ELECTRONIC TRANSPORT PROPERTIES OF INDIUM ANTIMONIDE NANOWIRE CLUSTERS SYNTHESIZED BY ELECTRODEPOSITION METHOD

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

March 2019

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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March 2019

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Indium antimonide (InSb) is a promising semiconducting material that has been implemented in various electronic applications due to its high carrier mobility and carrier density. In particular, studies of InSb nanowire clusters have yet to be explored in detail, despite the advantages of wire clusters can bring to the to the touch screen technologies and flexible devices. Therefore, the main focus of this thesis is to study the electronic transport properties within InSb nanowire clusters such as schottky barrier height (SBH), conductivity, carrier density, and carrier mobility. According to field emission scanning electron microscope-energy dispersive x-ray (FESEM-EDX) analysis, the clusters comprised of agglomerated, flowery-shaped nanowires and bulk InSb, with stoichiometric 1:1 ratio. The x-ray diffraction (XRD) analysis shows that the wire clusters exhibit polycrystalline nature, with several impurities present such as Sb, In_2O_3, Sb_2O_3, and Al_2O_3. In order to study the electrical transport behaviours of InSb nanowire clusters, two parameters, namely nanowire diameters and contact gap widths were chosen. For the effects of nanowire diameters, it was observed that most electronic transport properties such as conductivity (0.34 to 3.61 × 10^{-4} S/m), carrier density (7.41 to 7.49 × 10^{10} cm^{-3}), and carrier mobility (0.48 to 4.82 × 10^{-15} cm^2 V^{-1} s^{-1}) increases with increasing diameters (20 to 200 nm). This is due to several reasons such as decreased grain boundaries and scattering effects, as well as increased electron charge density, thus allowing easier movement of carriers throughout the metal-semiconductor-metal (MSM) junction. Meanwhile, SBH is shown to be inconsistent with increasing diameter, which is possibly because of the presence of InSb bulk structure that might have influenced the electronic transport within the wire clusters. For the effects of contact gap width, most of the electronic transport properties such as conductivity (1.67 to 4.58 × 10^{-5} S/m), carrier density (7.41 to 7.45 × 10^{10} cm^{-3}), and carrier mobility (0.23 to 0.61 × 10^{-15} cm^2 V^{-1} s^{-1}) were shown to increase with decreasing gap size (343.07 to 277.72 μm), while SBH decreases (0.68 to 0.66 eV). This is because of the closer distribution within nanowire clusters when the gap width decreases, and hence improving the current transport

throughout the MSM junction. Due to several factors such as presence of defects and less compact distribution compared to particle arrangements within bulk structure, thin film and single nanowire, nanowire clusters exhibit lower electronic transport properties. Nevertheless, further investigations on the semiconductor nanowire clusters will open more opportunities to discover its potentials in a wide variety of electronic components in the future.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

SIFAT-SIFAT PENGANGKUTAN ELEKTRONIK DALAM KLUSTER NANOWAYAR INDIUM ANTIMONIDE YANG DISINTESIS OLEH KAEDAH PENGELEKTROENDAPAN

Oleh

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Indium antimonide (InSb) ialah bahan semikonduktor berpotensi, yang telah dilaksanakan dalam pelbagai aplikasi elektronik oleh sebab mobiliti pembawa dan ketumpatan pembawanya yang tinggi. Khususnya, kajian terhadap kluster nanowayar InSb masih belum diterokai secara terperinci, walaupun dengan kelebihan kluster nanowayar yang boleh membawa kepada teknologi skrin sentuh dan peranti fleksibel. Oleh itu, fokus utama tesis ini adalah untuk mengkaji sifat-sifat pengangkutan elektronik dalam kluster nanowayar InSb seperti ketinggian halangan Schottky (SBH), kekonduksian, ketumpatan pembawa, dan mobiliti pembawa. Menurut analisis perwatakan mikroskop elektron pengimbasan pancaran medan-spektroskopi tenaga serakan (FESEM-EDX), kluster tersebut terdiri daripada nanowayar agglomerasi berbentuk bunga dan InSb pukal, dengan nisbah stoikiometrik 1:1. Pembelauan sinar-x (XRD) analisis menunjukkan kluster nanowayar mempunyai sifat polihabluran, dengan beberapa bendasing seperti Sb, In_2O_3, Sb_2O_3, and Al_2O_3. Bagi mengkaji sifat-sifat pengangkutan elektronik nanowayar kluster InSb, dua parameter, iaitu diameter nanowayar dan keluasan jurang kontak telah dipilih. Untuk kesan diameter nanowayar, dapat diperhatikan bahawa kebanyakan sifat pengangkutan elektronik seperti kekonduksian (0.34 kepada 3.61 × 10^{-4} S/m), ketumpatan pembawa (7.41 kepada 7.49 × 10^{10} cm^{-3}), dan mobiliti pembawa (0.48 kepada 4.82 × 10^{-15} cm^2 V^{-1} s^{-1}) meningkat dengan peningkatan diameter (20 kepada 200 nm). Ini adalah disebabkan oleh beberapa faktor seperti pengurangan sempadan butiran dan kesan-kesan penyerakan, serta peningkatan ketumpatan cas elektron, justeru memudahkan pergerakan pembawa sepanjang simpangan logam-semikonduktor-logam (MSM). Sementara itu, SBH menunjukkan ketidakaturan dengan peningkatan diameter, berkemungkinan disebabkan oleh kehadiran struktur pukal InSb yang telah mempengaruhi pengangkutan elektronik di dalam kluster-kluster nanowayar tersebut. Untuk kesan kelebaran jurang kontak, kebanyakan sifat pengangkutan elektronik seperti kekonduksian (1.67 kepada 4.58 × 10^{-5} S/m), ketumpatan

