Effect of the RF Power of PECVD on the Crystalline Fractions of Microcrystalline Silicon (\(\mu c\)-Si:H) Films and Their Structural, Optical, and Electronic Properties

Mario Moreno 1,*, Arturo Torres-Sánchez 1, Pedro Rosales 1, Alfredo Morales 1, Alfonso Torres 1, Javier Flores 2, Luis Hernández 1, Carlos Zúñiga 1, Carlos Ascencio 1 and Alba Arenas 1

1 Electronics Department, National Institute of Astrophysics, Optics and Electronics, Puebla 72840, Mexico; arts@inaoep.mx (A.T.-S.); prosales@inaoep.mx (P.R.); alfredom@inaoep.mx (A.M.); atorres@inaoep.mx (A.T.); luish@inaoep.mx (L.H.); czuniga@inaoep.mx (C.Z.); carlos.ascencio.401@gmail.com (C.A.); alba.arenas@inaoep.mx (A.A.)

2 Electronics Department, Meritorious Autonomous University of Puebla, Puebla 72590, Mexico; javier.floresme@correo.buap.mx

* Correspondence: mmoreno@inaoep.mx; Tel.: +52-(222)-266-31-00

Abstract: In this work, we report on the deposition of microcrystalline silicon (\(\mu c\)-Si:H) films produced from silane (\(\text{SiH}_4\)), hydrogen (\(\text{H}_2\)), and argon (\(\text{Ar}\)) mixtures using the plasma-enhanced chemical vapor deposition (PECVD) technique at 200 °C. Particularly, we studied the effect of RF power on the crystalline fraction (\(X_C\)) of the deposited films, and we have correlated the \(X_C\) with their optical, electrical, and structural characteristics. Different types of characterization were performed in the \(\mu c\)-Si:H film series. We used several techniques, such as Raman scattering spectroscopy, Fourier transform infrared spectroscopy (FTIR), atomic force microscopy (AFM), field emission scanning electron microscopy (FE-SEM), and transmission electron microscopy (TEM), among others. Our results show that RF power had a strong effect on the \(X_C\) of the films, and there is an optimal value for producing films with the largest \(X_C\).

Keywords: microcrystalline silicon; plasma-enhanced chemical vapor deposition; transmission electron microscopy; scanning electron microscopy

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) is a mature material that has been extensively studied because of its compatibility with silicon complementary metal–oxide–semiconductor (CMOS) technology, its low substrate temperature deposition (\(\leq 200 \degree \text{C}\)) via the plasma-enhanced chemical vapor deposition (PECVD) technique, the possibility of doping it (n- or p-type), and the fact that it can be deposited on large substrate areas (>1 m²), such as metal foils, glasses, and flexible substrates [1–3]. In photovoltaics and microelectronics, it has been extensively used for the development of large-area thin-film solar cells [4] and thin-film transistors (TFTs) [5,6].

However, a-Si:H has several drawbacks because of the short-range order of the atoms that make it up; this order is mainly related to the length of covalent bonds and the bond angle, which is only maintained between the nearest neighbor atoms [7]. As a result of this, a-Si:H has poor transport properties, low electron mobility (\(\mu_e\)), a large density of dangling bonds (defects), and degradation from light exposure (the Staebler–Wronski effect) [8,9].

Polycrystalline silicon (poly-Si) has a long-range order since it is composed of crystalline grains of sizes as large as 1 \(\mu\text{m}\) [10]. This results in better transport properties, such as larger \(\mu_e\) and better stability; however, it requires deposition temperatures of about 600 °C using the low-pressure chemical vapor deposition (LPCVD) technique.

Microcrystalline silicon (\(\mu c\)-Si:H) is a semiconductor material also produced by PECVD at low temperatures (\(\leq 200 \degree \text{C}\)) that exhibits different properties from those of a-Si:H and...
poly-Si. μc-Si:H films grow in crystalline columns of different orientations, separated by boundaries composed of amorphous silicon. The crystals in the columns have sizes in the order of hundreds of nanometers, and the crystalline fraction ($X_C$) of the films can be tailored by the deposition conditions. Compared with a-Si:H, μc-Si:H has higher room temperature conductivity, higher $\mu_e$, is more stable against radiation, and the bandgap ($E_g$) and absorption coefficient ($\alpha$) are different [11,12]. When compared with poly-Si, μc-Si:H has lower crystal sizes, a lower $X_C$, and lower $\mu_e$. Nevertheless, its lower deposition temperature allows for its integration on glass and flexible substrates, which is the main advantage over poly-Si.

