Transport phenomena in self-assembled nanowires

Self-assembled nanowires (NWs) are emerging as a versatile and powerful tool for the study of transport phenomena at the nanoscale. NWs can be shaped in the form complex axial and radial heterostructures in which normally incompatible materials can be combined into advanced – in some cases unprecedented – nanostructures. Such a level of flexibility makes it possible to explore innovative research directions. In particular, NW activities at NEST are presently focusing on the investigation of the interplay between nanomechanics and charge transport in self-assembled structures as well as Josephson coupling in devices combining superconductive elements and InAs/InP and InSb nanostructures.

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NWs represent a promising example of the bottom-up approach to nanoscience and technology [1-4]. The vapor-liquid-solid growth mechanism at the basis of NW technology makes it possible to design and fabricate in a very controllable way complex nanometer-scale structures without the need of delicate patterning procedures typical of any top-down approach. This allows the parallel and large scale fabrication of high-quality nanostructures and opens the way to cheap production of advanced nanomaterials and nanodevices. Research activities on NWs started at NEST in 2008, in parallel with the installation of a chemical beam epitaxy facility (see Activity Report X.Y) dedicated to the growth of InAs/InP and InSb semiconducting NWs. Nanostructures are being experimentally studied with two main objectives: (i) investigate the interaction between nanomechanical degrees of freedom and charge transport; (ii) investigate charge and heat transport at the nanoscale.

The first aim has started to be pursued in mid 2008 at NEST thanks to the project "Acoustoelectrics in self-assembled one-dimensional semiconductors" funded by INFM-CNR. The research initiative led to the design and fabrication of InAs NW-based field effect transistors (FETs) on GaAs and LiNbO3 piezoelectric substrates. These devices were used to investigate the influence of surface acoustic waves (SAWs) – excited on the substrate by means of interdigital transducers – on charge transport in the NWs. A typical InAs FET on LiNbO3 is visible in Fig.1a while an example of SAW-induced charge pumping can be seen in panel (b). In the studied devices both the piezoelectric potential associated to the SAW and the actual nanomechanical deformation of the NW can have an influence on free carriers in the nanostructure. Having successfully demonstrated the control of the NW electron system by SAW excitation [5], these results open the way to new single-electron pumping schemes which can have an impact for what concerns both metrology and the development of high-throughput single-photon sources. In order to reach these objectives, engineered InAs/InP nanostructures containing multiple barriers and quantum dots [6] are being investigated, in order to integrate them on LiNbO3 and to achieve a precise quantization of the number of charges pumped per SAW cycle. Such advanced NW heterostructures are being routinely fabricated at the NEST Center thanks to its new facility for chemical beam epitaxy of III-V semiconductors [7].
The second key target of the research activity – the study of charge and heat transport in nanoscale self-assembled structures – is being pursued by the development of hybrid devices combining InAs/InP and InSb NWs with superconductive elements. Figure 2a shows one of the concept devices which are being investigated at NEST: a hot-

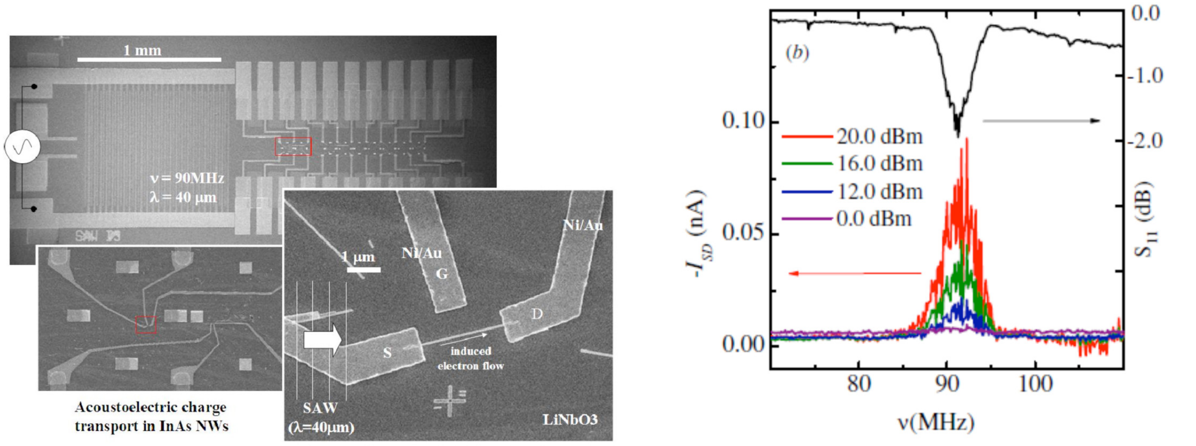

Fig. 1
SAW-pumping in InAs nanowires. (a) SEM micrographs at incremental magnifications of one of the studied InAs NW FET structures. The 90MHz SAW is induced by means of an interdigial transducer visible on the left side of lowest magnification picture. The NW device is fabricated on the SAW propagation path. (b) Acoustoelectric current measured at room temperature; the SAW resonance is visible on the top part of the plot as a reflection dip on the transducer.

