

Development of Low-Temperature Epitaxial Silicon Films and Application to Solar Cells

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Solar photovoltaic has become one of the potential solutions for current energy needs and for combating greenhouse gas emissions. The photovoltaics (PV) industry is booming, with a yearly growth rate well in excess of 30% over the last decade. This explosive growth has been driven by market development programs to accelerate the deployment of sustainable energy options and rapidly increasing fossil fuel prices. Currently, the PV market is based on silicon wafer solar cells (thick cells of around 150–300 μm made of crystalline silicon). This technology, classified as the first-generation of photovoltaic cells. The second generation of photovoltaic materials is based on the introduction of thin film layers of semiconductor materials. Unfortunately, the conversion efficiency of the current PV systems is low despite the lower manufacturing costs. Nevertheless, to achieve highly efficient silicon solar cell devices, the development of new high quality materials in terms of structure and electrical properties is a must to overcome the issues related to amorphous silicon (*a*-Si:H) degradation. Meanwhile, to remain competitive with the conventional energy sources, cost must be taken into consideration. Moreover, novel approaches combined with conventional mature silicon solar cell technology can boost the conventional efficiency and break its maximum limits. In our approach, we set to achieve efficient, stable and affordable silicon solar cell devices by focusing on the development of a new device made of epitaxial films. This new device is developed using new epitaxial growth phosphorous and/or boron doped layers at low processing temperature using plasma enhanced chemical vapor deposition (PECVD). The junction between the phosphorous or boron-doped epitaxial film of the device is formed between the film and the p or n-type crystalline silicon (c-Si) substrate, giving rise to (n *epi-Si*/p c-Si device or p *epi-Si*/n c-Si device), respectively. Different processing conditions have been fully characterized and deployed for the fabrication of different silicon solar cells architectures. The high quality epitaxial film (up to 400 nm) was used as an emitter for an efficient stable homojunction solar cell. Extensive analysis of the developed fine structure material, using high resolution transmission electron microscope (HRTEM), showed that hydrogen played a crucial role in the epitaxial growth of highly phosphorous doped silicon films. The main processing parameters that influenced the quality of the structure were; radio frequency (RF) power density, the processing chamber pressure, the substrate temperature, the gas flow rate used for deposition of silicon films, and hydrogen dilution. The best result, in terms of structure and electrical properties, was achieved at intermediate hydrogen dilution (HD) regime between 91 and 92% under optimized deposition conditions of the rest of the processing parameters. The conductivity and the

carrier mobility values are good indicators of the electrical quality of the silicon (Si) film and can be used to investigate the structural quality indirectly. The electrical conductivity analyses using spreading resistance profile (SRP), through the detection of active carriers inside the developed films, are presented in details for the developed epitaxial film under the optimized processing conditions. Measurements of the active phosphorous dopant revealed that, the film has a very high active carrier concentration of an average of $5.0 \times 10^{19} \text{ cm}^{-3}$ with a maximum value of $6.9 \times 10^{19} \text{ cm}^{-3}$ at the interface between substrate and the epitaxial film. The observed higher concentration of electrically active P atoms compared to the total phosphorus concentration indicates that more than half of dopants become incorporated into substitutional positions. Highly doping efficiency η_d of more than 50 % was calculated from both secondary ion mass spectroscopy (SIMS) and SRP analysis. A variety of proposed structures were fabricated and characterized on planar, textured, and under different deposition temperatures. Detailed studies of the photovoltaic properties of the fabricated devices were carried out using epitaxial silicon films. The results of these studies confirmed that the measured open circuit voltage (V_{oc}) of the device ranged between 575 and 580 mV with good fill factor (FF) values in the range of 74-76 %. We applied the rapid thermal process (RTP) for a very short time (60 s) at moderate temperature of 750°C to enhance the photovoltaic properties of the fabricated device. The following results were achieved, the values of V_{oc} , and the short circuit current (I_{sc}) were 598 mV and 27.5 mA respectively, with a fill factor value of up to 76 % leading to an efficiency of 12.5 %. Efficiency enhancement by 13.06 % was achieved over the reference cell which was prepared without using RTP. Another way to increase the efficiency of the fabricated device is to reduce the reflections from its polished substrate. This was achieved by utilizing the light trapping technique that transforms the reflective polished surface into a pyramidal texturing using alkaline solutions. Further enhancements of both V_{oc} and I_{sc} were achieved with values of 612 mV and 31mA respectively, and a fill factor of 76 % leading to an increase in the efficiency by up to 13.8 %. A noticeable efficiency enhancement by ~20 % over the reference cell is reported for the developed devices on the textured surfaces. Moreover, the efficiency of the fabricated epitaxial silicon solar cells can be boosted by the deployment of silicon nanocrystals (Si NCs) on the top surface of the fabricated devices. In the course of this PhD research we found a way to achieve this by depositing a thin layer of Si NCs, embedded in amorphous silicon matrix, on top of the epitaxial film. Structural analysis of the deposited Si NCs was performed. It is shown from the HRTEM analysis that the developed Si NCs, are randomly distributed, have a spherical shape with a radius of approximately 2.5 nm, and are 10-20 nm apart in the amorphous silicon matrix. Based on the size of the developed Si NCs, the optical band

