Synthesis and characterization of InGaAs nanowires grown by MOCVD

D Gustiono, E Wibowo and Z Othaman

1 Ibnu Sina Institute for Fundamental Science Studies, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia.
2 Agency for Assessment and Application of Technology, BPPT second building Jakarta 10340, Indonesia
3 Department of Physics, Faculty of Mathematic and Science, Universitas Negeri Semarang, Semarang, Indonesia.

E-mail: gustiono@ibnusina.utm.my

Abstract. Semiconductor nanowires have been intensively investigated in order to study their unique fundamental and application properties that develop at the nano-scale. One of main problems in the growth of III-V semiconductor nanowire is uniformity both of in dimension and composition of chemical elements. We synthesized InGaAs nanowire on GaAs (111) substrate at 400 °C – 480 °C temperatures for 30 minutes using MOCVD. The nanowires grow perpendicular to the substrate via direct impinging mechanism and they have hexagonal shape with diameter of 80-150 nm. Dimension of nanowire, length and diameter, increase with increases of growth temperature. Formations of tapering could be controlled with growth at lower temperature.

1. Introduction

Semiconductor nanowires attracted significant attention due to their potential applications as building blocks for future nanoscale circuits and optoelectronic devices. Semiconductor nanowire InGaAs is one of the most marvelous III–V ternary compounds offer amazing properties for applications in long wavelength optical transmission and integrated photonics applications [1,2]. The nanowire is also considered to be one of the fascinating materials suitable for transistor channels for large scale device applications due to its low electron effective mass [3,4]. Performance of nanowires depend on their physical and chemical properties, such as crystallinity, microstructure and chemical composition need to be uniform and well controlled [5,6].

Last decade, semiconductor nanowire with different compositions have been successfully grown using seed particles via vapor–liquid–solid (VLS), vapor–solid–solid (VSS), and solid–liquid– solid (SLS) mechanisms based on self-organized growth. [7-13]. In particular, III–V nanowire seed-particles assisted epitaxial growth using metal organic chemical vapor deposition (MOCVD) offers the ability to control the diameter and chemical composition [14]. The nanowire growth process, using gold as seed particles, promotes either VLS or VSS mechanism [14-16]. Initially, the gold nanoparticles on the semiconductor substrate surface form either a liquid (in case of VLS) or solid–
alloy (in case of VSS) with the group III species (source atoms) nanowire growth occurs with gold nanoparticles at the tip of each nanowire due to the source material precipitates out at the nanoparticle–semiconductor interface [7-9]. The diameter of NW is controlled by the size of the seed particle and its length is determined by the growth time and conditions [17].

In this work, we describe the growth of InGaAs nanowires by MOCVD. Cylindrical-hexagonal nanowire with diameter of 80-150 nm were grown perpendicular to the substrate. Dimension of nanowire, length and diameter, is going to increase with increases of growth temperature. Energy dispersive X-ray spectroscopy (EDX) analysis and transmission electron microscopy (TEM) observation of InGaAs nanowire is also reported.

2. Experimental procedures

We used GaAs(111) as substrate for the growth of nanowires and using MOCVD equipment as a technique of growth. The MOCVD chamber was maintained at low pressure 0.1 atm. Electronic grade hydrogen gas was used as the carrier for the ternary atoms to the growth chamber. Trimethylindium (TMIn), trimethylgallium(TMGa) and arsine (AsH₃) chemicals were used as precursors. GaAs with (111) energetically favorable growth direction was chosen as the substrate due to its low surface energy [2,19]. The substrate was immersed in 0.1% poly-L-lysine (PLL) solution for 3 min prior to the nanowires growth on the substrate. The negatively charged Au particles are attracted to the positively charged PLL layer and get embedded onto the substrate surface. The substrate was then cleaned with de-ionized water and subsequently blow-dried with nitrogen (N₂). It was then treated with 50% gold colloid solution (30 nm diameter gold particle) for 30 seconds. The substrate was then placed in MOCVD chamber after gold seed particles were deposited on substrate surface. It was then heated up to 600 °C under constant partial pressure of AsH₃ gas for 10 minutes to eliminate surface contamination and then cooled down to the desired growth temperature. When the growth temperature was reached, TMIn, TMGa, and AsH₃ were injected into the chamber. The flow rate of TMIn, TMGa, and AsH₃ were set at 100 sccm, 2 sccm and 32 sccm, respectively. The growth time was set at 30 minutes, growth temperature at 400 °C, indium mole fraction (x) at 0.41, and V/III ratio at 10. Field emission-scanning electron microscopy (FE-SEM) and TEM have been used to investigate the morphology of nanowires. The chemical composition of nanowires has been investigated using EDX analysis.

