hARNESS: Advanced NanoElectromechanical SystemS

Resonant nano-electro-mechanical systems (NEMS) have been showing outstanding performance as mass, force, charge and magnetic sensors. However, their predicted ultimate limits of detection are far from being achieved. One of the goals of the project was to study and analyze the different sources of dissipation and frequency instability that determine the final performance of NEMS devices. This has been hampering the commercial applications of NEMS, since they have not been living up to expectations. The second main goal was to convey specificity to NEMS-based gas sensors. Indeed, specificity is one of the main issues when discussing the analysis of complex gas mixtures, and the idea was to convey specificity to optimized NEMS devices in order to generate a product improving the State of the Art by several orders of magnitude. Finally, the third goal of the project was to broaden current fields of applications, in particular to use NEMS resonator to study stiffness of biologically relevant materials, rather than mass. The idea was to tackle these three goals by using piezoelectric (PZE) transduction due to its high linearity and non-dissipative nature. Three work packages were planned, one covering each one of the objectives mentioned above.

Work Package 1

The original idea was to fabricate ultra-thin piezoelectric layers that could be used as the fundamental part of the nanomechanical devices that would be used for the study of the frequency noise-source. Even though these ultra-thin layers could be fabricated almost from the beginning, their stability and insulating properties were a challenge at first. During our quest to obtain these thin layers, we unveiled an interesting fact. It is already known the fact that using AlN as a seed layer is beneficial for the overall piezoelectric behavior of the layer. We also have proof that this effect is independent of the seed layer thickness, even though the thicker the seed layer the better its crystallinity.

In collaboration with other institutions (in particular Caltech, CEA-LETI, and IISc) we have also been able to proof, after careful experimental work, that there is indeed a new type of noise that affects directly devices' resonance frequency and that it cannot be accounted for using the typical/known noise sources. This work shows the importance of studying frequency stability and the origins of frequency noise.

Finally, in collaboration with DTU and Uni Melbourne, we showed experimentally that laser power strongly affects cantilever resonance frequencies, and has a very strong dependence on the position of the laser within the cantilever.

Work Package 2

Within this Work Package, we first tackled the fabrication of micro-columns for gas chromatography. We did fabricate two generations of micro-columns. An example of some of the fabricated micro-columns can be seen in Figure 1. Even though it is true that micro-columns have existed for quite some time we brought a couple of additions to the state of the art, in particular we implemented SU-8 nozzles in the output of the columns to make it easier for a subsequent connection.

In parallel, we developed two separate fabrication process flows for graphene electromechanical resonators. The best results were offered by the transfer on already-patterned holes. As can be seen in attached Figure 1, we were able to obtain rather large yield of monolayer graphene membranes for radii below 5 microns, and we could fabricate resonators with radii of up to 200 microns in diameter. This provides ultra-high aspect ratios, of up to 600000:1, maximizing responsivity for some parameters. Unfortunately, we have not been able to successfully integrate the sensors with the microcolumns.

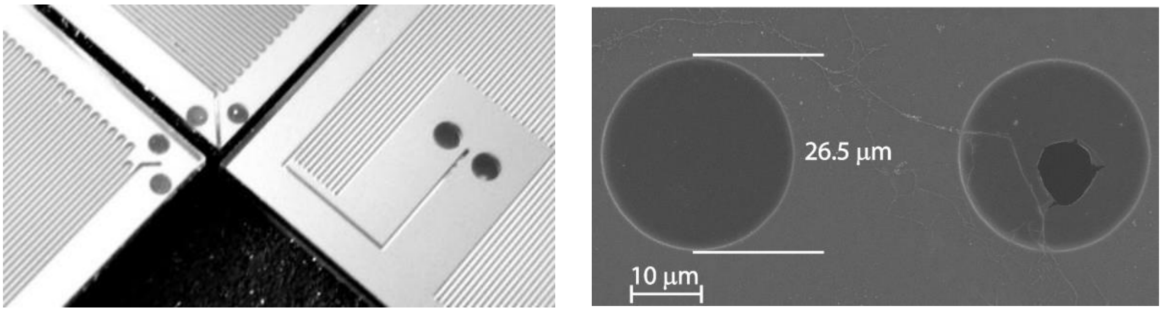

Figure 1 | (Left) Optical microscope image of three examples of gas microcolumns after successful fabrication. (Right) Scanning Electron Microscope (SEM) image of a 26.5 µm diameter graphene monolayer membrane. The largest size achieved is 200 microns in diameter, with a yield close to 20%. This means an overall aspect ratio of 600000:1.

Work Package 3

This Work Package has focused on the fabrication of suspended microchannel resonators (SMRs). These are devices that are hollow inside and that can conduct liquid internally, thus making it possible to do measurements with liquid but without increasing the dissipation. The fabrication is complete with piezoelectric material on top of the microchannels in order to attain integrated electrical transduction of the motion. An example of fabricated device can be seen in Figure 2.

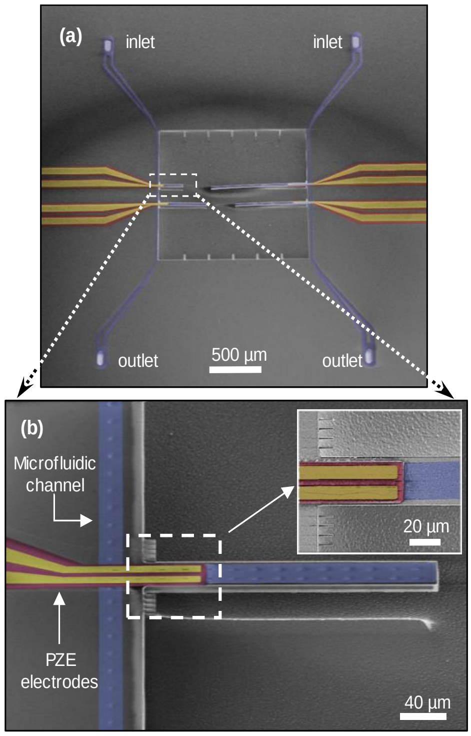

Figure 2 | Fabricated SMRs with integrated PZE transduction. (a) SEM image of two SMR arrays (top view). The path of the embedded microfluidic channel goes from inlet to outlet (purple color online). (b) Zoom-in on a 250 µm-long SMR.

In order to bring liquid samples into the SMRs, we developed a world-to-chip microfluidic interface enabling operation of the devices in vacuum at the same time that we could send liquid into the channels. We added some bypass channels in the connector to greatly facilitate the exchange of fluids between experiments: it allows for a reduction of the volume of liquid to be pushed through the SMRs a factor of 20x. According to the latest experiments, the vacuum level in the connector chamber was assessed to be 0.1 mbar. During experiments, the temperature chip is maintained stable with a thermoelectric temperature controller, implemented with a peltier module and a thermistor. The fluid delivery is achieved by a syringe pump.

Several experiments have been run on the fabricated devices, we have passed water, isopropanol, glycerol, ethanol, saline solutions, etc. Finally we have also studied the effect of bacteria population when passing through the channels. We believe these systems might be very interesting for a number of bio-related applications, like for example cell or bacteria studies, hydrogels monitoring, fast and reliable blood analysis, etc.

This project has been carried out by Prof. L.G. Villanueva's Group at EPFL. Contact: http://nems.epfl.ch