gap was found to be in the region of 1.8-2.2 eV. Due to the incorporation of Si NCs layer a noticeable enhancement in the I_{sc} was reported.

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Dedication

To my parents, my wife and my sons, Mohamed, Abdurrahman, Omar and Moaaz.

Table of Contents

Author's Declaration.....	ii
Abstract.....	iii
Acknowledgements	vi
Dedication.....	vi
Table of Contents	ix
List of Figures	xiii
List of Tables	xxii
Chapter 1 Introduction, motivation and research methodology	1
1.1 Motivation for the research	2
1.2 Methodology of the research	4
1.3 Structure of This Thesis	5
Chapter 2 Background on experimental procedure and silicon technology	7
2.1 Silicon Material Feedstock	7
2.1.1 Production of metallurgical grade silicon	7
2.1.2 Crystal Pulling Process	9
2.2 Ribbon silicon	12
2.3 Solar cell device physics.....	13
2.3.1 Homojunction structure	15
2.3.2 Solar cell output parameters	18
2.3.3 Heterojunction (a-Si/c-Si) structure.....	21
2.4 Processing Techniques for thin film technology.....	23
2.4.1 Physical vapor deposition (PVD).....	23
2.4.2 Chemical vapor deposition (CVD).....	23
2.4.3 Plasma Enhanced Chemical Vapor Deposition (PECVD)	24
2.5 A new route to epitaxy growth at low temperature by PECVD.....	30
2.5.1 PECVD Hydrogenated amorphous silicon	30
2.5.2 Microcrystalline silicon.....	34
2.5.3 Epitaxy growth using PECVD.....	35
2.6 Rapid Thermal annealing process	36
2.7 Issues related to annealing process: Hydrogen effusion process.....	38

