

# DEPOSITION ANGLE AS A CONTINUOUS PARAMETER: AUTOMATED GLAD GROWTH AND STRUCTURE-PROPERTY CORRELATIONS IN SILICON THIN FILMS

## KOT NANAŠANJA KOT ZVEZNI PARAMETER: AVTOMATIZIRANA RAST POD SPREMENLJIVIM POŠEVNIM KOTOM IN KORELACIJE MED STRUKTURO IN LASTNOSTMI SILICIJEVIH TANKIH PLASTE

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*Prejem rokopisa – received: 2026-04-20; sprejem za objavo – accepted for publication: 2026-06-26*

doi:10.17222/mit.2026.1733

This study aims to investigate the deposition angle as a continuous control parameter for tailoring the structural, optical, and morphological properties of silicon thin films grown by glancing-angle deposition (GLAD). Silicon thin films with a thickness of approximately 400 nm were deposited on glass substrates by electron-beam evaporation using automated control of the deposition angle in the range 0–80°. In contrast to conventional studies based on a limited number of discrete deposition angles, this approach enables a more systematic investigation of the progressive evolution of film properties with deposition geometry. X-ray diffraction analysis revealed a gradual decrease in peak intensity and crystallite size with increasing deposition angle, indicating a transition from relatively dense and ordered films at low angles to increasingly disordered structures at higher angles. Optical characterization showed marked angle-dependent changes in the transmittance, absorbance, and reflectance, consistent with an enhanced porosity, stronger light scattering, and a progressive shift in the optical response. Scanning electron microscopy confirmed the morphological evolution from compact and homogeneous layers to porous tilted columnar architectures as the deposition angle increased. These results demonstrate that the deposition angle is a key parameter governing the structure–property relationship in GLAD-grown silicon thin films and provide a useful basis for tailoring their properties for optoelectronic and photonic applications.

**Keywords:** Silicon thin films; GLAD; Deposition angle; Nanostructures; Optical properties; Electrical transport; Structure–property relationship

Namen študije, predstavljene v tem članku, je bil raziskati kot nanašanja kot parameter neprekinjenega nadzora za prilagajanje strukturnih, optičnih in morfoloških lastnosti tankih silicijevih plasti (filmov) izdelanih s postopkom nanosa pod spremenljivim (poševnim) kotom (GLAD; glancing angle deposition). Tanke silicijeve filme debeline približno 400 nm so avtorji nanašali na steklene podlage z elektronskim žarkom in uporabo avtomatiziranega nadzora kota nanašanja v območju med 0° in 80°. V nasprotju s konvencionalnimi študijami, ki temeljijo na omejenem številu diskretnih kotov nanašanja, ta pristop omogoča bolj sistematično preučevanje postopnega razvoja lastnosti filmov glede na geometrijo nanašanja. Rentgenska difrakcijska analiza (XRD) je pokazala postopno zmanjšanje intenzivnosti vrhov in velikosti kristalinitov z naraščajočim kotom nanašanja, kar kaže na prehod iz relativno gostih in urejenih filmov pri majhnih kotih v vse bolj neurejene strukture pri večjih kotih. Optična karakterizacija je pokazala izrazite od kota odvisne spremembe prepustnosti, absorpcije in odbojnosti, kar je skladno z večjo poroznostjo, močnejšim sipanjem svetlobe in postopnim premikom optičnega odziva. Vrstična elektronska mikroskopija (SEM) je potrdila morfološki razvoj od kompaktnih in homogenih plasti do poroznih nagnjenih stebričastih arhitektur z naraščajočim kotom nanašanja. Avtorji raziskave ugotavljajo, da je kot nanašanja ključni parameter, ki določa razmerje med strukturo in lastnostmi v tankih silicijevih filmih, izdelanih s postopkom GLAD, in zagotavlja uporabno osnovo za prilagajanje njihovih lastnosti za optoelektronske in fotonске aplikacije.

**Ključne besede:** tanki silicijevi filmi, GLAD postopek, kot nanašanja, nanostrukture, optične lastnosti, električni transport, korelacija med strukturo in lastnostmi

## 1 INTRODUCTION

Silicon thin films continue to attract considerable research interest because of their central role in microelectronics, optoelectronics, photovoltaics, and sensing technologies.<sup>1</sup> Their functional performance is strongly governed by their structural, optical, and electrical prop-

erties, which are highly sensitive to the deposition technique and growth conditions.<sup>2</sup> In recent years, increasing attention has been devoted to nanostructured silicon thin films, since controlling their morphology at the nanoscale offers new opportunities for tuning their physical properties and improving the performance of devices.<sup>3,4</sup>

Among the various thin-film deposition techniques, glancing-angle deposition (GLAD) has emerged as a powerful and versatile method for fabricating highly controlled nanostructured architectures.<sup>3,5,6</sup> By exploiting

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oblique vapor incidence, GLAD promotes the growth of tilted columnar structures, porous morphologies, and anisotropic thin films through the combined effects of atomic shadowing and limited adatom surface diffusion.<sup>3,5,6,8</sup> Owing to its flexibility, this approach has been widely applied to a broad range of materials and has demonstrated strong potential for applications in photonics, sensing, and energy-related devices.<sup>4,5</sup>

It is now well established that the deposition angle is a key parameter governing the growth mechanism and the resulting film morphology in oblique-angle deposition processes.<sup>5,7,9</sup> At relatively low deposition angles, surface diffusion remains sufficiently effective to promote the formation of denser and more homogeneous films. In contrast, increasing the deposition angle enhances the shadowing effects, leading to reduced packing density, stronger structural anisotropy, and the development of porous columnar architectures.<sup>5,7,9</sup> These microstructural changes directly affect the important physical properties such as crystallinity, optical transparency, light scattering, and electrical transport behavior. In porous silicon-based systems, for example, increased porosity and structural disorder have been associated with significant modifications in electrical properties and functional performance.<sup>10</sup>

Despite these advances, many previous studies on GLAD-grown thin films have been based on a limited number of discrete deposition angles, often restricted to a few selected values.<sup>5,7,9</sup> Although this approach provides useful qualitative trends, it does not fully capture the progressive evolution of film properties across the transition from compact to highly porous growth regimes. As a result, the relationship between the deposition geometry, microstructural development, and the resulting functional properties remains only partially understood, particularly for silicon thin films deposited under GLAD conditions.

