Effect of Sputtering and Annealing Parameters on properties of Silicon Quantum Dot Matrix

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Abstract

Fabrication of the third generation photovoltaic (PV) solar cell uses thin film deposition technique to deposit dielectrics such as SiO_2, Si_3N_4, SiC, and SiO_x. The layer works as a barrier layer, capping layer, tunneling medium, and an intermediate i- layer in the p-i-n structure solar cell. Control of physical parameters and morphology of thin film layer is essential for the synthesis of the quantum dots PV solar cell. The presented work use sputtering as deposition technique to fabricate SRO/SiO_2 multilayers on controlling the deposition parameters RF power, gas flow rate, and deposition time. Parameters (e.g. annealing temperature and annealing time) which helps quantum dots (QDs) to form during post deposition annealing are varied to control the size of QDs. The fabricated device is examined for physical and optical properties using spectroscopic techniques such as a surface profiler, SEM, FTIR, UV-Vis, and PL.

Key Words: RF Sputtering, Annealing, Si-QDs, Intermediate layer, SRO layer, Deposition rate, O_2 gas flow

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1. Introduction

Si-QDs tune the effective bandgap (E_g) of PV solar cell to absorb a broad range of solar spectrum [1, 2]. Si-QDs embedded with SiO_2 dielectric matrix gives quantum confinement effect which exhibits higher E_g as compared to bulk Si for the same solar spectrum [3]. When the QDs are close to each other, carriers can tunnel between them to form quantum dots superlattice [4]. The choice of deposition method and the annealing environment decide the properties of Si QDs matrix. Among many other techniques e.g. CVD, evaporation, sputtering is also used for fabricating the third-generation solar cell structures. In general, sputtering offers relatively high deposition rate of 4.4 nm/min to 10 nm/min at low operating temperatures between 27 ^{0}C to 300 ^{0}C. Various types of sputtering techniques reported in the literature are RF, Magnetic and DC.

RF sputtering offers the advantage of using both conducting and non-conducting target to deposit the dielectric matrix with high deposition rate and at low temperature [5, 6]. The paper reports use of RF sputtering for the fabrication of p-i-n structured QDs solar cell device. RF sputtering method is used to deposit multiple alternate layers of SiO_2-SRO functioning as intermediate layer [7] as shown in Fig. 1. Upon annealing, Si QDs are precipitate in SRO layer ($2SiO_x \rightarrow xSiO_2 + (2-x)\ Si$) [8]. The Si-QDs size and density vary with the variation of annealing temperature of the P-i-N structure solar cell [8].

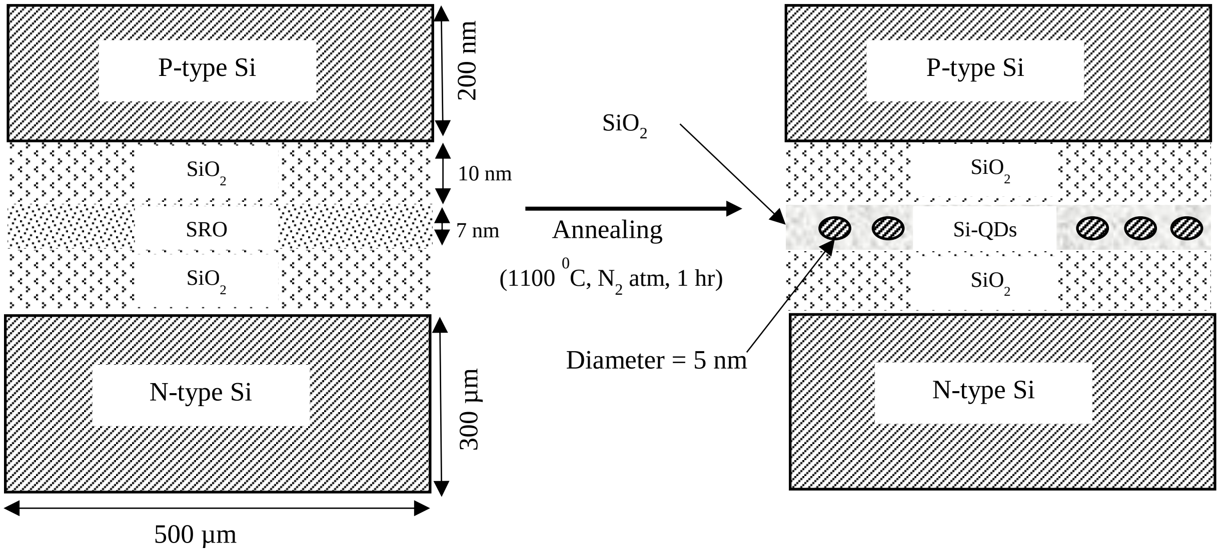


Fig. 1. p-i-n solar cell having SRO/SiO_2 intrinsic layer (left) and formation of Si-QDs after annealing in the intrinsic layer (right)

