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Section 11. Mechanical properties

Micromechanical properties of amorphous, nanocrystalline and transition phase hot-wire thin-silicon MEMS

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Abstract

Thin film silicon MEMS-based electrostatic bilayer microresonators are fabricated on glass substrates by hot-wire chemical vapor deposition with the silicon structural layer spanning the amorphous to nanocrystalline transition. Five sets of bridge and cantilever microresonators are fabricated with hydrogen dilutions of 0%, 60%, 85%, 90% and 95%. The silicon structural layers for 0% and 60% dilution are amorphous, for 90% and 95%, nanocrystalline, and for 85% dilution, an intermediate structure. All processing steps were carried out at temperatures $\leqslant 110$ °C. Microresonators are electrostatically actuated and the resulting deflection is optically monitored. The crystallinity of the structural layer does not have an observable effect in the rigidity of the resonators. The quality factor shows a maximum at 85% H_2 dilution, corresponding to a material with a structure intermediate between amorphous and nanocrystalline. A sharp decrease in quality factors is observed for higher dilutions.

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1. Introduction

Microelectromechanical systems (MEMS) technology use planar microelectronics fabrication techniques to produce three-dimensional structures, typically based on crystalline silicon, c-Si, or poly-Si [1]. Since the processing temperature for poly-Si is in the range ~500–900 °C [1], MEMS has typically been fabricated on c-Si substrates. Recently, MEMS based on thin film silicon technology fabricated at relatively low temperatures $\leqslant 300$ °C have been demonstrated [2]. Thin film technology offers several advantages for MEMS devices such as lower intrinsic stress, the possibility to use a wide range of substrates such as glass or plastics, and compatibility with CMOS backend processing [3,4].

For many sensor applications of microresonators, higher values of resonance frequency (f_{res}) and quality factor (Q) are desired. High values of f_{res} can be achieved by scaling down resonators dimensions, by using materials with high Young's modulus (E), by exciting higher level harmonics, or by designing a resonator that has high f_{res} vibration modes. High Q's are accomplished by minimizing the energy dissipation during resonator vibration ($1/Q \propto$ energy dissipation). The main dissipation mechanisms in micromechanical resonators are squeezed film air damping, thermoelastic dissipation, clamping and surface losses [5]. In this work, the dissipation due to squeezed film air damping is neglected since all measurements are performed in vacuum (at 10^{-6} Torr). Losses due to clamping depend on the design of the structure. Other mechanisms like thermoelastic dissipation and surface losses are related to material properties. In this paper, the effects of changing the structural property of the silicon thin film on the resultant microresonator performance are studied.

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2. Experimental

Bilayer (Al + thin film Si) microbridges with an underlying Al gate electrode are fabricated at temperatures $\leqslant 110$ °C on glass substrate using surface micromachining. To fabricate the device, a 0.15 μm-thick Al gate electrode is deposited by DC magnetron sputtering and patterned by wet etching. A 1 μm-thick sacrificial photoresist (PR) layer is then patterned by photolithography and hard-baked at 110 °C for one hour in nitrogen (N_2) atmosphere. The next step consists of the deposition of the structural thin film silicon layer at 100 °C. Five different H_2 dilutions 0%, 60%, 85%, 90% and 95% were used during deposition of silicon thin film for five process runs. The silicon structural layer is deposited by hot wire chemical vapor deposition (HWCVD) using a combination of SiH_4 and H_2. A thin layer of Al (0.15 μm) is deposited on top of the silicon film. This top Al layer functions as an electrical contact to ensure fast charging and discharging of the capacitor formed between the mechanical beam and the gate, satisfying the condition, $RC < 1/f_{\mathrm{res}}$, allowing the resonator to respond to applied signals at high frequencies. The Al on top is patterned by wet etching followed by patterning of the silicon thin film by reactive ion etching (RIE) to define the structural layer. In the final step the sacrificial PR is selectively removed using a commercial PR stripping solution, leaving an air-gap ~1 μm between the gate and the bridge [6].

The width, w, of the microbridges is 10 μm and the length, L, varies from 10 to 70 μm. The expected thickness of the silicon thin film structural layer was 0.4 μm but it ranges from 0.33 μm to 0.69 μm in extreme cases. For cantilevers, width, w and thickness are same as in bridges but their length, L, is exactly half of the bridges and varies from 5 to 35 μm.

The microresonator structures are electrostatically actuated by applying a voltage, V_G, between the gate electrode and the bridge or cantilever. Gate voltage, V_G, has DC and AC components, and can be described as, $V_G = V_{DC} + V_{AC}\sin(2\pi ft)$, where $V_{DC} \gg V_{AC}$, and f is the excitation frequency. The resulting deflection is monitored in vacuum at a pressure of $\sim 10^{-6}$ Torr by means of optical setup, described elsewhere [6].