For higher-performance devices, such as tandem solar cells (a-Si:H/μc-Si:H), it is necessary to have both large absorption in the ultraviolet/visible part of the electromagnetic spectrum, provided by an a-Si:H solar cell, and large absorption in the infrared part of the spectrum, provided by a μc-Si:H solar cell [13,14]. The latter is achieved with a large $X_C$ in the μc-Si:H film. For TFTs, high $\mu_e$ in the active layer is required to create faster devices, which is also achieved with a large $X_C$ in the μc-Si:H film [15].

Therefore, there is interest in controlling and optimizing the $X_C$ of μc-Si:H films using PECVD deposition conditions. In this work, we studied how RF power affects a film’s $X_C$ using silane (SiH$_4$), hydrogen (H$_2$), and argon (Ar) mixtures. RF power is an important parameter to control since it affects the $X_C$ of films; in addition, large RF values produce excessive powder in plasma [16], which can result in damage to the vacuum pumps of the deposition system. Therefore, producing μc-Si:H films with large $X_C$ values with relatively low RF power is an issue.

Several techniques were employed to characterize the structural, optical, and electrical properties of the films. We used Fourier transform infrared (FTIR) spectroscopy, Raman scattering spectroscopy, atomic force microscopy (AFM), field emission scanning electron microscopy (FE-SEM), and transmission electron microscopy (TEM). Moreover, several parameters were measured and calculated, such as the photoconductivity ($\sigma_{ph}$), activation energy ($E_A$), absorption coefficient ($\alpha$), and bandgap ($E_g$).

Our results show that RF power had a strong effect on the $X_C$ of the films, where the use of an optimized value results in films with a large $X_C$, but this also affects the electrical and optical parameters. From these results, we were able to select optimized films for applications in both thin-film transistors (TFTs) and thin-film solar cells where μc-Si:H films with a large $X_C$ are required.

2. Materials and Methods

A series of μc-Si:H films were deposited using a capacitively coupled PECVD reactor (Cluster Tool, MVSystems LLC, Arvada, CO, USA) at a radio frequency (RF) of 13.56 MHz with a chamber pressure of 1500 mTorr at a substrate temperature of 200 °C and a deposition time of 30 min. The gas mixture was composed of SiH$_4$ (10% in H$_2$), H$_2$, and Ar, and the RF power levels were 20, 25, 30, 35, 40, and 45 W. Table 1 shows the deposition conditions of the films, including the RF power density. For the deposition of microcrystalline semiconductors, a high H$_2$ dilution, a high chamber pressure, and optimized RF power are required; therefore, the latter is the parameter that was varied in the series. The films were characterized structurally, optically, and electrically, and we employed several techniques for the characterization.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pressure (mTorr)</th>
<th>RF Power (W)</th>
<th>RF Power Density (mW/cm$^2$)</th>
<th>SiH$_4$ 10% in H$_2$ (Sccm)</th>
<th>H$_2$ (Sccm)</th>
<th>Ar (Sccm)</th>
<th>H$_2$/SiH$_4$ Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>μc-Si:H-1</td>
<td>1500</td>
<td>20</td>
<td>69.2</td>
<td>10</td>
<td>41</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>μc-Si:H-2</td>
<td>1500</td>
<td>25</td>
<td>86.5</td>
<td>10</td>
<td>41</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>μc-Si:H-3</td>
<td>1500</td>
<td>30</td>
<td>103.8</td>
<td>10</td>
<td>41</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>μc-Si:H-4</td>
<td>1500</td>
<td>35</td>
<td>121.1</td>
<td>10</td>
<td>41</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>μc-Si:H-5</td>
<td>1500</td>
<td>40</td>
<td>138.4</td>
<td>10</td>
<td>41</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>μc-Si:H-6</td>
<td>1500</td>
<td>45</td>
<td>155.7</td>
<td>10</td>
<td>41</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>
Various substrates with a 1-square-inch area were used for the deposition of each film since they are necessary for different types of characterization. The substrates used were 1.1 mm thick corning glass 2934 (Corning, New York, NY, USA), 0.7 mm thick corning glass 1737 (Precision Glass & Optics, PG&O, Santa Ana, CA, USA), a 300 µm thick p-type <100> crystalline silicon wafer (Addison Engineering, San Jose, CA, USA), and 1.1 mm thick corning glass 2934 (Corning, New York, NY, USA) with 0.2 µm thick aluminum (Al) electrodes. For the fabrication of the electrodes, an Al metal layer with a thickness of 0.2 µm was evaporated via electron beam evaporation (e-beam evaporator, Oerlikon Balzers, Balzers Liechtenstein), and a photolithographic step was performed using a mask with patterns of $7 \times 2$ mm$^2$, separated by 2 mm, using a positive photoresist (AZ 1512 HS, MicroChemicals GmbH, Ulm, Germany). A mask aligner was used for UV exposure (Model 800, OAI, San Jose, CA, USA), and wet etching was employed to define the electrodes. Finally, the photoresist was removed with acetone in an ultrasonic bath for ten minutes.

