PHASE CHANGE ANALYSIS OF CRYSTALLINE SILICON THIN FILM GROWN BY VERY HIGH FREQUENCY – PLASMA ENHANCED CHEMICAL VAPOUR DEPOSITION AND RADIO FREQUENCY – MAGNETRON SPUTTERING

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DEDICATION

IN THE NAME OF ALLAH, ALMIGHTY GOD

To my lovely father and mother, Kadir Rosman Bin Nordin and Suraya Binti Kamaruddin who always give me unconditional support, love, motivation and prayers for over the years. To my family and my dearest Khairunnisya, who gives me inspirations and relentlessly to remind me things are possible to complete and achievable. Thank you for all your love and support. This thesis is dedicated to all of you.

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ABSTRACT

In this study, silicon thin films had been successfully produced by using Very High Frequency-Plasma Enhanced Chemical Vapour Deposition (VHF-PECVD) technique. The phase transition from amorphous to crystalline silicon along with crystallite types remains unknown, especially at VHF region up to 200 MHz. In this work, very high frequencies ranging from 35 MHz until 200 MHz were investigated. The deposition time were fixed for 3 minutes and 15 minutes, while Radio Frequency (RF) power were fixed at 20 W and 30 W. For comparison purpose, RF-Magnetron Sputtering technique was used to deposit silicon thin films with the same RF power at 20 W and 30 W. Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy and Raman spectroscopy were used to determine the phase transition of film structure from amorphous to crystal, while X-Ray Diffraction (XRD) technique was used to determine the crystallites in the samples for both deposition techniques. Morphology study was carried out using Field Emission Scanning Electron Microscope (FESEM) and Atomic Force Microscope (AFM). The transition from hydrogenated amorphous silicon (a-Si:H) to hydrogenated crystalline silicon (c-Si:H) in the thin film samples was observed as deposition frequency increased from 35 MHz to 200 MHz. Typical Si (111) and Si (311) crystalline were formed in VHF-PECVD samples while only Si (311) was formed in RF-Magnetron Sputtering. VHF-PECVD produced 248 nm and 250 nm film thicknesses compared to RF-Magnetron Sputtering at only 34 nm. Rougher films were produced by VHF-PECVD with maximum average surface roughness of 3.64 nm compared to RF-Magnetron sputtering at 0.38 nm. Therefore, it can be concluded that the transition of silicon film from amorphous to crystal occurred at high deposition frequency using VHF-PECVD technique, but were hardly seen for RF-Magnetron Sputtering samples as the deposited thin films were too thin.

ABSTRAK

Dalam kajian ini, filem tipis silkon telah berjaya dihasilkan melalui teknik pemendapan wap kimia peneguhan plasma-berfrekuensi sangat tinggi (VHF-PECVD). Perubahan fasa daripada amorf ke hablur silikon dengan jenis kristalit terhasil masih tidak diketahui, terutamanya pada frekuensi sangat tinggi sehingga 200 MHz. Dalam kerja ini, frekuensi sangat tinggi dalam julat 35 MHz sehingga 200 MHz telah dikaji. Tempoh masa pemendapan ditetapkan pada 3 minit dan 15 minit, manakala kuasa frekuensi radio (RF) pula ditetapkan pada 20 W dan 30 W. Bagi tujuan perbandingan, teknik percikan magnetron berfrekuensi radio diguna pakai untuk memendap filem tipis silikon dengan menggunakan kuasa RF yang sama, iaitu pada 20 W dan 30 W. Spektroskopi pantulan keseluruhan dikecilkan – infra merah transformasi Fourier (ATR-FTIR) dan spektroskopi Raman telah digunakan untuk menentukan perubahan fasa struktur filem daripada amorf kepada hablur, manakala teknik pembelauan sinar-X (XRD) digunakan untuk menentukan kristalit dalam sampel-sampel untuk kedua-dua teknik pemendapan. Kajian morfologi pula telah dijalankan menggunakan mikroskop elektron pengimbasan pancaran medan (FESEM) dan mikroskop daya atom (AFM). Transisi daripada amorf silikon berhidrogen (a-Si:H) kepada hablur silikon berhidrogen (c-Si:H) dalam sampel filem tipis telah dicerap apabila frekuensi pemendapan meningkat dari 35 MHz ke 200 MHz. Kristalit lazim Si (111) dan Si (311) telah terbentuk dalam kesemua sampel VHF-PECVD, manakala hanya kristalit Si (311) yang terhasil pada filem melalui teknik percikan magnetron berfrekuensi radio. VHF-PECVD menghasilkan filem berketebalan 248 nm dan 250 nm berbanding dengan teknik percikan magnetron berfrekuensi radio hanya pada 34 nm. Filem yang lebih kasar dihasilkan oleh VHF-PECVD dengan purata maksimum kekasaran permukaan mencecah 3.64 nm, berbanding percikan magnetron pada 0.38 nm. Oleh itu, kajian ini telah menyimpulkan bahawa berlakunya transisi filem silikon daripada amorf kepada hablur pada frekuensi pemendapan yang tinggi menggunakan teknik VHF-PECVD, namun perkara ini tidak dapat dilihat dengan jelas pada filem yang dihasilkan melalui teknik percikan magnetron kerana filem tipis termendap adalah terlalu nipis.

