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Driving and Sensing M/NEMS Flexural Vibration Using Dielectric Transduction †

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Abstract: We show that nanometer-scale dielectric thin films can act as efficient electromechanical transducers to simultaneously drive and sense the vibration of the first flexural mode of micro/nano-cantilevers. Here, 16 µm-long, 5 µm-wide and 350 nm-thick cantilevers are actuated by a 15 nm-thick silicon nitride layer, and electrically detected by charge measurement at megahertz frequencies. The displacement was also checked by optical interferometry, and the electromechanical transduction efficiency is extracted and compared to an analytical modelling.

Keywords: MEMS; high-K; dielectric actuation; charge detection

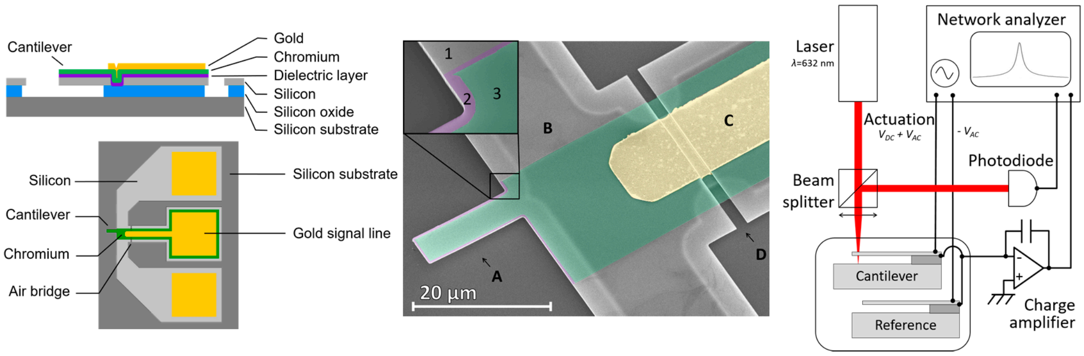
1. Introduction

NEMS devices offer great opportunities for applications in metrology and fundamental science, particularly when used as resonators [1]. However as the size is reduced, devices face the challenge of the efficiency of the electromechanical transduction. Capacitive and piezoelectric principles are commonly used in MEMS devices for both actuation and detection. At nanometer scale, issues are met. For example, piezoelectric actuation is dramatically impacted when the layer thickness is reduced under 100 nm, leading to a decrease in efficiency by orders of magnitude compared to the one expected from the bulk piezoelectric properties [2]. Besides, capacitive transduction strongly depends on the airgap width and a trade-off has to be made between efficiency and risk of failure due to stiction resulting from narrow air gaps. Conversely, high-K materials made for example by Atomic Layer Deposition (ALD) techniques are available in very thin films (<10 nm) and with a high quality. Such materials are compatible with silicon microtechnologies fabrication processes and make dielectric transduction a promising alternative for sensing and driving displacements at nanoscale. Actuation and detection have first been reported separately on cantilevers at a millimeter scale [3]. Recently, actuation has also been observed for micrometer scale devices [4]. Here, we report the simultaneous actuation and detection of MEMS/NEMS cantilever devices using high-K thin films as the electromechanical transducer.

2. Materials and Methods

In the present study, we used a 15 nm-thick low-stress silicon nitride film as the dielectric active layer. Its dielectric constant ε_d is about 8 and its Poisson's ratio ν_d is 0.23. It was deposited using low-pressure chemical vapor deposition (LPCVD) on a doped silicon-on-insulator wafer etched beforehand to create air bridges along the signal paths to reduce extra parasitic capacitances to ground. A 20 nm-thick chromium layer was used as a top electrode. The 5 µm-wide and 16 µm-long cantilevers were patterned from this stack using chemical and reactive ion etchings and released by chemical etching of the buried oxide.