Note that the films were deposited in the four substrates at the same time (for each RF power); therefore, a standard deviation of the films’ characteristics cannot be calculated at this time, and future work will be necessary.

The films deposited on corning glass 2947 were used for the following characterization. The films’ thicknesses were measured with a profilometer (Dektak XT, Bruker, MA, USA). For the analysis of the films’ roughness, we used an AFM (EasyScan, Nanosurf, Liestal, Switzerland). To determine the $X_c$ of the films, Raman spectroscopy was performed using a Raman spectrometer (LabRam HR 800, Horiba Jobin-Yvon, CA, USA) with a 632.8 nm laser.

The surface structural analysis of the selected film deposited on corning glass 2947 was performed using a high-resolution FE-SEM (JSM-7800F Prime, Jeol, Tokyo, Japan) with a Schottky field emission gun and an accelerating voltage range in the range of 10 V–30 kV. The transversal structural analysis of the same film was performed using a TEM (Talos F200X, FEI, OR, USA) with a 200 kV field emission gun (FEG) emitter.

FTIR spectroscopy characterization was performed on the films deposited on p-type <100> silicon wafers using an infrared spectrometer (Vector 22, Bruker, Massachusetts, USA). We also used a clean silicon wafer without native silicon oxide, for reference.

The absorption spectra on films deposited on corning glass 1737 substrates were calculated through transmittance measurements using a spectrophotometer (Lambda 3 Series, Perkin-Elmer, MA, USA) in a wavelength range of 400–900 nm, and the Tauc method was used for the $E_g$ determination [17]. The selection of corning glass 1737 was due to its large optical transmission (up to 90%) in a range of 400–2500 nm.

The films deposited on corning glass 2947 substrates with aluminum electrodes were used for electrical characterization. The $\sigma_{ph}$ of the films was obtained using a solar simulator (Oriel Sol 2A, Newport, CA, USA) with AM 1.5 standard radiation, providing a power intensity of 100 mW/cm$^2$. The films’ temperature dependence of conductivity ($\sigma(T)$) was measured in a vacuum at a pressure of 50 mTorr in a cryostat (Janis Research, MA, USA) with a substrate temperature range of 300–400 °K, and the $E_A$ of the films was determined.

3. Results

As mentioned previously, the μc-Si:H films were characterized structurally, optically, and electrically; therefore, this section is divided into different subsections containing the different types of analysis.

3.1. Structural Characterization

3.1.1. Thickness Measurements

A photolithographic step was performed on the μc-Si:H film series deposited on corning glass 2947 substrates using a mask aligner for UV exposure (Model 800, OAI, California, USA). To protect part of the films, we used a positive photoresist (AZ 1512 HS, from MicroChemicals GmbH, Ulm, Germany). The uncovered part was etched with carbon tetrafluoride (CF$_4$) plasma using a Reactive Ion Etching (RIE) system (micro RIE, Technics). After removing the photoresist with acetone in an ultrasonic bath for ten minutes, the
films’ thicknesses were measured using the profilometer described in the previous section. Table 2 shows the thicknesses of the different films deposited for 30 min, and the deposition rate \( V_d \) was calculated. We can see that the \( V_d \) is in a range of 0.80 to 1.09 Å/s.

