Silicon Nanowire Sensor from Electron Beam Lithography: Design, Fabrication and Characterization

by

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DEDICATION

Al- Fatihah to my brother, Allahyarham Harmanizam Abd Rahman, may Allah S.W.T bless you. Special dedication to my parents, Abd Rahman Aras and Hatijah Mat, and my siblings, who have supported me all the way since the beginning of my studies. May Allah S.W.T bless all of us, Amin.

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LIST OF ABBREVIATIONS

1D	One dimensional
Acc. Voltage	Accelerating voltage
AFM	Atomic Force Microscope
Al	Aluminum
Au	Aurum
BF	Bright Field
BOE	Buffered Oxide Etch
BOX	Buried-Oxide
CMOS	Complementary Metal-Oxide-Silicon
CVP	Chemical Vapor Deposition
DI	De-ionized
DK	Dark Field
DNA	Deoxyribonucleic Acid
dsDNA	Double-stranded DNA
E-beam	Electron-beam
EBL	Electron Beam Lithography
FET	Field Effect Transistor
GDS II Editor	Graphic Display System II Editor
H_2	Hydrogen
HPM	High Power Microscope
ICP-RIE	Inductive Coupled Plasma-Reactive Ion Etching
ISFET	Ion-Selective Field Effect Transistor
I-V	Current-Voltage
KOH	Kalium Hydroxide
LPM	Low Power Microscope
MBE	Molecular Beam Epitaxy
NW	Nanowire
PMMA	Polymethyl Methacrylate

PR	Photoresist
PVD	Physical Vapor Deposition
RIE	Reactive Ion Etching
RTA	Rapid Thermal Annealing
SEM	Scanning Electron Microscope
Si	Silicon
SiH_4	Silane
SiNW	Silicon Nanowire
SiO_2	Silicon Dioxide
SiOH	Silanol
SMU	Source Measurement Units
SOI	Silicon-On-Insulator
SPA	Semiconductor Parametric Analyzer
SPR	Surface Plasmon Resonance
ssDNA	Single-stranded DNA
TEM	Transmission Electron Microscopy
UV	Ultraviolet
VLS	Vapor Liquid Solid
WCM	Wet Cleaning Module
ZnO	Zinc Oxide

LIST OF SYMBOLS

d	Diameter
l_c	Carrier mean free path
W	Width
H^+	Hydrogen ion
I	Current (A)
R	Resistance (Ω)
V	Voltage (V)
S	Sensitivity
R_0	initial resistance (Ω)
ΔR	change in resistance (Ω)

SILIKON NANOWAYAR PENDERIA MENGGUNAKAN LITOGRAFI ALUR ELEKTRON: REKABENTUK, FABRIKASI DAN PENCIRIAN

ABSTRAK

Kajian ini menunjukkan proses pembangunan penderia SiNW yang memerlukan kedua-dua permintaan iaitu menghasilkan wayar berskala nano dan berintegrasi dengan kebiasaan proses CMOS. Sebelum proses fabrikasi yang sebenarnya, penderia SiNWs direka bentuk dengan menggunakan Elphy Quantum GDS II Editor dan AutoCAD. Sejumlah empat corak iaitu nanowayar, tanda penjajaran, petak elektrod dan kawasan penguji telah direkabentuk untuk menghasilkan peranti penderia SINWs yang lengkap. Dengan menggunakan silikon atas penebat sebagai bahan permulaan, nanowayar dihasilkan dengan menggunakan pendekatan atas-bawah yang melibatkan Mikroskop Pengimbas Elektron berasaskan kaedah Litografi Alur Elektron. Kesan pada lebar garis dan dos dedahan keatas struktur corak dikaji dengan menggunakan fotorintang negatif ma-N2403 untuk Litografi Alur Elektron. Pelbagai dos dedahan dalam lingkungan 50µC/cm^2 hingga 180µC/cm^2 pada pemecutan voltan 20kV dengan arus alur 0.075nA didedahkan ke atas fotorintang negatif tersebut. Nanowayar topeng kerintangan dihasilkan dengan sempurna iaitu mempunyai dimensi kurang daripada 100nm lebar pada dos dedahan berparameter 80µC/cm^2, 100µC/cm^2 dan 120µC/cm^2. Selepas itu, dua elektrod logam yang direka sebagai sumber dan salur keluar telah dibangunkan ke atas setiap nanowayar dengan menggunakan proses litografi konvensional. Ciri-ciri mofologi, elektrik dan kimia telah digunakan untuk melihat hasil peranti yang dibina. Bahagian-bahagian utama adalah untuk meneliti profil nanowayar dalam membuktikan ianya adalah berskala nano dengan menggunakan Hawk 3D-nanoprofiler dan untuk menguji prestasi peranti secara elektrik dengan menggunakan Semikonduktor Parametrik Analyzer (SPA) dalam hal berkaitan arus-voltan. SiNW terkecil dengan diameter 65nm yang dijajarkan dengan sempurna dengan pelapik elektrod telah diperoleh. Akhirnya, peranti yang dibina telah digunakan sebagai pengesanan tahap pH. Tiga jenis larutan penampan dengan pH 4, pH 7 dan pH 10 digunakan untuk menguji tindak balas elektrik peranti tersebut. SiNWs penderia menunjukkan nilai pernentangan tertinggi bagi pH 4 dan nilai penentangan terendah bagi pH 10. Dari segi kepekaan, peranti dengan nanowayar yang lebih kecil didapati lebih sensitif berbanding nanowayar yang lebih besar hasil daripada nisbah permukaan tinggi untuk isipadu.