Recent investigations have demonstrated that increasing the deposition angle affects the crystallinity, optical response, and electrical behavior of silicon and related thin films.<sup>12–14</sup> For instance, previous studies reported a reduction in crystallite size and an increase in structural disorder with increasing deposition angle.<sup>12,14</sup> Moreover, highly porous silicon can exhibit modified electronic behavior due to the influence of porosity and nanoscale connectivity on charge transport.<sup>13</sup> Defect-related phenomena, such as vacancy clusters and local chemical modifications, are also known to affect the structural and electronic properties of silicon-based systems.<sup>15,16</sup> Carrier transport in silicon is likewise strongly dependent on scattering mechanisms and mobility-limiting processes, as described by established transport models.<sup>17</sup> These literature findings highlight the importance of controlling the deposition geometry to better understand the relationship between growth conditions, microstructure, and functional properties.

In this work, silicon thin films were deposited by electron-beam evaporation using the GLAD technique with automated control of the deposition angle over the range 0–80°. This strategy enables a more systematic investigation of the progressive influence of deposition geometry on the structural, optical, and morphological properties of the films. By combining X-ray diffraction, optical spectroscopy, and scanning electron microscopy, the present study aims to establish clear structure-property correlations and to provide deeper insight into the growth mechanisms governing silicon thin films prepared by GLAD.

## 2 MATERIALS AND METHODS

### 2.1 Sample preparation and film deposition

Silicon (Si) thin films were deposited on glass substrates by electron-beam evaporation using the glancing-angle deposition (GLAD) technique, which is widely recognized for its ability to tailor thin-film morphology and functional properties. Previous studies have shown that the deposition angle is a key parameter governing the formation of tilted and porous columnar nanostructures through the combined effects of atomic shadowing, limited adatom surface diffusion, and growth-induced stresses.<sup>11,14</sup> These mechanisms promote anisotropic growth and strongly influence film density and microstructural evolution.

Despite these advances, most previous studies were based on a limited number of discrete deposition angles, which restricts the understanding of the progressive evolution of film properties and the associated growth dynamics.<sup>14</sup> Such an approach does not fully capture the gradual transition between dense and highly porous regimes, nor does it allow a precise correlation between microstructure and functional properties. In the present work, this limitation was addressed by using an automated angle-control approach over the range 0–80°.

Prior to deposition, the glass substrates were ultrasonically cleaned in acetone, ethanol, and distilled water, followed by air drying to remove any surface contaminants. The deposition process was carried out in a high-vacuum chamber with a base pressure below 10<sup>−5</sup> Pa, using high-purity silicon (99.99 %) as the source material. No external substrate heating was applied, and all depositions were performed at room temperature.

The deposition angle,  $\alpha$ , was automatically controlled and adjusted between 0° and 80° for the preparation of films at selected angular positions. The thickness of the deposited films was maintained at approximately 400 nm for all samples. Variation of the deposition angle directly modulated the shadowing effect, leading to a gradual transition from dense structures to more porous columnar morphologies, accompanied by changes in film density, defect distribution, and structural anisotropy.<sup>14–16</sup>

## 2.2 Characterization methods

The electrical properties were measured using the four-probe Van der Pauw method combined with Hall effect measurements in a magnetic field of 0.8 T. Optical properties were investigated by UV–Visible spectrophotometry in the wavelength range 200–1100 nm. These complementary characterization techniques enabled a direct correlation between deposition angle and the structural, optical, and electrical properties of the silicon thin films.

The observed electrical behavior, including variations in carrier mobility and resistivity, can be interpreted considering established transport models in silicon, which relate carrier mobility to structural disorder, defect density, and scattering mechanisms.<sup>15,17</sup> Compared with conventional approaches based on discrete deposition angles, the present methodology provides a more systematic understanding of the structure–property relationship and the growth mechanisms in GLAD-deposited silicon thin films.

## 3 RESULTS AND DISCUSSION

### 3.1. Structural evolution revealed by XRD

The analysis of the X-ray diffraction (XRD) patterns reveals a progressive evolution of the structure of silicon thin films as a function of the deposition angle, confirming the decisive influence of GLAD geometry on the microstructural organization of the material.

As illustrated in **Figure 1** (0°, 10° and 20°), films deposited at low angles exhibit intense and sharp diffraction peaks, characteristic of a dense, compact, and relatively well-organized structure. The high peak intensity reflects an improved structural coherence and a high degree of short-range order. As the deposition angle increases from 0° to 20°, a slight decrease in peak intensity accompanied by progressive peak broadening is observed, suggesting a reduction in crystallite size and the onset of structural disorder. At these low angles, atomic shadowing effects remain limited, allowing sufficient

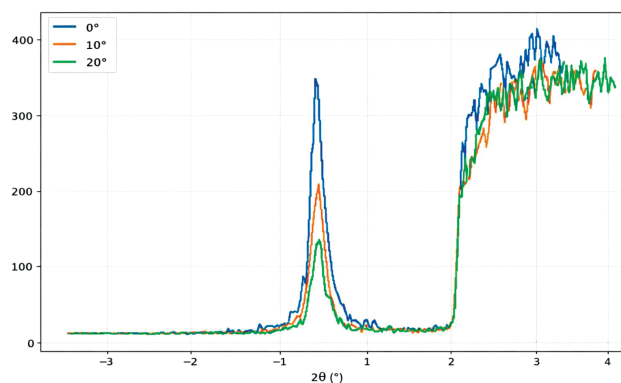


**Figure 1:** XRD patterns of Si thin films deposited at 0°, 10° and 20°, showing high peak intensity and sharp diffraction features at low deposition angles

adatom mobility and promoting homogeneous film growth.

