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ANALYZING THE EFFECTS OF SPIN-COATED PHOSPHOSILICATE GLASS ON THE CRYSTALLIZATION PROCESS OF SILICON THIN FILMS DEPOSITED VIA MAGNETRON SPUTTERING

Abstract

This study investigates the influence of spin-coated phosphosilicate glass (PSG) on the crystallization and electrical properties of silicon (Si) thin films deposited by magnetron sputtering, with a focus on optimizing their structural and electrical properties for potential applications in photovoltaics and microelectronics. The results demonstrate that higher spin-coating speeds lead to thinner and more uniform PSG layers, which in turn promote more efficient phosphorus diffusion and enhance film crystallization. Annealing at 950 °C resulted in enhanced dopant activation, improved crystallinity, and reduced sheet resistance. These structural and phase transformations were systematically analyzed by X-ray diffraction (XRD), providing detailed insight into the evolution of the Si thin films during thermal processing. In particular, the XRD results reveal a clear transition from the amorphous to the polycrystalline state, especially for samples processed at optimized spin speeds and elevated annealing temperatures. Optical characterization further showed that thermal annealing modified the reflectance and transmittance spectra and slightly increased the refractive index and extinction coefficient of the sputtered Si films. Overall, the combination of environmentally friendly spin-on doping with scalable physical deposition techniques represents a promising approach for the development of advanced photovoltaic technologies, offering a viable pathway toward sustainable and efficient device fabrication.

Keywords: silicon; crystallization; phosphosilicate glass; magnetron sputtering.

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Introduction

The rapid development of renewable energy technologies is driven by the global demand for sustainable energy sources and the urgent need to reduce dependence on fossil fuels [1]. In this context, photovoltaic (PV) technology has emerged as one of the most promising clean energy solutions due to its scalability, environmental compatibility, and strong potential to satisfy long-term energy demands [2]. Among the various materials used in PV devices, silicon (Si) remains the dominant choice in the industry, owing to its abundance, well-established processing infrastructure, and continuous performance improvements aimed at enhancing conversion efficiency while reducing manufacturing costs [3, 4]. One of the most promising approaches in Si solar cell advancement is the Tunnel Oxide Passivated Contact (TOPCon) technology [5]. The defining characteristic of TOPCon cells lies in the use of an ultra-thin tunnel oxide layer combined with a heavily doped polycrystalline Si (poly-Si) layer, forming a selective contact that significantly suppresses carrier recombination at the interface. The introduction of the thin SiO_x layer enables tunneling selectivity, facilitating electron or hole transport from the Si substrate to the n^+ or p^+ poly-Si layer while effectively suppressing minority carriers. As a result of these innovations, TOPCon cells have achieved notable progress in conversion efficiency, reaching up to 25.1% in laboratory environment placing them among the top-performing crystalline Si (c-Si) solar technologies [6, 7]. Such a combination of high efficiency potential and reduced recombination losses has made TOPCon technology particularly attractive for industrial-scale photovoltaic production. For example, recently TOPCon cells have been implemented by leading c-Si photovoltaic manufacturers as an effective approach to minimize recombination losses [8, 9].

In conventional TOPCon device fabrication, thin Si layers are most commonly deposited by plasma-enhanced chemical vapor deposition (PECVD) [10]. This technique offers good conformality and relatively low processing temperatures; however, it also suffers from several intrinsic limitations. In particular, PECVD-deposited Si layers often exhibit hydrogen incorporation, limited control over film density, and sensitivity to plasma-induced damage at the interface, which can adversely affect the electrical properties and thermal stability of subsequent poly-Si/SiO_x structures. Furthermore, conventional PECVD-based fabrication generally requires the use of hazardous precursor gases, including pyrophoric silane (SiH_4) for silicon deposition and toxic phosphine (PH_3) for in-situ phosphorus doping. These gas chemistries impose stringent safety regulations, increase equipment complexity, and contribute to higher manufacturing costs, particularly in industrial-scale production [11]. Moreover, achieving precise thickness control and high uniformity over large areas while maintaining low defect density remains challenging, especially under industrial throughput requirements.