Table 2. Properties of the series of µc-Si:H films obtained from structural characterization.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness (nm)</th>
<th>Deposition Rate (Å/s)</th>
<th>Average Roughness (nm)</th>
<th>RMS Roughness (nm)</th>
<th>Crystalline Fraction, ( X_C ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>µc-Si:H-1</td>
<td>181</td>
<td>1.09</td>
<td>1.12</td>
<td>1.46</td>
<td>64</td>
</tr>
<tr>
<td>µc-Si:H-2</td>
<td>160</td>
<td>0.88</td>
<td>1.21</td>
<td>1.67</td>
<td>75</td>
</tr>
<tr>
<td>µc-Si:H-3</td>
<td>161</td>
<td>0.89</td>
<td>1.57</td>
<td>1.95</td>
<td>64</td>
</tr>
<tr>
<td>µc-Si:H-4</td>
<td>164</td>
<td>0.91</td>
<td>1.23</td>
<td>1.65</td>
<td>69</td>
</tr>
<tr>
<td>µc-Si:H-5</td>
<td>157</td>
<td>0.87</td>
<td>1.57</td>
<td>2.12</td>
<td>69</td>
</tr>
<tr>
<td>µc-Si:H-6</td>
<td>145</td>
<td>0.80</td>
<td>1.86</td>
<td>2.48</td>
<td>67</td>
</tr>
</tbody>
</table>

3.1.2. Atomic Force Microscopy

The AFM characterization was performed on the µc-Si:H films deposited on corning glass 2947 substrates in an area of 4 × 4 µm². Figure 1 shows 3D images of the µc-Si:H films deposited using different RF powers. From these measurements, we extracted the average roughness \( S_a \) and the root-mean-square (RMS) roughness values, which are included in Table 2.

![AFM images of the series of µc-Si:H films deposited with different RF power levels](image)

Figure 1. AFM images of the series of µc-Si:H films deposited with different RF power levels: (a) RF = 20 W, (b) RF = 25 W, (c) RF = 30 W, (d) RF = 35 W, (e) RF = 40 W, and (f) RF = 45 W.
We employed the Scanning Probe Image Processor (SPIP) software as described in [18] to calculate the average roughness ($S_a$), which is defined by Equation (1):

$$S_a = \frac{1}{MN} \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} |z(x_k, y_l) - \mu|$$

(1)

where $M$ is the data number in the X point, $N$ is the data number in the Y point of the rectangular image, and $\mu$ is the mean height defined by Equation (2):

$$\mu = \frac{1}{MN} \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} z(x_k, y_l)$$

(2)

It is clear that there was an increase in film roughness upon increasing the RF power to deposit the films. It has been reported that larger roughness values in µc-Si:H films are associated with large crystal sizes [11]. However, in our characterization, we did not observe a relationship between surface roughness and the $X_C$. A possible explanation is that, with Raman spectroscopy, we are able to calculate the crystalline fraction ($X_c$), but we do not gain information on crystal sizes. For determining the sizes of crystals, other techniques can be used, such as X-ray diffraction and the Scherrer equation [19,20].

3.1.3. Raman Spectroscopy

As mentioned previously, Raman spectroscopy was used for the µc-Si:H films’ characterization; Figure 2a shows the Raman spectra of the films deposited with different RF power levels, where we can observe a pronounced peak at 520 cm$^{-1}$ in the spectra. The $X_C$ of the films was calculated using the following equation:

$$X_C = (I_C + I_B)/(I_C + I_B + I_A)$$

(3)

where $I_C$, $I_B$, and $I_A$ are the integrated intensities of peaks associated with the crystalline phase at 520 cm$^{-1}$, an intermediate phase (correlated with small crystal sizes) at 500-514 cm$^{-1}$, and the amorphous phase at 480 cm$^{-1}$, respectively [21]. Figure 2b shows the spectrum of a µc-Si:H film with deconvolution in three Gaussian peaks located at 520 cm$^{-1}$, 508 cm$^{-1}$, and 480 cm$^{-1}$. We determined the $X_C$ of the µc-Si:H films using Equation (3). Table 2 contains the $X_C$ (%) values calculated, where we observed that the $X_C$ was in a range of 64–75%, and the film deposited with an RF of 25 W (86.5 mW/cm$^2$) had the largest $X_C$.

![Figure 2](image-url)

**Figure 2.** (a) Raman spectra of the series of µc-Si:H films deposited with different RF power levels; (b) Raman spectra of the film deposited with an RF power of 25 W (86.5 mW/cm$^2$), where the deconvolution of the spectrum in three Gaussian peaks at 520 cm$^{-1}$, 508 cm$^{-1}$, and 480 cm$^{-1}$ is shown.

