Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp879-880

PS-8-05

Self-catalyst Growth of InAs and InAs/GaSb Heterostructure Nanowires on Si substrate by MOCVD

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Abstract

We demonstrate the self-catalyst (SC) growth of vertically aligned InAs and InAs/GaSb heterostructure nanowires on Si(111) substrate by Metal Organic Chemical Vapor Deposition (MOCVD). The effect of growth temperature on morphology and growth rate for SC InAs and InAs/GaSb heterostructure nanowires (NWs) are investigated. Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM) measurements reveal the morphology and shell thickness can be tuned by the growth temperature. Electron microscopy also shows the formation of GaSb both in radial and axial directions outside the SC InAs NW core at certain growth temperatures. These results show that the SC InAs and InAs/GaSb NW growth method can be used for future III-V based microelectronic applications.

1. Introduction

III-V NWs have been getting great attention for combining all the advantages of III-V semiconductors such as direct band gap, high carrier mobility and advanced band structure engineering with those of NW features such as free standing nature and efficient lateral strain relaxation [1]. Among all the III-V materials, InAs and GaSb have small effective masses and extremely high carrier (electrons and holes) mobilities. In addition to this, the low lattice mismatch of 0.6 % and unique type-II broken band alignment between them make this heterostructure system enable a new platform for the design of novel nanowire-based devices and fundamental quantum physics investigations [2,3]. Therefore, it is highly desirable to study the controlled growth of SC InAs NWs and SC InAs/GaSb heterostructure NWs.

2. Experimental

All SC InAs and InAs/GaSb nanowires were grown on p-type Si(111) substrates by using MOCVD system. Trimethylindium (TMIn), trimethylgallium (TMGa) and trimethylantimony (TMSb), arsine (AsH_3) were used as group III and group V precursors respectively. First of all, all Si(111) substrates were cleaned using RCA cleaning followed by dipping in diluted HF (1:50) for few seconds to remove native oxide and then loaded to MOCVD chamber. Before nanowires growth, substrates were annealed at 700°C for 10 min and cooled down to 400°C in H_2 atmosphere then AsH_3 was flown for 3min to get (111)B surface [4]. Then the temperature was increased to the InAs growth temperature in an AsH_3-rich environment. For the first set of experiments, the InAs NWs growth was carried out varying growth temperature between 550°C and 650°C with fixed 150 sec growth time, TMIn ($2.9x10^{-5}$ moles/min) and AsH_3 ($4.5x10^{-3}$ moles/min) flow rates. After the growth, InAs NWs were cooled down with the protection of AsH_3 flow. For the second set of experiments, after growing InAs core at 600°C, the temperature was decreased to GaSb growth temperature in the presence of AsH_3 flow. The GaSb growth was initiated by providing TMSb and TMGa for 30min. The GaSb growth temperature was varied between 470°C and 530°C with fixed V/III ratio of 1.0. Finally, the samples were cooled down under TMSb flow to the 300 °C.

After NWs growth, characterization of NWs was performed by Field-Emission SEM and High Resolution TEM.

3. Results & Discussion

Fig 1(a-e) shows the 45° SEM images of samples grown at various growth temperatures. It is clearly observed that all grown InAs NWs are non-tapered and vertical along <111> direction, which is perpendicular to Si substrate surface. Fig 1(f) graphically represents the growth temperature effect on InAs NW growth. As the growth temperature increases from 550°C to 600°C, NW length increases due to the enhancement of In adatom's mobility and diffusion length. When the diffusion length increases with temperature, the sidewall incorporation of In adatoms becomes less pronounced and as a result NW diameter decreases. At 600°C, the NW length reaches maximum value of (1650 ± 30) nm while the diameter reaches minimum value of (40 ± 5) nm giving the highest aspect ratio of 41.3. In contrast, as the temperature increases further to 650°C, NW length decreases slightly and diameter increases. The axial growth rate varies between 5nm/sec to 10nm/sec depending on the growth temperature, it increased as the growth temperature increased from 550°C to 600°C, then decreased as the temperature increased further to 650°C. Usually SC NW growth temperature window is very narrow, but we observed higher temperature window when high In and As flow rates were used. We also observed from the above experiments that, the growth temperature effect is more pronounced on NW diameter than on NW length when high flow rates were used.

To investigate the influence of growth temperature on the GaSb growth, a series of InAs/GaSb heterostructure

NWs were grown varying GaSb growth temperature between 470°C to 530°C with constant growth time (30 min) and V/III ratio (1.0). Fig 2(a-c) shows the 45° SEM images of InAs/GaSb heterostructure NWs grown in [111]B direction with varying GaSb growth temperatures. Continuous and non-tapered InAs/GaSb NWs has been obtained at all GaSb growth temperatures. GaSb growth temperature of 500°C and 530°C results in NWs with smooth surface along the whole NW. Decrease of the growth temperature to 470°C, however, increases the roughness of the GaSb shell. Fig 2(d) shows the graph between GaSb growth temperature and total diameter of InAs/GaSb NW. Total diameter of the InAs/GaSb NW increases as the GaSb growth temperature increases. It should be noted that, increase in the total diameter means that the GaSb shell growth rate increases as the growth temperature increases (expected GaSb shell thickness also shown in Fig 2(d)). Increase in growth rate with the growth temperature could be attributed to the kinetic processes of alkyl decomposition at the substrate surface limit decomposition.