In recent years, the physical vapor deposition (PVD) of Si-based materials has gained significant attention as a promising approach for overcoming specific technological challenges [12]. PVD techniques, including sputtering and evaporation, enable precise control over film thickness and uniformity, facilitating the formation of thin and homogeneous Si layers [13]. Among various deposition methods, magnetron sputtering stands out as one of the most efficient and versatile approaches [14, 15, 16]. Ex situ doping plays a crucial role in the fabrication of high-performance poly-Si passivating contacts by enabling the introduction and activation of dopants required to achieve the desired electrical properties [17]. Ex situ doping method include $POCl_3$ diffusion, ion implantation and spin-on doping (SOD), which are widely used for introducing dopants into silicon layers [18]. It also approaches substantial benefits in terms of processing flexibility, patterning potential, and industrial applicability [19]. Ex-situ doping using SOD solutions represents a promising approach for the fabrication of poly-Si contacts [20]. SOD has emerged as a cost-effective and environmentally friendly alternative to other methods. The application of SOD solutions offers a more straightforward and cost-effective fabrication route compared to conventional doping methods such as ion implantation, as the dopant solutions can be easily prepared and applied [21]. It should be noted that the fabrication of high-quality TOPCon passivating contacts requires careful optimization of the thermal processing conditions, particularly the annealing temperature and duration. These parameters govern not only the crystallization of the silicon layer but also dopant diffusion and activation, which together determine the structural and electrical quality of the poly-Si/SiO_x passivating contact. A comprehensive understanding of the simultaneous crystallization and doping processes is essential for achieving high-performance TOPCon structures while minimizing defect formation and preserving the integrity of the interfacial oxide [22]. Therefore, an optimal annealing temperature must be established, depending on the specific properties of both the n-type poly-Si layer and the interfacial oxide.

This work focuses on the fabrication and systematic investigation of Si thin films deposited by RF magnetron sputtering and subsequently doped using an ex-situ SOD approach based on PSG. The study aims to elucidate the role of thermal annealing and PSG-assisted phosphorus diffusion on the crystallization behavior, microstructural evolution, and electrical properties of sputtered Si films. Particular attention is given to the influence of annealing temperature and spin-coating parameters, dopant activation and sheet resistance. The results demonstrate a strong correlation between enhanced crystallinity and improved electrical performance of poly-Si films, highlighting the potential of combining RF sputtering with environmentally friendly SOD techniques for the development of high-quality poly-Si layers for photovoltaic applications.

Materials and methods

Monocrystalline p-type Si <100> Czochralski (CZ) wafers from JSC PCMP were used as a substrate. The resistivity of the Si wafers was 0.5-1.5 Ω· cm, the thickness was 200±15 µm and the area was 125 × 125 mm^2. Tetraethyl orthosilicate (TEOS, 99.0% Sigma-Aldrich, Germany), phosphoric acid (H_3PO_4, 85% AppliChem, Spain), ethanol (70% C_2H_5OH was purchased from a local supplier) and water (DI H_2O) were used in order to prepare doping solution. All the reagents were used for analytical grade and used without further purification.

A two-stage cleaning process was performed prior to deposition. First, the substrates were treated with hydrofluoric acid (HF, 3% Sigma-Aldrich, Germany), followed by Standard Clean 2 (SC-2) using a hydrochloric acid-hydrogen peroxide solution (HCl, 35% LaborPharma LTD, Kazakhstan : H_2O_2, LaborPharma LTD, Kazakhstan). Thin Si films were deposited using a MAGNA TM-200-01 system via RF sputtering using Si target (Kurt J. Lesker, Germany). The base pressure was set to Pa. The deposition was carried out at a power of 200 W, with a chamber pressure of 0.5 Pa and a substrate temperature of 100 °C. The Ar flow rate was precisely regulated using a needle valve to maintain a constant working pressure. Deposition rate was measured, and this value was subsequently used to calculate the deposition times necessary to achieve film thicknesses of 50 nm and 300 nm. Subsequently, under the same pressure conditions, additional films were deposited at a power of 250 W, also maintaining the substrate temperature at 100 °C. The distance between target and substrate was 90 mm. The processing parameters for sputtering are shown in Table 1. Thickness control was carried out by measuring XRR spectra.

Table 1 – Parameters for sputtering

Film thickness (nm)	Substrate	Pressure (Pa)	RF power (W)	Sputtering time (s)	Deposition rate (nm/s)	Target	Sputtering gas	Temperature of substrate (°C)
300	Silicon	0.5	200	3330	0.09	Silicon	Argon	100
			250	2400	0.13			
50	Silicon	0.5	200	555	0.09	Silicon	Argon	100
			250	400	0.13			

The subsequent step involved fabricating a doped Si layer by applying the phosphorus-containing solution via SOD. The phosphorus solution was prepared by mixing TEOS, 70% C_2H_5OH and 85% H_3PO_4, which served as both dopant and hydrolytic catalyst, with the phosphoric acid concentration set at 2 M (Figure 1) [23]. This solution was then applied onto amorphous silicon (a-Si) samples using SOD at three different rotation speeds: 1500 rpm, 3000 rpm, and 4500 rpm. An additional control sample was also prepared for comparative analysis. For all samples, the coating duration was fixed at 20 seconds, and a precise volume of 100 µL of phosphorus-containing solution was dispensed using a micropipette to ensure uniform deposition across the substrate surface.