2. Experimentation

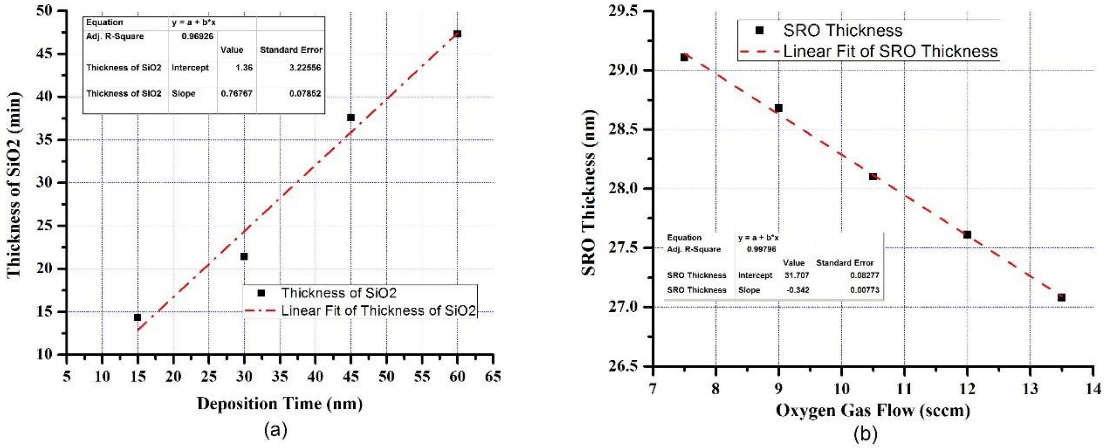
N-type phosphorous-doped Si wafer (1-10 Ω-cm resistivity, single side polished, thickness 275 ± 25 µm, <100> orientation, 2-inch diameter) is used as the substrate. The conventional substrate cleaning method is used to clean the Si wafers. The experimentation uses an in-house fabricated RF sputtering system (distance between target and substrate ~ 10 cm). To obtain a uniform deposition, the wafer is placed on the substrate holder rotating at a constant speed of 10 rpm. Si target (99.9% purity, 3-inch diameter, and 3 mm thickness with the copper backing plate) is used to deposit SRO/SiO_2 thin film layers. Rotary pump and diffusion pump creates a vacuum in the sputtering chamber. The base pressure is $9.7*10^{-7}$ mbar, and the working pressure is $4*10^{-3}$ mbar. RF power of 50 Watt is supplied to the Si target after a pre-sputtering period of 30 min. The details of SiO_2 and SRO deposition are tabulated in Table 1. The SiO_2 and SRO thin films are deposited on n-type Si substrate at room temperature. The stylus surface profiler (Veeco Dektak 150) measures the thickness of the SiO_2 layer deposited on the optically flat Si substrates.

Table 1. Thickness of SiO_2 and SRO for 50 Watt of RF power supply

SL. No.	**Ar Gas Flow (sccm)**	**SiO_2 Thin film layer Deposition**				**SRO Thin film layer Deposition**			
		Name of the Sample	**O_2 Gas Flow (sccm)**	**Deposition Time (min)**	**SiO_2 Thickness (nm)**	**Name of the Sample**	**O_2 Gas Flow (sccm)**	**Deposition Time (min)**	**SRO Thickness (nm)**
1	60	5_min	15	5	--	SRO_50%	7.5	30	29.11
2	60	10_min	15	10	--	SRO_60%	9.0	30	28.68
3	60	15_min	15	15	14.32	SRO_70%	10.5	30	28.1
4	60	30_min	15	30	21.39	SRO_80%	12.0	30	27.61
5	60	45_min	15	45	37.57	SRO_90%	13.5	30	27.08
6	60	60_min	15	60	47.31	--	--	--	--

3. Result and Discussion

The deposition rate increases with the increase in deposition time in a non-linear manner for a constant ratio of Ar/O_2 gas flow as shown in Fig. 2 (a). The obtained deposition rate for the SiO_2 thin films is about 0.76 nm/min. The SRO thickness decreases with the increase in O_2 gas flow as shown in Fig. 2 (b). The average deposition rate is around 0.9 nm/min for SRO thin film and is higher compared to SiO_2 deposition. The FTIR spectra (IRAffinity-1S, Shimadzu), as shown in Fig. 3 has the IR peak at 671, 1339, 1508, 1546, 2310, 2348, 2377, 3546, 3590 and 3855 in the 400-4000 cm^{-1} range.