pembawa (7.41 kepada 7.45 × 10^{10} cm^{-3}), dan mobiliti pembawa (0.23 kepada 0.61 × 10^{-15} cm^2 V^{-1} s^{-1}) dilihat meningkat dengan berkurangnya lebar jurang (343.07 kepada 277.72 μm), sementara SBH pula berkurang (0.68 kepada 0.66 eV). Ini adalah disebabkan oleh taburan kluster nanowayar yang makin dekat apabila lebar jurang berkurang, justeru memperbaiki pengangkutan arus sepanjang simpangan MSM. Oleh kerana beberapa faktor seperti kewujudan kecacatan dan kurangnya taburan yang padat dibandingkan dengan susunan zarah di dalam struktur pukal, selaput tipis, dan nanowayar tunggal, kluster nanowayar mempunyai sifat-sifat pengangkutan elektrik yang lebih rendah. Walau bagaimanapun, lebih banyak penyelidikan ke atas kluster nanowayar semikonductor akan membuka lebih peluang untuk menerokai potensinya di dalam pelbagai jenis komponen elektronik pada masa hadapan.

ACKNOWLEDGEMENTS

In the name of Allah s.w.t The Most Gracious, The Most Merciful. An utmost gratitude highly dedicated to Him for His abundant rahmah and bless. First and foremost, I would like to express my most sincere gratitude for my supervisor, Dr. Suriati binti Paiman for her continuous support of my Masters study, as well as her patience, motivation, enthusiasm, and immense knowledge. Her guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Masters research. Besides her, Dr. Nizam bin Tamchek as a co-supervisor also has contributed a lot to my research, especially in regards of understanding the important aspects in electronic transport behaviours. I would like to extend my special thanks to other lecturers as well such as Dr. Nurul Huda binti Osman, Dr. Josephine Liew Ying Chyi, Assoc. Prof. Dr. Roslina binti Mohd Sidek, Assoc. Prof. Dr. Suhaidi bin Shafie and Dr. Hussein Abdullah Hussein Baqiah for their insightful comments and helpful advices. Additionally, I am deeply grateful to the research team from Institute of Nanoelectronic Engineering (INEE), UniMAP, which consists of Prof. Dr. Uda bin Hashim, Mr. Mohd Aizat bin Abd Rane, Mrs. Nurshamira binti Shohaimi, Mohd Isa bin Ahmad Azan, Siti Fatimah binti Abdul Rahman, and Sharifah Nadzirah binti Syed Ahmad Ayob. These people have largely contributed on the fabrication of Al contact pads. I thank my fellow labmates, Osamah Ali Fayyadh, Ms. Azelah, Ms. Nurul Assikin, Ms. Nur Aliffah, and Mr. Shamsu Abubakar, for the stimulating discussions and all the times working together in order to complete our own journals and thesis. Last but not least, a most heartfelt gratitude for all my family and friends for their continuous support and love throughout my life. Financial supports from Ministry of Higher Education (MyBrain15) and UPM (GRF) are also greatly acknowledged.