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LIST OF ABBREVIATIONS

PECVD - Plasma Enhanced Chemical Vapour Deposition

PVD - Physical Vapour Deposition

VHF - Very High Frequency

RF - Radio Frequency

MEMS - Micro Electro Mechanical System

Si:H - Hydrogenated Silicon

c-Si:H - Crystalline Hydrogenated Silicon

a-Si:H - Amorphous Hydrogenated Silicon

Cz - Czochralski

VW - Volmer and Weber

SK - Stranski and Krastanov

FCC - Face Centered Cubic

TO - Transverse Optical

AFM - Atomic Force microscopy

FTIR - Fourier Transform Infrared

IR - Infra Red

ATR - Attenuated Total Reflectance

XRD - X-ray Diffraction

XRR - X-ray Reflectivity

FWHM - Full Width Half Maximum

FESEM - Field Emission Scanning Electron Microscope

SE - Secondary Electron

BSE - Back Scattered Electron

RMS - Root Mean Square

LIST OF SYMBOLS

Si - Silicon

SiO_2 - Silicon Dioxide

P - Phosphorus

B - Boron

SiH_4 - Silane

H - Hydrogen

Ar - Argon

O_2 - Oxygen

N_2 - Nitrogen

CH_4 - Methane

HF - Hydrofluoric Acid

MHz - Megahertz

eV - Electronvolt

W - Watt

mW - Milliwatt

cm - Centimeter

µm - Micrometer

nm - Nanometer

Å - Angstrom

mTorr - Millitorr

Pa - Pascal

k - 1000

^{o}C - Degree Celcius

cm^3 - Centimeter Cubic

a - Amorphous

c - Crystal

X_c - Raman Crystallinity

C_H - Hydrogen Content

R - Hydrogen Dilution Ratio

δ - Skin Depth

ρ - Bulk Resistivity

$\mu_{\circ}$ - Permeability of Vacuum

μ_r - Relative Permeability of Sample

f - Frequency

d - Spacing Between Atomic Planes

τ - Grain Size

D - FWHM XRD peak

λ - Wavelength

k - Constant for XRD measurement

θ - Angle

$\omega_{\circ}$ - Free Resonance Frequency

k - Spring Constant

m - Mass of Cantilever

z - Distance Between Tip of Cantilever and Sample

F_{Total} - Total Force Between Tip and Sample

E_1 - Original IR Signal

E_2 - Shift of IR Signal

Z - Atomic Number

R_a - Average Surface Roughness

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Silicon (Si) thin film has been in the semiconductor and solar cell industries since decades. Silicon plays an important role in these industries as it has metalloid properties, which not all elements have. In addition, silicon really perform effectively in its optical properties and electrical properties, making it become one of the famous elements to be used in these industries (1–7).

Atomic arrangement of Si thin film has always been part of the main course of the research. This is due to the fact that difference in atomic arrangement may possess different characteristics and therefore can be used for different applications. For example, in heterojunction type solar cell, thin film of hydrogenated amorphous silicon (a-Si:H) has been used due to increase the efficiency of solar cell, while for Micro-Electro Mechanical System (MEMS), its best application is its crystalline structure (c-Si:H) as crystal can withstand more pressure and better strength distribution (3,8,9). In term of surface morphology study, rougher film is needed for solar cell fabrication, which will increase the efficiency as the capabilities of rougher film to trap the incident light (10). The morphology condition also has been developed and doped with other materials to improve the capabilities of light trapping mechanism in related with the morphology condition of the film (11).