We perform actuation of the device using a bias voltage V_{DC} added to an alternative signal V_{AC} applied to the chromium electrode, across the dielectric thin film. Frequency of the alternative signal varies close to the fundamental mode resonance frequency. Simultaneously, we use differential excitation ($-V_{AC}$) of a reference cantilever to subtract from the signal the parasitic coupling due to the cantilever static capacitance. Resulting motional charges are then detected and amplified with a 10 V/pC gain and the resulting signal is processed using a network analyzer. To validate the charge detection, we also measure the resonance frequency by Fabry-Perot interferometry: a laser beam is reflected both by the vibrating resonator and the substrate. The resulting interferometry signal is modulated by the vibration, and detected by a photodiode for frequency response analysis. All the measurements are made at room temperature and under vacuum (P = 2.10^{-1} mBar). Schematic cross-section, example of a fabricated device and measurement set-up are shown in Figure 1.

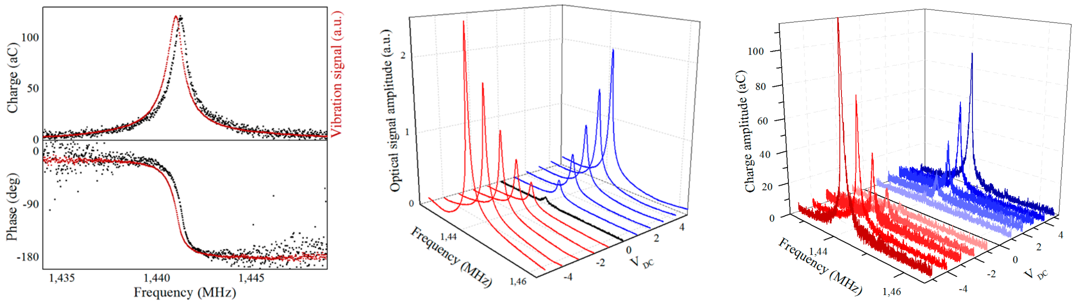


(**a**) (**b**) (**c**)

Figure 1. (**a**) Schematic cross-section (top) and top view (bottom) of a micro-cantilever; (**b**) Scanning electron microscope image of a fabricated device. A denotes the cantilever, B its anchor area connected to the charge amplifier, C the gold signal line, D the air bridge. Inset: close view of the junction of the cantilever with its anchor where 1 indicates the silicon structural layer, 2 the silicon nitride layer and 3 the chromium layer; (**c**) Optical and electrical measurement set-up of the device resonance frequency response.

3. Results

The 5 µm × 16 µm device is tested applying a 600 mV V_{AC} signal and a V_{DC} bias ranging from −5 to 5 V. Optical and capacitive measurements have similar features: a 1.441 MHz resonance frequency, and a quality factor Q of 2200. Figure 2 shows an example of capacitive and optical amplitude and phase measurements for V_{DC} = −5 V (a), and optical (b) and capacitive (c) amplitude frequency responses in magnitude versus V_{DC}.

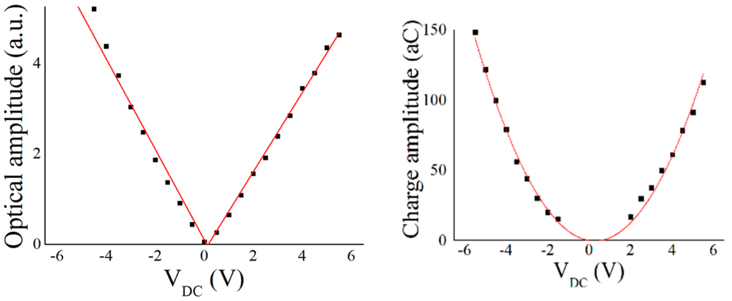


(**a**) (**b**) (**c**)

Figure 2. (**a**) Charge (black dots) and optical (red dots) measurements of the cantilever device resonance versus frequency when driven by V_{DC} = −5 V and V_{AC} = 600 mV applied to the chromium top electrode; (**b**) Measurement by optical interferometry of the magnitude signal close to resonance for V_{DC} values ranging from −5 to +5 V; (**c**) Charge magnitude measurement close to resonance for V_{DC} values ranging from −5 to +5 V. The charge curves were obtained by averaging 6 measurements.