2.8 Device structure.....	39
2.8.1 Crystalline silicon: passivated emitter, rear locally-diffused (PERL) structure	39
2.8.2 Thin film silicon solar	40
2.9 Structural and Material Characterization	43
2.9.1 High resolution transmission Electron microscope (HRTEM).....	43
2.9.2 Micro-Raman Spectroscopy	47
2.9.3 X-ray Diffraction (XRD).....	48
2.10 Impurity analysis and active dopant characterization	49
2.10.1 Secondary ion mass spectroscopy (SIMS)	49
2.10.2 Spreading resistance profile (SRP)	49
2.11 Summary	51
Chapter 3 Experimental Work: Development of phosphorous doped LT PECVD epitaxial Si films..	52
3.1 Development of surface preparation schemes.....	53
3.1.1 <i>Ex-situ</i> surface preparation process.....	54
3.1.2 <i>In-situ</i> surface preparation process	54
3.2 Development and Optimization of LT-PECVD process for epitaxial films	55
3.3 Films deposited with intermediate H-dilution regime	58
3.3.1 HRTEM analysis.....	58
3.3.2 Micro-Raman Analysis	64
3.4 Film deposited with high H-dilution regime	68
3.4.1 HRTEM analysis	68
3.5 Film deposited at different temperatures	69
3.5.1 HRTEM analysis	69
3.6 Impurity analysis of the deposited films	71
3.6.1 SIMS analysis	71
3.7 Analysis of the dopant activation in the deposited films	73
3.7.1 Spreading resistance profile	73
3.7.2 Doping efficiency	77
3.7.3 Effect of H-plasma treatment	78
3.7.4 Substrate temperature-dependence of conductivity	80
3.8 Effect of substrate orientation	82
3.8.1 HRTEM analysis	82

3.8.2 Spreading resistance profile	84
3.9 Post-deposition rapid thermal annealing	85
3.9.1 Optimization of the RTP annealing profiles	86
3.9.2 Impurity analysis of the annealed films.....	89
3.9.3 Hydrogen effusion analysis from the annealed films	90
3.9.4 Structural analysis of the annealed films	92
3.9.4.1 HRTEM analysis annealed films	92
3.9.5 Electrical properties of the annealed films	95
3.10 Summary and conclusions	96
Chapter 4 Experimental work: Development of LT PECVD boron doped (TMB) Quasi-Epitaxial Si films	98
4.1 Development of LT-PECVD quasi-epitaxial boron doped Si films	100
4.2 Structural analysis of the TMB quasi-epitaxial boron doped films	102
4.2.1 HRTEM analysis	102
4.2.2 Micro-Raman analysis	106
4.3 Impurity analysis of TMB boron doped films	108
4.3.1 Spreading resistance profile analysis	109
4.3.2 Post-deposition rapid thermal annealing	111
4.3.2.1 Spreading resistance profile analysis	111
4.4 Summary and conclusions.....	114
Chapter 5 Experimental Work: Fabrication, and characterization of homo and heterojunction diodes and epitaxial Si solar cells	116
5.1 Homojunction Diode Fabrication.....	117
5.1.1 Processing Conditions and Diode fabrication.....	117
5.1.2 Current-Voltage characteristics of the illuminated diodes	119
5.1.3 High Frequency Capacitance-Voltage Characterization	122
5.2 Epitaxial Si Solar cell fabrication	124
5.2.1 Anti-reflection coating and passivation schemes.....	124
5.2.2 Fabrication schemes for epitaxial silicon solar cells.....	126
5.2.3 Surface texturing and Light trapping	129
5.2.4 Metal grid configuration and mask design	133
5.3 Phosphorous doped epitaxial Si solar cell device characterizations.....	133

5.3.1 Emitter thickness influence.....	134
5.3.2 RTP annealing influence on the photovoltaic properties	137
5.3.3 Textured surface influence	138
5.3.4 Post-hydrogenation process.....	143
5.3.5 Devices fabricated at very low temperature	144
5.3.6 Room temperature fabricated and characterized cells	145
5.4 Fabrication and characterization of Boron doped devices	147
5.5 Summary and conclusions.....	150
Chapter 6 : Variations of the LT-PECVD process to include Si nanocrystals: Future work	153
6.1 Silicon nanocrystals (Si NCs) preparation	153
6.2 Characterization and analysis of the developed Si nanocrystals.....	145
6.2.1 HRTEM Analysis	154
6.2.2 XRD Characterization.....	156
6.2.2.1 As Deposited silicon nanocrystals.....	156
6.2.2.2 Post-deposition RTP process.....	159
6.2.3 Micro-Raman analysis	160
6.3 Device integration and photovoltaic properties	162
6.4 Summary and conclusions.....	164
Chapter 7 Conclusions and Contributions	166
References.....	172

List of Figures

Figure 2.1: Single crystal pulling by the Czochralski process, (a) schematic diagram, left (b) cross section of the pulling system (right).