At intermediate deposition angles (30°, 40° and 50°), as illustrated in **Figure 2**, the diffraction peaks become less intense and broader, indicating a progressive degradation of structural order and a transition toward a more disordered microstructure.

At intermediate angles, the diffraction peaks become less intense and broader, indicating a progressive degradation of structural order. This evolution corresponds to a transition region between compact and more open structures. In this angular range, shadowing effects become more pronounced and limit adatom surface diffusion, promoting the formation of a less dense and more disordered microstructure. The small differences observed between 30°, 40° and 50° suggest that the structural transition is already well established within this angular range, with reduced crystallinity compared to low-angle films.

At high deposition angles, **Figure 3** 60°, 70° and 80°, the XRD patterns reveal a markedly altered structural organization dominated by pronounced atomic shadowing effects. The diffraction peaks become significantly broadened and less intense, indicating a substantial loss of long-range order and a pronounced decrease in crystallite size. This behavior reflects the development of a highly porous and disordered microstructure.

The observed variations in peak intensity may be attributed to local reorientation of the growing columns and possible texture evolution; however, the overall structural trend clearly indicates the formation of anisotropic, columnar architectures. At these elevated angles, the limited surface diffusion of adatoms combined with enhanced shadowing leads to incomplete coalescence between the columns, resulting in a loosely packed structure with reduced density.

Consequently, film growth becomes increasingly non-compact, which directly impacts the apparent crystallinity and promotes a transition toward quasi-amorphous behavior at the highest deposition angles.

Overall, the XRD patterns presented in **Figures 1–3** clearly demonstrate that increasing the deposition angle induces a continuous transition from a dense and rela-

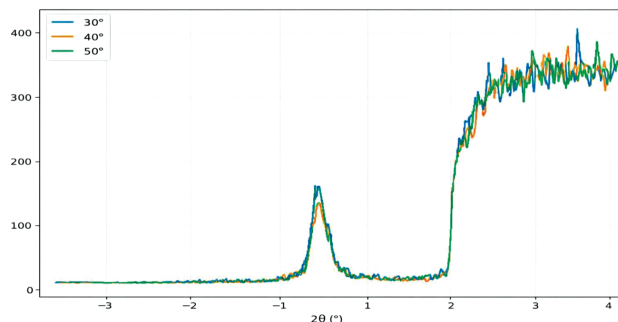


**Figure 2:** XRD patterns of Si thin films deposited at 30°, 40° and 50°, showing reduced peak intensity and broadening associated with increasing structural disorder

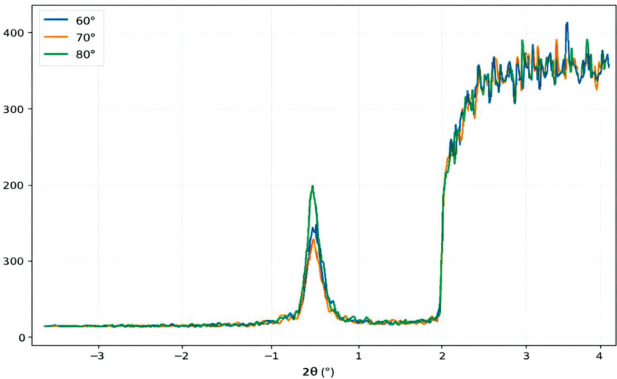


**Figure 3:** XRD patterns of Si thin films deposited at 60°, 70° and 80°, showing broadened peaks and reduced intensity, indicative of porous and disordered columnar growth

tively ordered structure to a porous, columnar, and disordered morphology. The progressive decrease in peak intensity, together with peak broadening, indicates a reduction in crystallite size and a loss of structural coherence. These observations are consistent with the GLAD growth mechanism, in which atomic shadowing becomes increasingly dominant as the deposition angle increases.

To quantitatively support these trends, the structural parameters extracted from the XRD patterns are summarized in **Table 1**. A systematic decrease in peak intensity and crystallite size, accompanied by an increase in the full width at half maximum (FWHM), is observed with increasing deposition angle. This evolution confirms a gradual transition from a compact and well-organized structure at low angles to a highly disordered, quasi-amorphous regime at high angles, governed by the combined effects of shadowing and limited adatom surface diffusion.

**Table 1:** Structural parameters of Si thin films as a function of deposition angle, including peak intensity, FWHM, crystallite size, and structural order

| Deposition angle (°) | Peak intensity (a.u.) | FWHM (rad) | Crystallite size D (nm) | Structural order |
|----------------------|-----------------------|------------|-------------------------|------------------|
| 0                    | 340                   | 0.010      | 8.5                     | High             |
| 10                   | 210                   | 0.012      | 7.5                     | High             |
| 20                   | 130                   | 0.014      | 6.8                     | Moderate         |
| 30                   | 160                   | 0.016      | 6.0                     | Moderate         |
| 40                   | 150                   | 0.018      | 5.3                     | Moderate         |
| 50                   | 145                   | 0.020      | 4.7                     | Low              |
| 60                   | 140                   | 0.023      | 4.1                     | Low              |
| 70                   | 135                   | 0.026      | 3.5                     | Very low         |
| 80                   | 130                   | 0.030      | 3.0                     | Quasi-amorphous  |

The structural evolution revealed by XRD analysis is expected to have a direct impact on the optical behavior of the films. Variations in crystallinity, density, and porosity induced by the deposition angle strongly influence light propagation within the material.

