APPLIED PHYSICS LETTERS VOLUME 82, NUMBER 3 20 JANUARY 2003

Mechanical gating of coupled nanoelectromechanical resonators operating at radio frequency

Laura Pescini,[a] Heribert Lorenz, and Robert H. Blick
Center for NanoScience and Sektion Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, 80539 München, Germany

(Received 27 August 2002; accepted 18 November 2002)

We report measurements on hybrid gold/silicon suspended nanostructures operating as electromechanical resonators in the rf regime. The device consists of two nanoresonators operating as mechanical gating elements. We demonstrate this gating mechanism by tuning the mechanical modes of the device. Detailed numerical calculations are performed to model the device. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1536032]

The exploration of mechanical functionality on the nanometer scale has recently attracted considerable attention, thus opening the field of nanoelectromechanical systems (NEMS). The operability of these systems as sensors and actuators has been most intensively demonstrated.[1–6] Among the crucial features of NEMS are the very high fundamental frequencies of operation given by the reduced size and the small force constants, translating in high force sensitivity, which makes NEMS attractive for applications, even as atomic force microscopy-based data storage systems.[7] Moreover, NEMS can provide solutions in telecommunications networks[8] or can be employed in automotive sensors.[9] Here, we investigate the mechanical properties of coupled nanostructures and demonstrate a mechanical gating mechanism for NEMS operating up to 200 MHz. Gating is facilitated by capacitive coupling of the various mechanical mode shapes.

The devices are made out of silicon-on-insulator materials. The top silicon layer has a thickness of 100 nm and the buried oxide (BOX) of 400 nm. The BOX provides electrical insulation, eliminating the possibility of conducting paths through the substrate. The devices are defined by high-resolution low-energy electron-beam lithography using two layers of positive electron resist, namely poly(methylmethacrylate). A 40 nm thin gold layer is evaporated on the structure to serve as an electrical conductor for the ac current fed through the device. A 20 nm Al film is evaporated to act as an etch mask in the following reactive ion etching of the silicon film which is performed using CF_4. The active devices are suspended by selective etching of the BOX in buffered hydrofluoric acid, which also removes the Al layer. The samples are finally dried in a critical point dryer in order to avoid surface tension of the solvents[10] and then bonded. A more detailed description of the fabrication process has been given elsewhere.[11] Such fabricated coupled NEMS are shown in Fig. 1.

Mechanical agitation of NEMS is either achieved by capacitive coupling,[12] surface acoustic waves,[13] or magnetomotively.[1] In the latter case, the motion is due to the Lorentz force which acts on the suspended device when an alternate current, whose frequency matches the eigenfrequency of the device, is supplied and an orthogonal magnetic field is present. The measurement setup is shown in the inset of Fig. 1. A network analyzer applies an ac signal to one of the wires (W2, in the following called signal line) and simultaneously detects the reflected power. When the wire is set into motion, a voltage drop is induced in the wire, therefore, a change in the reflected power is recorded. The samples are measured in a variable temperature insert mounted in a helium bath cryostat allowing a temperature variation from 1.5 up to 250 K. Moreover, in our experiment, a signal generator can be used to excite the other suspended nanowire (W1, in the following referred to as mechanical gating line).

The devices are initially characterized in their linear and nonlinear behavior as well as for temperature dependence of the mechanical response (the temperature dependence is discussed elsewhere).[14] Measurements in the linear regime, i.e., for small operating power, show that both nanoresonators have three main resonant oscillation modes at 127, 130, and 160 MHz. A deeper underetching of the beams allows one to observe up to 15 different modes.[15] Due to the control developed in sample preparation techniques, striking similarity of the resonance spectrum for the two resonators is achieved, as shown in Fig. 2(a). This is of great advantage for studying

