NEMO
Nanowire Electro-Mechanical-Optical systems

The NEMO (Nanowire Electro-Mechanical-Optical systems) project aims at unifying the optomechanical and electromechanical platforms using one-dimensional structures.

Optomechanics, the control of mechanical vibrations using radiation pressure in the visible/near-infrared spectral range, has recently flourished as one of the preferred platforms to investigate quantum mechanical effects. Among its advantages, the use of high-purity laser sources and the long decoherence time of photons are notewhorty.

Electromechanical devices can be coupled to LC circuits resonating in the microwave range, realizing easy on-chip integration through electrical contacts. Superconducting qubits can then enter the game and be directly coupled to the vibrational state of the mechanical object.

While electromechanics represents an ideal candidate as the ultimate quantum computing platform, the thermal decoherence of superconductive qubits represents a strong limitation to be overcome to realize a fully quantum technology. The realization of electro-opto-mechanical systems can be the solution to this long-standing issue. By coupling microwave circuits and optical cavities to the same mechanical resonator, processes such as frequency conversion, or the realization of new kind of devices can be envisaged. In particular, one-dimensional semiconductor wires offer a wide versatility in terms of electrical/optical/mechanical properties that can be accessed and controlled, adding or improving functionalities of the nanomechanical device.

The electrical properties of the system can be modulated via the mechanics considering that the nanowire moves in a gradient gating field. Alternatively, the same effect is classically obtained by considering a still wire subjected to strong asymmetric and modulating fields. As a starting point, we tested the electrical properties of III-V, bottom-up nanowires, when subjected to strong asymmetric field or fast oscillating fields. In the first case, we considered InP-InAs quantum-dots with unbalanced gates to achieve spin transitions in Coulomb blockade regime [1]. The strong nonlinearity associated with the single electron flow is a desirable feature for mechanical actuated nanowire device. In the second case, we investigated rectification in InAs-InSb heterostructured nanowires coupled to far field antennas [2]. Here, THz radiation is shined on the device and coupled to the Gate and Source electrodes. The fast THz modulation is easily followed by the nanowire thanks to its small capacitance; by modulating the gate, we can access and control the electron flow in the transistor channel: this is the analogue of the optomechanical transistor proposed in the project.

Despite their amazing electrical properties, of which we showed a few examples, integrating bottom-up nanowires in photonic structures is a difficult technological challenge which it still not solved. Top-down semiconductor nanowires, on the other hand, can be processed together with the rest of the photonic device and are, therefore, naturally integrated in the system. To this end, we developed a process to couple Si3N4 nanowires to LC superconducting circuits.

As a preliminary step, we investigated the electromechanical coupling in a Si optomechanical photonic crystal. The ability to process metals and achieve narrow electrode gaps while maintaining a pristine silicon surface (and thus high optical quality factors) have been addressed, fabricating devices with < 30 nm gaps and strong optical and electrical coupling constants [3]. It is important to note that the motion of semiconductor materials is rarely used for electromechanics, whereas metallic moving parts are routinely considered. Our final goal requires that the semiconductor motion modulates both the optical and electrical parts, making the realization and testing of this kind of device a crucial step for the final goal.

The electromechanical coupling suffers from high stray capacitance and exponentially grows with the reduction of the electrode gap size. To efficiently couple the nanowires, we have realized superconducting circuits on top of silicon nitride membranes, using metallic air bridges to reduce the total wire length. This made the stray capacitance as low as 2 fF, with more than one order of magnitude enhancement with respect to standard meander circuits on Si3N4/Si material. By the use of strain engineering, we developed techniques to control the gap size, reaching lengths as low as 25 nm. All these advances produced electromechanical nanowire devices with remarkable properties, where electromechanical lasing, strong coupling, almost-ground-state cooling and efficient wavelength conversion have been observed for a low frequency flexural mechanical mode (4 MHz) [4].

Using top-down nanowires it is possible to place a second, optical nanowire in such a way that the mechanics is capacitively coupled to the LC circuit on one side and to an optical cavity on the other. The realization of such device would be an even stronger demonstrator of electro-opto-mechanical coupling than the optomechanical transistor suggested in the NEMO project. Having demonstrated all the building blocks of the system (optomechanics and electromechanics separately), the outgoing institution is still working, in collaboration with the fellow, to join the two systems together to reach NEMO final goal.

Once realized, the real striking feature would be to operate the hybrid device in the quantum state, where single electronic, photonic and phononic excitations can be probed and controlled. A stringent requirement for this regime is to reach the ground state of the mechanical motion. In the ultra-cold dilution refrigerator temperature, a few hundreds of MHz mechanical mode would be naturally in the ground state, with no necessity for active sideband cooling. To prepare for this goal, we used the scalability properties of the semiconductor phononic crystal to design and realize electromechanical nanowire devices coupled with high-frequency breathing modes.

The simulated mode at 450 MHz would have a 0.1 phonon population at 10 mK, although the low number of intracavity photon due to the strong cavity filtering effect would prevent sensible optomechanical effects, being the latter linear in the photon number. To this end, we devised a new injection scheme, based on super-modes in coupled LC cavities. Adding as an external knob the possibility of DC tune the single cavity frequency, this device could overcome the main limitations of classical electromechanical systems (low frequency and mechanical Q) and insert new functionalities for superconducting resonators, like in-situ tunable filtering.

We believe that these results will represent a milestone towards the future hybrid-system-based quantum networks.

Main publications:

[1] L. Romeo, S. Roddaro, **A. Pitanti**, D. Ercolani, L. Sorba and F. Beltram, Electrostatic Spin Control in InAs/InP Nanowire Quantum Dots, Nano Letters 12, 4490 (2012).

[2] **A. Pitanti**, D. Coquillat, D. Ercolani, L. Sorba, F. Teppe, W. Knap, G. De Simoni, F. Beltram, A. Tredicucci and M. S. Vitiello, Terahetz detection by heterostructed InAs/InSb nanowire based field effect transistors , Applied Physics Letters 101, 141103 (2012).

[3] **A. Pitanti**, J. M. Fink, A. H. Safavi-Naeini, C. U Lei, J. T. Hill, A. Tredicucci and O. Painter, Linear and nonlinear capacitive coupling of electro-optomechanical photonic crystal cavities, submitted.

[4] J. M. Fink, **A. Pitanti**, R. Norte, L. Heinzle and O. Painter, Low stray capacitance and electromechanical coupling in nanowire coupled superconducting circuits, in preparation.

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