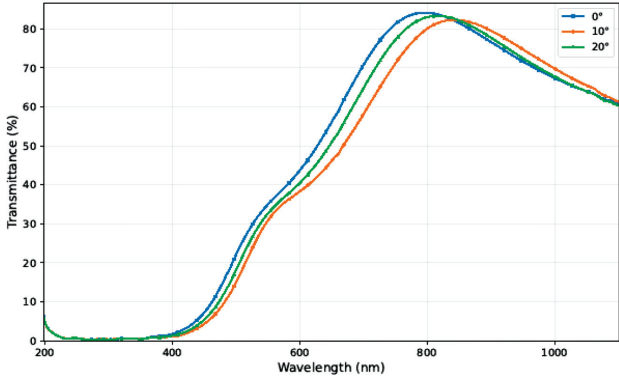


**Figure 4:** Transmittance spectra of Si thin films deposited at 0°, 10° and 20°, showing high transparency in the visible region and a clear dependence on deposition angle

### 3.2 Transmittance behavior as a function of deposition angle

To further investigate these effects, the optical properties were analyzed through transmittance spectra, as shown in **Figures 4, 5 and 6**.

The transmittance spectra of silicon thin films exhibit a strong dependence on the deposition angle, reflecting the progressive structural modifications previously revealed by XRD analysis.

As shown in **Figure 4**, films deposited at low angles (0°, 10° and 20°) exhibit high transmittance in the visible region, reaching values above  $\approx 80\%$ . This behavior is consistent with their dense and relatively well-ordered structure. The smooth spectral evolution and the gradual increase in transmittance with wavelength indicate low light scattering and limited absorption losses, characteristic of compact and homogeneous films.

With increasing deposition angle, the optical response begins to evolve. As illustrated in **Figure 5**, films deposited at intermediate angles (30°, 40° and 50°) show a slight decrease in the overall transparency, accompanied by modifications in the spectral shape and a moderate shift of the absorption edge. These changes reflect the transition toward a less dense microstructure, as pre-

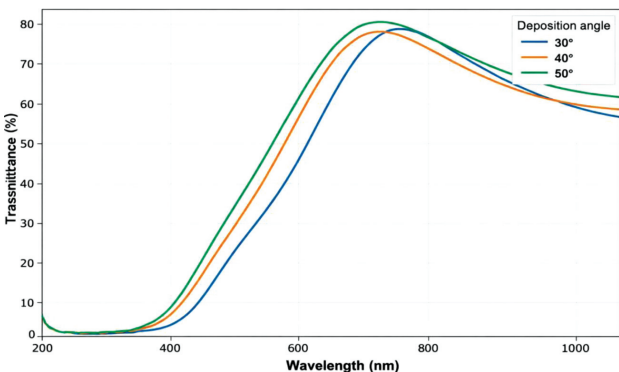


**Figure 5:** Transmittance spectra of Si thin films deposited at 30°, 40° and 50°, showing reduced transparency and modified optical response with increasing deposition angle

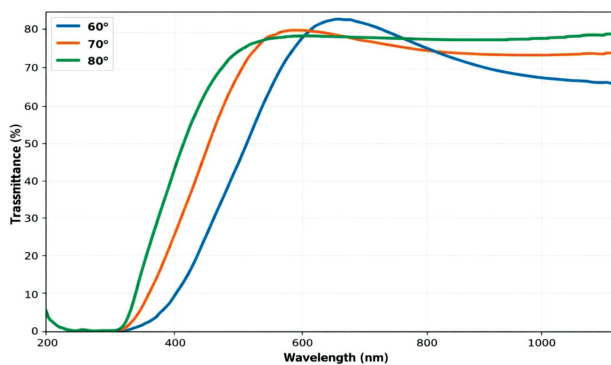


**Figure 6:** Transmittance spectra of Si thin films deposited at 60°, 70° and 80°, showing angle-dependent optical behavior associated with increased porosity and light scattering

viously evidenced by XRD analysis. The increasing influence of atomic shadowing enhances porosity and structural disorder, leading to stronger light scattering and reduced optical transmission.

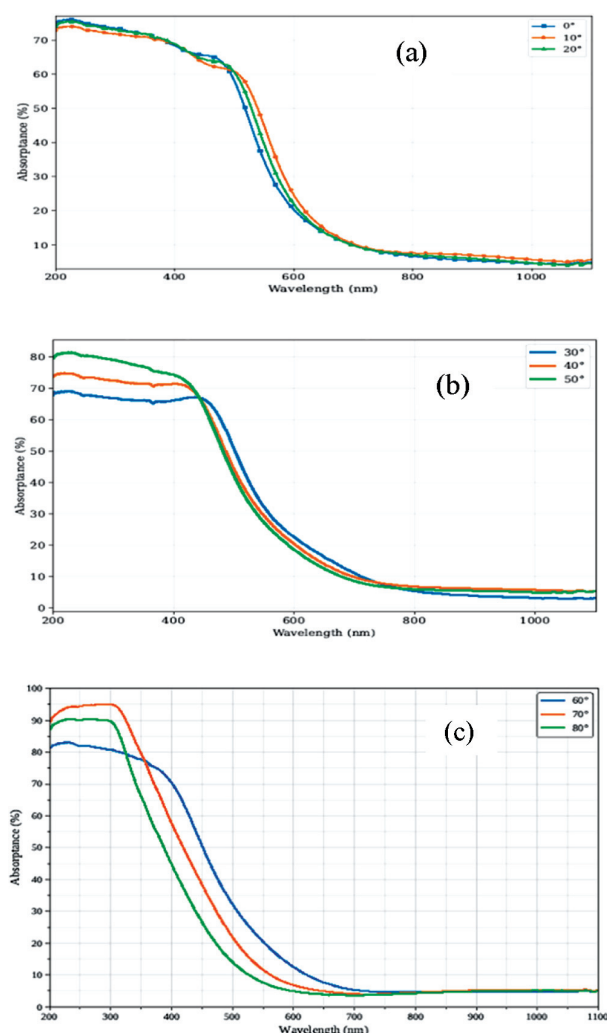


**Figure 7:** Absorbance spectra of Si thin films as a function of deposition angle. a) at 0°, 10° and 20°, (+b) at 30°, 40° and 50°, and (+c) at 60°, 70° and 80°

At higher deposition angles, the modifications become more pronounced. As presented in **Figure 6**, films deposited at 60°, 70° and 80° exhibit noticeable changes in their transmittance spectra. Although the overall transmittance remains relatively high, a clear shift of the absorption edge toward shorter wavelengths is observed. This behavior is attributed to the development of highly porous and tilted columnar structures, which reduce the effective refractive index and enhance light scattering within the films. The apparent widening of the optical band gap may also be associated with increased structural disorder and reduced film density.