3. Results and discussions

![Figure 1. SEM images of InGaAs nanowires grown on GaAs (111) substrate at 400 °C (a), 420°C (b), 450°C (c) and 480°C (d) temperatures using MOCVD.](image)

Figure 1. SEM images of InGaAs nanowires grown on GaAs (111) substrate at 400 °C (a), 420°C (b), 450°C (c) and 480°C (d) temperatures using MOCVD.
Figure 1 shows SEM images of InGaAs nanowires grown on GaAs (111) substrate from 400 °C to 480 °C temperatures for 30 minutes. InGaAs nanowires grow in multiple orientations, where orientations toward <111> are dominant. The nanowires have cylindrical shape with length about 0.2-1.5 μm and diameter about 80-150 nm as seen in figure 1(a). Nanowires grow by direct impinging mechanism via VSS mechanism where source atoms of precursors directly fall onto gold seed particles to form a liquid solution and partially molten state of an alloy [18]. A gold seed particle serves as a preferential site for the decomposition of the source atom via absorption and diffusion mechanism. Dimension of the nanowire increase with increases temperatures as shown in figure 1(b), figure 1(c) and figure 1(d). Increasing of growth temperature may give additional energy to source atoms or precursors, therefore precursor atoms fall onto the substrate surface obtain extra energy to move through substrate surface via diffusion mechanism. Since the seed particles act as the preferential sites for the decomposition of the source atoms which lead to nucleation. Source atoms from the substrate surface tend to move towards the seed particles and contribute to the growth of the nanowires via diffusion mechanism and induce tapering, whereby the top of the nanowire is highly small compared to the base one as seen in figure 1(d).

In addition, it can be observed in figure 1 that the InGaAs nanowires grown were of different diameters and lengths. The distribution of diameter and surface density of nanowires was due to the annealing effect (temperature and time) on the distribution of gold particles on the surface of substrate before the growth precursors were injected. Since they can obtain some extra energy, the adjacent gold particles could combine together to form the larger size through the Ostwald ripening mechanism [19]. On the other hand, gold particles that did not combine together retain their sizes. Besides, the incorporation of significant amount of precursor into the seed particle is another way to change the size of seed particle. Consequently, seed-particle-assisted nanowires grown have different diameters. Hence, Ostwald ripening and incorporation of growth precursor both can change the size of the gold seed particle. Due to the presence of these mechanisms, some nanowires were grown with diameter around six times larger than the diameter of gold particle. Moreover, nanowires with smaller diameter grow shorter than the larger ones due to different growth rate. The classical analysis of Givargizov concluded that narrower wires grow more slowly due to Gibbs–Thomson effect [20]. Other studies, however, show the opposite, narrow wires growing more rapidly [21].

Figure 2. (a) Typical of SEM image of InGaAs nanowire grown at 400 °C temperature on GaAs (111) substrate using MOCVD. (b) EDX analysis of top, mid and bottom regions of the InGaAs nanowire.
Figure 2 show a typical SEM image of InGaAs nanowire grown on GaAs (111) substrate at 400 °C temperature for 30 minutes (a). The body of nanowires are formed by stacking of hexagonal shape, where stacking mode is caused by planar defects as twinning as seen in figure 2(a). EDX analysis has been used to investigate the chemical composition of individual InGaAs nanowire from various detection positions: tip, middle and bottom as shown in figure 2(b). Gold was still detected but uncounted even on the tip of the nanowire. This is likely due to very small amount of gold compared to the other elements of the nanowire. This phenomenon also proves that the increasing size of seed particle was mainly contributed by incorporation of growth precursor into the seed particle rather than Ostwald ripening mechanism. Therefore, the composition of seed particle is more likely from gold–precursor alloy nanoparticles.

Figure 3 shows one set of TEM images of InGaAs nanowire grown on GaAs (111) substrate at 420 °C temperature for 30 minutes at low and high resolutions. Figure 3(a) confirms again about the morphology of nanowire revealed dark region at top part of nanowire is gold seed particles and mid till bottom parts have tapered. Movement and diffusion of substrate atomics toward the seed particles induce tapering. TEM image also confirm the validity of the absorption, diffusion and precipitation process during direct impinging mechanism. As a result, gold–precursor alloy nanoparticles can only be found at the tip of NW, not elsewhere along the nanowires. Besides, TEM images provide evidence of the occurrence of Ostwald ripening and incorporation of growth precursor into the seed particle. The sidewalls of the nanowires are extremely flat, except for at the twin boundary where constriction can be seen clearly. The constriction is suggested accommodates mismatches at the twin boundary as shown in figure 3(b). Lattice space or range of atomic planes (110) was determined about 0.3433 nm and it was also determined that crystal structure of the nanowire is typical zinc-blende as shown in figure 1(c).