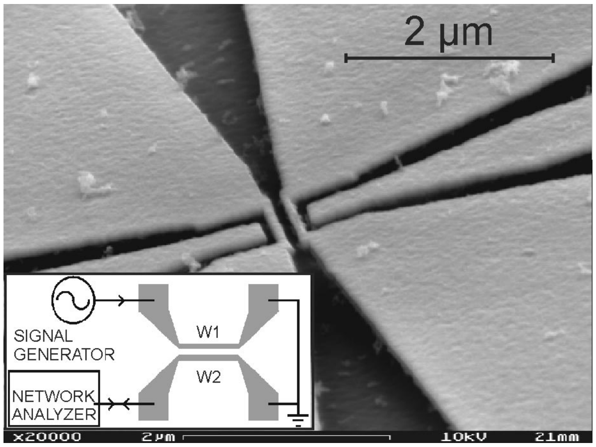

FIG. 1. (a) Electron-beam micrograph of a fabricated NEMS (tilted view). The two suspended resonators have a width of 80 nm and a length of 920 nm. The spacing between the wires and between each wire and its sidegate is also about 80 nm. dc biasing the sidegates allows one to tune the resonance frequency of the wires. Inset: The measurement setup consists of a signal generator which sends one frequency signal and a network analyzer which acquires the reflected signal power.

---

[a] Electronic mail: laura.pescini@physik.uni-muenchen.de

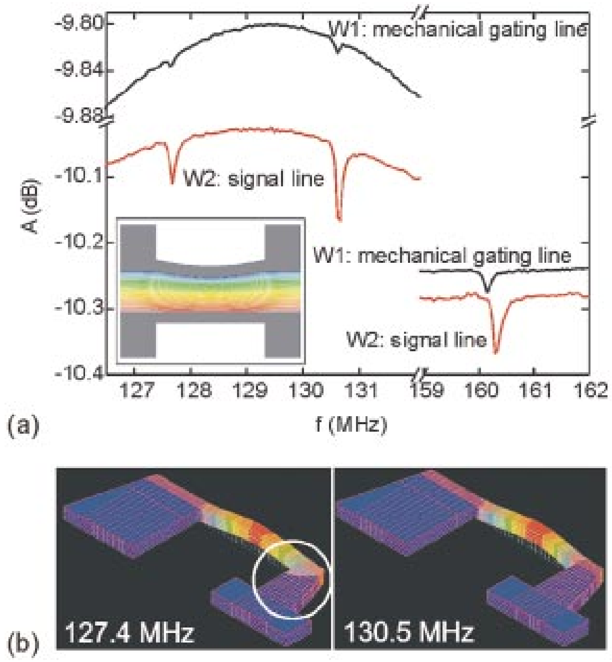

FIG. 2. (Color) (a) Mechanical resonances of the two nanoresonators showing the highly reproducible frequency spectrum. The plot shows amplitude of the reflected signal vs frequency. The inset gives the electrostatic field distribution between the two wires. (b) Modes of oscillation of the two resonators: The finite-element simulation for the first two modes. The white circle points out the difference between the two eigenmodes.