I certify that a Thesis Examination Committee has met on 27 March 2019 to conduct the final examination of Intan Nur Ain binti Arifin @ Mohd Ripin on her thesis entitled ("Electronic Transport Properties of Indium Antimonide Nanowire Clusters Synthesized by Electrodeposition Method") in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AAO	Anodic Alumina Oxide
Ag/AgCl	Silver Chloride electrode
Al_2O_3	Aluminium Oxide
$C_4H_6O_6.H_2O$	Tartaric Acid
CVD	Chemical Vapor Deposition
EDX	Energy Dispersive X-Ray Spectroscopy
EBL	Electron Beam Lithography
FE-SEM	Field Emission Scanning Electron Microscope
FETT	Field Effect Transistor
HCL	Hydrochloric Acid
HPM	High-Powered Microscope
In	Indium
$InCl_3$	Indium(III) Chloride
In_2O_3	Indium(III) Oxide
InSb	Indium Antimonide
MSM	Metal-Semiconductor-Metal
NaOH	Sodium Hydroxide
PVD	Physical Vapour Deposition
SBH	Schottky Barrier Height
Sb	Antimony
$SbCl_3$	Antimony(III) Chloride
Sb_2O_3	Antimony(III) Oxide
Si	Silicon
SiO_2	Silicon Dioxide
UV	Ultraviolet
XRD	X-Ray Diffraction

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

In recent years, nanoscale science and technology have become a significant aspect in producing components for optoelectronic and microelectronic devices. This is because current device fabrication aims for miniaturization of designs with better performance, making them easier to carry and store. For example, transistors, the basic switches that enable all modern computing, have been demonstrated capable of performing at the nanoscale size, comparable to the bulk transistors (Amuru, Ragini, & Reddy, 2016). Furthermore, these nanoscale materials possess a significant advantage than their bulk counterparts, in which their optical, electronic, and magnetic properties can be tailored by changing their sizes accordingly. This is because of the quantum confinement effects that often dominate the materials once their sizes reach nano-scale level (Suresh, 2013).

Among the nanostructures, nanowires have attracted much interest among researchers. A nanowire is defined as one-dimensional, cylindrical-shaped nanostructure, with the diameter of the order of a nanometer (10^{-9} m) and the length of the order of a micrometer (10^{-6} m). Unlike other low-dimensional systems, nanowires have two quantum-confined directions but one unconfined direction available for electrical conduction (Dresselhaus et al., 2010). This allows nanowires to be used in devices that require electrical conduction instead of tunnelling transport. There are several types of nanowires, with the most commonly investigated materials being metal and semiconductor nanowires. Semiconductors in general have the ability to alter their conductivity either by doping or various stimulations such as electric current, electromagnetic field, and even light. Thus, it is possible to create various devices from semiconducting nanowires that can amplify, switch, or convert sunlight into electricity, or produce light from electricity (Dasgupta & Yang, 2014).

In particular, indium antimonide (InSb) is one of the semiconductors that exhibits outstanding electronic characteristics. This material is comprised of group III (In) and group V (Sb) elements, and has been reported to possess one of the highest carrier mobility (7.7×10^4 cm^2 V^{-1} s^{-1}) and carrier density (2.0×10^{16} cm^{-3}) among III-V semiconductor group (Rode, 1971). Thus, InSb nanowires make for an excellent candidate for electronic applications that aim for low power and high-speed performance (Hnida et al., 2015).

1.2 Motivation and Problem Statement

As nanotechnology developed, significant advancement has been made in the past two decades where various types of nanowire assemblies can be incorporated into devices depending on their specific functions and performance (Liu, Liang, and Yu, 2012). Nanowire assemblies can be in the form of nanowire arrays, single nanowire or nanowire clusters, as can be seen in Figure 1.1. Nowadays, nanowire clusters or networks have found its importance in various photoelectronic and thermoelectronic devices (Rojo et al., 2013; Xue et al., 2017). For example, flat panel displays and touch screen technologies have implemented nanowire clusters into their devices. This is because they require large amount of nanowires that are electrically connected in close vicinity (Rojo et al., 2013). Despite the growing interest of these technologies, the electronic transport properties of nanowire clusters has yet to be much understood, in comparison to the single nanowire or nanowire arrays. The previous studies may have mentioned about electrical conductivity, but rarely go deeper into other electrical coefficients such as carrier density and mobility (Nilsson et al., 2011; Fang et al., 2015).

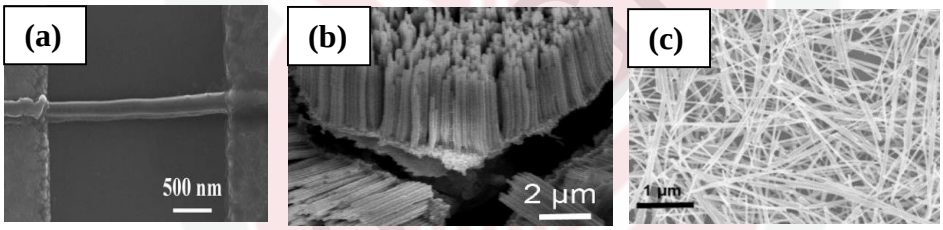

Figure 1.1: Types of nanowire assembly. (a) Single nanowire (Qi et al., 2014)**, (b) Nanowire arrays** (Fang et al., 2015)**, and (c) Nanowire clusters** (Langley, 2014)