Overall, the transmittance results confirm the structural evolution identified by XRD analysis. Increasing the deposition angle induces a gradual transition from dense and homogeneous films to porous and columnar structures, resulting in enhanced light scattering and significant modifications of the optical response. The observed shift of the absorption edge and the variations in transmittance highlight the strong influence of microstructural parameters such as density, porosity, and structural disorder on light propagation. These findings demonstrate that the deposition angle is a key parameter for tuning the optical properties of GLAD-deposited silicon thin films and for establishing a direct correlation between structure and optical behavior.

**Table 2:** Transmittance characteristics of Si thin films as a function of deposition angle, including maximum transmittance, peak wavelength, average transmittance, and optical behavior

| Deposition angle (°) | Max transmittance (%) | Peak wavelength (nm) | Average transmittance (%) | Optical behavior    |
|----------------------|-----------------------|----------------------|---------------------------|---------------------|
| 0                    | 85                    | 780                  | 70                        | High transparency   |
| 10                   | 83                    | 800                  | 68                        | High transparency   |
| 20                   | 82                    | 800                  | 66                        | Slight scattering   |
| 30                   | 79                    | 750                  | 64                        | Moderate scattering |
| 40                   | 78                    | 730                  | 62                        | Moderate scattering |
| 50                   | 80                    | 700                  | 60                        | Increased disorder  |
| 60                   | 83                    | 650                  | 58                        | Strong scattering   |
| 70                   | 80                    | 600                  | 57                        | Strong scattering   |
| 80                   | 78                    | 580                  | 56                        | Highly porous       |

To obtain a more comprehensive understanding of the optical properties, the analysis was extended to the absorbance spectra, which provide direct insight into optical transitions and the evolution of the electronic structure of the films.

### 3.3 Absorbance evolution and optical response

As shown in **Figure 7**, these results complement the transmittance data and further confirm the strong dependence of the optical response on the deposition angle. The absorbance spectra clearly reveal the influence of the microstructural modifications induced by the GLAD

geometry on the light–matter interaction in silicon thin films.

As shown in **Figure 7a**, films deposited at low angles ( $0^\circ$ ,  $10^\circ$  and  $20^\circ$ ) display high absorbance in the ultraviolet and near-visible regions, followed by a gradual decrease with increasing wavelength. This behavior is characteristic of dense and relatively homogeneous films. The well-defined absorption edge indicates a relatively ordered structure with limited defect states. The small variations observed between these angles suggest that the microstructure remains largely compact, although slight shifts in the absorption edge may already reflect the onset of structural modifications.

As illustrated in **Figure 7b**, films deposited at intermediate angles ( $30^\circ$ ,  $40^\circ$  and  $50^\circ$ ) exhibit more noticeable changes in the absorbance intensity along with a clearer shift of the absorption edge. These modifications are consistent with the structural transition identified by XRD analysis, corresponding to a decrease in film density and an increase in structural disorder. While the films maintain strong absorption in the UV-visible region, the observed spectral shift indicates changes in the electronic structure, likely associated with increased porosity and alterations in the local atomic environment.

At higher deposition angles, the optical response becomes significantly modified. As presented in **Figure 7c**, films deposited at  $60^\circ$ ,  $70^\circ$  and  $80^\circ$  show the most pronounced changes in their absorbance spectra. A strong absorbance is observed in the UV-visible region, followed by a sharper decrease beyond the absorption edge. The shift of the absorption edge toward shorter wavelengths suggests an apparent widening of the optical band gap. This behavior can be attributed to the formation of highly porous and columnar structures, which reduce the effective optical density and enhance disorder-related effects. Additionally, the reduced absorbance at longer wavelengths indicates weaker absorption in the near-infrared region, consistent with the lower density and more open microstructure of films deposited at high angles.

Overall, the absorbance spectra clearly confirm the progressive structural evolution induced by increasing the deposition angle. The observed variations in absorbance intensity and the systematic shift of the absorption edge reflect significant changes in film density, porosity, and structural disorder. These results highlight the strong influence of microstructure on the electronic and optical properties of the films. In particular, the apparent widening of the optical band gap at high angles is closely linked to the development of porous columnar structures. Therefore, the deposition angle emerges as a key parameter for tuning the absorbance behavior and controlling the optical response of GLAD-grown silicon thin films.

To provide a more quantitative analysis of the absorbance behavior, the data extracted from **Figures 7a-7c** were compiled in **Table 3**. While the graphical representation highlights the evolution of the absorbance spectra with deposition angle, it remains limited for an accurate comparison of key optical parameters. Therefore, **Table 3** summarizes the main characteristics, including maximum absorbance values, absorption edge positions, and their variation with deposition angle. This tabulated representation enables a clearer comparison between different deposition conditions and offers deeper insight into the relationship between GLAD-induced microstructural evolution and the resulting optical properties of the films.

