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High-Quality InSb Nanostructures Grown by Molecular-Beam Epitaxy

Dong Pan, Xuezhe Yu and Jianhua Zhao

State Key Laboratory of Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, China

Phone: +86-10-82305174 E-mail: pandong@semi.ac.cn

Abstract

High-quality single-crystalline InSb materials are highly desired for searching for and manipulation of Majorana Fermions in solid state, a fundamental research task in physics today, and for development of novel high-speed nanoelectronic and infrared optoelectronic devices. However, growth of such InSb materials remains challenging in material science. Here, we report the growth of high-quality one-dimensional (1D) InSb nanowires and two-dimensional (2D) InSb nanosheets on InAs nanowire stems by molecular-beam epitaxy (MBE). We find that the Sb/In beam equivalent pressure (BEP) ratio can be varied to effectively control the morphological transformation of the InSb nanostructures from 1D nanowires to the novel 2D nanosheets. The grown InSb nanowires and nanosheets are pure zinc-blende (ZB) single crystals and have a high electron mobility. These novel, high material quality, free-standing InSb single-crystalline nanostructures have the great potential not only for applications in high-speed electronics and infrared optoelectronics but also for realization of novel quantum devices for the studies of fundamental physics.

1. Introduction

As a technologically important III-V semiconductor, InSb is the most desired material system for applications in high-speed, low-power electronics and infrared optoelectronics owing to its highest electron mobility and narrowest bandgap among all the III-V semiconductors. Recently, epitaxially grown InSb nanostructures have been widely anticipated to have potential applications in spintronics, topological quantum computing, and detection and manipulation of Majorana Fermions, due to the small effective mass, strong spin-orbit interaction and giant g factor in InSb [1-4]. All these applications require a high degree of InSb growth control on its morphology and especially crystal quality [5]. Unfortunately, because of the intrinsic largest lattice parameter of InSb among all the III-V semiconductors, epitaxial growth of InSb faces an inevitable difficulty in finding a lattice-matched substrate. Growth of high-quality single-crystalline InSb materials remains challenging in material science.

Here, we report the growth of high-quality InSb nanostructures by MBE. We find that high-quality InSb nanowires can be grown on InAs nanowire stems using Ag as catalysts. It is found that the Sb/In BEP ratio can be varied to effectively control the morphology and the size of the InSb nanowires. In addition, we develop a new route toward growth of single-crystalline, layered InSb materials. We demonstrate the successful growth of free-standing, 2D InSb nanosheets on 1D InAs nanowires by MBE. The grown InSb nanosheets are pure ZB single crystals. The length and width of the InSb nanosheets are up to several micrometers and the thickness is down to ∼10 nm. The InSb nanosheets show a clear ambipolar behavior and a high electron mobility.

2. Experimental design

All the InSb nanostructures were grown in a solid source MBE (VG80) system. Commercial p-type Si (111) wafers were used as the substrates. Before loading the Si substrates into the MBE chamber, they were immersed in a diluted HF (2%) solution for 1 min to remove the surface contamination and native oxide. After cleaning, a Ag layer of 2 Å nominal thickness was deposited on the substrate in the MBE growth chamber at room temperature and then annealed *in situ* at 650 ^{0}C for 20 min to generate Ag nano-particles. InAs nanowire stems were grown for 20 min at 505 ^{0}C with an As/In BEP ratio of 30. Then the group-V source was abruptly switched from As to Sb without any variation of substrate temperature. All the InSb segments (if no specific description) were grown for 80 min at different Sb/In BEP ratios by increasing the Sb flux while keeping the In flux constant.

3. Results and discussion

Fig. 1 shows transmission electron microscope (TEM) images of a typical InSb nanowire grown on InAs nanowire stem using Ag as catalysts. We observe that the nanowire has a two-segment structure with a narrow base diameter and a wide upper-segment diameter, which is similar to nanowires grown using Au and other catalysts [5,6]. High-resolution TEM images as shown in Fig. 1 indicate that the InAs grows along the <0001> direction with a hexagonal wurtzite (WZ) phase and the InSb grows along the <111> direction with a cubic ZB phase. Clearly, an atomically sharp structure interface (from WZ to ZB) can be observed at the InAs/InSb interface section.

We find that the morphology of InSb strongly depends on the Sb/In BEP ratio, and the InSb nanosheets can be realized by tailoring the Sb/In BEP ratio. For the sample grown with low Sb/In BEP ratio of 1-20, InSb and InAs form core-shell or axial heterostructure nanowires. Further increasing the Sb/In BEP ratio, the resulting InSb nanowires have diameters obviously larger than that of the InAs segment (a diameter increases from 130 to 589%). By increasing the Sb/In BEP ratio to the range of 27-80, new geometrically structured materials with each consisting of a 2D InSb nanosheet and a 1D InAs nanowire stem are obtained. Fig. 2 (a)-(b) shows the side-view magnified scanning electron microscope (SEM) images of InSb nanosheets grown with an characterized by electrical measurements. The electrical measurements show that these InSb nanosheets exhibit a high electron mobility and an ambipolar behavior. An electron mobility of ~18500 $cm^2\ V^{-1}\ s^{-1}$ can be obtained at 60 mK [8].