A series of Si thin film samples were annealed in a tube furnace under a nitrogen atmosphere at one atmospheric pressure. The furnace was heated at a rate of 10 °C/min, requiring approximately 75, 85 and 95 min to reach the target temperatures of 750 °C, 850 °C and 950 °C, respectively. Upon reaching the target temperature, the samples were held for 30 min. After annealing, the samples were allowed to cool naturally inside the furnace to room temperature over approximately 2 h. One additional sample was kept without annealing and used as a control to evaluate the influence of thermal processing. After the annealing process, the oxide layer formed on the surface of the samples was removed using a 3% HF solution.

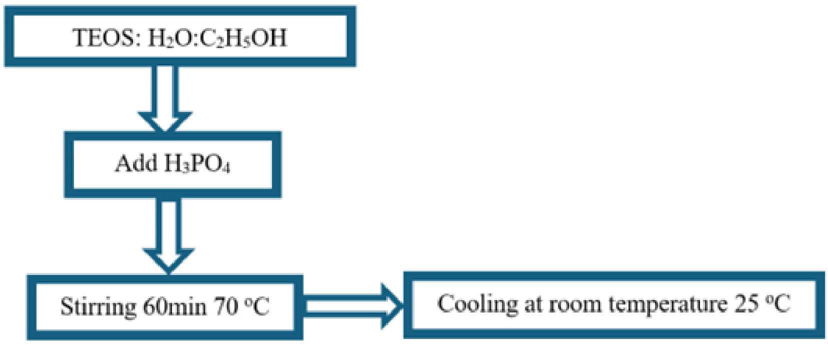

Figure 1 – Diagram illustrating the sequence of steps for preparing the phosphorus-containing solution

Sheet resistance of the films was measured using the four-point probe method with a Keithley 2400 SourceMeter (SMU). The crystal structure of the silicon thin films was characterized by Grazing-incidence X-ray diffraction (XRD) method using a ComplexRay C6 diffractometer equipped with a CuKα X-ray source (λ = 0.154 nm). The diffraction patterns were recorded over a 2θ range of 20°–60° with a step size of 0.05° and a counting time of 30 sec per step. The incident angle in GIXRD mode was set to 1°. For clearer presentation, the XRD spectra were smoothed using tools available in Origin software. The optical properties of the films were measured on Evolution 300 installation and surface morphology were measured by SEM using JEOL JSM-IT210 system.

Results and discussions

To identify the most optimal temperature for Si thin film that yields high-quality poly-Si, the films were annealed in the absence of PSG layers. XRD analysis was performed to evaluate the crystallinity of all samples. The diffraction patterns were recorded, focusing on characteristic Si peaks at approximately 2θ = 28°, 47°, and 56°, corresponding to the (111), (220), and (311) crystallographic planes of Si, respectively [24]. The intensity and sharpness of these peaks were used to assess the degree of crystallization.

The XRD patterns of the Si thin films annealed at different temperatures are presented in figure 2. The XRD spectra of the control deposited a-Si sample is featureless, indicating its amorphous nature.

However, after annealing, three main diffraction peaks emerge, confirming the crystallization of the Si films. Based on the XRD results, annealing at 850 °C and 950 °C produced the most intense and stable diffraction peaks, indicating that these temperatures are optimal for further investigation. The enhanced peak intensities suggest improved crystallization and higher structural quality of the poly-Si films. In particular, a strong (111) diffraction peak was observed under these conditions, indicating a predominant <111> crystallographic orientation, which is typical of anisotropic crystallization behavior in Si [25].

