1.3.6 Semiconductor nanowires: VLS growth and quantum transport

Self-assembled nanowires (NWs) are emerging as a versatile and powerful tool for the investigation of transport phenomena at the nanometer scale. NWs are strongly anisotropic monocrystalline nanostructures that can be fabricated by exploiting a nanoparticle-mediated growth technique known as vapor-solid-liquid (VLS) mechanism. This nanofabrication approach yields complex axial/radial nano-heterostructures in which materials that are incompatible in standard epitaxy can be combined with large flexibility. These peculiar properties make NWs attractive for what concerns both innovative fundamental research directions [1] and device implementations beyond current CMOS technology [2]. NW-related activities at NEST started in 2008, but in few years they have led to various high-impact publications that today make NEST an important player in the international NW community. Here we describe in particular our investigations on growth physics and on the development of InAs/InP single-electron transistors and superconductor-semiconductor hybrid devices.

NWs are promising demonstration of the bottom-up approach to nanoscience and nanotechnology [1,2]. The VLS mechanism for NW growth is a unique nanofabrication tool that makes it possible to design and create complex free-standing nanostructures with no need for delicate patterning procedures and complex device architectures typical of other top-down strategies. This allows the parallel fabrication of high-quality nanostructures and opens the way to large-scale production of advanced nanomaterials and nanodevices. NEST research activities on NWs started in 2008, in parallel with the installation of a chemical beam epitaxy (CBE) facility dedicated to the growth of semiconducting NWs. Since then, investigation efforts at NEST focused on two complementary fronts: (i) the progress of growth science and technology for the fabrication of innovative nanostructures; (ii) the development of novel devices based on NWs designed and realized at NEST.

Growth activities. Our Riber Compact-21 CBE system was installed in 2008 and it is still exclusively dedicated to the growth of III-V semiconductor NWs. The growth chamber is equipped with three reconfigurable injectors for the precursors of the group III (In, Ge), group V (As, P) and for the doping species (Se). The specific epitaxy technique was chosen based on the experience of leading groups worldwide and on the good trade-off between the degree of control and flexibility offered by this technology. Protocols for the fabrication of optimized InAs NWs were quickly established during few months following the installation and state-of-the-art technology for the growth of InAs/InP nano-heterostructures was established at NEST during the first two years of activity.

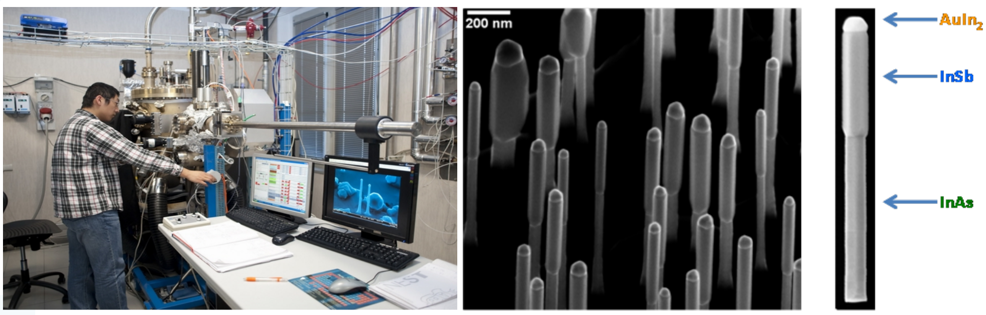

Figure 1. Left hand side, picture of the growth laboratory and of the Riber Compact-21 chemical beam epitaxy system. Right hand side: monocrystalline InAs/InSb NW heterojunctions recently developed at NEST. The nanoparticle catalyzing the growth process is clearly visible on the top of the NWs.

Subsequent research efforts further focused on: (i) new challenging materials such as InSb-based NW heterostructures (see Fig. 1), which are particularly attractive because of their high carrier mobility, small effective mass and strong quantum confinement and spin-related effects [3-8]; (ii) non-standard growth techniques, for instance based on alternative catalyst metals such as Pd [9,10]; (iii) the fine calibration of the NW parameters and structural properties of grown NWs, which are of course crucial to device implementations [11,12].