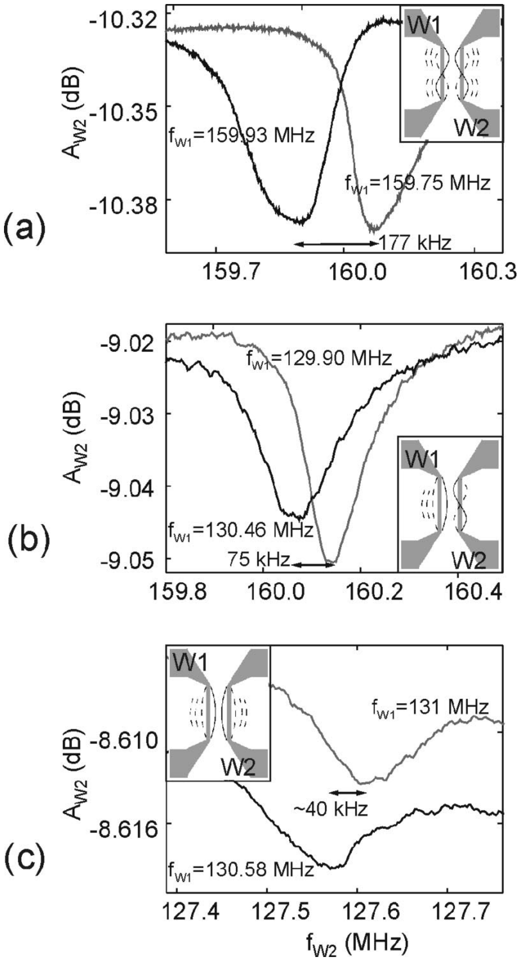

FIG. 3. (a)–(c): Tuning of the signal line resonance curve is realized by applying a signal to the gating wire. Shown is the resonance curve of W2. In each plot, the two curves correspond to two different frequencies sent to W1, as indicated. The shift of the W2 resonance amounts 177 kHz (a), 75 kHz (b), and 40 kHz (c), depending on the interacting mechanical modes, which are schematically depicted in the insets.

the mechanical interaction between the two resonators since they share the same frequency spectrum of oscillation. In general, the displacement of the beam center $y(t)$ is described by the second-order differential equation

$$y''(t)+\mu y'(t)+\omega_0^2 y(t)=F(t), \tag{1}$$

where μ is the damping coefficient, ω_0 is the eigenfrequency of the resonator, and $F(t)$ is the driving force, $F(t)=F_0\cos(\omega t)$.[16] The nonlinearity arises when the driving force excites too large displacements in the oscillator that is anharmonic motion, which is described by a term $\alpha y^3(t)$ in Eq. (1). Two adjacent mechanical resonators affect each other, particularly when their resonance frequencies are similar. For our system, the capacitance between the two resonators at rest is on the order of 100–200 aF and $\delta C/\delta d \propto 1/d$, with d as the separation between the wires. An additional term F_C is introduced in Eq. (1) which represents the contribution of the capacitive coupling to the driving force and has the form $F_C(t)=C(t)V^2(t)/d(t)$, with $V(t)$ as the potential difference between the resonators. The electrostatic potential and the capacitance between the two resonators are calculated with the program Maxwell equation finite integration algorithm (MAFIA). The electrostatic potential between the two wires is shown in the inset of Fig. 2(a), assuming a potential difference of 2 V between the wires. A frequency shift is expected in the spectrum of the two resonators as a consequence of the coupling and especially due to the fact that the coupling deforms the eigenmodes.[17] This shift is observed in our measurements, as discussed next.

In Fig. 2(b), we present a calculation performed with SOLVIA, a finite-element analysis program for structural and mechanical stress analysis, helpful to gain insight in the mechanical modes of nanoresonators. For the measured structure, it has been possible to reproduce the oscillation frequencies at 127 MHz, 130 MHz, and 160 MHz. It turns out that the first two are both ground mode oscillations, the first involving a portion of the leads [marked by the circle in the left-hand side graph of Fig. 2(b)], the second based only in the suspended wire. For the resonance at 160 MHz, we find an oscillation mode more similar to a sinusoidal shape.

In Fig. 3, the measurements showing the interaction of one frequency mode with another are presented. The three plots refer to the gating of one frequency mode of W2 by an oscillation of W1, respectively, 160 MHz with 160 MHz [Fig. 3(a)], 160 MHz with 130 MHz [Fig. 3(b)], and 127 MHz with 130 MHz [Fig. 3(c)]. In each plot, the resonance curve of the signal line (resonator W2) is shown for two different values of the frequency sent to the gating line (resonator W1). The tuning action of W1 on W2 is evident in the frequency shift. If the gating line is out of resonance, i.e., if the signal generator operates at a frequency far from the three modes no frequency shift is observed for W2. The insets of Fig. 3 sketch the scenarios for the coupling modes in which the different deformation of the eigenmodes leads to a high-frequency modulation of the capacitive coupling. The flexibility of the device is improved by the in-plane sidegates. In fact, by dc biasing these electrodes, the mechanical resonance can be shifted, as shown elsewhere.[18]