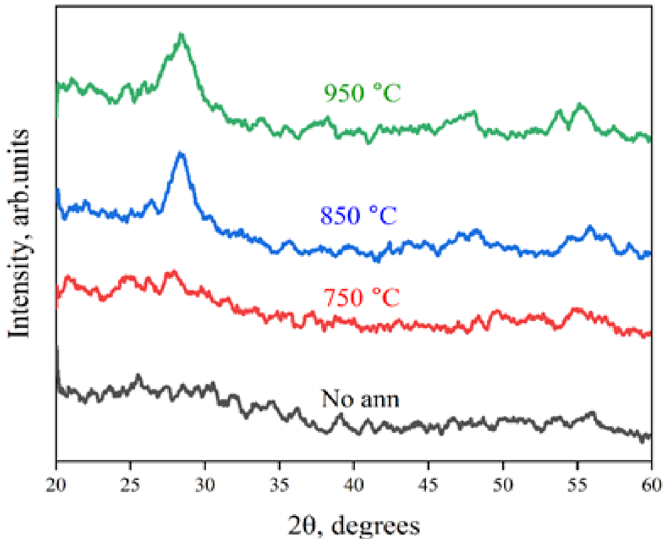

Figure 2 – XRD patterns of poly-Si films annealed at different temperatures ranging from 750 °C to 950 °C

Figure 3 demonstrates the effect of sputtering power, annealing temperature and spin coating speed of the PSG layer on the XRD patterns of RF-sputtered poly-Si films. It seems that the sample lacking a spin-coated PSG layer (0 rpm, depicted by the black curve in the XRD spectrum) exhibited the lowest diffraction peak intensity, indicating a predominantly amorphous film structure. An increase in spin speed corresponded with progressively sharper and more intense diffraction peaks near 28°, indicative of enhanced crystalline order. The samples processed at 3000 rpm and 4500 rpm showed the most pronounced and narrow peaks. Additionally, when evaluating the impact of varying RF power during sputtering, the sample deposited at 250 W displayed marginally higher peak intensity compared to that at 200 W, suggesting that elevated RF power facilitates improved crystallization by supplying greater energy during film growth, thereby resulting in denser and more crystalline films.

The integral area under the main diffraction peaks in the XRD spectrum was analyzed (Figure 4). The integral area increases with annealing temperature and reaches a maximum at 950 °C, indicating a higher crystalline fraction and improved crystallinity of the Si thin films. The integral area represents the total diffracted intensity, which is directly related to the amount of crystalline material present in the sample. An increase in the integral area of the diffraction peaks indicates a higher proportion of crystalline material relative to amorphous atoms. This trend indicates that the crystallization process improves with the increase in the integral area of the diffraction peaks, resulting in a more ordered crystal structure and enhanced crystalline quality of the Si thin films. Therefore, expansion of the diffraction peak integral area at higher annealing temperatures demonstrates that the applied annealing conditions successfully optimize the crystalline properties of the films and validate the proposed processing approach.

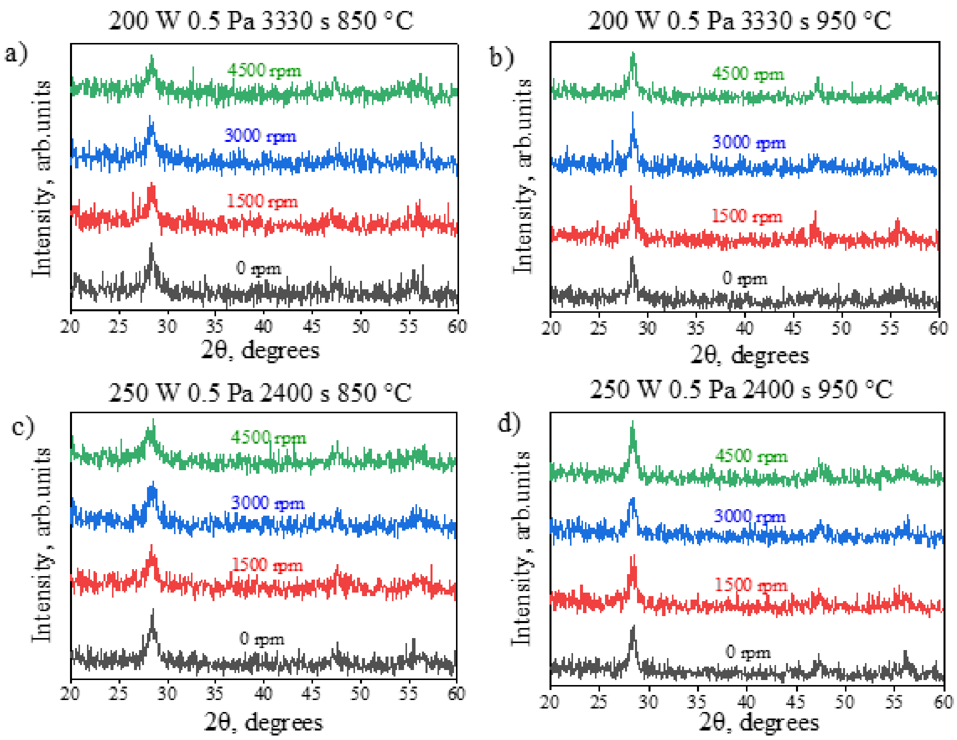

Figure 3 – XRD patterns of poly-Si films deposited by RF magnetron sputtering at different sputtering powers and annealing temperatures: (a) 200 W, 850 °C; (b) 200 W, 950 °C; (c) 250 W, 850 °C; and (d) 250 W, 950 °C