Figure 2.2: Single crystal pulling by the float zone pulling method.

Figure 2.3: The radiation spectrum for a black body at 5762 K, an AM0 spectrum, and an AM1.5 global spectrum.

Figure 2.4: Energy band diagram at thermodynamic equilibrium for a p/n junction.

Figure 2.5: J-V characteristics of a p/n junction in the dark conditions and under illumination.

Figure 2.6: Simple solar cell circuit model.

Figure 2.7: Energy band diagram of amorphous-crystalline silicon heterojunction at equilibrium.

Figure 2.8: Schematic diagram of a PECVD system.

Figure 2.9: Growth modes.

Figure 2.10: Two dimensional representation of atomic bonding in (a) crystalline silicon and (b) a-Si:H.

Figure 2.11: Schematic representation of the density of states (DOS) in a-Si:H, E_v and E_c are the mobility edges of the valence and conduction band, respectively.

Figure 2.12: Schematic diagram showing the prominent microstructure features of μ c-Si:H, from left to right the film composition changes from highly crystalline to predominantly amorphous.

Figure 2.13: Schematic diagram of a cross section through the single-wafer RTP reactor.

Figure 2.14: Hydrogen evolution rate versus temperature for undoped GD a-Si:H films, film thickness $\sim 0.6 \mu\text{m}$.

Figure 2.15: Passivated emitter, rear locally-diffused (PERL) cell with a double layer anti-reflection coating.

Figure 2.16: Schematic view of Kaneka's new thin-film poly-Si solar cell with STAR (naturally Surface Texture and enhanced Absorption with back, Reflector).

Figure 2.17: The structure of the HIT cell.

Figure 2.18: Schematic diagram of TEM.

Figure 2.19: Illustration of a Spreading Resistance measurement on a bevelled sample.

Figure 3.1: Relatively low resolution cross-Sectional TEM Bright Field micrograph of epitaxial growth sample deposited at 91.6 % hydrogen dilution using EP1 processing conditions; (Notice the smooth interface between the substrate and the epitaxial film).

Figure 3.2: Cross-sectional HRTEM micrographs of epitaxial emitters developed at 300°C using LT PECVD, and using EP1 conditions, the $\langle 111 \rangle$ planes shown in both single crystal substrate and in Epitaxial emitter, (SADP is shown: the left for Si substrate and the right for the developed epitaxial emitter (scalable bar=2nm)).

Figure 3.3: High resolution TEM bright filed image of the epitaxial bulk showing the lattice atomic structure and extended crystallographic perfection and orientation of 50 nm thick films, combined on the top right with selected area electron diffraction (SAED) pattern using (CBED) convergent beam electron diffraction, (EP1 conditions is applied).

Figure 3.4: HRTEM of lattice structure of the upper surface (in contact with the glue) of 50 nm film and included the Fast Fourier transformation analysis (FFT) near the surface, (EP1 conditions are applied), the 91.6 % HD is used.

Figure 3.5: Micro-Raman analysis of the developed epitaxial silicon films deposited in PECVD at 300°C under different hydrogen dilution regime, the structure probed using 328 nm UV laser. (Note: the processing conditions EP1 are applied).

Figure 3.6: Micro-Raman analysis of the developed epitaxial silicon films deposited in PECVD at 300°C under different power density at constant hydrogen dilution, using EP1 deposition conditions, the structure probed using 328 nm UV laser.

Figure 3.7: High resolution TEM micrographs of phosphorous doped silicon films, developed using very high hydrogen dilution regime 99% and developed using EP2 processing conditions.