As mentioned in Section 2, for the deposition of µc-Si:H, three conditions are required, which are the high dilution of SiH$_4$ in H$_2$, higher chamber pressure, and higher RF power.
levels than those used for the deposition of a-Si:H. During the deposition of the μc-Si:H films, a H₂ etching process can occur [22,23]. From our results, we can see that the etching process is sensitive to the RF power; on the one hand, low RF power produces μc-Si:H with a low X_C, while on the other hand, high RF power can promote the H₂ etching process, also affecting the X_C.

3.1.4. Field Emission Scanning Electron Microscopy

We selected the film with the largest X_C (μc-Si:H-2) for scanning electron microscopy analysis (FE-SEM). Figure 3a shows the surface of the μc-Si:H film obtained using FE-SEM with a magnification of 50,000× and an accelerating voltage of 3 kV for the electron beam; we can see that the film surface is composed of grains. Figure 3b shows an amplified image with a magnification of 200,000× and an accelerating voltage of 3 kV, and we can see that the silicon grains are approximately 30–80 nm.

![Figure 3](image)

**Figure 3.** Field emission scanning electron microscopy (FE-SEM) analysis of the surface of the μc-Si:H film deposited with an RF power of 25 W (86.5 mW/cm²): (a) magnification at 50,000×; (b) magnification at 200,000×.

One important aspect is that the film was not prepared for observation; it was analyzed as it was deposited. The quality of the image is an indication that the film is electrically conductive, and this is of importance for the development of TFTs. In Section 3.3, the electrical characterization of the films is reported.

3.1.5. Transmission Electron Microscopy

Even though grains can be observed on the surface of the μc-Si:H film shown in Figure 3, the bulk of the microcrystalline semiconductors was composed of crystalline columns [11,24]. Therefore, in order to analyze the transversal structure of the μc-Si:H film, we used TEM characterization, as described in the previous section. Figure 4a shows a dark-field transversal view of the film (μc-Si:H-2) in an area of 250 × 250 nm², obtained with an accelerating voltage of 200 keV. In the image, it can be seen that the film effectively grows in crystalline columns, and these columns are of different orientations. Figure 4b shows an amplified transversal view of an area of 50 × 50 nm², obtained with an accelerating voltage of 200 keV. In this image, we can see, with more detail, different orientations of silicon atoms, and moreover, practically all the area is microcrystalline.
Figure 4. Transmission electron microscopy (TEM) analysis of the surface of the µc-Si:H film deposited with an RF power of 25 W (86.5 mW/cm²): (a) area observed at 250 × 250 nm²; (b) area observed at 50 × 50 nm².

3.2. Optical Characterization

3.2.1. Fourier Transform Infrared Spectroscopy

FTIR spectroscopy was used to characterize the films, as described in Section 2. Figure 5 shows the absorbance spectra of the µc-Si:H film series in a range of 570–2150 cm⁻¹, where several bands are observed, corresponding to different vibration modes.

Figure 5. FTIR absorbance spectra of the series of µc-Si:H films deposited at different RF power levels.

We observed a band located close to 640 cm⁻¹, which is associated with SiH bonds in bending mode [25]. At approximately 890 cm⁻¹ is a band associated with SiH₂ bonds in bending mode [26]. Moreover, two bands associated with Si-O bonds at 750 cm⁻¹ and 1100 cm⁻¹ are observed [26]. Finally, the band at 2000–2200 cm⁻¹ is attributed to SiH, SiH₂, and SiH₃ stretching modes [27].

The total H₂-bonded content (C_H) of the films was calculated by integrating the area under the Si-H peak at 640 cm⁻¹ and using Equation (4) [28]:

\[
C_H (\%) = \frac{A_\omega}{N_{Si}} \int \frac{\alpha(\omega)}{\omega} \, d\omega
\]  

(4)
where \( \int \alpha(\omega)/\omega \, d\omega \) is the area of the deconvolution of the peak at 640 cm\(^{-1}\); \( \alpha \) is the absorption coefficient at frequency (\( \omega \)); \( A_{\omega} \) is the oscillator strength in wagging mode at 640 cm\(^{-1} \) (\( A_{640} = 1.6 \times 10^{19} \text{ cm}^{-2} \)) [28]; and \( N_{\text{Si}} = 5 \times 10^{22} \text{ cm}^{-3} \), the atomic density of pure silicon. Table 3 includes the calculated H\(_2\)-bonded content for the \( \mu \text{c-Si:H} \) films, which are in a range of 7.0 to 13.1%.

