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Semiconductor nanowires have been extensively studied due to their potential application in various fields such as electronic and optoelectronics devices and they have become a major component of technology roadmap for semiconductors. The goal of my thesis is to understand the dynamics of the nucleation and growth mechanisms of catalyst-free III-V semiconductor axial and radial heterostructured nanowires grown by chemical beam epitaxy on silicon substrate. In particular the morphology, structure and transport properties of heterostructured nanowires have been investigated.

Project 1. Growth and Strain Relaxation Mechanisms of InAs/InP/GaSb Core-multishell Nanowires

InAs/GaSb core-shell NWs have attracted great attention because of their peculiar properties which provide a platform for many useful applications. As a matter of fact, both InAs and GaSb have very small effective masses with high electron and hole mobility, respectively. Moreover, they have a type-II broken band gap alignment and a very low lattice mismatch of 0.6%. All these properties make InAs/GaSb core-shell NWs suitable for applications in devices like tunnel field effect transistors [1], Esaki diodes [2], frequency multipliers [3], and for the study of spin states [4], and electron-hole hybridization [5]. Indeed, electronic devices fabricated with these heterostructures combine closely-spaced n-type and p-type conductors, and can display negative differential resistance due to transport across the broken gap junction [2]. Further interesting electronic configurations can be achieved if carriers in the InAs core and GaSb shell are decoupled though the presence of a thin barrier. Therefore InAs/InP/GaSb core-multishell (CMS) NWs have been realized.

My activity is focused on the optimization of the growth of InAs/InP/GaSb CMS NWs by catalyst-free chemical beam epitaxy on Si (111) substrates. The morphological, structural and compositional analysis of the NWs as a function of growth parameters were carried out by scanning and transmission electron microscopy and by energy-dispersive X-ray spectroscopy. Morphological study shows that InP shell grow coherently around InAs core, by following the same {110} side facets of InAs core while GaSb shell consists of twelve side facets in which six relates to {110} and six belongs to {211} family of planes. Strain release mechanism in InAs/InP/GaSb CMS NWs as a function of InP shell thickness has been studied by HR-TEM imaging, STEM Moiré patterns, and geometric phase analysis (GPA) methods. From the STEM-Moiré patterns we found that when the thickness of InP shell is 1 nm the facets at the NW corners are not well developed and few dislocations appear. When the thickness of InP shell is above 1 nm, all the facets of NWs are well developed and NWs are free of dislocations. However, when thickness of InP shell reached to 8 nm we found some dislocations and steps at the interfaces. The strain measurements performed from GPA maps suggest that the lattice parameters of the three materials in the direction parallel to interface are the same of InAs while in the direction perpendicular to interface InP and GaSb have their own relaxed lattice parameters and therefore the strain is released through a tetragonal distortion. This work helps us in an understanding of strain relaxation behavior which is beneficial for the fabrication of more efficient devices based on these type of nanowires.

NOTE: A manuscript reporting the above results is in preparation and it will submitted on Crystal growth and Design Journal.

Project 2. Transport measurements of InAs/InP/GaSb Core-multishell Nanowires

In order to study effect of InP barrier to the optimized catalyst-free InAs/InP/GaSb CMS NWs, we have fabricated devices in shell-to-shell and core-to-shell configuration. Transport properties were measured as a function of temperature and backgate voltage, by using the electrodes that selectively contact either the InAs core or the GaSb shell. Low-temperature transport measurements at 4.2 K in shell-to-shell configuration disclose a weak negative differential resistance (NDR) for 5nm thick InP barrier which suggest that we still have transport between core and shell due to tunneling effect. We performed the same measurements in InAs/InP/GaSb CMS NWs with 10 nm thick InP barrier and we found that the NDR is quenched at room and low temperatures. It shows a clear indication that charge carriers in the core and shell are decoupled by a 10 nm thick layer of InP barrier which makes these new CMS nanowires a suitable system with radial transport for investigating the coexistence of electron and hole carriers.

NOTE: A manuscript is in preparation.

Project 3. Growth of Self-Assisted InAs/InSb Axial Heterostructured Nanowires

The third activity is focused on the growth of self-catalyzed InAs/InSb axial heterostructured NWs. InAs and InSb have gained much attraction because they have very fascinating properties such as narrow bandgaps (0.35 eV and 0.17 eV, respectively), extremely high bulk electron mobilities, small effective masses, strong spin–orbit interactions, and giant g factors [6]. The combination of these special and unique aspects of these nanowires make them suitable candidate for the applications of high-speed and low-power electronics, infrared optoelectronics, spintronics, topological quantum computing, and detection and manipulation of Majorana fermions [7]. In order to investigate the growth mechanisms of axial InAs/InSb heterostructured NWs to realize axial heterostructured NWs with optimized aspect ratio we have measured their morphology by scanning electron microscopy. Diameter of the In particle D_{In}, diameter of the InSb segment D_{InSb}, length of the InSb segment L_{InSb}, aspect ratio of the InSb segment (L_{InSb}/ D_{InSb}), and contact angle of metal nanoparticle (NP) have been measured as a function of time, In and Sb flux. We have found that both quantities D_{In} and D_{InSb} as function of growth time increase continuously by following each other as a function of growth time while at the beginning of the growth contact angle is less than 90° and as long as the growth time increases to 15 minutes the contact angle of the particle increases but then it remains constant around 105 ± 5° even for longer growth duration. The InSb segment length and diameter increases as the growth time increases but the InSb length increases faster as compared to the diameter. Then we studied effect of group III and we found that under In-rich conditions both D_{In} and D_{InSb} increase with group III flux and the axial growth rate is constant. While using Sb rich growth conditions, the size of In particle decreases as Sb flux increases, while the diameter of the InSb segment remains almost constant. So it means that the radial growth rate of InSb does not depend upon group V flux, neither on the In particle size. While we have seen that length increases as the Sb flux is increased, while the diameter of InSb is constant at any Sb flux. We can conclude that the Sb flux strongly affects the NP shape (R, H and contact angle) and the axial InSb growth rate, whereas it doesn't affect the InSb radial growth. We are planning to study structural properties and the nanoparticle composition of InAs/InSb NWs with TEM in collaboration with Francesca Rossi from IMEM-CNR and the growth mechanisms of InAs/InSb axial heterostructured NWs will be theoretical modelled through the collaboration with Prof. Vladimir Dubrovskii from the University of San Petersburg.

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