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CHARACTERIZATION OF ALUMINUM-DOPED HYDROGENATED AMORPHOUS SILICON CARBIDE (a-SiC:H(Al)) PREPARED BY DC MAGNETRON SPUTTERING

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Abstract: *In this work, we investigated the optical, structural, and electrical properties of aluminum-doped hydrogenated amorphous silicon carbide thin films (a-SiC:H(Al)). The samples were prepared by DC magnetron sputtering with a silicon carbide (6H-SiC) target, where the plasma was generated from a gas mixture of argon and hydrogen. Doping was carried out in situ by co-sputtering aluminum strands symmetrically placed on the target. By varying the number of strands, different samples were obtained.The samples were characterized by optical transmission, scanning electron microscopy (SEM), infrared spectroscopy (FTIR), and electrical measurements (I–T). The incorporation of aluminum atoms into the a-SiC:H matrix affects the optical properties of the films, leading to a decrease in the optical band gap from 2.3 to 1.7 eV. In addition, good agreement was observed between the optical and structural parameters obtained from the different techniques.Electrical measurements clearly reveal that the doping effect enhances the electrical conductivity of doped samples, increasing from* 6×10^{-11} *to* 10^{-7} $\Omega^{-1}\cdot cm^{-1}$ *compared to the conductivity of undoped samples.*

Keywords: *Amorphous silicon carbide; DC magnetron sputtering; Al doping; hetejojunction.*

1. Introduction

Due to its abundance and the well-established maturity of its fabrication processes, crystalline silicon (c-Si) remains the most widely used semiconductor in both research and industrial applications. However, silicon carbide (SiC) has attracted considerable attention owing to its outstanding physical and electronic properties, such as a wide band gap [1], high breakdown electric field [2], high thermal conductivity [3], and excellent mechanical hardness [4].

Despite these advantages, the high cost associated with the growth of crystalline SiC has motivated the development of alternative materials. In this context, hydrogenated amorphous silicon carbide (a-SiC:H) represents a promising compromise between performance and fabrication cost for optoelectronic applications.

The first amorphous SiC thin films were reported by Mogab and Kingery in 1968 [5]. Later, Anderson and Spear demonstrated in 1976 the deposition of hydrogenated amorphous silicon carbide (a-SiC:H) by glow-discharge decomposition of precursor gases [6]. Since then, several deposition techniques have been developed, including plasma-enhanced chemical vapor deposition (PECVD) [7,8], glow discharge, and RF/DC magnetron sputtering [9–11]. Among these methods, DC magnetron sputtering is particularly attractive due to its simplicity, reproducibility, and relatively high deposition rate [12].

In recent years, a-SiC:H has attracted growing interest for optoelectronic applications such as light-emitting devices, Bragg reflectors, and microcavity structures [13,14]. The possibility of tuning its optical and electrical properties through doping makes this material even more versatile.

In this work, aluminum-doped a-SiC:H thin films are investigated. Aluminum is known as an effective p-type dopant in SiC due to its shallow acceptor level [15], which can enhance electrical conductivity. The films are deposited by DC magnetron co-sputtering using aluminum grains placed on a SiC target. The aim of this study is to investigate the correlation between microstructure, optical properties, and electrical behavior as a function of aluminum doping, and to optimize the deposition parameters for potential applications in optoelectronic devices.

2. Experimental details

Aluminum-doped hydrogenated amorphous silicon carbide (a-SiC:H(Al)) thin films were deposited by DC magnetron sputtering onto Corning 7059 glass substrates (for optical and electrical measurements) and double-side polished crystalline silicon substrates (for FTIR analysis).

The deposition system is equipped with a DC power supply operating in power-control mode. The substrate holder includes a heating system allowing precise control of the deposition temperature. A polycrystalline 6H-SiC target (3-inch diameter) was used. The plasma was generated using a gas mixture of high-purity argon and hydrogen (99.999%), introduced into the chamber via mass flow controllers.

Aluminum doping was achieved in situ by co-sputtering aluminum strands homogeneously distributed on the target surface. The number of aluminum strands was varied to control the doping level, while other deposition parameters were kept constant. The sputtering power was fixed at 150 W, the substrate temperature at 250 °C, and the argon and hydrogen flow rates at 10 and 5 sccm, respectively.

After deposition, the samples were maintained under a hydrogen atmosphere to prevent oxidation through surface passivation.