Furthermore, only limited number of materials are being employed in the devices that implement nanowire clusters, such as metal or indium tin oxide (ITO). This is due to their capability of being synthesized in abundance with good structural, optical, and electronic transport properties (Hecht, Hu, and Irvin, 2011; Hu, Wu, and Cui, 2011). Nanowire-based thin film transistors (NW-TFT) is one of the applications that aim to utilize nanowire clusters with high carrier mobilities and densities as a mean to produce flexible and wearable device in the future (Duan, 2007). However, such device is still limited to silicon and metal nanowires due to difficulty in assembling the compound semiconductors onto the device substrate (Duan, 2007). Therefore, it is great opportunity to explore compound semiconductors such as InSb in the form of nanowire clusters in order to realize its potential in future electronic applications.

As a mean to understand the electronic behaviour of InSb nanowire clusters, two parameters are chosen in this study, which are nanowire diameter and contact gap width. The two parameters have been reported to have significant influence

on the electronic transport properties of nanowires (Ford et al., 2009; Averine and Kuznetzov, 2008). Due to the enhanced surface-to-volume ratio, the properties of nanostructures in general are highly dependent on its size (Shin et al., 2016). For nanowires, reducing its diameter will cause the contribution of surface electrons to increase while also increasing the scattering effects (Dayeh, 2010). However, these observations have mainly been reported on the single nanowire measurements. With bundles of nanowires distributed closely together as well as its different configuration from single nanowire, it is expected that the nanowire clusters will exhibit different electronic transport behaviours.

Another parameter to be studied is contact gap width. For this parameter, several studies have reported on the decrease of transit time of the carriers and detector response when the gap fingers of interdigitated electrodes are reduced (Averine and Kuznetzov, 2008). However, it is to be noted that distribution of nanowire clusters can also be affected as a result from having narrower wedge, or contact gap width (Basu and Cross, 2015). This is especially evident for the samples that are dispersed using conventional dropcasting method, which fluid viscosity and surface tension of the distilled water heavily influence the distribution of nanowire clusters after dried (Baek et al., 2018). Although these studies have verified that different gap widths will affect distribution of wire clusters, they have yet to explore further on its optical or electronic transport properties. Hence, the study on the electronic behaviours of nanowire clusters under different gap widths is important in order to benefit various applications that use large-area of substrates for placing the randomly distributed nanowire clusters (Rojo et al., 2013).

1.3 Scope of the Study

This study aim to explore the electronic transport properties of InSb nanowire clusters which are synthesized via template-assisted electrodeposition method. The growth method is a technique that utilizes a porous anodic alumina oxide (AAO) template as a working electrode, enabling the In and Sb ions from electrolyte solution to gather and form into nanowires in the pores of the template. The template is then removed, leaving only the freely-aligned nanowires stored inside the distilled water and later dispersed on a substrate when needed for characterizations. The nanowires will be synthesized according to the optimized growth parameters (Kharudin, 2017) in hope of obtaining good structural properties. Simple, fast, and cost-efficient electronic measurement technique is considered in order to create the electrical contact for the InSb nanowire clusters. Therefore, basic electrical contact pads via typical photolithography steps are fabricated. The electrical characterization is carried out using two aluminium (Al) metal contact pads that connect to the dropcasted nanowires, forming an MSM junction. The current-voltage (I-V) plot obtained from two-point probe measurements determines the electronic behaviour of the nanowire clusters. Schottky barrier height (SBH), conductivity carrier density, and carrier mobility are all important electrical coefficients, and can be extracted from the I-V measurements. Diameter of the AAO pore template (which influences the diameter of the nanowires) and gap width of the contact pads are

chosen as parameters in this study in order to investigate their influences on the electronic transport properties of InSb nanowire clusters.

1.4 Research Objectives

This study focuses on the following objectives:

1. To synthesize InSb nanowires using anodic alumina oxide (AAO) template with 20 nm, 100 nm, and 200 nm pore diameters via electrodeposition method, and then fabricate the aluminium contact pads with different width of gaps ranging from 100 to 400 μm using photolithography method.
2. To determine the structural properties of the deposited InSb nanowires using Field Emission Scanning Electron Microscope (FESEM), Energy Dispersive X-Ray Analysis (EDX), and X-Ray Diffraction Pattern (XRD).
3. To investigate the schottky barrier height (SBH), electrical conductivity, carrier density, and carrier mobility of InSb nanowire clusters with different nanowire diameters and width of gaps using two-point probe measurement.

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