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Scanning acoustic force microscopy characterization of thermal expansion effects on the electromechanical properties of film bulk acoustic resonators

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This letter demonstrates the application of scanning acoustic force microscopy for the characterization of film bulk acoustic resonators beyond detection of the gigahertz vibration amplitude and acoustic wave field imaging. We present a method to measure thermal expansion effects on these resonators by modulating the driving signal amplitude and then varying the modulation frequency from a few hertz to several tens of kilohertz. For the particular device considered here, we show the influence of thermal expansion effects on its electromechanical response and the acoustic wave field images. The thermal relaxation time constant of the resonator is measured and compared with a theoretical estimation based on the heat transfer analysis of the system. © 2005 American Institute of Physics. [DOI: 10.1063/1.1866508]

The area of rf devices has made some of the most impressive recent advances in the field of micro and nanoelectromechanical systems (MEMS). rf mechanical resonators are constantly improving in quality factors, integration capabilities and size, allowing more-efficient, lower-cost wireless communications components, such as filters, duplexers, or mixers.^{1–4} This progress in design and fabrication demands an accompanying development of experimental techniques which are suitable for the electromechanical characterization of the emerging prototypes. Several laser interferometer based methods have been proposed.^{5–7} Besides subangstrom scale resolution in vibration amplitude detection, optical methods have one particularly interesting feature: they can simultaneously measure both amplitude and phase of acoustic vibrations in the gigahertz (GHz) range. However, these methods offer limited lateral resolution for mode shape imaging, usually on the micrometer scale. As an alternative, scanning acoustic force microscopy (SAFM) provides a comparable vibration amplitude resolution with a nanometer-scale lateral resolution.^{8,9} Specifically developing SAFM to study mechanical resonators takes advantage of its superior lateral resolution and experimental versatility, and it can also provide methods to obtain further information about the physical properties and performance of these devices.

In this work, we show that SAFM allows not only the detection of the vibration amplitude of rf mechanical resonators in the GHz range but also the study of other relevant properties, in particular, thermal expansion effects, and their influence on the electromechanical response of the resonator. The resonator considered here is an Agilent Technologies' film bulk acoustic resonator (FBAR), which consists of a free-standing piezoelectric AlN pentagonal membrane with side lengths about 100 μm and overlapping Mo electrodes.^{1,3,4} The membrane is designed to have a main thickness vibration mode with a resonance frequency around 1.9 GHz. Before the SAFM experiments, electrical characterization of the particular device under study showed a reso-

nance peak at 1.898 GHz in the power reflection coefficient.

Figure 1 shows the SAFM experimental setup used in this work. The scanning force microscope (Digital Instruments D3100) is operated in air, in the standard contact mode. Standard Si_3N_4 cantilevers with a nominal stiffness of 0.4 N/m and a resonance frequency of $f_{\text{can}} \approx 80$ kHz are used. The microscope tip is placed in contact with the top electrode of the resonator membrane, which is driven by an amplitude-modulated (AM) signal. In the experiments shown here, the FBAR is driven slightly above the resonance frequency of its main thickness mode for reasons explained later. The modulation frequency f_{mod} is kept below f_{can} to allow the cantilever to oscillate at f_{mod} and follow the amplitude-modulated envelope of the resonator vibration. The amplitude of the vibration is then measured by using the modulation signal as the reference for the lock-in amplification of the microscope's cantilever deflection signal. The capability of this technique to measure the rf frequency response and to image acoustic wave fields in solidly mounted resonators has been previously demonstrated by Safar *et al.*⁹ In that work, f_{mod} was kept constant at a value in the 2–20 kHz range. In fact, beside the upper limit for f_{mod} imposed by f_{can} (typically 5–80 kHz), the microscope feedback

FIG. 1. (a) Experimental setup. (b) Optical micrograph of the FBAR resonator under study. The white square indicates the area scanned with the SAFM.

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FIG. 2. $100 \times 100 \mu\text{m}$ FBAR vibration amplitude images and profiles at $f_{\text{RF}} = 1.934 \text{ GHz}$, $V_{\text{drive}} = 1.1 \text{ V}$, $f_{\text{mod}} = 10 \text{ kHz}$ (a) and $f_{\text{mod}} = 1 \text{ kHz}$ (b).

bandwidth (typically 1–10 KHz) also establishes a lower limit for f_{mod} . If f_{mod} is set below the feedback bandwidth, the feedback will compensate for the cantilever oscillation that follows the resonator vibration envelope by oscillating the microscope's vertical piezo. Here, we show how opening the feedback loop and then varying f_{mod} from a few hertz to several kilohertz provides further relevant information about the properties of mechanical resonators.