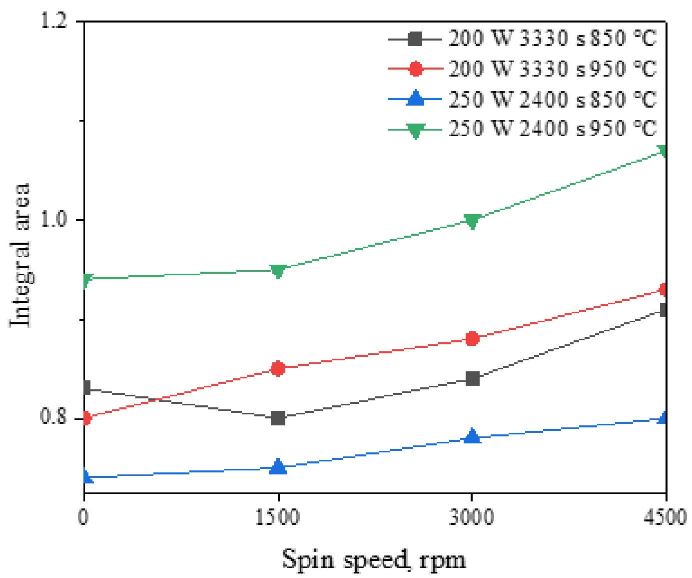

Figure 4 – Integral area of thin Si films as a function of deposition spin speed (rpm) during RF sputtering at powers of 200 W and 250 W at temperatures of 850 °C and 950 °C

Based on the XRD results, the sample deposited at a sputtering power of 250 W and annealed at 950 °C showed the highest diffraction peak intensity, suggesting enhanced crystallinity. Consequently, this sample was selected for subsequent optical property analysis. For the optical measurements, reflectance spectra were obtained from Si thin films deposited on high-resistivity p-type Si substrates, while transmittance spectra were recorded on quartz substrates.

Figure 5a and 5b present optical analyses of reflectance and transmittance spectra of the sputtered Si thin films before and after tube furnace annealing. The optical measurements reveal that annealing influences the optical response of the deposited films over the investigated wavelength range. After annealing, the reflectance spectrum exhibits a slight increase in the visible region (300–600 nm) and decrease in the near-infrared region (approximately 850–950 nm). In addition, the reflectance minimum around 750 nm becomes more pronounced, indicating a modification of the interaction between the incident light and the Si thin films after thermal treatment. The transmittance spectra retain a similar overall profile before and after annealing. However, a slight reduction in transmittance is observed throughout most of the measured wavelength range. These changes suggest that thermal annealing alters the optical characteristics of the sputtered Si films while preserving their general optical behavior.

Both reflectance and transmittance data were analyzed using SCOUT software. By processing the obtained optical spectra, key parameters such as film thickness, refractive index (n), and extinction coefficient (k) were measured. According to the SCOUT software analysis, thickness showed before annealing 320 nm and after annealing 293 nm. Meanwhile Figure 5c presents the wavelength dependence of the refractive index (n) and extinction coefficient (k) of the sputtered Si thin films before and after thermal annealing. It can be observed that the refractive index increases slightly after annealing over the entire investigated wavelength range. Nevertheless, both samples exhibit a similar spectral behavior, with the refractive index reaching its maximum value in the short-wavelength region followed by a gradual increase toward longer wavelengths. The extinction coefficient also increases after annealing, particularly in the wavelength range below approximately 500 nm, whereas at longer wavelengths the values of k approach zero for both samples. This behavior indicates reduced optical absorption in visible and near-infrared regions. The changes in the optical constants after annealing are consistent with the modification of the optical response observed in the reflectance and transmittance spectra. These results further confirm that thermal annealing influences the optical properties of the sputtered Si thin films through structural changes induced during the heat treatment. Therefore, the UV-Vis measurements complement the structural characterization and provide a more comprehensive evaluation of the sputtered Si thin films for potential TOPCon solar-cell applications.