Quantum transport phenomena and devices in NWs. The VLS technology offers a practical method to produce nanostructures whose electron Hamiltonian and behavior can be designed with great freedom, thanks to the controlled definition of nanometer-scale artificial potential barriers and to the combination of different material systems. In particular, NWs can be used to strongly confine carriers in three-dimensional axial/radial heterostructures and to obtain device architectures with properties that it would be impossible or impractical to achieve using more standard epitaxy and nanofabrication methods. In addition, NW are free-standing nanostructures which can be easily removed from the growth substrate and coupled with different materials such as for instance superconductors or ferromagnets. This possibility can be exploited to induce, investigate and control transport phenomena in the NWs.
One of the main driving ideas behind NW research activities at NEST in 2008-2013 was the investigation of transport phenomena based on the combination between strongly correlated electron-systems found in superconductors and the quantum systems attainable using NWs. In hybrid nanodevices, strong electron correlations can be induced in NW-based quantum conductors and used to explore a wide range of fundamental charge and heat transport phenomena as well as device applications, including innovative transistor concepts and high-sensitivity detectors. In this context, NWs provide a valuable enabling technology to realize unique device architectures. Research efforts at NEST successfully demonstrated advanced hybrid devices based on uniform InAs NWs in which the charge flow can be controlled using quantum pumping [13], superconductive quantum interference [14] as well as out-of-equilibrium effects [15]. In order to fully exploit the possibility offered by the VLS approach, an important part of the activities was also devoted to the investigation of single-electron physics in strongly confined quantum dots based on InAs/InP heterostructured NWs, building on the established expertise of the laboratory staff on the field [16,17]. In this specific case, we successfully demonstrated the field-effect control of the charge and spin configuration of quantum dots up to an electronic temperature of about 50K [18-20], opening a new route to the implementation of single-electron transistors and detectors which are able to work at room temperature, without the need of a cryogenic equipment. Finally, NEST research activities addressed additional relevant NW transport aspects which are expected to be important for practical device applications, in particular for what concerns the role of telegraph noise [21], the interaction between charge transport and mechanical degrees of freedom [22], and perspectives for the realization of large-scale NW devices [23].

References
[1] Nanoelectronics from the bottom up, Nature Mater. 6, 841 (2007). W. Lu, C. M. Lieber.