SILICON NANOWIRE SENSOR FROM ELECTRON BEAM LITHOGRAPHY: DESIGN, FABRICATION AND CHARACTERIZATION

ABSTRACT

This study demonstrates the process development of silicon nanowires (SiNWs) sensor requires both the fabrication of nanoscale diameter wires and standard integration to CMOS process. Prior to actual fabrication process, the SiNWs sensor is designed via Elphy Quantum GDS II Editor and AutoCAD. A total of four designs namely nanowire, alignment mark, electrode pad and test channel are designed in order to create a complete SiNWs sensor device. By using silicon-on-insulator (SOI) wafer as a starting material, the nanowires is fabricated using a top-down approach which involved Scanning Electron Microscope (SEM) based Electron Beam Lithography (EBL) method. The effect of line width and exposure dose on the pattern structure is investigated experimentally using the negative photoresist ma-N2403 for EBL. The exposure doses for the resist layer are varied in the range of 50µC/cm^2 to 180µC/cm^2 at 20 kV accelerating voltage with a beam current of 0.075nA. The nanowires resist masks are well developed with dimension less than 100 nm in width for the dose exposure parameters of 80µC/cm^2, 100µC/cm^2 and 120µC/cm^2. Subsequently, the two metal electrodes which are designated as source and drain are fabricated on top of individual nanowire using conventional lithography process. Morphological, electrical and chemical characteristics have been proposed to verify the outcome of the fabricated device. The major parts are to observe the nanowire profile in order to meet the nano-scale dimension by using Hawk 3D-nanoprofiler and to test the device performance electrically by using Semiconductor Parametric Analyzer (SPA) in terms of I-V relations. It is found that, the smallest SiNW with diameter of 65nm is well aligned with electrode pads have been obtained. Finally, the fabricated device is performed as pH level detection. Three types of standard aqueous pH buffer buffer solutions which are pH 4, pH 7 and pH 10 are used to test the electrical response of the device. The SiNWs sensor show the highest resistance value for pH 4 and the lowest resistance value for pH 10. In terms of sensitivity, the device with smaller nanowire is found to be more sensitive than larger nanowire as a result of the high surface-to-volume ratio.

CHAPTER 1

BACKGROUND

1.1 Introduction

This introductory chapter starts a brief explanation of the background and roadmap of nanotechnology, followed by the overview of the nanowire sensor device. Next, the objectives and scopes of this research are described in detail. Lastly, the organization of dissertation is addressed.

1.2 Nanotechnology

Nanotechnology entails the control of matter at the scale of 1 to 100 nanometers to create the functional materials, devices and systems (Wang, 2005). The word "nano" means 10^{-9}, so a nanometer (nm) is one billionth of a meter which in comparison states that a typical dimension of 10nm is 1000 times smaller than the diameter of a human hair (Hunt & Mehta, 2006). Discovery of these nanoscale things such as carbon nanotubes and nanowires, had provided researchers with an opportunity to construct electronic interfaces with components which sizes are comparable to the size of biological molecules (Noy, Artyukhin, & Misra, 2009) such as proteins, viruses, deoxyribonucleic acid (DNA), ions and molecules as illustrated in Fig. 1.1.