Table 3. Properties of the series of \( \mu \text{c-Si:H} \) films obtained using optical and electrical characterization; \( X_C \) is included to correlate it with the other film parameters.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Crystalline Fraction, ( X_C ) (%)</th>
<th>( C_H ) (%)</th>
<th>( E_g ) (eV)</th>
<th>( \sigma_{\text{RT}} ) (( \Omega \text{cm} ))(^{-1} )</th>
<th>( \sigma_{\text{ph}} ) (( \Omega \text{cm} ))(^{-1} )</th>
<th>( \sigma_{\text{ph}}/\sigma_{\text{RT}} )</th>
<th>( E_A ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu \text{-Si:H-1} )</td>
<td>64</td>
<td>10.3</td>
<td>2.46</td>
<td>6.9 \times 10^{-4}</td>
<td>1.1 \times 10^{-3}</td>
<td>1.6</td>
<td>0.18</td>
</tr>
<tr>
<td>( \mu \text{-Si:H-2} )</td>
<td>75</td>
<td>9.4</td>
<td>2.2</td>
<td>6.4 \times 10^{-4}</td>
<td>1.0 \times 10^{-3}</td>
<td>1.8</td>
<td>0.19</td>
</tr>
<tr>
<td>( \mu \text{-Si:H-3} )</td>
<td>64</td>
<td>9.4</td>
<td>2.37</td>
<td>1.2 \times 10^{-3}</td>
<td>1.8 \times 10^{-3}</td>
<td>1.5</td>
<td>0.17</td>
</tr>
<tr>
<td>( \mu \text{-Si:H-4} )</td>
<td>69</td>
<td>7.0</td>
<td>2.10</td>
<td>2.2 \times 10^{-4}</td>
<td>1.4 \times 10^{-3}</td>
<td>6.4</td>
<td>0.23</td>
</tr>
<tr>
<td>( \mu \text{-Si:H-5} )</td>
<td>69</td>
<td>7.2</td>
<td>2.42</td>
<td>2.3 \times 10^{-4}</td>
<td>3.3 \times 10^{-4}</td>
<td>1.4</td>
<td>0.22</td>
</tr>
<tr>
<td>( \mu \text{-Si:H-6} )</td>
<td>67</td>
<td>13.1</td>
<td>2.48</td>
<td>8.3 \times 10^{-5}</td>
<td>1.4 \times 10^{-3}</td>
<td>1.7</td>
<td>0.28</td>
</tr>
</tbody>
</table>

3.2.2. Absorption Coefficient and Determination of the Bandgap

The absorption (\( \alpha \)) spectra of the \( \mu \text{c-Si:H} \) films deposited on corning glass 1737 substrates were calculated via transmittance measurements using a spectrometer (Perkin-Elmer, Lambda Series) in a wavelength range of 400–900 nm and the Pointwise Unconstrained Minimization Approach [29,30]. Figure 6 shows the \( \alpha \) spectra of the \( \mu \text{c-Si:H} \) film series in a range of 2 to 3.5 eV. The films with lower \( X_C \)s have more absorption in the UV region of the spectra (2.5–3.5 eV), which is in agreement with our previous work, where higher \( \alpha \) in the UV region was observed in films with a lower fraction of large crystalline grains [31].

![Figure 6. Absorption coefficient of the series of \( \mu \text{c-Si:H} \) films deposited at different RF power levels.](image-url)

The above is related to the fact that a-Si:H has a larger absorption coefficient in the UV region of the electromagnetic spectrum than \( \mu \text{c-Si:H} \). On the other hand, \( \mu \text{c-Si:H} \) has a larger absorption coefficient in the infrared region than a-Si:H [13,14]; these properties are related to their structural arrangements. The \( \mu \text{c-Si:H} \) films with lower \( X_C \)s have a larger amorphous fraction, and therefore, they have larger absorption in the UV region.