To further investigate the surface characteristics of the deposited Si thin films, SEM analysis was performed, as shown in Figure 5d. The SEM image reveals a continuous and relatively uniform film surface without visible cracks or delamination. The homogeneous surface morphology indicates that the deposition process produced high-quality Si films.

The box plots in Figure 6 illustrate the distribution of sheet resistance values for phosphorus-doped poly-Si films under different sputtering powers, spin coating speeds, film thicknesses and annealing temperatures. In figure 6a, which depicts 300 nm-thick films deposited at 200 W and annealed at 850 °C, sheet resistance noticeably decreases as spin speed increases. Notably, films deposited at 250 W consistently demonstrate lower sheet resistance compared to those deposited at 200 W, reflecting enhanced film uniformity, and improved electrical conductivity at higher sputtering power. Upon annealing at 950 °C (figure 6b), all samples exhibited a significant reduction in sheet resistance. Si films deposited at 250 W exhibited low and uniform sheet resistance across spin speeds, demonstrating effective dopant activation via high temperature annealing. In contrast, 200 W samples showed higher resistance and variability, indicating reduced dopant activation efficiency. Figure 6c presents the sheet resistance of 50 nm-thick films annealed at 850 °C. These thinner films exhibit consistently low sheet resistance across all spin speeds, particularly at 250 W sputtering power, with minimal variation. This behavior suggests that thinner films promote more efficient phosphorus diffusion and dopant activation, even at lower annealing temperatures, especially when combined with higher sputtering power. Overall, the box plots demonstrate that higher sputtering power, increased spin speed, greater annealing temperature, and reduced film thickness all contribute to lower and more uniform sheet resistance, indicating better electrical performance of the phosphorus-doped poly-Si films.

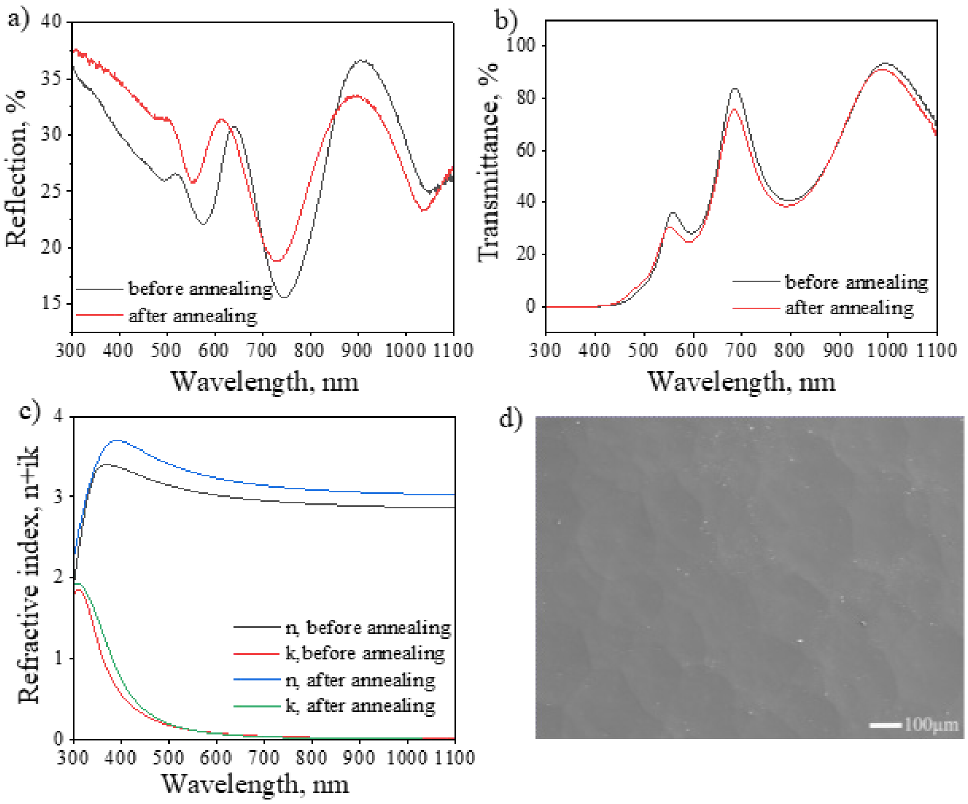

Figure 5 – a) reflection and b) transmittance spectra of silicon thin films before and after annealing, c) dependence of the refractive index and extinction coefficient of silicon thin films, d) SEM image of the Si thin film surface

