METAL-INSULATOR INTERFACE LOSSES IN MULTIMATERIAL RESONATORS

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We present an extensive study shedding light on the role of surface and bulk losses in micromechanical resonators. With very high quality factors (Qs) values (up to $10^7$) at room temperature and $Q \cdot f$ products (above $10^{13}$ Hz), stoichiometric Si$_3$N$_4$ membranes [1, 2] and strings [3] have become a centerpiece of many research projects, particularly in opto-mechanics [4, 5]. Recently it has been shown that metallized membranes enable the design of exciting new opto-electro-mechanical systems that allow e.g. the optical detection of electrical signals with unprecedented sensitivity [6]. For these applications and for MEMS resonators in general there has been a continuous effort to find materials and systems that provide as high Qs as possible. The thorough understanding of the underlying loss mechanisms is crucial to optimize Q.

Q can be defined as the ratio between the energy stored in a resonator over the energy loss every cycle. Due to their large intrinsic residual stress, resonating membranes and string are able to store more energy, thus increasing Q even though dissipated energy per cycle remains the same. Models based on this idea, considering only material losses are able to reproduce the behavior of Q as a function of mode number, and even suggest ways to control extra losses for multi-material resonators [7, 8]. However, the data reported in the literature does not provide information on the relative importance of surface vs. bulk losses for these systems. In this work, we quantify both bulk and surface losses, evidencing the importance of proper surfaces, not only in the physical boundaries of the resonator, but also in the interface between different materials.

We fabricate a set of Si$_3$N$_4$ square membranes ($L = 250, 500, \text{ and } 1000 \mu m$; $t_{Si_3N_4} = 50, 100, \text{ and } 200 nm$), by simple KOH micromachining of Si wafers. Aluminum is then deposited on top of some of the samples ($t_{Al} = 50, 100, \text{ and } 200 nm$); and finally samples are annealed at 400°C. Characterization is performed in vacuum ($P \leq 10^{-5} \text{ mbar}$), at room temperature, using a piezoshaker actuator and a Polytec Doppler vibrometer to detect the motion. We study the 81 first flexural vibrational modes measuring their resonance frequencies and quality factors. This provides us with more than 3000 experimental points. The frequency of the modes is very accurately described (see Fig.1) by $f_{n,m} = v_{eff} \sqrt{n^2 + m^2}/2L$, where $n$ and $m$ are the mode numbers in the $x$ and $y$ directions, respectively, and $v_{eff}$ is the effective sound speed in the membrane.

![Figure 1: Experimentally obtained frequencies (scattered points, scaled by the length) for the 81 first flexural modes vs. mode number for 13 membranes with different dimensions.](image-url)
where \( v_{\text{eff}} \) is the effective speed of sound for each particular multimaterial stack. In fact, we can use the measured frequency values to extract residual stress and density for both Si\(_3\)N\(_4\) and Al (see Fig. 2).

We then use a model that considers only bulk losses for both materials. This model is a modification of the one presented elsewhere [8], accounting for the fact that the metal thickness will cause the neutral axis to shift with respect to the monomaterial case. We find that the resonators purely made of Si\(_3\)N\(_4\) can be represented by an imaginary Young’s modulus of \( \approx 0.2 \) GPa (Fig. 3, top-left), i.e. this behavior can be purely explained using bulk losses. However, when we put metal layers of different thicknesses, it is clearly visible that we need a more complex model. Our approach is to account for surface losses both at the interface between Si\(_3\)N\(_4\) and Al, and at the Al top surface. By doing so, we are able to fit the loss parameters to: \( E_{\text{loss,}Si_3N_4} = 0.2 \pm 0.1 \) GPa, \( E_{\text{loss,}Al} = 0.1 \pm 0.05 \) GPa, \( E_{\text{Al-top}}^* = 2 \pm 0.5 \sqrt{N/m} \), \( E_{\text{interface}}^* = 20 \pm 5 \sqrt{N/m} \) with a confidence interval close to 75% (Fig. 4).

We therefore quantify the importance of interface losses in multimaterial resonators, opening an important and interesting line or research to optimize the interfaces (by for example pre-deposition surface treatments) in order to minimize dissipation.
REFERENCES