Figure 3.8: High resolution TEM bright filed images of the developed silicon films at room temperature (25°C) on (100) Cz-Si and using process conditions EP1, (scalable bar=5nm).

Figure 3.9: SIMS analysis of phosphorous, oxygen, carbon and hydrogen in the bulk and at the interface of nearly 400 nm thick epitaxial Si films grown at 300°C by PECVD using EP1 condition. (Notice; the abrupt phosphorous profile which provides a perfect steep junction for solar cells).

Figure 3.10: Measured resistivity of the developed epitaxial (91.6% HD) and *a* Si:H (no hydrogen dilution), of 200 nm thickness films deposited using PECVD on (100) oriented substrate, under EP1 processing conditions.

Figure 3.11: Measured conductivity of the developed epitaxial silicon films under different hydrogen dilution regime on (100) oriented substrate using LT PECVD chamber, (Ep1 deposition conditions is applied).

Figure 3.12: Measured active dopant (SRP) and dopant concentration (SIMS) profiles of heavily phosphorous doped 200 and 400 nm epitaxially grown emitters at 300°C, respectively. (EP1 processing conditions is used).

Figure 3.13: Free carrier concentration of the phosphorous doped epitaxial silicon films using wet cleaning process (solid line) and hydrogen plasma treatment (dot line), at 300°C and applying EP1 processing conditions under 91.6 % HD.

Figure 3.14: Conductivity-substrate temperature dependent of the developed silicon films deposited on (100) oriented silicon substrate at 91.6 % HD under varied temperature using EP1 processing conditions

Figure 3.15: HRTEM micrograph of the developed silicon films on (110) oriented substrate at 300°C at 91.6 % HD and using EP2 deposition conditions. (scalable bar in the right micrograph=2nm).

Figure 3.16: Spreading resistance profile (SRP) of the developed silicon films on (110) and (111) silicon substrate at 300°C (a) resistivity and (b) and carrier concentration, (EP1 processing conditions is used).

Figure 3.17: Applied temperature profile, (A) RTP, with pulsed heating and cooling steps annealed at a peak temperature of 750°C applied in 4 cycles for 25 sec.

Figure 3.18: Applied temperature profile, (B) RTP, with two-steps annealing profile (10 min at 400°C) with a maximum annealing temperature of 750°C for 60s.

Figure 3.19: Applied temperature profile, (C) RTP, with multisteps and different heating and cooling rates with a peak temperature at 850°C for 60s.

Figure 3.20: Phosphorous concentration and junction depth for epitaxial Si films after applying the different RTP temperature profiles, (EP1 processing conditions were used).

Figure 3.21: Hydrogen content of the as grown epitaxial Si emitters and under different selected RTP profiles, (EP1 deposition conditions were used).

Figure 3.22: Cross-sectional HRTEM micrographs of epitaxial emitter/Si interface and the fine structure of the bulk after applying (A) RTP profile

Figure 3.23: Cross-sectional HRTEM micrograph of epitaxial emitter/Si interface and the fine structure of the bulk after applying (B) RTP profile. (scalbar=2 nm).

Figure 3.24: Cross-sectional HRTEM micrographs of epitaxial emitter/Si interface and the fine structure of the bulk after applying (C) RTP temperature profile.

Figure 3.25: Spreading resistance profile for the free carrier concentration of epitaxial silicon films deposited at 300°C, 91.6 % HD, before and after applying RTP (C), (EP1 deposition conditions are applied).

Figure 4.1: Bright Field micrograph of a very high resolution TEM Cross-Sectional image using process 1, deposition conditions as follows, 97 % HD, 900 mTorr, 47 power density and 2 of c(TMB) at 260°C, inset FFT for the different areas of interest (a) the amorphous phase, (b) the epitaxial interface and (c) the crystalline silicon substrate.