Figure 2 shows two images of the FBAR vibration amplitude obtained at a driving frequency of 1.934 GHz. Except for f_{mod} , which is 10 kHz in (a) and 1 kHz in (b), both images were taken with the same parameters. Simply decreasing the feedback control parameters allowed us to reduce the effective feedback bandwidth and to use these values of f_{mod} just inside the limit of the feedback bandwidth. Image (a) shows the rf vibration pattern that results from the excitation of high order Lamb wave modes at frequencies above the main thickness mode, as reported in other studies.^{6,9,10} This standing-wave pattern consists of a short wave-length structure with 2–5 μm features aligned parallel to the sides of the membrane. Remarkably, the vibration amplitude image suffers an important change when f_{mod} is reduced, as shown in image (b). A superimposed background vibration emerges beneath the same rf vibration pattern. This background vibration causes an overall increase in amplitude, plus a relative increase at the center of the membrane with respect to the external regions. This is more clearly observed in the cross sections shown below the images. The profile from image (a) shows the peaks and valleys arising from the rf vibration, while the profile from image (b) also shows a superimposed background curve with a maximum in the center of the scan line.

To determine the cause of the observed background vibration, we have measured the behavior of its amplitude versus both the drive voltage and the modulation frequency. The main thickness mode of a FBAR is a uniform amplitude mode⁷ that would have been difficult to separate from the observed f_{mod} dependent background vibration. However, the high order vibration pattern observed at 1.934 GHz and the nanometer-scale lateral resolution of SAFM allow us to separate the rf and the background vibration by detecting the amplitude on a local point of the membrane surface that corresponds to a valley of the rf pattern. This ensures that the measured amplitude comes exclusively from the background vibration. The microscope feedback loop was open during these measurements. The acquisition of each curve took a few seconds, and thus thermal drifts are not expected to have

FIG. 3. FBAR vibration amplitude vs drive voltage at different modulation frequencies (a) and vs modulation frequency at $V_{\text{drive}} = 1.1 \text{ V}$ (b) obtained on a surface point without rf vibration.

any relevant influence. Figure 3(a) shows the behavior of the amplitude versus the drive voltage at different modulation frequencies. For a given drive voltage, the lower values of f_{mod} imply the higher values of the amplitude. Other authors, using a laser interferometer on similar FBAR resonators, expected a linear relationship between the rf vibration amplitude and the drive voltage.⁷ However, the slope of the logarithmic plot reveals a V^2 amplitude dependence. The previously mentioned studies used a nonmodulated driving signal, which suggests that the driving signal modulation is responsible for the observed V^2 amplitude dependence.

Figure 3(b) shows the measured dependence of the background vibration amplitude on f_{mod} at a constant drive voltage of 1.1 V. The amplitude remains constant at 5.6 nm for modulation frequencies below 500 Hz, and then it decreases monotonically. This behavior can be explained as follows: when a rf driving signal is applied to the FBAR, part of the energy is absorbed by the membrane and converted into heat.⁴ Heat transfer from the membrane to the surroundings sets a thermal equilibrium, and the membrane reaches an equilibrium temperature T_{eq} . As a result, the membrane expands and bows proportionally to T_{eq} . With low- f_{mod} AM driving signals, the membrane reaches its equilibrium temperature and maximum bowing amplitude in each modulation cycle. This will happen below a critical f_{mod} , producing a flat amplitude dependence on f_{mod} like the one observed below 500 Hz in Fig. 3(b). However, a high f_{mod} will prevent the membrane from reaching its equilibrium temperature and maximum bowing amplitude in each modulation cycle, so the membrane temperature and the bowing amplitude decrease as the modulation cycle shortens. This will produce an amplitude reduction like the one shown in Fig. 3(b) above 500 Hz.

The critical modulation frequency that marks the transition described earlier depends on the relaxation time required to establish temperature equilibrium between the membrane and the surroundings, τ . A comparison between an experimental value of τ obtained from Fig. 3(b) and a theoretical estimation follows: the system's temperature equation states that the rate of change of the membrane's internal energy must equal the net rate of energy generation inside the membrane plus the net rate of heat conduction from the membrane to the substrate

$$m_{\text{th}} \frac{\partial T}{\partial t} \approx \frac{V^2}{R} - \frac{K_{\text{air}}}{z_{\text{gap}}} a(T - T_{\infty}), \quad (1)$$