In summary, we have investigated the interaction of mechanical nanoresonators operating in the rf regime. We found that this interaction can be used to tune the frequency of operation of the system. This experiment has been possible due to the achieved reproducibility of the frequency spectra of the device. The main advantage of our approach is the integrability of the device into existing silicon electronics and its reliability. Finally, we find that the specific geometry of the clamping points plays a major role in determining the modes of oscillation and must be accurately considered while designing new systems. Deep underetching of the leads allows the occurrence of many modes of oscillation and, hence, a highly flexible mechanical gating of diodes or quantum dots.[19]

The authors would like to thank F. W. Beil for help with the finite-element computer program SOLVIA and M. Vogel for help with the program MAFIA. They are also grateful to S. Manus for technical support. The authors acknowledge financial support from the Deutsche Forschungsgemeinschaft.

[1] A. N. Cleland and M. L. Roukes, Appl. Phys. Lett. **69**, 2653 (1996).

[2] I. W. Rangelow and H. Löschner, J. Vac. Sci. Technol. B **13**, 2394 (1995).

[3] D. W. Carr and H. G. Craighead, J. Vac. Sci. Technol. B **15**, 2760 (1997); D. W. Carr, L. Sekaric, and H. G. Craighead, *ibid.* **16**, 3821 (1998).

[4] E. S. Kolesar, P. B. Allen, J. T. Howard, J. M. Wilken, and N. C. Boydston, J. Vac. Sci. Technol. A **17**, 2257 (1999).

[5] R. Gooch, T. Schimert, W. McCardel, B. Ritchey, D. Gilmour, and W. Koziarz, J. Vac. Sci. Technol. A **17**, 2295 (1999).

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

[7] M. Despont, J. Brugger, U. Drechsler, U. Dürig, W. Häberle, M. Lutwyche, H. Rothuizen, R. Stutz, R. Widmer, G. Binnig, H. Rohrer, and P. Vettiger, Sens. Actuators **80**, 100 (2000).

[8] J. A. Walker, J. Micromech. Microeng. **10**, R1 (2000).

[9] D. Bishop, P. Gammel, and C. R. Giles, Phys. Today **54**, 38 (2001).

[10] R. Maboudian and R. T. Howe, J. Vac. Sci. Technol. B **15**, 1 (1997).

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

[12] A. Erbe, C. Weiss, W. Zwerger, and R. H. Blick, Phys. Rev. Lett. **87**, 096106 (2001).

[13] F. W. Beil, A. Wixforth, and R. H. Blick, Proceedings of the IEEE International Conference on Sensors, Orlando, Florida, 11–14 June, 2002.

[14] F. W. Beil, L. Pescini, A. Kraus, A. Erbe, E. Höhberger, and R. H. Blick (unpublished).

[15] L. Pescini, D. K. Maude, H. Lorenz, and R. H. Blick (unpublished).

[16] G. Duffing, *Erzwungene Schwingungen bei veränderlicher Eigenfrequenz und ihre technische Bedeutung* (Vieweg, Braunschweig, 1918).

[17] J. Söderkvist, J. Acoust. Soc. Am. **90**, 693 (1991).

[18] A. Tilke, A. Erbe, L. Pescini, H. Krömmer, R. H. Blick, H. Lorenz, and J. P. Kotthaus, Superlattices Microstruct. **27**, 597 (2000).

[19] J. Kirschbaum, E. M. Höhberger, R. H. Blick, W. Wegscheider, and M. Bichler, Appl. Phys. Lett. **81**, 280 (2002).