Figure 4.2: Bright Field micrograph of a very high resolution TEM Cross-Sectional image using process 2, using process 2 deposition conditions as follows, 90.16 % HD, 400 mTorr, 47 power density and c(TMB)=0.4 at 300°C ; (Note: the teeth like structure), with FFT for the different areas of interest (a) the amorphous phase, (b) the epitaxial interface and (c) the crystalline silicon substrate.

Figure 4.3: Raman measurements for the selected processes 2 and 3, at 90 and 99 % hydrogen dilution, respectively.

Figure 4.4: Measured free carrier concentration using spreading resistance profile (SRP) of the two different films processed using two different processing conditions, (process 1 and process 6).

Figure 4.5: Measured resistivity using of by spreading resistance profile (SRP) for two different films under two different processing conditions, (process 1 and process 6).

Figure 4.6: Active carrier concentration profiles measured by SRP technique, deposited using process 2 and 4 process conditions, and annealed in RTP for 60 sec at 750°C.

Figure 4.7: Resistivity of the annealed boron doped silicon films using different processing conditions

Active carrier concentration profiles measured by SRP technique, deposited using process 2 and 4 process conditions, and annealed in RTP for 60 sec at 750°C.

Figure 5.1: Schematic diagram of the prepared LT PECVD homojunction test structure diodes.

Figure 5.2: I-V characteristics of the *Al front contact/ (n⁺Si epitaxy film)-EP2 conditions / (p) c-Si/Al back contact* structure with the as deposited films.

Figure 5.3: I-V characteristics of the *Al front contact/ (n⁺Si epitaxy film)-EP1 conditions / (p) c-Si/Al back contact* structure with the as deposited films.

Figure 5.4: High frequency, capacitance-Voltage characterization of the fabricated 4mm² diodes using epitaxy films under EP1 processing conditions and after applying RTP (A) and (C) temperature profiles. (Film thickness = 50 nm).

Figure 5.5: Relationship between W^2 and V for n⁺Si epitaxy films / p-type homojunction using process conditions EP1 for as deposited and after applying RTP (A), (film thickness = 50 nm).

Figure 5.6: Illustration of different routes of epitaxy growth silicon solar cell fabrication on planar and textured surfaces.

Figure 5.7: Sketch of the structure of the fabricated devices (a) developed device on plane polished Si surfaces (b) developed devices on textured surfaces.

Figure 5.8: Optical microscope images surface texturing using Alkaline (KOH and IPA, 7 and 3 %, respectively) composition for light trapping (a) surface morphology after 30 min at 70°C (b) After applying Piranha (c) Aluminium metal grid on the textured c-Si wafer.

Figure 5.9: Schematic diagram of the designed metal grid contact pattern for the fabricated epitaxial silicon solar cells (a) Top view of the designed metal grid (b) three dimensional metal grid (fingers and busbar).

Figure 5.10: Measured I-V curves under illumination for various emitter thicknesses using the following structure; *Al (front grid)/ SiN_x:H /n⁺ epitaxy Si /p-type Cz/ Al (back contact)*, using EP1 processing conditions and developed at 300°C, on (100) flat silicon substrate.

Figure 5.11: Internal QE of 50 nm epitaxial silicon solar cell fabricated at 300°C, using the following structure; *Al (front grid)/ SiN_x:H /n⁺ epitaxial Si /p-type Cz/ Al (back contact)* and under EP1 processing conditions on (100) flat silicon substrate.

Figure 5.12: Internal QE of 50 nm epitaxial silicon solar cell fabricated at 300°C, using the following structure; *Al (front grid)/ SiN_x:H /(50 nm) n⁺ epitaxial Si /p-type Cz/ Al (back contact)* and under EP1 processing conditions and annealed by RTP at 750°C for 60 sec, on (100) flat silicon substrate.

Figure 5.13: HRTEM micrographs of epitaxial silicon films deposited using EP1 processing conditions on (111) textured pyramidal facet inset bar=20nm, (a) the tip of the pyramidal, inset bar=20 nm (b) the V shaped pyramidal facet valley (c) Interface and quasi-epitaxial on pyramidal facet, inset bar=5 nm.