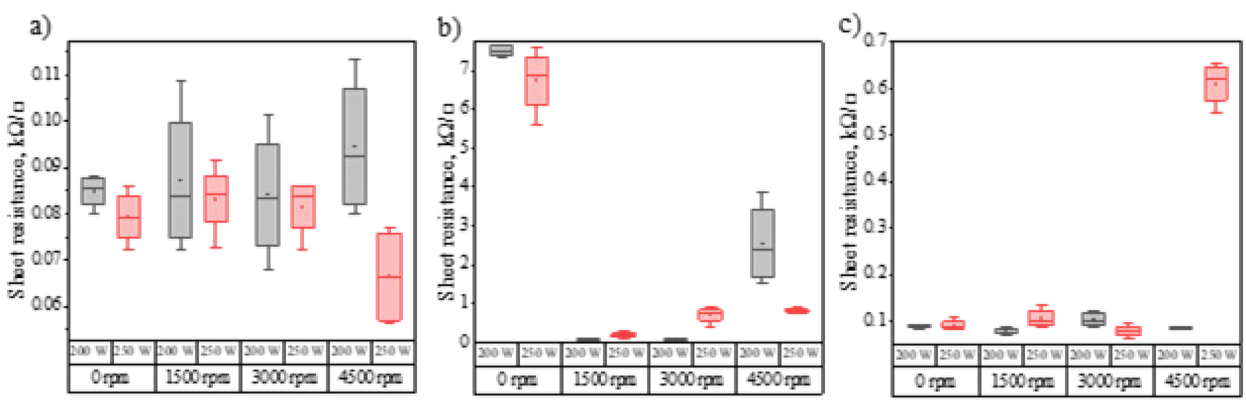

Figure 6 – Sheet resistance of (a, b) 300 nm poly-Si films deposited by RF magnetron sputtering at various power levels and spin speeds (rpm) and annealed at (a) 850 °C; (b) 950 °C, and (c) 50 nm poly-Si films deposited under similar conditions and annealed at 850 °C

Overall, the results reveal a clear relationship between deposition conditions, dopant diffusion and the resulting properties of the poly-Si films. XRD analysis and sheet resistance measurements show that improved crystallinity are key factors for governing electrical performance. These effects are promoted by optimized RF sputtering power, appropriate PSG spin-coating parameters and elevated annealing temperature. As a result, the sheet resistance becomes lower and more uniform. The findings also indicate that PSG-assisted spin-on doping influences not only phosphorus incorporation but also the crystallization behavior of sputtered Si. From a technological perspective, careful control of the thermal budget and deposition parameters is essential. The combined RF sputtering and SOD approach therefore represents a promising route for fabricating high-quality poly-Si layers for advanced Si-based photovoltaic applications.

Conclusion

This paper examines the influence of spin-coated PSG layers on the crystallization behavior and electrical performance of Si thin films deposited by RF magnetron sputtering. The work was focused on optimizing structural and electrical properties for potential photovoltaic and microelectronic applications. The experimental results were demonstrated that the PSG layer effectively enhances phosphorus diffusion during thermal annealing, thereby promoting the formation of high-quality poly-Si. It was found that higher spin speeds at 3000-4500 rpm with annealing at 950 °C, produced thinner and more uniform dopant layers, which facilitated efficient dopant incorporation and improved film crystallinity. Furthermore, among XRD analysis, it was confirmed that a distinct transformation from a-Si to poly-Si was successfully obtained. Meanwhile, annealing at 950 °C yielded the most favorable results, characterized by enhanced dopant activation and reduced sheet resistance. The optical measurements additionally demonstrated that annealing altered the reflectance and transmittance spectra and resulted in slight increases in the refractive index and extinction coefficient of the Si films. Finally, the application potentiality of the effectiveness of the SOD technique as a controllable and environmentally friendly alternative to conventional diffusion processes was demonstrated. In summary, the combined approach of SOD and RF magnetron sputtering provides a scalable, efficient, and environmentally sustainable pathway for fabricating high quality Si thin films suitable for photovoltaic and microelectronic device applications.