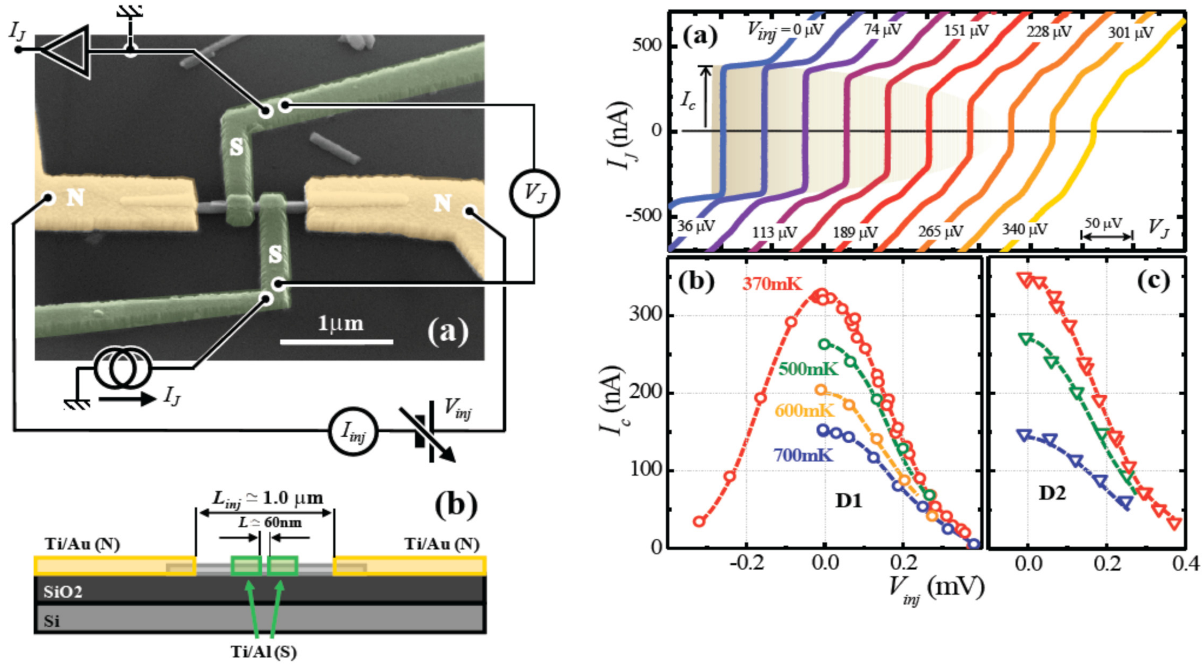

Fig. 2
Hot electron InAs nanowire Josephson transistor. Panel (a) and (b): the device core consists of an InAs nanowire contacted by two superconductive electrodes (green) to form a Josephson junction. The nanowire is also connected to two normal electrodes (yellow) at the two ends which can serve as hot-electron injectors and tune the Josephson coupling between the central electrodes. The modulation of the supercurrent as a function of the injection voltage and for different bath temperatures is visible in panel (c) and the suppression of the supercurrent on two typical devices is summarized in panels (d) and (e).

electron Josephson transistor. The device, developed in 2009, consists of a Josephson junction which is formed by an InAs NW channel contacted by two superconductive leads (green) and which can be controlled very efficiently by the injection of out-of-equilibrium carriers from normal-state control electrodes (yellow) fabricated at the two ends of the NW. Superconductive elements can play different crucial roles in this sort of nanostructures [8]. When a superconductor is put in contact with a normal region through a transparent interface, pairing correlations leak out on the normal side and induce new transport properties and make it possible, for instance, to observe a Josephson current in a normal-state conductor, as in the case of Fig.2. In addition, superconductors can also play a key role as energy filters and as low-thermal conductivity electron leads. In the device of Fig.2a they thus also allow to easily bring out of equilibrium the central section of the NW and to observe a marked suppression of the supercurrent for an injection voltage of barely few hundred of microVolts (see Fig.2b). These results are the basis of a wider research activity involving more advanced InAs/InP quantum systems, which open the way to a number of concept devices with an impact both in terms of fundamental physics and low-temperature applications [8].

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