The bandgap (\( E_g \)) can be calculated using the Tauc plot method. Figure 7a shows the Tauc plots of the different \( \mu \text{c-Si:H} \) thin films; \( \alpha \) is related to the \( E_g \) of the material via the expression of Tauc, that is, Equation (5):

\[
(\alpha h \nu)^{1/2} = B(\nu - E_g)
\] (5)
where \( h \) is Planck’s constant, \( v \) is the frequency of the photon, and \( B \) is a constant. From the plot, \((ahv)^{1/2} vs. (hv)\); the extrapolation of \((ahv)^{1/2} \) to \( a = 0 \) (when \( a > 10^3 \text{ cm}^{-1} \)) provides the \( E_g \). This procedure is accurate for direct bandgap materials such as a-Si:H, but for indirect bandgap materials, such as \( \mu c\)-Si:H, it could provide erroneous results. To obtain more accurate results, we followed the process reported in [17], where a baseline in the sub-bandgap region of the Tauc plot was used, as shown in Figure 7b for the film marked as \( \mu c\)-Si:H-2. The extrapolation of the curve with the baseline provides the \( E_g \) value. The \( E_g \) values are in a range of 2.1 to 2.48 eV and are shown in Table 2.

![Tauc plots](image)

**Figure 7.** (a) Tauc plots of the series of \( \mu c\)-Si:H films deposited with different RF powers; (b) extraction of \( E_g \) for the film marked as \( \mu c\)-Si:H-2.

### 3.3. Electrical Characterization

#### 3.3.1. Room Temperature Conductivity and Photoconductivity

To determine the room temperature conductivity (\( \sigma_{RT} \)) and photoconductivity (\( \sigma_{ph} \)) of the films, current–voltage (I–V) measurements were performed in the dark and under illumination, respectively, on the samples deposited on corning glass 2947 with aluminum contacts. Measurements under light were made using the ORIEL SOL 2 solar simulator, which provides light with a standard AM 1.5 spectrum and a power density of 100 mW/cm\(^2\). In both measurements, an electrometer (Keithley6517A) was used, configured as a voltage source and current meter.

Figure 8a–f show the current–voltage (I–V) characteristics of the films in the dark and under AM 1.5 radiation, applying a voltage ranging from 0 to 18 V. With the current values and the geometrical parameters of the films, the \( \sigma_{RT} \) and \( \sigma_{ph} \) were calculated. Table 3 shows the \( \sigma_{RT} \) and \( \sigma_{ph} \) values and the photo-response (\( \sigma_{ph}/\sigma_{RT} \)) of the deposited \( \mu c\)-Si:H films. The film marked as \( \mu c\)-Si:H-3 has the highest \( \sigma_{RT} \) value, while the film labeled as \( \mu c\)-Si:H-4 has the largest \( \sigma_{ph}/\sigma_{RT} \) value.

A \( \mu c\)-Si:H film is structurally composed of a crystalline fraction, an amorphous fraction, and voids [31,32]. If the film has a large \( X_C \), its \( \sigma_{RT} \) value is large as well; on the other hand, if the film has a low \( X_C \) (and a large amorphous fraction), its \( \sigma_{RT} \) value is lower. However, we did not see a correlation between the \( X_C \) and the \( \sigma_{RT} \). A possible reason is the undesirable oxygen doping of the films during deposition, which can increase the \( \sigma_{RT} \). In fact, the film with the lowest \( E_A \) (as shown below) had the largest \( \sigma_{RT} \), which makes sense since doping reduces the \( E_A \).

Furthermore, oxygen doping can be the reason for larger \( \sigma_{RT} \) values in these \( \mu c\)-Si:H films than those reported in the literature [33]. Moreover, in \( \mu c\)-Si:H, the \( \sigma_{ph} \) is affected by the \( X_C \) of the film and the SiH\(_4\) concentration during deposition. It has been reported that

![Graphs](image)
in \( \mu \text{-Si:H} \) intrinsic films with large XCSs the change from \( \sigma_{\text{RT}} \) to \( \sigma_{\text{ph}} \) is lower than one order of magnitude [33].