There are many ways to deposit silicon thin film, such as by using Radio Frequency (RF) Magnetron Sputtering, Plasma Enhanced Chemical Vapour Deposition (PECVD), spin coating and others (12). All these techniques have their own advantages and drawbacks. Typically, in conventional PECVD, silane (SiH_4) and hydrogen (H_2) gases are used as precursor while argon gas (Ar) is used as plasma source. These gases will produce the deposition of hydrogenated silicon (Si:H) thin film (13). In contrast, sputtering technique uses a solid target as main source of Si film since sputtering is a type of Physical Vapour Deposition (PVD), with only Ar is involved for plasma generation process.

The transition from a-Si:H to c-Si:H thin film depends on several PECVD parameters such as temperature, working pressure, power density and plasma excitation frequency. In 2004, C. Das et al. have shown in their studies that the transition from amorphous to crystal occurred along with the increment of crystal size as the temperature of substrate increased from 180^{o}C to 370^{o}C (1). For sputtering, usually post annealing is needed to provide the transition from amorphous to crystalline if the film deposited at low temperature with low RF power, otherwise, higher temperature is needed during deposition compare to PECVD (14–16). Apart of temperature, pressure also plays important role. Different working pressure can provide significant change to the sample. W. Li et al. (2009), found that the working pressure of PECVD above 300 Pa with hydrogen to silane flow rate ratio, or also known as hydrogen dilution ratio, R, ranging from 300 to 500 led to better crystallinity of the silicon thin film compared to below 300 Pa, with no trace of silicon crystal in the analysis (17). It has also been shown in a study by G. Lihui et al. (1998), at 13.56 MHz, deposition rate improved from 0 Torr until 4 Torr, then decreased when the pressure set increased to 8 Torr (18). Meanwhile, for Magnetron Sputtering, deposition pressure also affects the film deposition rate, as chamber pressure will affect the mean free path of adatoms. According to S. B. Hashim et al., (2012), Si film deposited by RF sputtering shown decrement of deposition rate as the deposition pressure increased from 5 mTorr to 8 mTorr (19).

In correlation of RF power and crystallinity of the sample, P. Pratim et al. (2002) have shown that the transition of hydrogenated Si (Si:H) thin film from a-Si:H to c-Si:H exists as RF power up to 285 mW/cm^2 in PECVD (20). Furthermore, S. Q. Xiao et al. (2010) also shown the same transition of Si by varying the power densities from 16.7 mW/cm^3 to 20.8 mW/cm^3 (21). This also provide similarities with the results from Magnetron Sputtering deposition technique. According to Y. Bouizem et al. (2013), the transition can be seen into crystalline silicon film when RF power increased from 180 W to 200 W (22).

On the other hand, excitation frequency for both PECVD and Magnetron Sputtering may affect the atomic structure Si thin film. H. Haijie et al. (2014) stated that the driving frequency may affect the state of Si film in Magnetron Sputtering. In their study, 2 MHz and 60 MHz excitation frequency set caused increased in crystal compared to conventional RF excitation frequency (23). Meanwhile in PECVD, according to M. Fukawa et al. (2001), frequency does affect the atomic structure of the thin film. The frequencies used were ranging from 13.56 MHz to 40 MHz. The results shown that the crystallinity increased as the excitation frequency increased to 40 MHz (24). In 2001, J. Takuya Matsui et al. did study the performance of solar cell in polycrystalline Si thin film, which grown by PECVD at 100 MHz. From the results, it clearly shown that polycrystal can be existing at that particular frequency (6). Correlation of the deposition of thin film using Very High Frequency (VHF) PECVD and crystallinity of the thin film can be shown in these previous studies (1,7,25–28). This strengthen the theory that higher frequency can affect the structure of the thin film. Typical Si crystallites grown at VHF frequencies are Si (111), Si (220) and Si (311) (1,26,28).

Conventionally, the RF excitation frequency in PECVD is around 13.56 MHz. Therefore, many studies had been carried out at this frequency. However, until now, there are still lacking in studies related with structural and morphology properties in frequency range until 200 MHz. Hence, phase change analysis from amorphous to crystalline in VHF deposition technique will be fundamental for this research with the effect of the phase change towards film structure and morphology. In this research, conventional RF-Magnetron Sputtering also will be included and discussed together with VHF-PECVD in Chapter 4.