Optical transmission measurements were performed in the UV–Vis–NIR range (300–2500 nm), allowing the determination of film thickness, refractive index, and absorption coefficient. FTIR measurements were carried out in the range 400–4000 cm^{-1} using a Perkin-Elmer spectrometer to analyze the chemical bonding structure.

Electrical conductivity was measured using a Keithley 617 electrometer in coplanar configuration as a function of temperature. Aluminum contacts were deposited by thermal evaporation, to ensure good electrical contact.

3. Results

3.1 Structural properties

The surface and cross-sectional morphologies of undoped and aluminum-doped a-SiC:H thin films are presented in Figure 1 and Figure 2 respectively. A clear correlation is observed between the surface topography and the internal microstructure of the layers. The undoped a-SiC:H sample exhibits a columnar morphology characterized by well-developed vertical columns extending throughout the entire film thickness (~1.2 μm), with a rough surface associated with a growth mechanism dominated by the shadowing effect. This growth mode is commonly observed in sputtering deposited thin films when adatom mobility is limited [16].

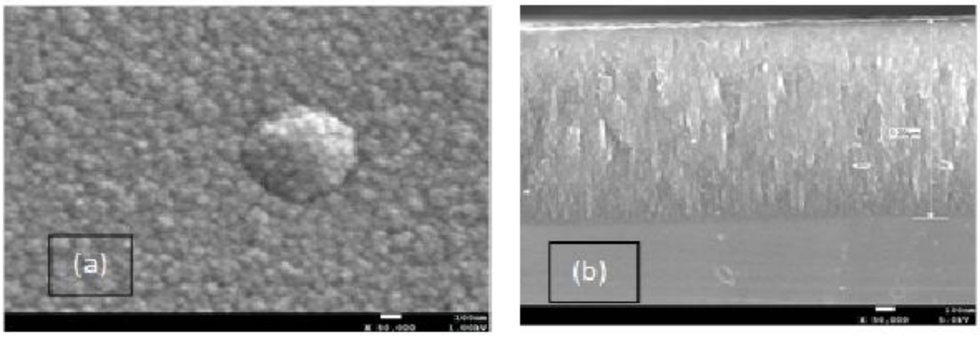

Figure 1. SEM images of surface morphology (a) and cross section (b) of undoped a-SiC:H thin films

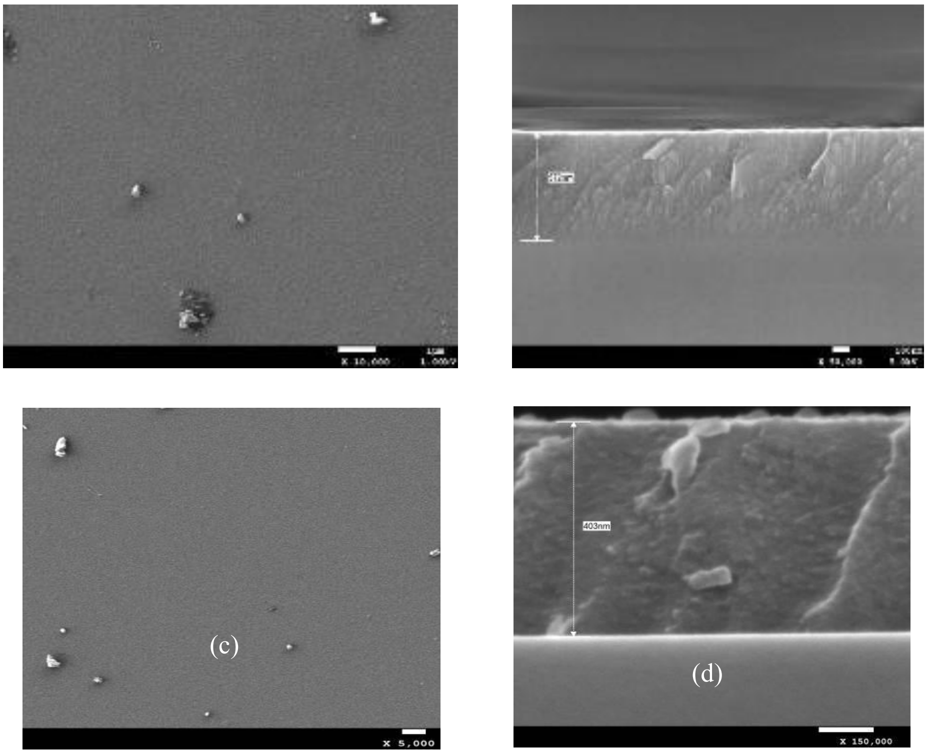

Figure 2. SEM images of surface morphology and a cross-section of doped a-SiC:H thin films. (a,b) doped with 5 strands of Al ; (c,d) with 8 strands of Al.