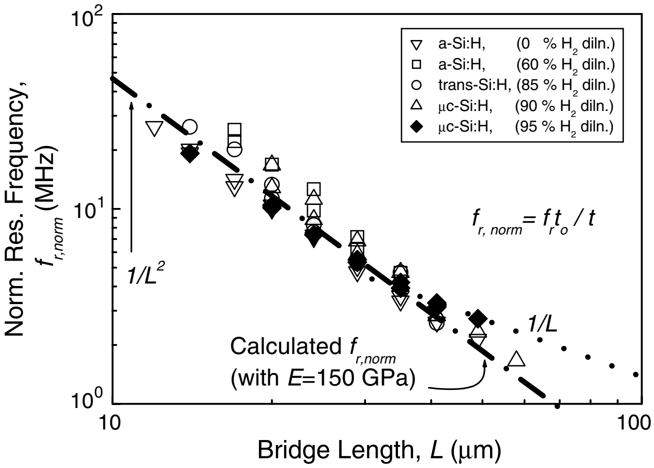

Fig. 1. Normalized resonance frequencies (fundamental) ($f_{\mathrm{r,norm}}$), of bridges with structural layer deposited at different dilutions (0–95%) by HWCVD as a function of L. The dash-dotted line represents the calculated values of $f_{\mathrm{r,norm}}$ for bridges with same lengths with clamped–clamped condition. The dotted line shows a $1/L$ dependence.

3. Results and discussion

Fig. 1 shows normalized resonance frequencies ($f_{\mathrm{r,norm}}$) for bridges with length (L) varying from 10 to 70 μm and structural layer deposited at different H_2 dilutions. $f_{\mathrm{r,norm}}$ is derived from the resonance frequency (f_{r}) of the bridge as, $f_{\mathrm{r,norm}} = f_{\mathrm{r}}(t_{\mathrm{o}}/t)$. Here, t_{o} is the average structural layer thickness of five different dies, each from samples deposited at different H_2 dilutions with the same location on the substrate and t is the thickness on the particular die where the microstructure under consideration is located. Resonance frequencies are higher for the shorter structures and they follow a $1/L^2$ dependence. f_{r} of the fundamental flexural vibration mode for bilayer bridges (Al + silicon thin film) is given approximately by [7]

$$f_{\mathrm{r}} = \frac{1}{2\pi}\sqrt{\pi^4\left(a_{\mathrm{n}}+\frac{1}{2}\right)^4\frac{(EI)_{\mathrm{eff}}}{\mu_{\mathrm{eff}}L^4}+\pi^2\left(a_{\mathrm{n}}+\frac{1}{2}\right)^2\sigma_0\frac{wt_{\mathrm{eff}}}{\mu_{\mathrm{eff}}L^2}}, \quad (1)$$

where $a_{\mathrm{n}} = a_1 = 1.00562$ for the first flexural mode for clamped–clamped bridge [8], $(EI)_{\mathrm{eff}}$ is effective rigidity of bilayer structure, μ_{eff} is mass per unit length of bilayer suspended structure, and L is length of the structure. The first term in Eq. (1) represents the contribution from the rigidity of the structure and the second term, from its residual axial stress. Values of $(EI)_{\mathrm{eff}}$ and μ_{eff} can be calculated by [9],

$$(EI)_{\mathrm{eff}} = \left(\frac{wt_{\mathrm{b}}^3}{12}\right)\left(\frac{t_{\mathrm{t}}E_{\mathrm{b}}E_{\mathrm{t}}}{t_{\mathrm{t}}E_{\mathrm{t}}+t_{\mathrm{b}}E_{\mathrm{b}}}\right)\left[4+6\left(\frac{t_{\mathrm{t}}}{t_{\mathrm{b}}}\right)+\left(\frac{E_{\mathrm{b}}}{E_{\mathrm{t}}}\right)\left(\frac{t_{\mathrm{b}}}{t_{\mathrm{t}}}\right)\right.$$
$$\left.+4\left(\frac{t_{\mathrm{t}}}{t_{\mathrm{b}}}\right)^2+\left(\frac{E_{\mathrm{t}}}{E_{\mathrm{b}}}\right)\left(\frac{t_{\mathrm{t}}}{t_{\mathrm{b}}}\right)^3\right], \quad (2)$$

and

$$\mu_{\mathrm{eff}} = (t_{\mathrm{t}}\rho_{\mathrm{t}} + t_{\mathrm{b}}\rho_{\mathrm{b}})w, \quad (3)$$

where w is width of the bridge, t_{t} is thickness of the top layer (Al) of the bridge, t_{b} is thickness of the bottom layer (thin film silicon) of the bridge, E_{t} is Young's modulus of the top Al layer (70 GPa), E_{b} is Young's modulus of the bottom Si layer (150 GPa), ρ_{t} is density of the top layer (2700 kg/m^3) and ρ_{b} is density of the bottom layer (2330 kg/m^3). The dashed-dotted line in Fig. 1 shows the calculated values of $f_{\mathrm{r,norm}}$ for a a-Si:H/Al bilayer bridge when the stress in the structure, σ_0 is zero. Within the variation introduced by the fabrication process, the values of the measured $f_{\mathrm{r,norm}}$ for all bridges fall around the dashed-dotted line which represents the calculated or expected values of resonance frequencies using a Young's modulus of 150 GPa for the silicon layer, independently