1.3.2 Quantum transport in semiconductor nanowires

Semiconductor nanowires (NWs) are strongly anisotropic single-crystalline nanostructures that can be grown using a bottom-up approach. This class of nanostructures can embed complex axial and radial heterostructures with materials that would be rather hard to combine in standard epitaxy owing to excessive lattice mismatch. This design flexibility offers a set of unique opportunities for the investigation and exploitation of quantum transport phenomena at the nanoscale. Since 2008, research efforts have focused on advanced single-electron systems based on InAs/InP NWs, on which now the NEST has a well-established expertise and a variety of national and international collaborations. More recently, activities have included the investigation of hybrid systems combining superconductive elements and semiconductor NWs for the investigation of coherent-transport phenomena and topological phase transitions

1. Quantum heterostructures

The quantum behavior of electrons in NWs can be controlled and tailored by designing suitable axial and/or radial heterostructures. Radial heterostructures offer a very promising research direction and have been used to implement bipolar nanodevices where an electron and hole system can coexist within a few nanometers. Historically, these systems have notoriously been rather hard to implement, but can be naturally obtained in a NW embedding a radial broken-gap InAs/GaSb heterojunction [5], as sketched in Fig.1a. We demonstrated NW architectures where the core and the shell can be separately contacted, as visible in the scanning electron microscope (SEM) picture in Fig.1b. In these devices, the voltage-dependent interband tunneling between InAs and GaSb gives rise to a marked negative differential resistance, see Fig. 2c. The achievement of closely spaced electron and hole systems in NWs also provides a very promising workbench for the investigation of interactions in low dimensions and of bipolar thermoelectric phenomena.

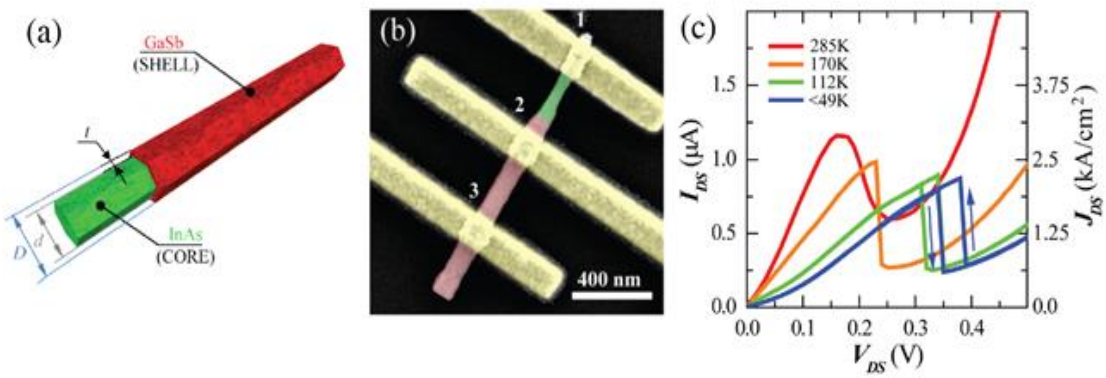

Figure 1. (a) Sketch of a radially heterostructured NW embedding a broken-gap GaSb/InAs junction. (b) Scanning electron micrograph of one of the studied devices, which integrate independent contacts to both the core (green) and shell (red) of the nanostructure. (c) Radial conduction displays a marked negative differential resistance, providing a clear fingerprint of bipolar transport through the broken gap heterojunction. From [5].

A different class of heterostructured NWs we studied includes axial InAs/InP systems, which are particularly promising for the creation of strongly confined quantum dot systems and clean tunnel barriers. Following the ground-breaking research carried out at NEST during the past years, recent activities focused on the adoption of these systems as active elements in different contexts such as microwave (MW) resonators [1], nanoscale thermoelectricity and electron tunneling spectroscopy.