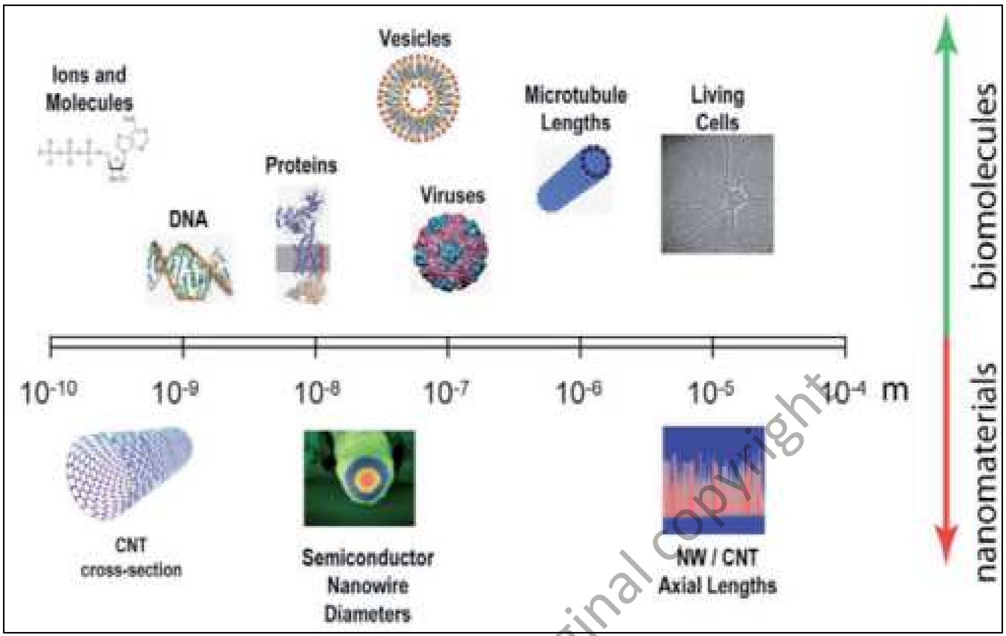

Figure 1.1: Nanometer scale chart. Comparison of natural things and manmade things in terms of dimensions (Noy et al., 2009).

Despite the current excitement and recent waves of visionary predictions, nanotechnology is not entirely a new area (P. Wagner, 2005). The reality is back in 29th December 1959, Nobel Laureate Richard P. Feynman had given a talk at the annual meeting of the American Physical Society in the California Institute of Technology, which had become one of the twentieth century's classic science lecturers. In the talk which titled "There's Plenty of Room at the Bottom", he presented a technological vision off extreme miniaturization several years before the word "chip" became part of the lexicon (Bhushan, 2006; Mansoori, 2005). He also discussed about the problem of manipulating and controlling things on a small scale. Extrapolating from known physical laws, a technology using the ultimate toolbox of nature which building nanoobjects atom by atom or molecule by molecule was envisioned by the renown scientist, Feynman (Bhushan, 2006).

Consequently in 1974, Norio Taniguchi, a Japanese researcher had first coined the term ‘nanotechnology’ which in engineering at length scales less than a micrometer (Prasad, 2008). However it is noted that a futurist K. Eric Drexler has been widely credited for popularizing the term in the mainstream. In his book Engines of Creation published in 1986, Drexler envisioned a world in which tiny machines are able to build other structures with exquisite precision by physically manipulating individual atoms (Drexler, 2006). Thus, since 1980’s has led to many on inventions and discoveries in the fabrication of nanoobjects which have become a demonstration to Feynman’s vision (Bhushan, 2006).

In 1991, carbon nanotubes were discovered by Sumio Iijima at NEC Fundamental Research Laboratories in Tsukuba, Japan (L. Williams & Adams, 2007). Then, scanning probe microscopes which is capable of imaging and manipulating surface-bound molecules with atomic-scale precision, have been around for about 15 years and now commonly used in all fields such as material science (P. Wagner, 2005). Nanotechnology is considered to be a general purpose technology which still has most of its experts located in academia and government-funded basic research centers. Table 1.1 summarizes the chronicles of major nano events since 1960s in nanotechnology development.

In nanotechnology, there are two commonly techniques that become approach for fabrication process which known as bottom-up approach and top-down approach. The bottom-up approach attempts to build nanodevices from atomic or molecular component, meanwhile the top-down approach is basically based on the lithographic techniques to pattern bulk material (Parak, Simmel, & Holleitner, 2008). In this research work, the top-down approach was chosen to form resist mask and fabricate the nanoscale structures. The differences between these two nanotechnology fabrications approaches will be summarized in Chapter 2, Section 2.2.3.