4. Discussion

The dielectric actuation exploits electrostatic pressure on the dielectric film, which depends on the square of the voltage applied across the film. As we use a superposition of V_{DC} and V_{AC}, we expect the vibration amplitude at resonance frequency to be linear with V_{DC}. Similarly, as the electrical detection principle is based on the variation of charges in the capacitor formed by the device, the detected charge is proportional to the V_{DC} bias. Consequently, during simultaneous actuation and detection, the measured charge variation has a parabolic dependence versus the bias. The Figure 3 shows the optical and charge measurements fitted with linear and parabolic functions respectively.



(**a**) (**b**)

Figure 3. Fitted measurements of the vibration signals at resonance versus V_{DC}. Optical measurements (**a**) were made for V_{AC} = 140 mV and capacitive measurements (**b**) for V_{AC} = 600 mV.

For V_{DC} = −5 V and V_{AC} = 600 mV, and taking into account the oxide over etching, the expected variation of charge is 195 aCI as calculated by an analytical approach inspired from Reference [5]:

$$Q_m(f_{res}) = \frac{Q}{K_{eff}}\left[0.68\frac{ew}{t}\frac{\nu_d}{1-\nu_d}\epsilon_0\epsilon_d V_{DC}\right]^2 V_{AC} \tag{1}$$

where the thickness and width of the cantilever are respectively e = 320 nm and w = 5 µm, and the thickness, Poisson ratio, and dielectric coefficient of the silicon nitride layer are t = 15 nm, υ_d = 0.23, and $\varepsilon_d \approx 8$ respectively.

The measured charge for these driving conditions is 125 ± 25 aC, which is slightly lower than the theoretical value. From this measurement, and using a calibration of the optical set-up based on the thermomechanical noise method, we can calculate the transduction efficiency of the device, defined as the ratio between the beam displacement and its charge: η = 361 ± 70 pN/V. Again, the result is comparable to the theoretical value, 452 pN/V, obtained using the Reference [5] approach:

$$\eta = 0.68\frac{ew}{Lt}\frac{\nu_d}{1-\nu_d}\epsilon_0\epsilon_d V_{DC}. \tag{2}$$

The 20% difference between the two values can be explained by measurements uncertainties and by the fact that the chromium electrode does not cover exactly the whole cantilever surface.

Table 1 summarizes the results and the main parameters of the cantilever device and its dielectric transducer.

5. Conclusions

To conclude, simultaneous dielectric actuation and detection were successfully demonstrated for flexural devices with a nanometer scale active layer thickness. Results are in a good agreement with theoretical calculations, including the transduction efficiency. Using high-K thin-film materials with higher dielectric constants such as Al_2O_3 (ε_d = 9) and HfO_2 (ε_d = 20) would be a promising way to achieve efficient actuation and detection with even greater efficiencies. Such devices are currently under fabrication and will be presented in a later study.

Table 1. Summary of the device and dielectric transducer parameters.

Cantilever Parameters		**Transducer Parameters**	
Length	16 µm	Material	Si nitride
Width	5 µm	Thickness	15 nm
Si thickness	320 nm	Permittivity	$\varepsilon_d \approx 8$
Eff. stiffness	1.38 N/m	Transducer efficiency theoret.	452 pN/V at $V_{DC} = -5$ V
f_{res} analytic.	1.45 MHz	Transducer efficiency exp.	361 pN/V at $V_{DC} = -5$ V
f_{res} experim.	1.441 MHz		
Q factor	2200		
Q_m theror. Charge at $V_{DC} = -5$ V, $V_{AC} = 600$ mV	195 aC		
Q_m exp.charge at $V_{DC} =-5$ V, $V_{AC} = 600$ mV	125 aC		

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Conflicts of Interest: The authors declare no conflict of interest.

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