In contrast, Al-doped a-SiC:H films display a more compact and less columnar structure, accompanied by a smoother surface, indicating a transition toward a denser and more homogeneous microstructure. The film thickness is significantly reduced (~400 nm), suggesting that aluminium incorporation influences the deposition rate or sputtering yield [17]. This evolution is attributed to increased surface mobility and nucleation density, promoting more isotropic growth. These microstructural modifications are likely to significantly affect the optical and electrical properties of the films [18].

3.2 infrared characterization

Figure 3 shows the Fourier transform infrared (FTIR) absorbance spectra recorded in the wavenumber range of 400–3500 cm⁻¹ for an undoped sample and samples with different Al contain.

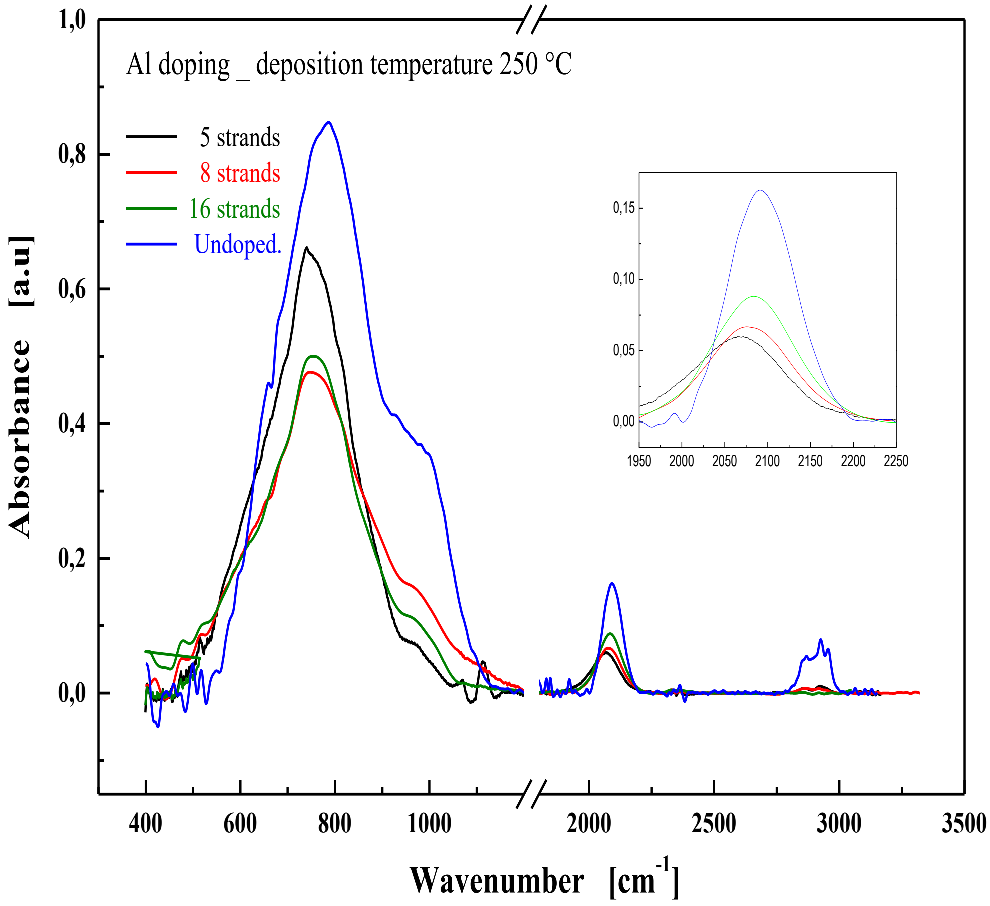

Figure 3. FTIR spectra of Al-doped a-SiC:H deposited by DC magnetron co-sputtering at 250 °C.

The main absorption bands are observed in the regions 540–800, 960–1100, 2000–2100, and 2800–3000 cm⁻¹ [19,20]. The band located between 2800 and 3000 cm⁻¹ is attributed to the stretching vibrations of $C–H_n$ bonds in sp² and sp³ configurations [21], while the band in the range of 2000–2100 cm⁻¹ corresponds to the stretching vibrations of $Si–H_n$ bonds. The band between 960 and 1100 cm⁻¹ is associated with the rocking and twisting modes of $Si–CH_3$ groups, whereas the strong band centred around 780 cm⁻¹ is characteristic of the Si–C stretching mode [22].