[2] International Technology Roadmap for Semiconductors 2012, Emerging Research Devices (http://www.itrs.net/)
[3] InAs/InSb nanowires heterostructures grown by chemical beam epitaxy, Nanotechnology **20**, 505605 (2009). D. Ercolani, F. Rossi, A. Li, S. Roddaro, V. Grillo, G. Salviati, F. Beltram, L. Sorba.
[4] Growth mechanism of InAs–InSb heterostructured nanowires grown by chemical beam epitaxy, J. Crystal Growth **323**, 304 (2011). L. Lugani, D. Ercolani, F. Beltram, L. Sorba.
[5] Growth of InAs/InAsSb heterostructured nanowires, Nanotechnology **23**, 115606 (2012). D. Ercolani, M. Gemmi, L. Nasi, F. Rossi, M. Pea, A. Li, G. Salviati, F. Beltram and L. Sorba.
[6] Electron beam induced current in InSb-InAs nanowire type-III heterostructures, Appl. Phys. Lett. **101**, 063116 (2012). C. Y. Chen, A. Shik, A. Pitanti, A. Tredicucci, D. Ercolani, L. Sorba, F. Beltram, H. E. Ruda.
[7] Faceting of InAs-InSb heterostructured nanowires, Crystal Growth and Design **10**, 4038 (2010). L. Lugani, D. Ercolani, F. Rossi, G. Salviati, F. Beltram, and L. Sorba.
[8] Modeling of InAs-InSb nanowires grown by Au-assisted chemical beam epitaxy, Nanotechnology **23,** 095602 (2012). L. Lugani**,** D. Ercolani, L. Sorba, N. V. Sibirev, M. A. Timofeeva, V. G. Dubrovskii
[9] Pd–assisted growth of InAs nanowires, Crystal Growth and Design **10**, 4197 (2010). S. Heun, B. Radha, D. Ercolani, G. U. Kulkarni, F. Rossi, V. Grillo, G. Salviati, F. Beltram, and L. Sorba.
[10] Coexistence of Vapor-Liquid-Solid and Vapor-Solid-Solid Growth Modes in Pd-Assisted InAs Nanowires, Small **6**, 1935 (2010). S. Heun, B. Radha, D. Ercolani, G. U. Kulkarni, F. Rossi, V. Grillo, G. Salviati, F. Beltram, and L. Sorba
[11] Raman sensitivity to crystal structure in InAs nanowires, Appl. Phys. Lett. **100,** 143101 (2012). J. K. Panda, A. Roy, A. Singha, M. Gemmi, D. Ercolani, V. Pellegrini, L. Sorba
[12] Se-doping dependence of the transport properties in CBE-grown InAs nanowire field effect transistors, Nanoscale Res. Lett. **7,** 1 (2012). L. Viti, M. S. Vitiello, D. Ercolani, L. Sorba, A. Tredicucci.
[13] A Josephson quantum electron pump, Nature Phys. **7**, 857 (2011). F. Giazotto, P. Spathis, S. Roddaro, S. Biswas, F. Taddei, M. Governale, and L. Sorba
[14] Hybrid InAs nanowire-vanadium proximity SQUID, Nanotechnology **22**, 105201 (2011). P. Spathis, S. Biswas, S. Roddaro, L. Sorba, F. Giazotto, F. Beltram.
[15] Hot-electron effects in InAs nanowire Josephson junctions, Nano Research **4**, 259 (2011). S. Roddaro, A. Pescaglini, D. Ercolani, L. Sorba, F. Giazotto, and F. Beltram.
[16] Singlet-triplet transition in a few-electron lateral $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ quantum dot, Appl. Phys. Lett. **96**, 142107 (2010). F. Deon, V. Pellegrini, F. Carillo, F. Giazotto, G. Biasiol, L. Sorba, F. Beltram.
[17] Electronic properties of quantum dot systems realized in semiconductor nanowires, Semicond. Sci. Technol. **25**, 024007 (2010). J. Salfi, S. Roddaro, D. Ercolani, L. Sorba, I. Saverlyev, M. Blumin, H. E. Ruda, F. Beltram.
[18] Electrostatic spin control in InAs/InP nanowire quantum dots, Nano Lett. **12**, 4490 (2012). L. Romeo, S. Roddaro, A. Pitanti, D. Ercolani, L. Sorba, and F. Beltram.
[19] Manipulation of electron orbitals in hard-wall InAs/InP nanowire quantum dots, Nano Lett. **11**, 1695 (2011). S. Roddaro, A. Pescaglini, D. Ercolani, L. Sorba, F. Beltram.
[20] Contacts shielding in nanowire field effect transistors, J. Appl. Phys. **111,** 064301 (2012). A. Pitanti, S. Roddaro, M. S. Vitiello, A. Tredicucci
[21] Probing the Gate-Voltage-Dependent Surface Potential of Individual InAs Nanowires Using Random Telegraph Signals, ACS Nano **5**, 2191 (2011). J. Salfi, N. Paradiso, S. Roddaro, S. Heun, S. V. Nair, I. G. Savelyev, M. Blumin, F. Beltram, H. E. Ruda.
[22] Charge pumping in InAs nanowires by surface acoustic waves, Semicond. Sci. Technol. **25**, 024013 (2010). S. Roddaro, E. Strambini, V. Piazza, F. Beltram.
[23] Large-Area Ohmic Top Contact to Vertically Grown Nanowires Using a Free-Standing Au Microplate Electrode, ACS Appl. Mat. & Int. **4,** 1860 (2012). B. Radha, D. Jayaraj, G.U. Kulkarni, S. Heun, D. Ercolani, L. Sorba.