**Table 3:** Absorbance characteristics of Si thin films as a function of deposition angle, including maximum absorbance, absorption-edge position, average absorbance, and optical behavior

| Deposition angle ( $^\circ$ ) | Max absorbance (%) | Absorption edge (nm) | Average absorbance (%) | Optical behavior   |
|-------------------------------|--------------------|----------------------|------------------------|--------------------|
| 0                             | 75                 | 520                  | 45                     | Dense structure    |
| 10                            | 74                 | 530                  | 43                     | Slight disorder    |
| 20                            | 76                 | 540                  | 42                     | Moderate disorder  |
| 30                            | 68                 | 550                  | 40                     | Increased disorder |
| 40                            | 73                 | 540                  | 38                     | Porous structure   |
| 50                            | 80                 | 530                  | 36                     | Highly porous      |
| 60                            | 82                 | 500                  | 34                     | Strong disorder    |
| 70                            | 95                 | 450                  | 32                     | Strong absorption  |
| 80                            | 90                 | 430                  | 30                     | Highly porous      |

### 3.4 Reflectance behavior and scattering effects

Following an analysis of the transmittance and absorbance, the reflectance spectra provide complementary insight into surface morphology, refractive index contrast, and light scattering mechanisms induced by the GLAD process. As shown in **Figures 8a-8c**, the reflectance behavior strongly depends on the deposition angle, reflecting the progressive microstructural evolution of the films. As illustrated in **Figure 8a**, films deposited at low angles ( $0^\circ$ ,  $10^\circ$  and  $20^\circ$ ) exhibit moderate reflectance accompanied by well-defined interference fringes. These features indicate smooth, dense, and homogeneous surfaces with low roughness. The presence of clear maxima and minima is characteristic of coherent optical interference, suggesting a relatively uniform refractive index and limited light scattering within the films.

As shown in **Figure 8b**, increasing the deposition angle to intermediate values ( $30^\circ$ ,  $40^\circ$  and  $50^\circ$ ) leads to a decrease in overall reflectance along with a noticeable attenuation of interference fringes. This behavior reflects the onset of structural inhomogeneity and increased surface roughness. The development of a granular morphology and enhanced shadowing effects promote diffuse scattering and induce local variations in the effective re-

fractive index, thereby reducing the coherence of the reflected light.

At higher deposition angles, the modifications become more pronounced. As presented in **Figure 8c**, films deposited at 60°, 70° and 80° exhibit a significant reduction in reflectance, particularly in the visible region, along with the near disappearance of interference fringes. This evolution is consistent with the formation of highly porous and tilted columnar structures characteristic of the GLAD regime. The increased porosity lowers the effective refractive index and enhances multiple scattering and light trapping effects, leading to a strong attenuation of the reflected signal.

Overall, the reflectance spectra clearly confirm the strong influence of deposition angle on the optical response of the films. The transition from dense and smooth structures at low angles to porous and columnar morphologies at high angles results in a progressive decrease in reflectance and a shift from an interfer-

ence-dominated regime to a scattering-dominated behavior. These findings are consistent with the trends observed in transmittance and absorbance analyses, highlighting the strong correlation between microstructure and optical properties. Therefore, the deposition angle plays a key role in controlling light reflection and scattering, offering an effective means to tailor the optical performance of GLAD-deposited silicon thin films.

To provide a quantitative evaluation of the reflectance behavior, the parameters extracted from **Figures 8–10** are summarized in **Table 4**. While the spectra illustrate the evolution of reflectance with deposition angle, they do not allow precise comparison of key optical features. **Table 4** therefore presents the main characteristics, including maximum and minimum reflectance values as well as peak positions, enabling a clearer comparison between different deposition conditions and a more rigorous correlation with the underlying microstructural evolution.

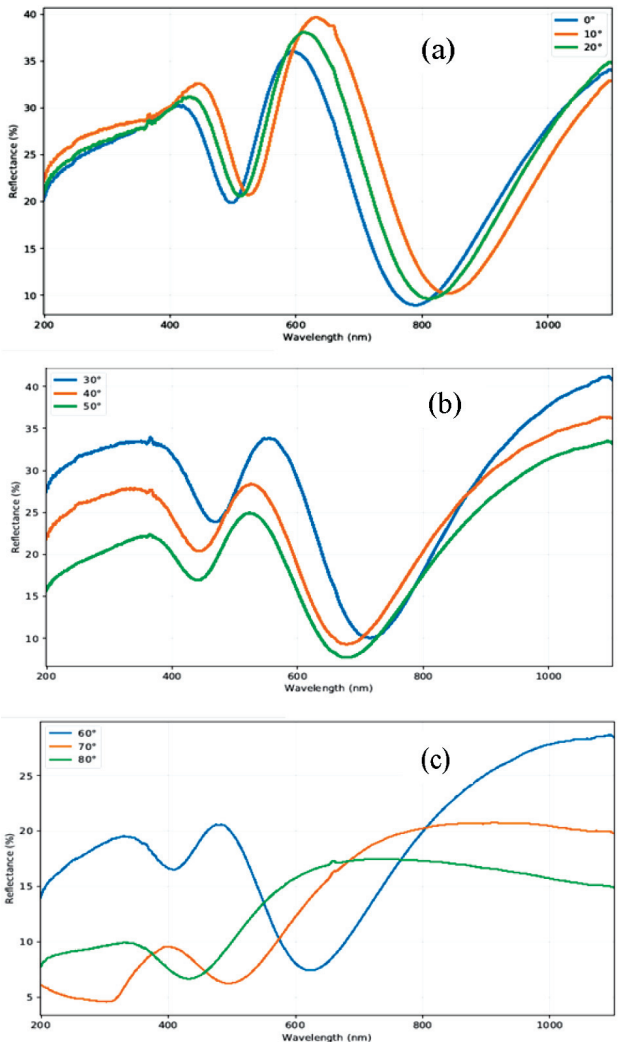


**Figure 8:** Reflectance spectra of Si thin films as function of deposition angle. a) at 0°, 10° and 20°, b) at 30°, 40° and 50°, and c) at 60°, 70° and 80°

**Table 4:** Reflectance characteristics of Si thin films as a function of deposition angle, including maximum reflectance, minimum reflectance, peak wavelength, and optical behavior

| Deposition angle (°) | Max reflectance (%) | Min reflectance (%) | Peak wavelength (nm) | Optical behavior     |
|----------------------|---------------------|---------------------|----------------------|----------------------|
| 0                    | 36                  | 9                   | 620                  | Dense film           |
| 10                   | 40                  | 10                  | 650                  | Smooth surface       |
| 20                   | 38                  | 9                   | 630                  | Slight roughness     |
| 30                   | 42                  | 11                  | 550                  | Moderate roughness   |
| 40                   | 36                  | 10                  | 580                  | Increased scattering |
| 50                   | 33                  | 8                   | 600                  | Porous structure     |
| 60                   | 29                  | 7                   | 500                  | Strong scattering    |
| 70                   | 21                  | 6                   | 700                  | Diffuse surface      |
| 80                   | 17                  | 7                   | 750                  | Highly porous        |

### 3.5 Morphological evolution observed by SEM

To further elucidate the microstructural evolution of the films, scanning electron microscopy (SEM) observations were performed, as shown in **Figure 9**. These images provide direct visual evidence of the morphological changes induced by the variation of the deposition angle.

