Novel paradigms for biological sensing based on nanomechanical systems: from microcantilevers to nanowires

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The development of ultrasensitive protein spectrometers and ultrasensitive biological sensors will speed up the identification of disease biomarkers and their rapid detection [1,2]. Nanomechanical resonators have emerged as promising candidates for ultrasensitive mass sensors [3,4]. The continuous advancements in top-down micro- and nanofabrication techniques has made possible increasingly smaller nanomechanical resonators with detection limits in the subattogram range. Moreover, resonant nanowires and nanotubes fabricated by bottom-up methods can weigh masses below a zeptogram ($1.66\ 10^{-21}$ g). However, the implementation of these devices is hindered by several obstacles such as the need of operation in high vacuum, low specificity and low reproducibility and still little understanding of the effect of biomolecular adsorption on the mechanical properties of nanoresonators.

In this talk, I will present our recent developments oriented to apply nanomechanical systems for biological detection. In particular, I will present two novel paradigms for sensing that opens the door to develop ultrasensitive biological sensors. The first approach that is no longer depending on the extreme miniaturization of the devices is the use of coupled nanomechanical resonators fabricated by standard silicon technology [5,6] (Fig. 1). When the resonators are identical, the vibration of the eigenmodes is delocalized over the array. In a similar way to the Anderson's localization, the addition of the mass on one of the resonators leads to the spatial localization of the eigenmodes. Since vibration localization is insensitive to uniform adsorption, coupled nanomechanical resonators allows decoupling of unspecific and specific molecular adsorption in differentially sensitized resonators.

The second approach uses resonant nanowires/nanotubes and it is based on the fact that if a molecule alights on a perfectly axisymmetric resonant nanobeam, the frequency degeneration of the stochastic two-dimensional orbits is abruptly broken, and the vibration can be described as the superposition of two orthogonal vibrations with different frequency. The measurement of the frequency degeneration breakage enables the determination of the adsorbate's mass and stiffness, and the azimuthal direction from which the adsorbate arrives [7]. We experimentally demonstrate such sensing paradigm with resonant silicon nanowires, which serves to add kPa resolution in Young's modulus determination to their currently established zeptogram mass sensitivity. The proposed method provides a unique asset for ultrasensitive mass and stiffness spectrometry of biomolecules by using nanowire-like resonant structures.

References

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Figures

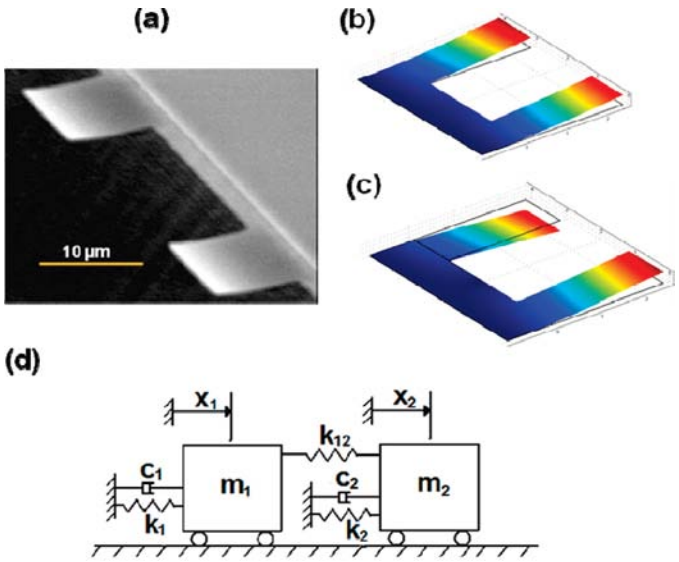

Figure 1. *(a) Scanning electron micrograph of a system of coupled cantilevers. The cantilevers were fabricated in low stress silicon nitride. The length, width, and thickness of the cantilevers were 25, 10, and 0.1 µm, respectively. The gap between the cantilevers is 20 µm. The structural coupling between the cantilevers arises from the overhang connecting the cantilevers at the base, which is about 8 µm long. (b) Symmetric and (c) antisymmetric mode of vibration of this coupled array. (c) A lumped parameter model for this coupled array.*

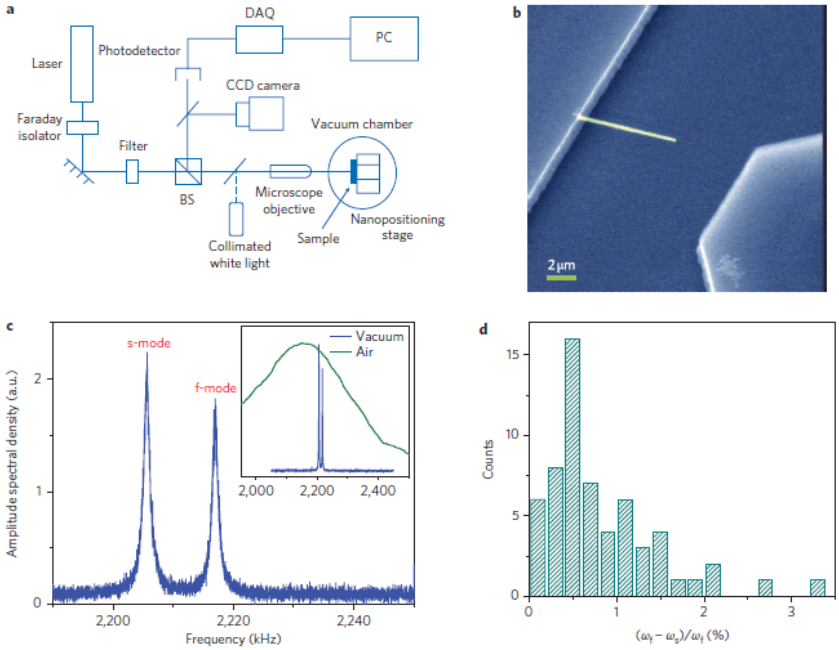

Figure 2*. Thermal displacement fluctuations of silicon nanowires. a, Schematic of the optical interferometer used to detect the out-of-plane nanowire vibrations. The nanowire sample was placed in a vacuum chamber at approximately 1× 10^{-6} torr and room temperature. The spot size was 0.7 µm and the incident power 0.5 mW. Picometre-scale modulation of the height of the nanowire above the substrate results in a measurable intensity modulation due to the interference between the light reflected from the nanowires and from the substrate.b, Scanning electron micrograph (SEM) of a typical nanowire used in this work. Nanowires anchored normal to the trench wall were selected, with lengths and diameters of 5–10 mm and 100–300 nm, respectively. c, A fast Fourier transform of the signal from the photodetector is dominated by the displacement thermal fluctuation of the nanowires. Only a single resonant peak can be seen in air (green line in inset), but two resonant peaks can be clearly seen in vacuum (blue lines). Depending on the nanowire dimensions, the resonance frequencies range from 2 to 6 MHz. s-mode and f-mode refers to the spliting of the resonance frequency into slower and faster vibration modes vibrating at orthogonal directions. d, Histogram of the relative frequency separation between the two close resonance peaks observed in vacuum.*