Figure 5.14: Measured I-V curves under illumination for textured (100) silicon wafer using the following structure; *Al (front grid)/ SiN_x:H /(50 nm)n⁺ Quasi-epitaxial Si /p-type Cz/ Al (back contact)*, using EP1 processing conditions and developed at 300°C.

Figure 5.15: Internal QE for textured (100) silicon wafer using the following structure; *Al (front grid)/ SiN_x:H /(50 nm)n⁺ Quasi-epitaxial Si /textured p-type Cz/ Al (back contact)*, using EP1 processing conditions and developed at 300°C.

Figure 5.16: Measured I-V curves under illumination for post-hydrogenated epitaxial silicon films, the hydrogenation process is, 350°C, hydrogen flow of 50 (sccm), the pressure was kept at 250 (mTorr) for 1.0 hr, (without plasma ignition), on (100) flat silicon substrate.

Figure 5.17: Internal QE of 50 nm epitaxial silicon solar cell fabricated at 150°C, using the following structure; *Al (front grid)/ SiN_x:H /(50 nm) n⁺ epitaxial Si /p-type Cz/ Al (back contact)* and under EP1 on (100) flat silicon substrate.

Figure 5.18: Internal QE of 20 nm silicon solar cell fabricated at room temperature (25°C), using the following structure; *Al (front grid)/ SiN_x:H /(20 nm) n⁺ Si films/p-type Cz/ Al (back contact)* and under EP1 on (100) flat silicon substrate.

Figure 5.19: Measured IV characteristics of 50 nm boron doped quasi-epitaxial silicon solar cells on n-type flat substrate and annealed using RTP (C).

Figure 5.20: Schematic diagram of the fabricated 20 nm boron doped quasi-epitaxial silicon solar cells on the textured surface and deposition of 50 nm phosphorous doped epitaxial layer (using EP1 conditions) as back surface filed.

Figure 5.21: Measured IV characteristics of 25 nm boron doped quasi-epitaxial silicon solar cells on n-type textured substrate and annealed using RTP (C) with 50 nm heavily doped epitaxial layer on the back surface to create BSF.

Figure 6.1: Fig.6.1: Representative of HRTEM images for the developed silicon nanocrystals at 300°C, the inset indicate the electron diffraction pattern.

Figure 6.2: X-ray diffraction pattern of the developed Si nanocrystals at 300°C, 0.7 Torr and 50 mW/cm² chamber pressure and power density, respectively on (111) silicon substrate.

Figure 6.3: Post-deposition thermal annealing influence on the developed Si nanocrystals at 550°C for 0.5h.

Figure 6.4: Micro-Raman spectra of the developed Si nanocrystals, the spectra for *a* Si and crystalline substrate are presented.

Figure 6.5: A Schematic drawing of the fabricated device with Si nanocrystals embedded into amorphous silicon matrix.

Figure 6.6: Measured IV of the fabricated epitaxial silicon solar cell (dashed line) and with applying nanocrystals layer on cell front surface (solid line), using the following structure; *Al (front grid)/ SiN_x:H /3 nm nanocrystals layer-50 nm n⁺ epitaxial Si /p-type Cz/ Al (back contact)* and under EP1 processing conditions on (100) flat silicon substrate.

List of Tables

Table 3.2: Different processing conditions for phosphorous doped epitaxial growth silicon.

Table 4.1: The deposition parameters used for the low temperature boron doped quasi-epitaxial silicon films on (100) n-type Cz wafers.

Table 5.1 The optimized etching conditions using reactive ion etching (RIE) for diodes isolation.

Table 5.2: Diode parameters using EP2 process conditions and after applying selected RTP (C) temperature profile.

Table 6.1: Calculated Si nanocrystals Si NCs size from x-ray and Micro-Raman spectra.