The growth mechanisms of the InSb nanowires and nanosheets are also discussed. The InSb nanowires are epitaxially grown on InAs nanowires in a Ag-assisted vapor-liquid-solid manner. The formation of the InSb nanosheets is attributed to a combination of vapor-liquid-solid and lateral growth.

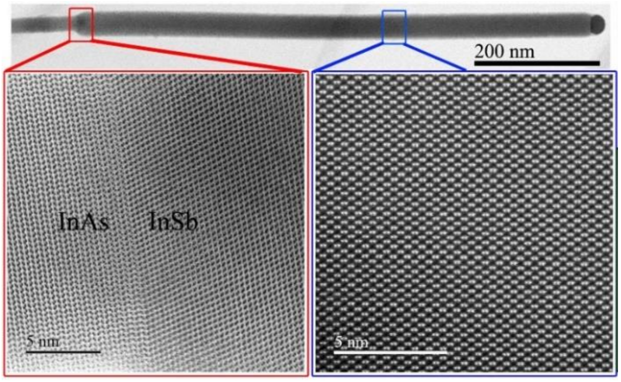

Fig. 1 TEM images of a typical InSb nanowire grown on InAs nanowire stem using Ag as catalysts.

Sb/In BEP ratio of 80. It is clear that the InSb nanosheets can be grown on ultrathin InAs nanowires (~10 nm in diameter) that are oriented perpendicular to the substrate surface with a pure WZ crystal structure [7]. As can be seen, the grown InSb nanosheets have parallelogram shapes. The thicknesses of the InSb nanosheets show significant variation, as measured from SEM images, from ~67 nm, to ~30 nm, and to the ultrathin value of ~10 nm.

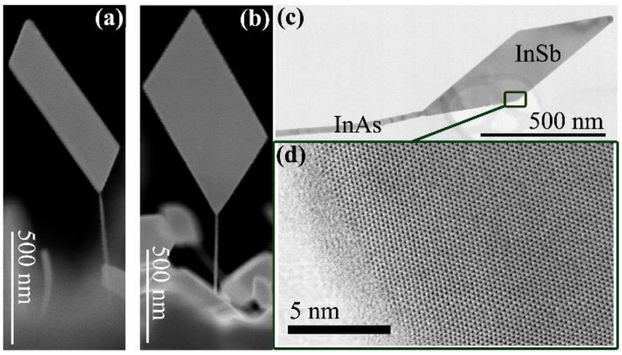

Fig. 2 SEM and TEM images of typical InSb nanosheets grown on InAs nanowire stems using Ag as catalysts by MBE.

High-resolution TEM images of the side sections (Fig. 2(d)), the corner sections and the section near the tip of the InSb nanosheets and the associated Fourier transform (not shown here) illustrate that the InSb nanosheets have a perfect ZB crystal structure, free from stacking faults or WZ regions. Although the stacking faults have been observed in Ag-catalyzed and self-seeded InSb nanowires by other groups, detailed TEM observations of our grown InSb nanosheets with different shapes and sizes all reveal that the InSb nanosheets are fully single-crystalline, completely free from stacking faults and twinning defects.

The length and width of the InSb nanosheets can be controlled directly by tailoring the InSb growth time. The length and width of the grown InSb nanosheets can be up to several micrometers and the thickness can be down to ~10 nm. Electronic properties of the grown InSb nanosheets were

4. Conclusions

In conclusion, we have realized fabrication of high-quality InSb nanowires using Ag catalysts. In particular, we demonstrate a new growth route of high-quality 2D InSb layers by MBE. These InSb layers are free-standing 2D InSb nanosheets grown on 1D InAs nanowires, which is independent of conventional buffer-layer engineering. The morphology and size of InSb nanosheets can be controlled by tailoring the Sb/In BEP ratio and growth time. The length and width of the grown InSb nanosheets can be up to several micrometers and the thickness can be down to ~10 nm. The InSb nanosheets are pure ZB single crystals. The electrical measurements show that these InSb nanosheets exhibit a high electron mobility and an ambipolar behavior. Our work opens a conceptually new approach to obtaining high-quality narrow bandgap semiconductor nanostructures and will speed up the applications of InSb nanostructures in nanoelectronics, optoelectronics, and quantum electronics and in the development of topological quantum computation technologies.

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References

[1] S. A. Wolf *et al.*, Science **294** (2001) 1488.

[2] J. D. Sau, S. Tewari, S. Das Sarma, Phys. Rev. Lett. **104** (2010) 040502.

[3] V. Mourik, K. Zuo, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, L. P. Kouwenhoven, Science **336** (2012) 1003.

[4] M. T. Deng, C. L. Yu, G. Y. Huang, M. Larsson, P. Caroff, H. Q. Xu, Nano Lett. **12** (2012) 6414.

[5] S. R. Plissard, *et al.*, Nature Nanotech. **8** (2013) 859.

[6] H. So, D. Pan, L. X. Li, J. H. Zhao, Nanotechnology **28** (2017) 135704.

[7] D. Pan *et al.*, Nano Lett. **14** (2014) 1214.

[8] D. Pan, D. X. Fan, N. Kang, J. H. Zhi, X. Z. Yu, H. Q. Xu, J. H. Zhao, Nano Lett. **16** (2016) 834.