1.2 Problem Statement

As mentioned earlier, there are many possible parameters that can be altered to obtain crystalline Si deposition. Even in conventional RF frequency, crystalline Si still can be produced at higher substrate temperature, which is higher than 100°C and above; high hydrogen dilution ratio, optimum deposition pressure and deposition power (2,29–31). However, the crystallinity remain unknown if the deposition frequency is increased up to 200 MHz. Perhaps, VHF can produce higher Si crystallinity, at much lower temperature. Meanwhile, RF-Magnetron Sputtering usually needs either higher than 200°C or post annealing process to produce crystalline Si with chamber pressure more than 4 Torr. Therefore, the deposition of Si film by RF-Magnetron Sputtering with similar temperature and deposition pressure as VHF-PECVD will provide information in term of film crystallinity along with phase change from amorphous to crystalline state (32)(33).

On the other hand, another significant consequence that can relate is hydrogen content, C_{H}. According to the previous studies, crystallinity of the Si film will affect the amount of C_H in the film (1,34,35). The reduction of C_H in the film may give high purity of Si film. Consequently, this study may give a knowledge regarding the effect of VHF toward C_H in the Si thin film.

Typical polycrystalline usually produced in Si film are Si (220), Si (111) and Si (311). Among of these three crystallites, the possibilities and transition from one crystallite to another still remain unclear. There were several studies shown that disappearing certain XRD peaks as the substrate temperature increased at VHF-PECVD deposition (1,29). Therefore, this study is an opportunity to investigate the effect of VHF plasma excitation towards the crystallite types in the Si film. For RF-Magnetron Sputtering, type of crystallite form at low temperature remained unknown, as majority of previous study need high temperature. This eventually can support information with related to crystallinity regarding types of crystallite which can be formed at low temperature.

The unknown film morphology condition and deposition rate at VHF plasma excitation ranging to 200 MHz may rise questions. These two things are significantly important especially in the solar cell performance (10,36,37). C. Das et al. stated that, the surface roughness is related with the crystallinity in the sample. Nevertheless, it will reduce as the deposition temperature increase (1). Regardless with the statement, it is an opportunity to determine the effect of VHF plasma excitation toward surface roughness. On the other hand, deposition rate and morphology condition for film grown by RF-Magnetron Sputtering without involvement of high temperature could be known.

1.3 Objectives

The objectives of the research are:

(a) To determine the effect of VHF plasma excitation in PECVD to the transition of a-Si:H to c-Si:H, and the amount of hydrogen content in the Si film by using Raman spectroscopy and ATR.

(b) To analyse the crystallite types of silicon thin film deposited using VHF-PECVD and RF-Magnetron Sputtering, using XRD.

(c) To characterise the surface morphology of the Si thin film deposited using VHF-PECVD and Magnetron Sputtering by using AFM and FESEM.

1.4 Scope of the Study

In this study, only two types of film deposition techniques were used; VHF-PECVD and RF-Magnetron Sputtering. The deposition temperature was set to 180°C in order to have minimal defect densities at the samples (2,38). The frequencies were varied and increased gradually from 35 MHz to 200 MHz for VHF-PECVD, while for RF-Magnetron Sputtering, fixed at 13.56 MHz. All samples were deposited on Si (100) wafer, doped with boron. This is to provide a study that can be benefits to MEMS and solar cell application whereby film usually deposited on Si substrate or another Si film (16,39). For characterisation, XRD, Raman spectroscopy and FTIR were used to determine the transition of film structure from a-Si:H to c-Si:H along with the C_H for selected PECVD films. While for deposition rate and morphology study, FESEM and AFM analysis had been done. All data then were compared with RF-Magnetron Sputtering samples.

1.5 Significant of the Study

To date, there is still no study related with crystallite types and Raman crystallinity, X_c of VHF-PECVD deposition of silicon thin film carried out at higher frequency up to 200 MHz. As a consequence, the results can be used as reference for other researcher to grow specific crystal orientation. The amount of hydrogen content, C_H also significant in this study as researcher may keep updating on the way to produce high purity of Si thin film, with less amount of hydrogen bonded silicon. On the other hand, fixed at 180^{o}C will give set of results with low defect density. Consequently this will beneficial for those researchers who want to study the effect of high frequency deposition with low defect densities (38). All the data also will be discussed along with RF-Magnetron Sputtering. This definitely will give extra information regarding Si thin film fabrication by these two techniques, thus enlightens not only the academia, but also the semiconductor and solar cell industries.