A comparison between the FTIR spectra of doped and undoped films reveals significant changes, particularly a decrease in the intensity of the band located between 960 and 1100 cm⁻¹. This behaviour indicates a reduction in $Si–CH_n$ bonds with increasing aluminium concentration [20]. This effect can be attributed to the incorporation of aluminium atoms, which inhibit the formation of $Si–CH_n$ bonds by preferentially substituting silicon atoms in the network [22].

Furthermore, the band around 2100 cm⁻¹ is also influenced by the aluminium content, showing a noticeable decrease in intensity along with a slight shift toward lower energies.

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3.3 UV-VIS-NIR optical transmission measurements

The optical band gap of the films was determined using the Tauc relation for amorphous semiconductors [23], in which the absorption coefficient (α) and the photon energy (hν) are related by:

$$(\alpha h\nu)^{1/2}=f(h\nu) \qquad (1)$$

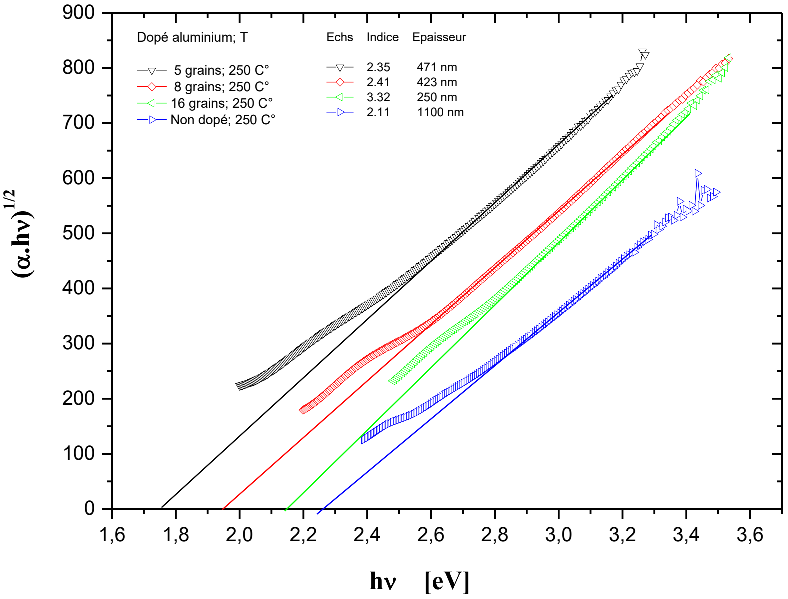

Figure 4. Evolution of the absorption coefficient (αhν) ½ as a function of (hν) for the layers of a-SiC: H deposited at various aluminum contents

In the table 1 we summarize the optical parameters which are he optical gap and the refractive index of the samples prepared at different Aluminum contents. In this table the deposition rate is also given.

Table 1: Parameters derived from the optical transmission spectra

Samples	**Number of Al** strands	**Optical gap (eV)**	**refractive index**	**Deposition speed** (Å/s)
E1	Undoped	2.27	2.11	5.2
E2	5	2.15	2.35	2.6
E3	8	1.95	2.41	2.3
E4	16	1.75	3.32	1.4

The optical band gap (Eg) is obtained by extrapolating the linear region of the $(\alpha h\nu)^{1/2}$ versus (hν) plot to the energy axis, as shown in Figure 4, it is observed that the absorption edge shifts toward lower photon energies with increasing aluminium content in the material. Consequently, the optical band gap decreases from 2.3 to 1.7 eV. This reduction in the optical gap can be attributed to a decrease in the carbon content [24]. This interpretation is supported by infrared spectroscopy results, which reveal a reduction in the intensity of Si–C and C–Hn bonds. Therefore, the incorporation of aluminium may inhibit the formation of these bonds.