Figure 3. Typical of TEM images of InGaAs nanowire grown at 420°C temperature on GaAs (111) substrate using MOCVD were observed at low, low and high resolutions.
4. Conclusions

Semiconductor nanowire InGaAs has been grown at low growth temperature using MOCVD. The InGaAs nanowire has cylindrical-hexagonal shape grow perpendicular to the substrate via VSS direct impinging mechanism. The bodies of nanowire have planar defect and their crystal structure is typical zinc-blende. The In/Ga ratio on the tip, middle and bottom of nanowires were slightly different but tends to have uniform chemical composition. The growth temperature give effect of increases of length and diameter of nanowires and at lower temperature, tapering could be controlled.

Acknowledgments

We thank to the Ministry of Higher Education of Malaysia for the financial support via RU grants with Vote No: 78339 and 02J85.

References

[1] D. M. Cornet and R. R. La Pierre 2007 Nanotechnology 18, 385305
[2] Y. Kim, H. J. Joyce, Q. Gao, H. H. Tan, C. Jagadish, M. Paladagu, J. Zou and A. A. Suvorova, T. Sato, Y. Kobayashi, J. Motohisa, S. Hara and T. Fukui 2008 J. Cryst. Growth 310, 5111
[3] T. Sato, J. Motohisa, J. Noborisaka, S. Hara and T. Fukui 2008 J. Cryst. Growth 310, 2559
[4] T. Sato, Y. Kobayashi, J. Motohisa, S. Hara and T. Fukui 2008 J. Cryst. Growth 310, 5111
[5] M. E. Messing, K. Hillerich, J. Johansson, K. Deppert and K. A. Dick 2009 Gold Bull. 42, 172
[6] H. J. Joyce, Y. Kim, Q. Gao, H. H. Tan and C. Jagadish 2007 Proc. 2nd IEEE Int. Conf. Nano/ Micro Engineered and Molecular Systems, Bangkok, Thailand.
[7] S. Kodambaka, J. Tersoff, M. C. Reuter and F. M. Ross 2009 Phys. Rev. Lett. 96, 096105
[8] D. Jishiaishvili, V. Kapaklis, X. Devaux, C. Politis, E. Ketelia, N. Makhatadze, V. Gobronidze and Z. Shoilashvili 2009 Adv. Sci. Lett. 2, 40.
[9] E. J. Schwalbach and P. W. Voorhees 2008 Nano Lett. 8, 3739
[10] H. Adhikari, A. F. Marshall, C. E. D. Chidsey and P. C. McIntyre 2006 Nano Lett. 6, 318
[11] J. L. Lensch-Falk, E. R. Hemesath, F. J. Lopez and L. J. Lauhon 2007 Am. Chem. Soc. 129, 10670
[12] M. Omari, N. Kouklin, G. Lu, J. Chen and M. Gajdardziska-Josifovska 2008 Nanotechnology 19, 105301
[13] K. W. Kolinski 2006 Solid State and Mater. Sci. 10, 182
[14] H. J. Joyce, Q. Gao, H. H. Tan and C. Jagadish 2007 Proc. 20th Annual Meeting of the Lasers and Electro-Optics Society, Lake Buena Vista, Florida, USA
[15] K. A. Dick, K. Deppert, L. Samuelson and W. Seifert 2007 J. Cryst. Growth 298, 631
[16] H. J. Joyce, Y. Kim, Q. Gao, H. H. Tan and C. Jagadish 2006 Proc. Int. Conf. Nanoscience and Nanotechnology, Brisbane, Australia
[17] L. Samuelson, C. Thelander, M. T. Bj¨ork, M. Borgstr¨om, K. Deppert, K. A. Dick, A. E. Hansen, T. M˚artensson, N. Panev, A. I. Persson, W. Seifert, N. Sk’old, M. W. Larsson and L. R. Wallenberg 2004 Physica E 25, 313
[18] X. Duan and C. M. Lieber 2004 Adv. Mater. 12, 4
[19] G. Cao, 2003 Nanostructures and Nanomaterials: Synthesis, Properties and Applications (Imperial College Press, London).
[20] E. I. Givargizov, 1975 J. Cryst. Growth 31, 20.
[21] K. A. Dick, D. Knut, L. Samuelson and W. Seifert 2006 J. Cryst. Growth 297, 326