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_3N_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.

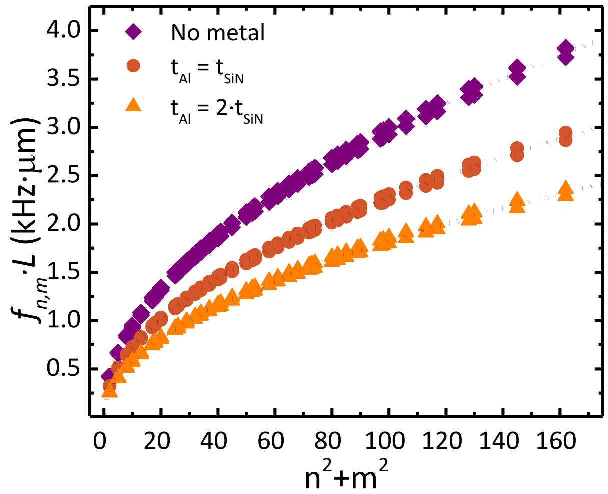

Figure 1: Experimentally obtained frequencies (scattered points, scaled by the length) for the 81 first flexural modes vs. mode number for 13 membranes with different dimensions..

We fabricate a set of Si_3N_4 square membranes ($L = 250, 500,$ and $1000\,\mu m$; $t_{Si_3N_4} = 50, 100,$ and $200\,nm$), by simple KOH micromachining of Si wafers. Aluminum is then deposited on top of some of the samples ($t_{Al} = 50, 100, and\ 200\,nm$); and finally samples are annealed at 400ºC. Characterization is performed in vacuum ($P \leq 10^{-5}\ mbar$), 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 v_{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_3N_4 and Al (see Fig. 2).

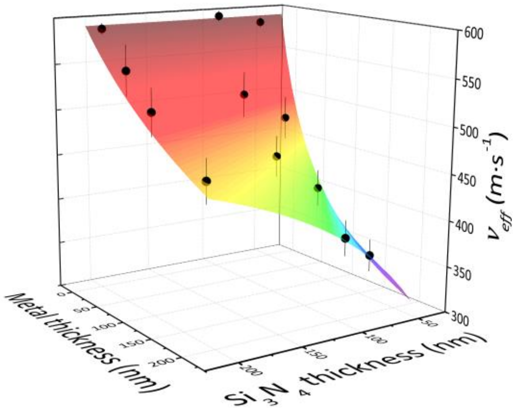

Figure 2: $v_{eff}=\sqrt{\frac{\sigma_{Si_3N_4}t_{Si_3N_4}+\sigma_{Al}t_{Al}}{\rho_{Si_3N_4}t_{Si_3N_4}+\rho_{Al}t_{Al}}}$ *for different membranes, allowing us to determine material properties for Al and* Si_3N_4*.*

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_3N_4 can be represented by an imaginary Young's modulus of ≈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_3N_4 and Al, and at the Al top surface. By doing so, we are able to fit the loss parameters to: $E_{loss,Si_3N_4}=0.2\pm0.1\ GPa, E_{loss,Al}=0.1\pm0.05\ GPa, E^*_{Al-top}=2\pm0.5\frac{N}{m}, E^*_{interface}=20\pm5\frac{N}{m}$ 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.

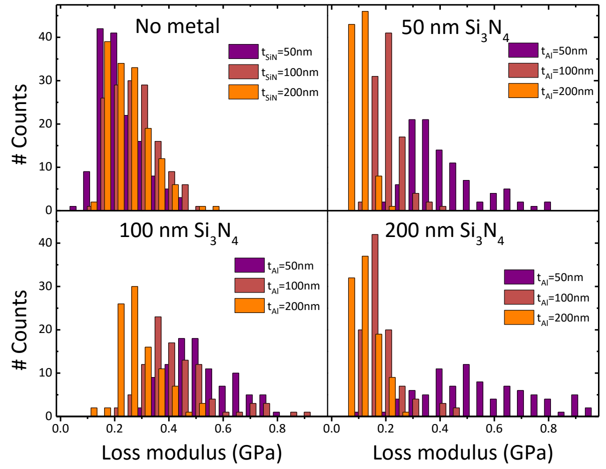

Figure 3: Histograms of the calculated imaginary components of the Young's modulus for Si_3N_4 *(top-right) and Aluminum (rest of graphs) for different thicknesses using a model considering only bulk losses.*

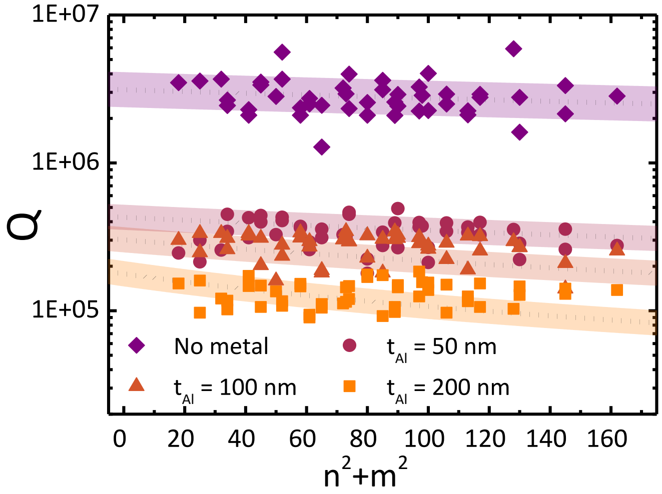

Figure 4: Q factors (scattered data) for 1mm long membranes with $t_{Si_3N_4}=50\ nm$ *and different metal thicknesses. Dotted black lines show the theoretical prediction using a model that accounts for surface losses. Shaded regions correspond to the (~ 75%) confidence intervals of the fit.*

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