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3.4 Electrical measurements:

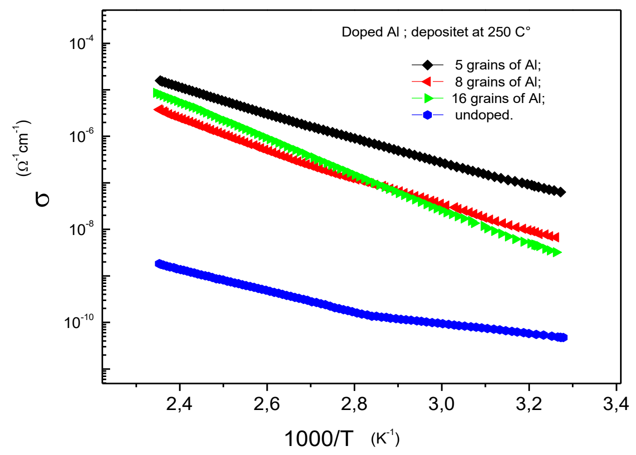

Figure 5 : Variation of the electrical conductivity in darkness as a function of the aluminum content of the coplanar structure of a-SiC: H

We present in the Figure 5 the evolution of the electrical conductivity as a function of temperature in the representation of Arrhenius at different Aluminum contents. We see that the conductivity increases with temperature and it shows linearity with the inverse of temperature, this linearity corresponds to a thermally activated conduction mode which can be described by the following expression:

$$\sigma = \sigma_0 \exp\left(-\frac{E_a}{k_B T}\right) \qquad (2)$$

σ_0 represents the conductivity at room temperature, E_a is the activation energy and k_B is the Boltzmann constant.

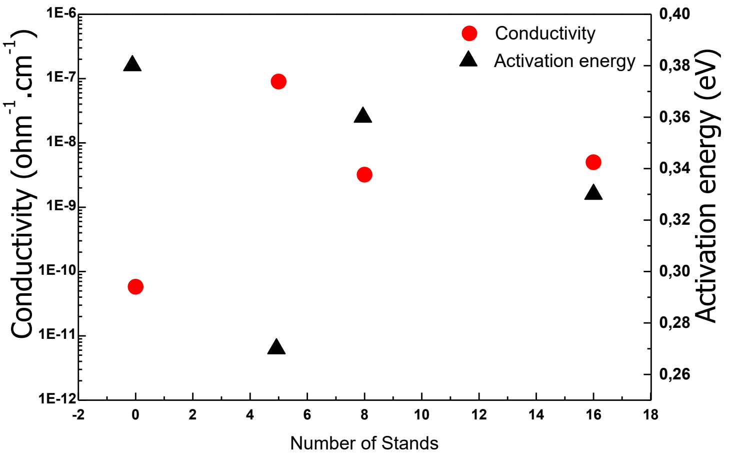

Figure 6: Variation of the electrical conductivity and activation energy, in dark, as a function of the aluminum content in ac coplanar configuration of a-SiC: H material.

the Figure 6 shows the evolution of the electrical conductivity (σ) recorded in the dark and the evolution of the activation energy (Ea), versus the number of aluminium stands. It is observed that the low-doping sample has the highest conductivity, this shows that the

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increase in doping leads to an increase in the defects in the matrix which decrease the conductivity of the material, also a small amount of substituted aluminium atoms give a doping effect. In addition, it's showed in the previous studies that hydrogen passivate the doping agent, annealing of the samples at high temperatures can activate the doping and increase the conductivity. Indeed, the conductivity of a-Si:H doped with boron increases by four decades when it is annealed from 150 °C to 450°C [25].

4. Conclusion

In this work, the effect of aluminium doping on the optical, electrical, and structural properties of a-SiC:H thin films deposited by DC magnetron sputtering was investigated. The results show that the incorporation of aluminium significantly modifies the optical properties of the material. A decrease in the optical band gap from 2.3 to 1.7 eV is observed as the dopant concentration increases. This behaviour is attributed to changes in the chemical bonding and a reduction in carbon content; the presence of aluminium in the matrix inhibits the formation of Si–C and C–H_n bonds, as confirmed by FTIR analysis.

From an electrical standpoint, the conductivity strongly depends on the doping level. An optimal behaviour is observed at low aluminium concentrations, where a small amount of substitutional Al atoms is sufficient to enhance the electrical conductivity, which increases from 10^{-11} to 10^{-7} (S/cm). However, excessive doping leads to the formation of structural defects acting as trapping and scattering centers, resulting in a decrease in conductivity.

In addition, the increase in the number of aluminium grains on the target surface reduces the effective sputtering area, leading to a decrease in the deposition rate and, consequently, the film thickness. Finally, a significant difference in morphology between doped and undoped films is observed, indicating a modification of the growth mechanism and highlighting the influence of the dopant on the film density and compactness.

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