REFERENCES

1. Das C, Jana T, Ray S. Optoelectronic and Structural Properties of Undoped Microcrystalline Silicon Thin Films: Dependence on Substrate Temperature in Very High Frequency Plasma Enhanced Chemical Vapor Deposition Technique. *Jpn J Appl Phys*. 2004. 43:3269–3274.
2. Kondo M, Matsuda A. Low Temperature Growth of Microcrystalline Silicon and Its Application to Solar Cells. *Thin Solid Film*. 2001. 383(1–6):4–9.
3. Korte LÃ, Conrad E, Angermann H, Stangl R, Schmidt M. Solar Energy Materials & Solar Cells Advances in a-Si : H / c-Si Heterojunction Solar Cell Fabrication and Characterization. *Sol Energy Mater Sol Cells*. 2009. 93:905–910.
4. Calva EB, Monroy BM, Dutt A, Santana G, Ingeniería D De, Procesos D, et al. The Role of Crystalline Fraction on The Photoconductive Response in Polymorphous Silicon Materials for Thin Films Solar Cells . *Inst Electr Electron Eng*. 2000. 595–597.
5. Boisen A, Dohn S, Keller SS, Schmid S, Tenje M. Cantilever-like micromechanical sensors. *Rep Prog Phys*. 2011. 74:1-30.
6. Matsui T, Tsukiji M, Saika H, Toyama T, Okamoto H. Correlation between Microstructure and Photovoltaic Performance Thin Film Solar Cells of Polycrystalline Silicon. *Japan Soc Appl Phys Correl*. 2002. 41:20–27.
7. Chen Q, Wang J, Zhang Y, Lu J. Activation Energy Study of Intrinsic Microcrystalline Silicon Thin Film Prepared by VHF-PECVD. *Opt*. 2016. 127(18):7312–7318.
8. Kahn H, Tayebi N, Ballarini R, Mullen RL, Heuer AH. Fracture Toughness Of

Polysilicon MEMS Devices. *Sens Actuators* 82. 2000. 82:274–80.

9. Boyce BL, Grazier JM, Buchheit TE, Shaw MJ. Strength Distributions in Polysilicon MEMS. *J microelectromechanical Syst*. 2006. 16(2):179–90.

10. Scholtz L, Ladanyi L, Mullerova J. Influence of Surface Roughness on Optical Characteristics of Multilayer Solar Cells. *Appl Phys*. 2014. 12:631-638.

11. Müller J, Rech B, Springer J, Vanecek M. TCO and Light Trapping in Silicon Thin Film Solar Cells. *Sol Energy*. 2004. 77(6):917–930.

12. Kern W, Schuegraf KK. D*eposition Technologies And Applications: Introduction and Overview*'. 2nd ed. California: William Andrew. 2002.

13. Matsuda A. Growth Mechanism of Microcrystalline Silicon Obtained from Reactive Plasmas. *Thin Solid Films*. 1999. 337:4–9.

14. Touir H, Dixmier J, Zellama K, Morhange JF, Elkaim P. Bimodal Crystal Size Distribution in Annealed R.F. Magnetron Silicon Films: A memory Effect Of The Local Order Inhomogeneities in The Initial Amorphous State. *J Non Cryst Solids*. 1998. 227–230:906–10.

15. Neslein IL, Ryg M, Christensen CC. Polycrystalline Silicon Thin Films on Glass by Aluminum-Induced Crystallization. *Scand J Clin Lab Invest*. 1994. 46(10):2062–2066.

16. Pal P, Chandra S. RF Sputtered Silicon for MEMS. *J Micromechanics Microengineering*. 2005. 15(8):1536–46.

17. Li W, Xia D, Wang H, Zhao X. Hydrogenated Nanocrystalline Silicon Thin Film Prepared by RF-PECVD at High Pressure. *J Non Cryst Solids*. 2010. 356:2552–2556.

18. Guo L, Kondo M, Fukawa M, Saitoh K, Matsuda A. High Rate Deposition of Microcrystalline Silicon Using Conventional Plasma-Enhanced Chemical

Vapor Deposition. *Japanese J Appl Physics*. 1998. 37:116–118.