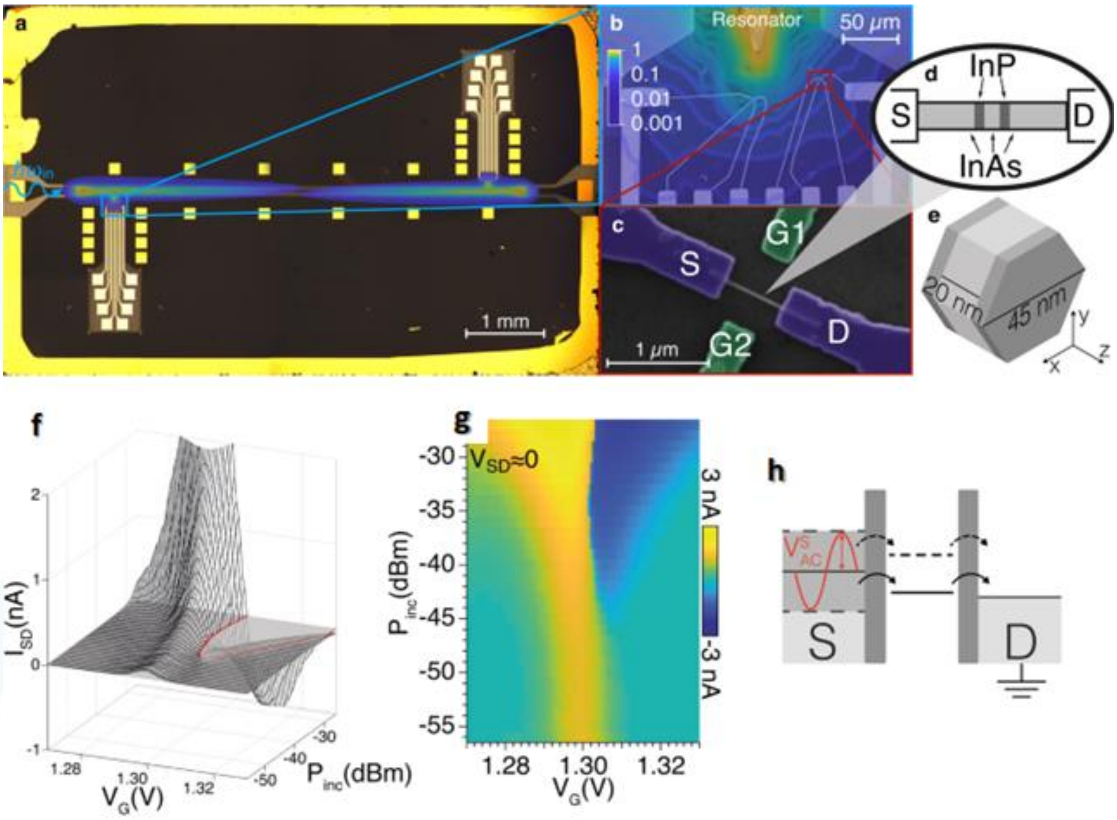

Figure 2. (a) Optical overview of the full device including InAs/InP NWs and an YBCO/sapphire coplanar resonator. (b) and (c) SEM close-up of the antenna tip and of the NW device. False colors in panels (a) and (b) represent the numerically simulated electric field strength of the fundamental resonator mode (normalized to the maximum value). (d) Schematic diagram of the InAs/InP NW QD. (e) Sketch of the NW QD showing InAs (light grey) and InP (dark grey) sections. (f) and (g) Evolution of the $I_{SD}(V_G)$ characteristics in the presence of a microwave drive of frequency ω_0 and increasing power P_{inc}. Three dimensional plots and maps are plotted for gate voltage around V_G=1.30 V at the temperature T = 2K. Solid lines indicate the contour of regions with negative I_{SD}. (h) Energy diagrams illustrating the MW-assisted tunneling through the dot levels ε′ and ε″.