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МАГНЕТРОНДЫ ТОЗАҢДАТУ ӘДІСІМЕН ШӨКТІРІЛГЕН КРЕМНИЙДІҢ ЖҰҚА ҚАБЫҚШАЛАРЫНЫҢ КРИСТАЛДАНУ ПРОЦЕСІНЕ СПИН-КОАТИНГ ӘДІСІМЕН ЖАҒЫЛҒАН ФОСФОР-СИЛИКАТТЫ ӘЙНЕКТІҢ ӘСЕРІН ТАЛДАУ

Аңдатпа

Бұл зерттеу магнетрондық бүркумен кремний (Si) жұқа қабықшаларының кристалдануы мен электрлік қасиеттеріне центрифугалау әдісімен қапталған фосфосиликат шынысының (PSG) әсерін зерттеді, олардың құрылымдық және электрлік қасиеттерін фотоэлектрика мен микроэлектроникадағы әлеуетті қолдану үшін оңтайландыруға назар аударады. Центрифугалау әдісінің жылдамдығының жоғарылауының нәтижелері PSG қабаттарының жұқа және біркелкі болуына әкелетінін көрсетті, бұл өз кезегінде фосфордың тиімдірек диффузиясын жеңілдетеді және қабықшаның кристалдануын жақсартады. 950°C температурасында күйдіру қоспаларының белсенділігінің жоғарылауына, кристалдылықтың жақсаруына және меншікті кедергінің төмендеуіне әкелді. Бұл құрылымдық және фазалық түрлендірулер рентгендік дифракция (XRD) көмегімен жүйелі түрде талданды, бұл термиялық өңдеу кезінде Si жұқа қабықшаларының эволюциясын егжей-тегжейлі түсінуге мүмкіндік берді. Атап айтқанда, XRD нәтижелері аморфты күйден поликристалды күйге айқын ауысуын көрсетті, әсіресе центрифугалау әдісімен қаптау жылдамдығында және күйдіру температурасының жоғарылауында өңделген үлгілері үшін. Оптикалық сипаттамалар термиялық күйдірудің шағылысу және өткізу спектрлерін өзгерткенін, сонымен қатар тұндырылған кремний қабықшаларының сыну көрсеткіші мен жұтылу коэффициентін аздап арттырғанын көрсетті. Жалпы алғанда, экологиялық таза центрифугалау әдісінің физикалық тұндыру әдістерімен үйлесімі, озық фотоэлектрлік технологияларды әзірлеудің перспективті тәсілін білдіреді, бұл тұрақты және тиімді құрылғыларды жасауға мүмкіндік береді.

Түйін сөздер: кремний, кристаллизация, фосфосиликат шыны, магнетрондық бүрку.

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АНАЛИЗ ВЛИЯНИЯ ФОСФОРОСИЛИКАТНОГО СТЕКЛА, НАНЕСЕННОГО МЕТОДОМ СПИН-КОАТИНГА, НА ПРОЦЕСС КРИСТАЛЛИЗАЦИИ ТОНКИХ ПЛЕНОК КРЕМНИЯ, ОСАЖДЕННЫХ МЕТОДОМ МАГНЕТРОННОГО РАСПЫЛЕНИЯ

Аннотация

В данном исследовании изучается влияние фосфосиликатного стекла (PSG), нанесенного методом центрифугирования, на кристаллизацию и электрические свойства тонких пленок кремния (Si), осажденных магнетронным распылением, с акцентом на оптимизацию их структурных и электрических свойств для потенциального применения в фотовольтаике и микроэлектронике. Результаты показывают, что более высокие скорости центрифугирования приводят к более тонким и однородным слоям PSG, что в свою очередь способствует более эффективной диффузии фосфора и улучшает кристаллизацию пленки. Отжиг при 950 °C привел к усилению активации легирующих примесей, улучшению кристалличности и снижению удельного сопротивления. Эти структурные и фазовые превращения были систематически проанализированы с помощью рентгеновской дифракции (XRD), что позволило получить подробное представление об эволюции тонких пленок Si в процессе термической обработки. В частности, результаты XRD показывают четкий переход от аморфного к поликристаллическому состоянию, особенно для образцов, обработанных при оптимизированных скоростях центрифугирования и повышенных температурах отжига. Оптическая характеристика дополнительно показала, что термический отжиг изменил спектры отражения и пропускания, а также незначительно увеличил показатель преломления и коэффициент поглощения напыленных кремниевых пленок. В целом, сочетание экологически чистого метода легирования с помощью центрифугирования с масштабируемыми методами физического осаждения представляет собой многообещающий подход к разработке передовых фотоэлектрических технологий, предлагая жизнеспособный путь к устойчивому и эффективному изготовлению устройств.

Ключевые слова: кремний, кристаллизация, фосфосиликатное стекло, магнетронное напыление.