19. Hashim SB, Mahzan NH, Herman SH, Rusop Mahmood M. Room-Temperature Deposition of Silicon Thin Films by RF Magnetron Sputtering. *Adv Mater Res*. 2012. 576:543–547.
20. Pratim P, Dutta N, Chaudhuri P, Williamson DL, Vignoli S, Longeaud C. Properties of Si : H Thin Films Deposited by rf-PECVD of Silane – Argon Mixtures With Variation of the Plasma Condition. 2002. 302:123–127.
21. Xiao SQ, Xu S, Wei DY, Huang SY, Zhou HP, Xu Y. From Amorphous to Microcrystalline: Phase Transition in Rapid Synthesis of Hydrogenated Silicon Thin Film in Low Frequency Inductively Coupled Plasmas. *J Appl Phys*. 2010. 108(11):1-6.
22. Bouizem Y, Abbes C, Kefif K, Sib JD, Benlakehal D, Kebab A, et al. Radiofrequency Power Effects on The Optical and Structural Properties of Hydrogenated Silicon Films Prepared by Radiofrequency Magnetron Sputtering. *Thin Solid Films*. 2013. 545:245–50.
23. He H, Ye C, Wang X, Huang F, Liu Y. Effect of Driving Frequency on Growth and Structure of Silicon Films Deposited by Radio-Frequency and Very-High-Frequency Magnetron Sputtering. *ECS J Solid State Sci Technol*. 2014. 3(5):74–78.
24. Fukawa M, Suzuki S, Guo L, Kondo M. High Rate Growth of Microcrystalline Silicon Using a high-Pressure Depletion Method With VHF Plasma. *Sol Energy Mater Sol Cells*. 2001. 66:217–223.
25. Lupina G, Strobel C, Dabrowski J, Lippert G, Kitzmann J, Krause HM, et al. Plasma-Enhanced Chemical Vapor Deposition of Amorphous Si on Graphene. *Appl Phys Lett*. 2016. 108(19):1-5.

26. Juneja S, Sudhakar S, Srivastava AK, Kumar S. Morphology and Micro-Structural Studies of Distinct Silicon Thin Films Deposited Using Very High Frequency Plasma Enhanced Chemical Vapor Deposition Process. *Thin Solid Films*. 2016. 619:273–280.

27. Strobel C, Leszczynska B, Merkel U, Kuske J, Fischer DD, Albert M, et al. High Efficiency High Rate Microcrystalline Silicon Thin-Film Solar Cells Deposited at Plasma Excitation Frequencies Larger Than 100MHz. *Sol Energy Mater Sol Cells*. 2015. 143:347–53.

28. Matsui T, Kondo M. Advanced Materials Processing for High Efficiency Thin-Film Silicon Solar Cells. *Sol Energy Mater Sol Cells*. 2013. 119:156–162.

29. Kamei T, Kondo M, Matsuda A. Significant Reduction of Impurity Contents in Hydrogenated Microcrystalline Silicon Films for Increased Grain Size and Reduced Defect Density. *Japanese J Appl Physics*. 1998. 37(3 A):265-268.

30. Kondo M, Fukawa M, Guo L, Matsuda A. High Rate Growth of Microcrystalline Silicon at Low Temperatures. *J Non Cryst Solids*. 2000. 269:84–9.

31. Amrani R, Pichot F, Chahed L, Cuminal Y. Amorphous-Nanocrystalline Transition in Silicon Thin Films Obtained by Argon Diluted Silane PECVD. *Cryst Struct Theory Appl*. 2012. 1:57–61.

32. Cerqueira MF, Andritschky M, Rebouta L, Ferreira JA, da Silva MF. Macrocrystalline Silicon Thin Films Prepared by RF Reactive Magnetron Sputter Deposition. *Vacuum*. 1995. 46(12):1385–1390.

33. Jun SI, Rack PD, McKnight TE, Melechko A V., Simpson ML. Low-Temperature Solid-Phase Crystallization of Amorphous Silicon Thin Films Deposited by Rf Magnetron Sputtering With Substrate Bias. *Appl Phys Lett*.

2006. 89(2):1-3.

34. Langford AA, Fleet ML, Nelson BP, Lanford WA, Maley N. Infrared Absorption Strength and Hydrogen Content of Hydrogenated Amorphous Silicon. *Phys Rev B*. 1992. 45(23):13367–13377.

35. Samanta S, Das D. Nanocrystalline Silicon Thin Films from SiH_4 Plasma Diluted by H_2 and He in RF-PECVD. *J Phys Chem Solids*. 2017. 105:90–98.

36. Brinza M, Rath JK, Schropp REI. Thin Film Silicon n-i-p Solar Cells Deposited by VHF PECVD at 100°C Substrate Temperature. *Sol Energy Mater Sol Cells*. 2009. 93(6–7):680–683.

