motion. At the smallest offset frequency of 1 kHz, the beam reflects the input signal as a broad band of excitations.

## III. Conclusions

In summary, we have shown a new approach towards realizing nanomachined mechanical mixers. Due to the high eigenfrequencies of such a nanoelectromechanical system of the order of some 100 MHz, integration into standard silicon transistor technolocy is to be expected. In order to do this, the device has to work at $B = 0$ to make operation at room temperature possible. This can be achieved by choosing a different driving mechanism. The gates on both sides of the beam can be used for capacitive driving and detection [10]. Applying surface acoustic waves as a driving mechanism of nanomechanical structures has recently proven to be successful. Thus mechanical excitation at room temperature completely without magnetic fields is possible [11]. These driving mechanisms will allow integration into standard devices in the future.

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