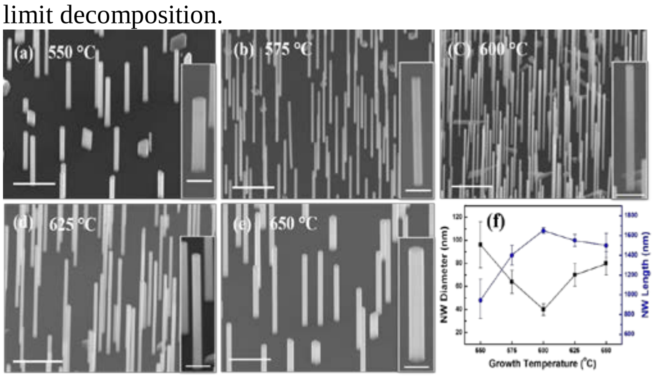

Fig 1 45° SEM images of SC InAs NWs with different growth temperatures of (a) 550°C (b) 575°C (c) 600°C (d) 625°C (e) 650°C. Inserts in (a)-(e) are high magnification images. Scale bars are 1μm in (a)-(e) and 200nm in the inserts. (f) Corresponding length/diameter versus growth temperature plot.

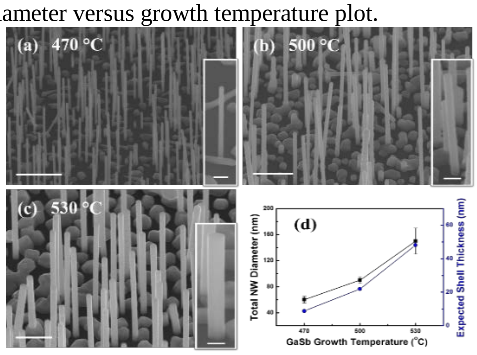

Fig 2 45° SEM images of InAs/GaSb heterostructure NWs with various GaSb growth temperatures of (a) 470°C (b) 500°C (c) 530°C. Inserts in (a)-(c) are high magnification images. Scale bars are 1μm in (a)-(c) and 200nm in the inserts. (d) Corresponding Total diameter/expected GaSb shell thickness versus growth temperature plot.

To verify the GaSb radial and axial growth variation with growth temperature, InAs/GaSb NWs were examined by HRTEM. Fig 3(a-c) shows HAADF-STEM images of InAs/GaSb heterostructure NWs grown at 470°C, 500°C and 530°C respectively. All InAs/GaSb NWs exhibited the clear contrast between the core and the shell. As seen, the dark line corresponding to the interface is straight and does not exhibit any roughness. So we believe the interface is abrupt. Fig 3 (a-c) inserts shows the axial growth behavior of GaSb with growth temperature variation. Substrate temperatures of 500°C and lower shows no sign of GaSb axial growth, shows only uniform and continuous InAs/GaSb core-shell NWs. Above 500°C the GaSb axial growth was found (Fig 3(c)) and axial GaSb length increases with temperature. Fig 3(d) shows the graph between the GaSb shell thickness and axial length versus GaSb growth temperature. The GaSb shell thickness is in good agreement with the expected value from SEM analysis. The radial growth rate varied between 0.44 nm/min to 1.67 nm/min and the axial growth rate varied between zero to 3.2 nm/min depending on the growth temperature. Both the growth rates increase as the temperature increases.

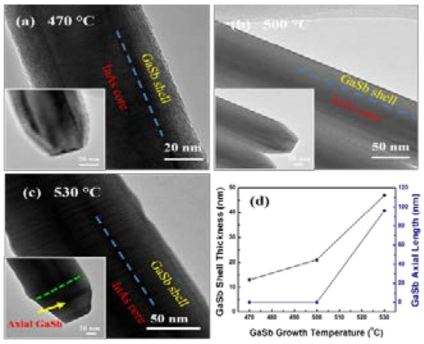

Fig 3 HAADF-STEM image of InAs/GaSb heterostructure NWs with different growth temperatures of (a) 470°C (b) 500°C (c) 530°C and (d) Plot between GaSb shell thickness/axial length versus growth temperature.

4. Conclusions

Self-catalyst growth of vertically aligned InAs and InAs/GaSb heterostructure nanowires on Si(111) substrate by MOCVD has been demonstrated. SC InAs and InAs/GaSb heterostructure NWs were grown by varying the growth temperature and keeping other growth parameters constant. Control on diameter and length of SC InAs NWs and GaSb shell thickness were achieved by controlling growth temperature. Uniform thickness and smooth GaSb shell around SC InAs NWs were achieved at 500 °C.

Acknowledgements

This work was sponsored by TSMC, NCTU-UCB I-RiCE program and Ministry of Science and Technology Taiwan under grant no. MOST 106-2911-I-009-301.

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