37. Isabella O, Krč J, Zeman M. Modulated Surface Textures for Enhanced Light Trapping in Thin-Film Silicon Solar Cells. *Appl Phys Lett*. 2010. 97(10):10110601-10110603.

38. Matsuda A. Thin-Film Silicon Growth Process and Solar Cell Application. *Jpn J Appl Phys*. 2004. 43(12):7909–7920.

39. Peng S, Wang D, Yang F, Wang Z, Ma F. Grown Low-Temperature Microcrystalline Silicon Thin Film by VHF PECVD for Thin Films Solar Cell. *J Nanomater.* 2015. November:1–5.

40. Askeland D, Fulay P, Wright W. *The Science and Engineering of Materials.* 6th ed. Stamford: Cengage Learning. 2010.

41. Viera G, Mikikian M, Bertran E, Cabarrocas PRI, Boufendi L. Atomic Structure of The Nanocrystalline Si Particles Appearing in Nanostructured Si Thin Films Produced in Low-Temperature Radiofrequency Plasmas. *J Appl Phys*. 2002. 92(8):4684–4694.

42. Shimura F. S*emiconductor Silicon Crystal Technology*. Cambridge, Massachusetts: Academic Press. 1989.

43. Descoeudres A, Barraud L, Bartlome R, Choong G, De Wolf S, Zicarelli F, et al. The Silane Depletion Fraction As an Indicator for The Amorphous/Crystalline Silicon Interface Passivation Quality. *Appl Phys Lett.* 2010. 97(18):1-3.

44. Yan B, Yue G, Yang J, Guha S. High Efficiency Amorphous and Nanocrystalline Silicon Thin Film Solar Cells on Flexible Substrates. *19th Int Work Act Flatpanel Displays Devices - TFT Technol FPD Mater*. 2012. 108:67–70.

45. Merdzhanova T, Woerdenweber J, Beyer W, Kilper T, Zastrow U, Meier M, et al. Impurities in Thin Film Silicon : Influence on Material Properties and Solar Cell Performance. *J Non Cryst Solids*. 2012. 358:2171–2178.

46. Brune H. Growth Modes. *Encycl Mater Sci Technol*. 2004. 10:3683–3692.

47. Gilmer GH, Grabow MH. Models of Thin Film Growth Modes. JOM. 1987. 39(6):19–23.

48. Martinu L, Zabeida O, Klemberg-Sapieha JE. *Plasma Enhanced Chemical Vapor Deposition of Functional Coatings*. Department of Engineering Physics ´Ecole Polytechnique de Montr´eal: Elsevier Inc. 2010.

49. Peck JA, Zonooz P, Curreli D, Panici GA, Jurczyk BE, Ruzic DN. High Deposition Rate Nanocrystalline and Amorphous Silicon Thin Film Production via Surface Wave Plasma Source. *Surf Coatings Technol*. 2017. 325:370–376.

50. Curtins H, Wyrsch N, Shah AV. High Rate Deposition of Amorphous Hydrogenated Silicon: Effect Of Plasma Excitation Frequency. *Electron Lett.* 1987. 23(5):228–230.

51. Swann S. Magnetron Sputtering. *Phys Technol*. 1988. 4(19):57–73.

52. Chaoumead A, Sung YM, Kwak DJ. The Effects of RF Sputtering Power and

Gas Pressure on Structural and Electrical Properties of ITiO Thin Film. *Adv Condens Matter Phys*. 2012. 1-7.

53. Seto JYW. The Electrical Properties of Polycrystalline Silicon Films. *J Appl Phys*. 1975. 46(12):5247–5254.
54. KOYNOV SCL S. Kinetic Model of Silicon-Hydrogen Network Formation. *J Non Cryst Solids*. 1991. 137-138:649-652.
55. Han D, Lorentzen JD, Weinberg-Wolf J, McNeil LE, Wang Q. Raman Study of Thin Films of Amorphous to Microcrystalline Silicon Prepared by Hot Wire Chemical Vapor Deposition. *J Appl Phys*. 2003. 94(5):2930–2936.
56. Kondo M, Fujiwara H, Matsuda A. Fundamental Aspects of Low Temperature Growth of Microcrystalline Silicon. 2003. 430(03):130–4.
57. Kim J, Kwak D, Park S, Ko H, Cho D-I. Why Is (111) Silicon a Better Mechanical Material for MEMS?. *Thin Solid Films.* 2003. 2:1–4.
58. Omar MF. *Design And Development Of VHF-Pecvd for Nanostructure Silicon Carbide Thin Film Deposition*. PhD Thesis. Universiti Teknologi Malaysia (UTM); 2015.
59. Larkin PJ. *IR and Raman Spectroscopy Principles and Spectral Interpretation*. USA: Elsevier. 2011.
60. HORIBA. Strain Measurements of a Si Cap Layer Deposited on a SiGe Substrate Determination of Ge Content. *HORIBA JOBIN YVON Appl Note*. 1–3.
61. Abou-ras D, Kirchartz T. *Advanced Characterization Techniques for Thin Film Solar Cells*. 1st ed. Weinheim, Germany: Wiley-VCH. 2011.
62. Mossad A, Kobayashi H. Hydrogen Effect on Nanostructural Features of Nanocrystalline Silicon Thin Films Deposited at 200° C by PECVD. *J Non*