At low deposition angles (0°, 10° and 20°), the films exhibit smooth, dense, and homogeneous surfaces, as observed in the top-view images. The cross-sectional views reveal compact and uniform layers, characteristic of a diffusion-dominated growth regime where adatom mobility remains sufficiently high to ensure continuous film formation.

As the deposition angle increases to intermediate values (30°, 40° and 50°), the morphology progressively evolves toward a more granular and heterogeneous structure. The surface becomes rougher, and the cross-sectional images reveal the onset of columnar features. This transition marks the increasing influence of atomic shad-

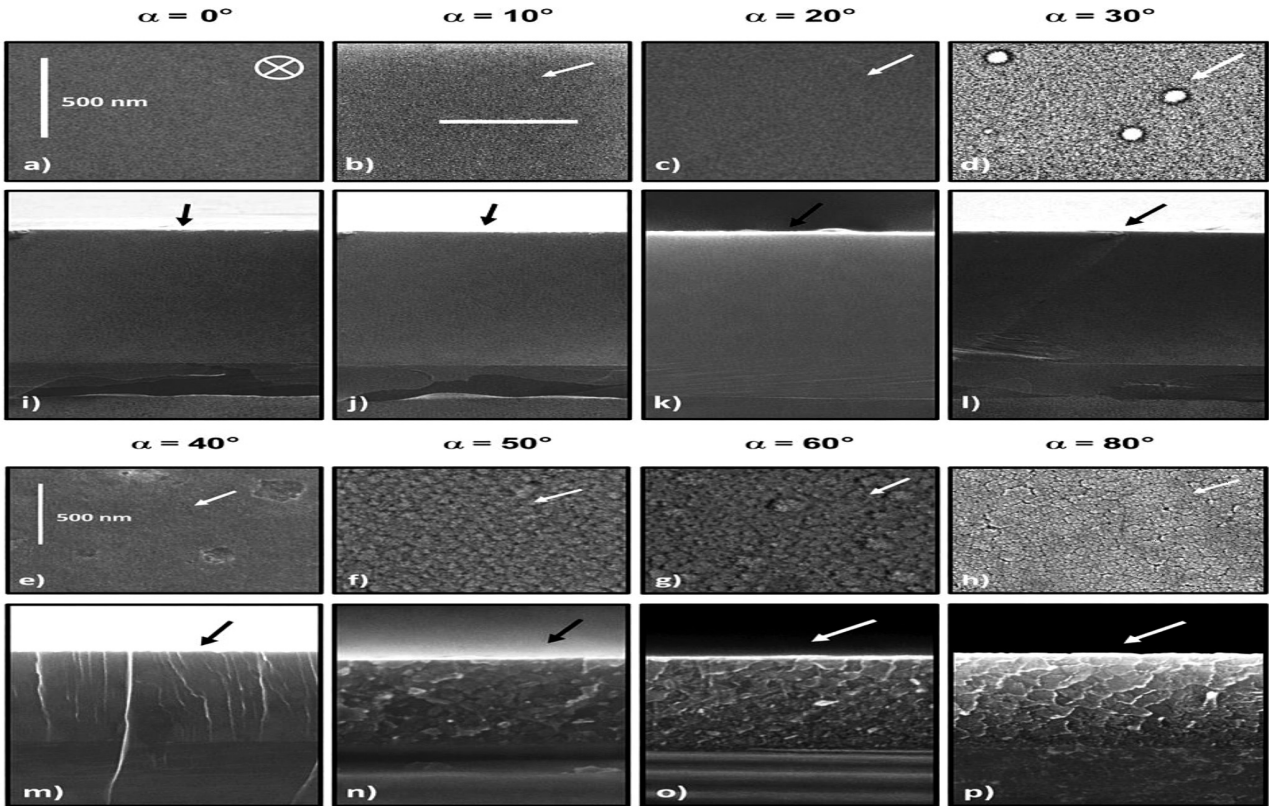


**Figure 9:** SEM images of Si thin films deposited at angles from 0° to 80°: top-view images (a–h) and cross-sectional images (i–p), showing the transition from dense and smooth films at low angles to porous tilted columnar morphologies at high angles

owing effects, which limit lateral growth and promote the development of separated structural domains.

At high deposition angles (60°, 70° and 80°), the films exhibit highly porous and well-defined tilted columnar structures. The columns become clearly distinguishable, with increased spacing between them, reflecting a shadowing-dominated growth regime. This pronounced structural anisotropy results in high porosity and reduced film density, in agreement with the structural and optical results obtained from XRD, transmittance, absorbance, and reflectance analyses.

To complement the qualitative SEM observations presented in **Figure 9**, a quantitative analysis of the morphological evolution was performed. While the images

clearly illustrate the transition from dense to porous columnar structures, a more systematic description of the key morphological parameters is necessary.

Accordingly, the main features extracted from the SEM images, including surface morphology, cross-sectional structure, porosity level, and growth mechanism, are summarized in **Table 5**. This tabulated representation enables a clearer comparison between the different deposition conditions and provides a more rigorous understanding of the relationship between deposition angle, microstructure, and growth dynamics.

