Coupling Resonant Carbon Nanotube and Microcantilever to Improve Mass Responsivity by Detectability Product

F. Torres, G. Abadal, J. Teva, A. Uranga, J.Ll. López and N. Barniol
Dep. Enginyeria Electrònica, Universitat Autònoma de Barcelona (UAB), 08193 Bellaterra, SPAIN
Francesc.Torres@uab.cat

Nanoelectromechanical systems based on resonant beams have been used in fundamental magnitude sensing applications as mass transducers with zg resolution [1]. Mass resolution, δm (i.e. minimum mass detectable) depends on mass responsivity of the beam, $\Re$, and the minimum detectable change on resonance frequency, δf, by $\delta m=\Re^{-1}\cdot\delta f$. Here, $\Re=df_{res}/dM_{eff}$, relates changes produced on the resonance frequency of a certain vibration mode and its corresponding effective mass, by the mass to be measured, and can be approximated by $\Re\approx -f_{res}/2\cdot M_{eff}$; δf will strongly depends on the quality factor, Q, of the resonance mode. So, it clearly follows that in order to reduce δm, $\Re$ has to be maximized by reducing the effective mass and increasing the resonance frequency, which can be simultaneously accomplished by scaling down the beam dimensions. However, a reduction of transducer dimensions implies a decrease of detectability. This magnitude can be quantified in the capacitive transduction case by the motional resistance $R_m=(2\cdot\pi\cdot f_{res}\cdot M_{eff}\cdot s^2)/(Q\cdot C^2\cdot V^2)$, which will strongly depends on the transducing capacitance, C, the transducing gap, s, and the applied voltage V. As an example, nanocantilever beams with capacitive readout show responsivities in the range of Hz/ag but have to be monolithically integrated with an amplifier in order to be detectable [2]. On the other hand, the resonance of microcantilever beams can be detected without any on-chip amplification but have responsivities in the range of Hz/fg [3].

This work reports on how the hybrid system that results from the combination of a microcantilever mechanically coupled to a carbon nanotube (CNT) takes advantage of the responsivity of the smaller component (CNT) and of the detectability of the larger one (microcantilever), giving rise to an improvement of the figure of merit responsivity by detectability product. As a proof of concept device, we have fabricated and tested an on-plane vibrating double cantilever (figure 1). The large cantilever is clamped to an anchor and capacitively coupled to an excitation electrode placed parallel 700nm apart. In order to characterize the first lateral resonance mode, modal analysis using finite element method (FEM) software (Coventor [4]) and measurements of the transmission frequency response have been performed. Transmission curves have been obtained by applying an AC+DC voltage to the driver electrode and detecting the capacitive induced current with a network analyzer connected to the double cantilever. A responsivity calibration experiment has been performed by placing spheres of γ-Fe_2O_3, 15.4 pg in mass by means of an AFM tip (see figure 1). As a result of the sphere deposition, transmission peaks have shifted to lower frequencies as it is shown in figure 2.

It is possible to improve the mass responsivity by the substitution of the silicon based small cantilever by a carbon nanotube. This system has a very little M_{eff} that improves both the motional resistance of the whole system (decreasing it) and the mass responsivity. Our purpose is to use the large cantilever as a detectable part of the device and the CNT as a mass sensing part of the device. We have performed FEM simulations of the combined device to confirm the mass responsivity improvement, through the figure of merit $\Re\cdot R_m^{-1}$, that is summarized in table I. The CNT was 50 nm wide and 20 um long. The FEM simulations show a significant decrease of the amplitude of vibration of the large cantilever with CNT respect to the same system without CNT. This amplitude reduction, that reduces the detectability of the system, can be partially compensated by increasing the V_{dc} applied to the system (see R_m).

References:

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[3] J. Teva, G. Abadal, F. Torres, J. Verd, F. Pérez-Murano, N. Barniol, Ultramicroscopy, **106** (2006) 808-814.
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Figures:

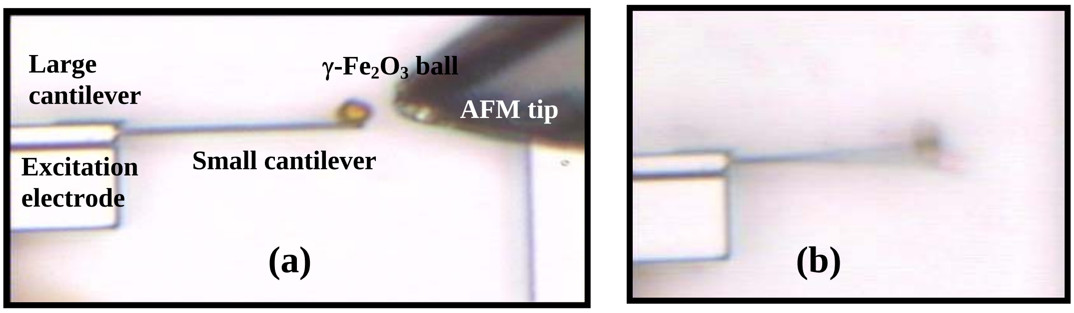

Figure 1: (a) Optical image showing a detail of the larger cantilever connecting to smaller one plus γ-Fe_2O_3 ball. (b) Optical image of the cantilever and the added ball resonating at the first resonant mode.

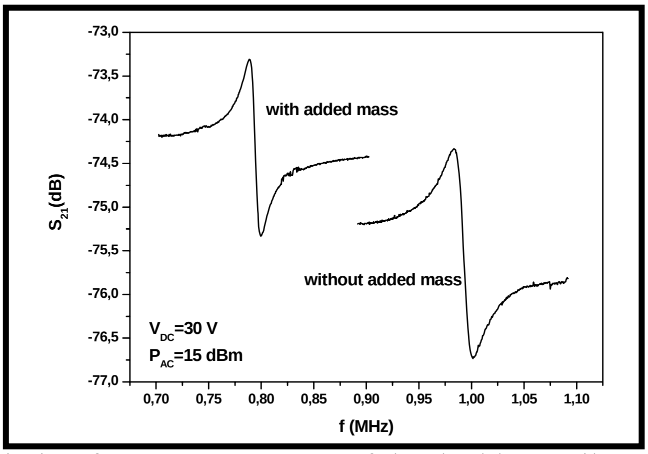

Figure 2: Transmission frequency response of the double cantilever corresponding to the first lateral mode with and without the added ball.

	f_{res} (MHz)*	$\Re$ (Hz/ag)	R_m (MΩ)	$\Re \cdot R_m^{-1}$ (Hz/ag·MΩ)
Large cantilever	1.667	0.003	2.3	$1.4 \cdot 10^{-3}$
Small cantilever* **	1.16	0.025	5.0	$5.07 \cdot 10^{-3}$
Coupled system (Silicon based)**	0.995	0.013	2.3	$5.6 \cdot 10^{-3}$
Coupled system (Large cantilever + CNT)**	**0.33**	**5.6**	**2.3**	**2.43**

Table I: Comparison between different systems that reflects the differences as a mass sensor between the proposed systems.