where V and R are the applied voltage and resistance across the membrane, K_{air} is the thermal conductance of air, z_{gap} is the air gap between the membrane and the substrate, and a is the active area of the membrane. Both the AlN film and the two Mo electrodes with its relative thickness t , density ρ , and specific heat C are included in the thermal mass of the membrane, $m_{\text{th}} = a(t_{\text{AlN}}\rho_{\text{AlN}}C_{\text{AlN}} + t_{\text{Mo}}\rho_{\text{Mo}}C_{\text{Mo}})$. The earlier equation considers a uniform temperature across the membrane section and a heat transfer from the membrane to the surroundings dominated by heat conduction to the substrate. A justification of these approximations for the derivation of the temperature equation of free standing MEMS can be found elsewhere.^{11,12} If an AM driving signal is considered, the electrical power dissipation term V^2/R provides a periodic heat generation at f_{mod} inside the membrane. Then, assuming a bowing amplitude directly proportional to the membrane temperature, the frequency response of the membrane bowing is governed by the first order thermal frequency response of the system¹¹

$$A_{\text{bow}}(f_{\text{mod}}) = A_0(1 + 4\pi^2 f_{\text{mod}}^2 \tau^2)^{-0.5}, \quad (2)$$

where A_0 is the maximum bowing amplitude and $\tau = (z_{\text{gap}} m_{\text{th}}) / (K_{\text{air}} a)$ is the thermal relaxation time. Using the bulk values for the density and specific heat of AlN and Mo, the thickness of the AlN membrane (1.1 μm), Mo electrodes (0.3 μm top and 0.4 μm bottom) and the air gap (3 μm),¹³ an estimation of $\tau = 0.39$ ms can be obtained. On the other hand, fitting Eq. (2) to the plot in Fig. 3(b) produces $\tau = 0.21$ ms, in reasonable agreement with the theoretical estimation.

In conclusion, we have shown that SAFM is capable of electromechanical characterization of rf mechanical resonators beyond detection of the rf vibration amplitude. A background vibration observed in the amplitude images at low modulation frequencies is attributed to thermally induced bowing of the membrane due to the driving signal modulation, which produces heating and cooling cycles in each

modulation period. The consistency between the experimental and estimated thermal relaxation time of the resonator membrane together with the observed dependence of the amplitude on V_2 and f_{mod} , support this conclusion. Thermal dissipation processes represent a major source of power dissipation and Q -factor limitation in rf resonators. The ability of this technique to provide experimental values of the characteristic parameters of such dissipation mechanisms demonstrates its enormous usefulness for the characterization of rf MEMS devices.

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¹R. Ruby and P. Merchant, *Proceedings of the 1994 IEEE Frequency Control Symposium* (IEEE, Piscataway, NJ, 1994), p. 135.

²K. M. Lakin, J. R. Belsick, J. P. McDonald, K. T. McCarron, and C. W. Andrus, *Tech. Dig. IEEE MTT-S*, 2002, p. 1487.

³R. Ruby, P. Bradley, J. D. Larson III, and Y. Oshmyansky, *Electron. Lett.* **35**, 794 (1999).

⁴J. D. Larson III, R. Ruby, P. Bradley, J. Wen, S. L. Kok, and A. Chien, *Proceedings of the 2000 IEEE Ultrasonics Symposium* (IEEE, Piscataway, NJ, 2000), p. 869.

⁵G. G. Fattinger and P. T. Tikka, *Appl. Phys. Lett.* **79**, 290 (2001).

⁶J. E. Graebner, H. F. Safar, B. Barber, P. L. Gammel, J. Herbsommer, L. A. Fetter, J. Pastalan, H. A. Huggins, and R. E. Miller, *Proceedings of the 2000 IEEE Ultrasonics Symposium* (IEEE, Piscataway, NJ, 2000), p. 635.

⁷K. L. Telschow, V. A. Deason, D. L. Cottle, and J. D. Larson III, *Proceedings of the 2000 IEEE Ultrasonics Symposium* (IEEE, Piscataway, NJ, 2000), p. 631.

⁸T. Hesjedal, E. Chilla, and H.-J. Fröhlich, *Appl. Phys. Lett.* **70**, 1372 (1997).

⁹H. Safar, R. N. Kleiman, B. P. Barber, P. L. Gammel, J. Pastalan, H. Huggins, L. Fetter, and R. Miller, *Appl. Phys. Lett.* **77**, 136 (2000).

¹⁰A. San Paulo, X. Liu, and J. Bokor, *Tech. Dig. IEEE MEMS*, 2004, p. 169.

¹¹R. Hickey, D. Sameoto, T. Hubbard, and M. Kujath, *J. Micromech. Microeng.* **13**, 40 (2003).

¹²S. Sherrit, X. Bao, D. A. Sigel, M. J. Gradziel, S. A. Askins, B. P. Dolgin, and Y. Bar-Cohen, *Proceedings of the 2001 IEEE Ultrasonics Symposium* (IEEE, Piscataway, NJ, 2001), p. 1097.

¹³R. Ruby (private communication).