2. Hybrid nanowire-based devices

The most common material choice in NW-based transport experiments is InAs, since this semiconductor material displays a favorable pinning of the Fermi energy at the surface of the nanostructure, leading to a natural electron population despite the very small dimension of the NW. For the same reason, NWs are very promising for the creation of hybrid devices where superconductive elements are coupled to the nanostructure via transparent tunnel junctions. An important part of NW transport activities focused on the investigation of Josephson coupling between NWs and different superconductors such as Al [6] and Pb [4], see Fig.3a and 3b. Activities targeted first of all the fundamental investigation of proximity effect in NWs, but highlighted potential applications of these systems in the context of topological quantum computation [6]. In view of this perspective, a crucial ingredient is spin-orbit interaction, which is rather strong in In-based nanowires. Selected activities have thus also targeted the study of the still not fully understood nature of spin-orbit interaction in InAs nanowires, and in particular of its dependence on external electric fields induced by field-effect electrodes [2], see Fig.3c-3h. A further crucial ingredient for the implementation of a reliable quantum technology is of course electron cooling. A very intriguing possibility consists in exploiting quantum phenomena such as tunneling between different materials such as superconductors and semiconductors to directly cool electrons in the active region of a quantum device, as well-established in the case of metallic nanostructures and recently demonstrated by us in a set of experiments on tunnel-coupled Al-InAs NW devices [3].

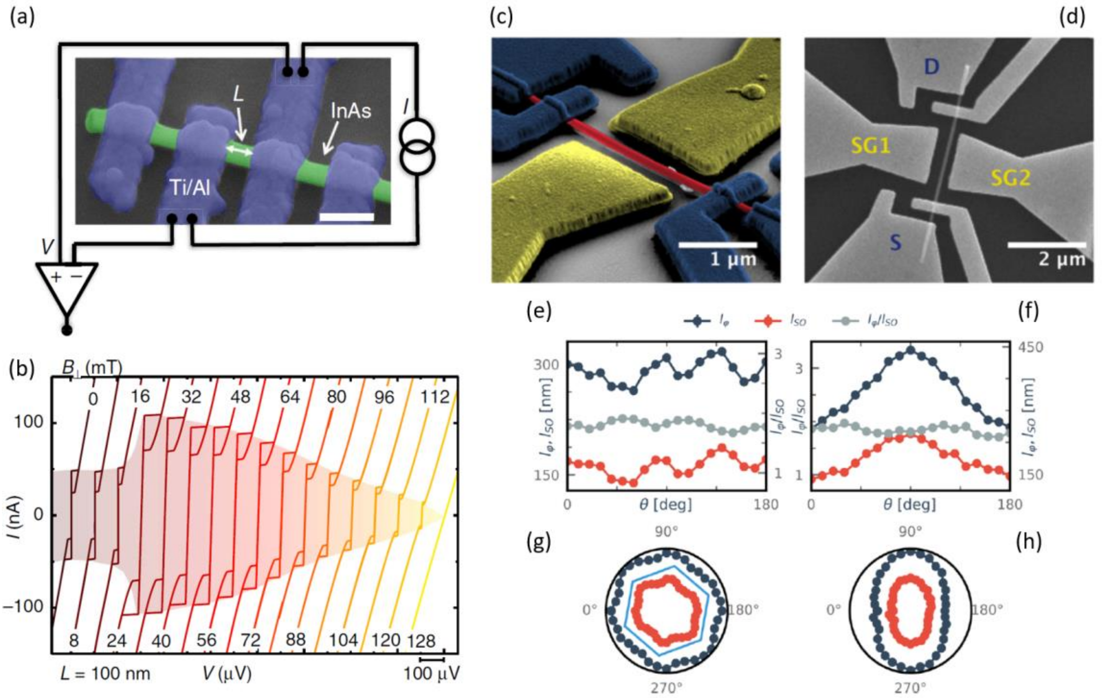

Figure 3. (a) Typical hybrid device for the investigation of proximity effects in InAs nanowires. (b) Magnetic field enhancement of the supercurrent through an Al-InAs-Al Josephson nanojunction. (c) and (d) Scanning electron micrograph of a suspended nanowire structure for the investigation of the field-effect dependence of spin-orbit interaction in InAs nanowires. Vectorial dependence of transport parameters extracted from weak localization/antilocalization data as a function of the orientation of the electric field applied to the suspended nanowire. From [2, 6].

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