![Figure 8. I–V characteristics of the \( \mu \text{-Si:H} \) films deposited at different RF power levels in the dark and under AM 1.5 radiation: (a) RF = 20 W, (b) RF = 25 W, (c) RF = 30 W, (d) RF = 35 W, (e) RF = 40 W, and (f) RF = 45 W.](image)

3.3.2. Temperature Dependence of Conductivity and Activation Energy

Temperature dependence of conductivity (\( \sigma(T) \)) measurements were performed on the films deposited on corning glass 2947 with aluminum contacts. The samples were collocated inside a cryostat at a pressure of 60 mTorr. Voltage was applied in a range of \(-20 \text{ to } 20 \text{ V}\) on the samples, and the current was measured using an electrometer (Keithley6517A) in a range of temperature of 27 to 127 °C. Finally, the dark conductivity (\( \sigma_D \)) was calculated using the films’ geometrical parameters. Figure 9a shows the Log(\( \sigma_D \)) vs. 1/kT, where k is the Boltzmann constant, and T is the temperature.
From the optical characterization, we observed that the total H\(_2\) content (C\(_H\)) of the \(\mu c\)-Si:H films was in a range of 7.0–13.1%, which agrees with the results reported in [28,34].
Furthermore, we observed that the $E_g$ values of the $\mu$c-Si:H film series were in a range of 2.1–2.48 eV; these values are larger than those reported in [35] and are also larger than those values of a-Si:H, which are in a range of 1.6–1.88 eV [36]. The film with the largest $X_C$ had an $E_g$ of 2.2 eV, and we did not observe any trend related to the deposition RF power.

The electrical characterization gave us information on several parameters of the $\mu$c-Si:H films. The $\sigma_{RT}$ was in a range of $8.3 \times 10^{-5}–1.2 \times 10^{-3}$ ($\Omega$cm)$^{-1}$, while the film with the largest $X_C$ had a $\sigma_{RT}$ of $6.4 \times 10^{-4}$ ($\Omega$cm)$^{-1}$. This value is larger than those reported in the literature [24], and it is possibly related to unintentional doping with O during the deposition of the films. The above is corroborated by a peak at 1000–1200 cm$^{-1}$ in the films’ absorbance spectra obtained via FTIR spectroscopy, which was related to Si-O bonds. Furthermore, the small $E_A$ values were in a range of 0.18 to 0.28 eV, indicating that the films are not intrinsic.

On the other hand, the $\sigma_{ph}$ values were in a range of $1.4 \times 10^{-4}–1.8 \times 10^{-3}$ ($\Omega$cm)$^{-1}$, and the $\sigma_{ph}/\sigma_{RT}$ ratio was in a range of 1.5–6.4. The film with the lowest $X_C$ had the largest $\sigma_{ph}/\sigma_{RT}$ ratio (of 6.4), which agrees with the fact that the more amorphous a film is, the more photoconductive it is.

It is important to produce $\mu$c-Si:H films with large $X_C$ values since this is related to both larger $\mu_e$ and larger absorption in the infrared region of the electromagnetic spectrum [13–16]. These properties are important for the development of faster TFTs and tandem (a-Si:H/$\mu$c-Si:H) solar cells with high conversion efficiency, respectively. Moreover, it is important to control the deposition RF power since large values produce excessive powder in the deposition chamber and can damage the vacuum pumps of the PECVD deposition system. In this work, we demonstrated that a high RF power is not necessary to obtain $\mu$c-Si:H films with a large $X_C$, and consequently, the powder formed in the deposition chamber was reduced significantly, preserving the integrity of the vacuum pumps.

5. Conclusions

In this work, we studied $\mu$c-Si:H films deposited using the PECVD technique at 200 °C with a SiH$_4$, H$_2$, and Ar mixture. Particularly, we focused our study on the effect of the deposition RF power and the $X_C$ of $\mu$c-Si:H films, and these were correlated with their structural, optical, and electrical properties. We found an optimal RF power value of 25 W (an RF power density of 86.5 mW/cm$^2$) for producing films with high $X_C$ values (75%), coupled with a high $H_2$/SiH$_4$ ratio (of 50) and a high chamber pressure (of 1500 mTorr). Even though the films were deposited without any unintentional doping, they were highly conductive, and furthermore, they had low $E_A$ values, indicating their non-intrinsic nature. Using electron microscopy, we observed that, effectively, the films grew in crystalline columns, and these columns were of different orientations. We can stress that producing $\mu$c-Si:H films with high $X_C$s will result in high-performance devices, such as TFTs and a-Si:H/$\mu$c-Si:H tandem solar cells, where high $\mu_e$ and high absorption in the infrared spectrum are necessary, respectively. Finally, we produced $\mu$c-Si:H films with large $X_C$ values using relatively low RF power densities, significantly reducing powder formation in the plasma and preserving the integrity of the vacuum pumps of the PECVD system.


Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported by the National Council of Humanities, Sciences and Technologies of Mexico (CONAHCYT).
References


**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.