(a)

(b)

Fig. 2. Thickness measurement using surface profiler (a) SiO_2 at different deposition time for a constant Ar: O_2 proportion; (b) SRO at 30 min of deposition time for variable Proportion of Ar: O_2 ratio

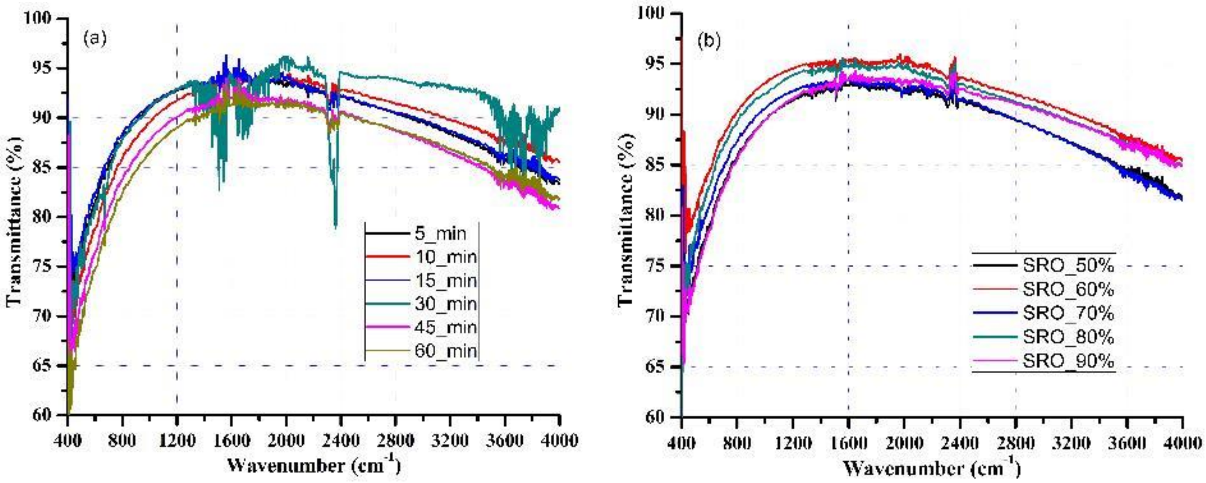


Fig. 3. IR spectra transmittance changes with the change in (a) deposition time for SiO_2 layer; (b) Oxygen gas flow for SRO layer

4. Future work:

With the knowledge about the deposition rates, devices with 10/20/30 layers of SRO/SiO_2 will be fabricated to study the effect of number of layers i.e. thickness of i-layer. Next step is to investigate the effect of annealing temperature (between 800 ^{0}C to 1100 ^{0}C) on the size and density of QDs formed in i-layer. A comparative analysis using the results of UV-Vis and PL spectroscopy will be reported. The obtained results will be verified using FEG-SEM and HRTEM.

References

[1] E. Cho, S. Park, X. Hao, D. Song, G. Conibeer and M. A. Green, "Silicon quantum dot/crystalline silicon solar cell," *Nanotechnology,* vol. 19, no. 24, p. 245201, 2008.

[2] I. Perez-Wurfl, X. Hao, A. Gentle, D. Kim, G. Conibeer and M. A. Green, "Si nanocrystal p-i-n diodes fabricated on quartz substrates for third generation solar cell applications," *Applied Physics Letters,* vol. 95, no. 15, p. 153506, 2009.

[3] P. Kale and C. Solanki, "Silicon quantum dot solar cell using top-down approach," *International Nano Letters,* vol. 5, pp. 61-65, 2015.

[4] M. Green, G. Conibeer, D. Konig, E. Cho, D. Song and e. al, "Progress with all-silicon tandem cells based on silicon quantum dots in a dielectric matrix," *Proceedings 21st EU PVSEC, Dresden,* 2006.

[5] F. Rebib, E. Tomasella, L. Thomas, J. Cellier, T. Sauvage and M. Jacquet, "Study of Reactive RF Sputtering Process of Silicon Target Under Ar-O2-N2 Atmospheres," *Plasma Processes and Polymers,* vol. 4, no. S1, pp. S986-S990, 2007.

[6] M. Vila, C. Prieto, J. Garcia-Lopez and M. Respaldiza, "Influence of the target and working gas on the composition of silicon nitride thin films prepared by reactive RF-sputtering," *Nuclear Instruments and Methods in Physics Research,* vol. 211, no. 2, pp. 199-205, 2003.

[7] H. Seifarth, R. Grotzschel, A. Markwitz, W. Matz, P. Nitzsche and L. Rebohle, "Preparation of SiO2 films with embedded Si nanocrystals by reactive r.f. magnetron sputtering," *Thin Solid Films,* vol. 330, no. 2, pp. 202-205, 1998.

[8] X. Hao, A. Podhorodecki, Y. Shen, G. Zatryb, J. Misiewicz and M. Green, "Effects of Si-rich oxide layer stoichiometry on the structural and optical properties of Si QD/SiO2 multilayer films," *Nanotechnology,* vol. 20, no. 48, p. 485703, 2009.