Cryst Solids. 2014. 385:17–23.

63. William D. Callister J. *Materials Science and Engineering*.7th ed. Department of Metallurgical Engineering The University of Utah: John Wiley & Sons, Inc; 2013.

64. Guo L, Ding J, Yang J, Ling Z, Cheng G. Nanostructure, Electrical and Optical Properties of P-Type Hydrogenated Nanocrystalline Silicon Films. *Vaccum*. 2011. 85(6):649–653.

65. Patterson AL. The Scherrer Formula for X-ray Particle Size Determination. *Phys Rev*. 1939. 56(10):978–982.

66. Yasaka M. X-ray Thin Film Measurement Techniques. *Rigaku J*. 2010. 26(2):1–9.

67. Nanotechnology P. *Nano-R TM AFM User ' s Manual*. Santa Clara, United States:Pacific Nanotechnology. 2002.

68. Ramer G, Lendl B. Attenuated Total Reflection Fourier Transform Infrared Spectroscopy. *Encycl Anal Chem*. 2013. 2013:1-27.

69. Yuehui HU, Guanghua C, Yueying WU, Shengyi YIN, Zhuo G a O. Infrared Transmission Spectra and Hydrogen Content of Hydrogenated Amorphous Silicon. *Sc. In China Ser. G Phy. Mech. Astr*. 2004. 47(3):381–92.

70. PerkinElmer. FT-IR Spectroscopy Attenuated Total Reflectance (ATR). PerkinElmer Tec Note. 1-4.

71. Billah A. *Investigation Of Multiferroic And Photocatalytic Properties Of Li Doped Bifeo3 Nanoparticles*. Master of Science. European University of Bangladesh; 2016.

72. Rohaida CH, Foo CT, Nor Azillah Fatimah O, Nor Azwin S, Mohd Saari R, Meor Sulaiman MY, et al. Field Emission Scanning Electron Microscope (Fe-

Sem) Facility in BTI. *Mater Charact*. 2016. 1-6.

73. Inaba K. X-Ray Thin-Film Measurement Techniques. *Rigaku J.* 2008. 24(1):10–15.

74. SmartLab R. *X-Ray Diffraction Analysis For Thin Film Samples (Training Textbook)*. Japan:Rigaku Corporation. 2009.

75. Hitachi. Ultra-high Resolution Scanning Electron Microscope SU8000 Series. Hitachi High-Tech. 1-16.

76. Ltd. J. Product Guide: Scientific / Metrology Instruments / Industrial Equipment / Medical Equipment. *Prod Guid*. 2016. 1(81):3–4.

77. Yuan Y, Zhao W, Ma J, Yang Z, Li W, Zhang K. Structural Evolution of Nanocrystalline Silicon in Hydrogenated Nanocrystalline Silicon Solar Cells. *Surf Coatings Technol*. 2017. 320:362–365.

78. Ganguly G, Matsuda A. Defect Formation During Growth of Hydrogenated Amorphous Silicon. *Phys Rev B*. 1993. 47(7):3661–3670.

79. Danesh P, Pantchev B, Grambole D, Schmidt B. Effect of Film Thickness on Hydrogenated Amorphous Silicon Grown With Hydrogen Diluted Silane. *Appl Phys Lett*. 2002. 80(14):2463–2465.

LIST OF PUBLICATIONS

1. Kadir Rosman NH, Ismail AK, Omar MF. Structural Properties Of Si:H Thin Film Grown By VHF- PECVD. *The European Proceedings of Social & Behavioural Sciences 2018.* May 12-13, Johor Bahru:Future Academy. 2018. 515–523.