To provide a comprehensive and unified understanding of the film behavior, a global correlation between structural, optical, and morphological properties was es-

**Table 5:** Morphological characteristics of Si thin films as a function of deposition angle, including surface morphology, cross-sectional structure, porosity level, and growth mechanism

| Deposition angle (°) | Surface morphology | Cross-sectional structure | Porosity level | Growth mechanism   |
|----------------------|--------------------|---------------------------|----------------|--------------------|
| 0                    | Smooth, compact    | Dense, uniform layer      | Very low       | Normal growth      |
| 10                   | Slightly rough     | Dense structure           | Low            | Limited shadowing  |
| 20                   | Homogeneous        | Compact layer             | Low            | Early shadowing    |
| 30                   | Granular surface   | Beginning of columns      | Moderate       | Shadowing onset    |
| 40                   | Rough surface      | Columnar tendency         | Moderate       | Shadowing growth   |
| 50                   | Grain-like         | Columnar structure        | High           | Competitive growth |
| 60                   | Highly granular    | Tilted columns            | High           | Strong shadowing   |
| 70                   | Clustered grains   | Well-defined columns      | Very high      | Columnar growth    |
| 80                   | Highly porous      | Tilted porous columns     | Extremely high | GLAD regime        |

**Table 6:** Summary of the angle-dependent structural, optical, and morphological properties of Si thin films

| Angle (°) | Intensity | FWHM  | $D$ (nm) | $T_{\max}$ (%) | $T_{\text{avg}}$ (%) | $A_{\max}$ (%) | $A_{\text{avg}}$ (%) | $R_{\max}$ (%) | $R_{\min}$ (%) | Morphology    | Porosity       |
|-----------|-----------|-------|----------|----------------|----------------------|----------------|----------------------|----------------|----------------|---------------|----------------|
| 0         | 340       | 0.010 | 8.5      | 85             | 70                   | 75             | 45                   | 36             | 9              | Dense         | Very low       |
| 10        | 210       | 0.012 | 7.5      | 83             | 68                   | 74             | 43                   | 40             | 10             | Smooth        | Low            |
| 20        | 130       | 0.014 | 6.8      | 82             | 66                   | 76             | 42                   | 38             | 9              | Compact       | Low            |
| 30        | 160       | 0.016 | 6.0      | 79             | 64                   | 68             | 40                   | 42             | 11             | Granular      | Moderate       |
| 40        | 150       | 0.018 | 5.3      | 78             | 62                   | 73             | 38                   | 36             | 10             | Rough         | Moderate       |
| 50        | 145       | 0.020 | 4.7      | 80             | 60                   | 80             | 36                   | 33             | 8              | Porous        | High           |
| 60        | 140       | 0.023 | 4.1      | 83             | 58                   | 82             | 34                   | 29             | 7              | Columnar      | High           |
| 70        | 135       | 0.026 | 3.5      | 80             | 57                   | 95             | 32                   | 21             | 6              | Clustered     | Very high      |
| 80        | 130       | 0.030 | 3.0      | 78             | 56                   | 90             | 30                   | 17             | 7              | Highly porous | Extremely high |

tablished. While the previous analyses (XRD, transmittance, absorbance, reflectance, and SEM) revealed clear trends as a function of the deposition angle, their separate interpretation remains insufficient to fully capture the underlying structure–property relationship.

In this context, the key parameters extracted from each characterization technique, including XRD intensity, FWHM, crystallite size, optical properties, and morphological features such as structure and porosity, are compiled in **Table 6**. This integrated representation highlights the continuous and correlated evolution of all properties with increasing deposition angle.

The results clearly demonstrate a progressive transition from dense, well-organized structures at low angles to highly porous, columnar, and disordered architectures at high angles. This transition is consistently accompanied by a reduction in crystallite size, an increase in structural disorder, a modification of optical responses, and a significant change in surface morphology.

Importantly, this global analysis confirms that the deposition angle acts as a key continuous parameter governing the growth mechanism and the resulting physical properties of the films. The strong correlation observed between structural, optical, and morphological characteristics demonstrates that the GLAD process enables precise tuning of material properties through controlled variation of the deposition geometry.

#### 4 CONCLUSION AND PERSPECTIVES

In this work, silicon thin films were successfully deposited by electron-beam evaporation using the glancing-angle deposition (GLAD) technique with automated control of the deposition angle over a broad angular range from 0° to 80°. This approach enabled a systematic investigation of the influence of deposition geometry on the structural, optical, and morphological properties of the films. Compared with conventional approaches based on a limited number of isolated deposition angles, the present methodology provides a clearer description of the progressive transition from compact to porous growth regimes. The main findings of this study can be summarized as follows:

Increasing the deposition angle induced a continuous transformation of the films from dense and relatively homogeneous layers at low angles to porous, tilted columnar structures at high angles.

X-ray diffraction analysis revealed a progressive decrease in crystallite size and structural order with increasing deposition angle, confirming the growing influence of atomic shadowing and limited adatom surface diffusion.

Optical characterization showed marked angle-dependent variations in transmittance, absorbance, and reflectance, indicating enhanced light scattering and significant modifications of the optical response as the microstructure evolved.

SEM observations confirmed the morphological transition suggested by the structural and optical analyses, showing the development of increasingly porous and tilted columnar architectures at high deposition angles.

The combined structural, optical, and morphological results demonstrate a strong correlation between deposition angle, microstructure, and film properties, confirming that deposition geometry is a key parameter for tailoring the functional behavior of GLAD-grown silicon thin films.

These findings provide a useful framework for understanding and controlling the structure–property relationships in nanostructured silicon-based coatings. From an application point of view, the ability to tune film density, porosity, and optical response through controlled deposition conditions offers promising prospects for the development of silicon thin films for optoelectronic, photonic, and sensing applications.

Future work may focus on extending this approach to other material systems and multilayer architectures, as well as investigating the influence of additional growth parameters such as substrate temperature, deposition rate, and post-deposition treatment. A more detailed analysis of charge-transport behavior, supported by dedicated electrical results and modeling, would also provide deeper insight into the relationship between microstructure and carrier transport in porous nanostructured films. Finally, the development of predictive models linking deposition parameters to functional properties

would be valuable for the optimization of GLAD-based thin-film design.

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