Optical properties and crystallinity of hydrogenated nanocrystalline silicon (nc-Si:H) thin films deposited by rf-PECVD

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Abstract
Hydrogenated nanocrystalline silicon (nc-Si:H) thin films prepared in a home-built radio-frequency (rf) plasma enhanced chemical vapour deposition (PECVD) system have been studied. The rf powers were fixed in the range of 5 W–80 W. The optical properties and crystallinity of the films were studied by X-ray diffraction (XRD), Micro-Raman scattering spectroscopy, high resolution transmission electron microscope (HRTEM), and optical transmission and reflection spectroscopy. The XRD and Micro-Raman scattering spectra were used to investigate the evidence of crystallinity in order to determine the crystallite sizes and crystalline volume fraction in the films. The HRTEM image of the film was used to correlate with the crystallinity that was determined from XRD and Micro-Raman scattering spectra. Optical constants such as refractive index, optical energy gap, Tauc slope, Urbach energy and ionic constants were obtained from the optical transmission and reflectance spectra. From the results, it was interesting to found that the optical constants showed a good correlation with the crystallinity within the variation of rf power. Also, the ionic constants of the films showed an indication of the degree of crystallinity in the films. The variation of the optical energy gap with the rf power based on structure disorder and the quantum confinement effect is discussed.

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1. Introduction

Hydrogenated nanocrystalline silicon (nc-Si:H) thin films have been extensively studies in recent years especially in opto-electronic device applications such as solar cells, thin film transistors (TFTs) and sensor devices [1–3]. The nc-Si:H is a biphasic material consisting of a small amounts of a crystalline volume fraction of nanocrystallites embedded within an amorphous matrix. Presence of this crystalline phase inclusions improves the structure of the films by enhancing the solar cell conversion efficiency and reducing the light induced effect, improving the stability of the TFT devices and increasing the mobility of carriers to improve the efficiency of devices [1–3]. Also, this material is a promising candidate due to its wider band gap and near-direct band gap nature [4]. This characteristic is very much dependent on crystallite size and crystalline volume fraction in films and those parameters controlling the optical properties of the films. However, the main difficulty with nc-Si:H is precise control of the size of crystallite and their uniform distribution, otherwise it is very difficult to get the desired properties.

The optical properties are important, as they provide direct information on the electronic characteristics of the films such as dielectric and ionic constants. These optical constants can be determined from the optical reflectance and transmission spectra such as refractive index, n₀, optical energy gap, E_G, Tauc slope, B, Urbach energy, E_U and ionic constant, β. However, these constants have strong correlation with the crystallinity of the films such as crystallite size, crystalline volume fraction, X, even the distribution of the crystalline grains on the films. Understanding this correlation will provide better control in the deposition of the device quality of nc-Si:H thin films for opto-electronic applications.

In this work, nc-Si:H thin films have been deposited by continuous deposition using a home-built rf-PECVD system at different rf powers. The optical properties and crystallinity of the films were characterized by X-ray diffraction (XRD), micro-Raman scattering spectroscopy, high resolution transmission electron microscope (HRTEM), and optical transmission and reflection spectroscopy. The objective of this work is to study the relation of the presence of nc-Si embedded within an amorphous matrix with optical properties of the films. We also aim to study the effect of substrate on the crystallinity of the films under different variations of rf power.

2. Experiments

Hydrogenated nanocrystalline silicon (nc-Si:H) thin films were deposited on p-type (111) crystal silicon (c-Si) wafers and quartz...
substrates using a home-built 13.56 MHz radio-frequency (rf) plasma enhanced chemical vapour deposition (PECVD) system from the discharge of mixed silane (SiH₄) and hydrogen (H₂) gases described in our earlier publication [5]. The reactor was capacitively coupled by two parallel electrodes with a distance of 5 cm and area of 28 cm². Prior to deposition, hydrogen plasma treatment was done on the surface of the substrates for 10 min at a chamber pressure of 0.8 mbar to clean the substrate surface from any contamination. The deposition pressure and substrate temperature were maintained at 0.8 mbar and 250 °C respectively, during the deposition. The SiH₄ and H₂ gases flow-rates were fixed at 2 and 100 sccm respectively, producing a H₂ to SiH₄ flow-rate ratio of 50. The total deposition time was fixed at 60 min. Five sets of samples were prepared with different rf powers of 5, 15, 25, 60 and 80 W which correspond to rf power densities of 179, 536, 893, 2143 and 2857 mW/cm².

The X-ray diffraction (XRD) measurement was carried out using a SIEMENS D5000 X-ray diffractometer, with Cu Kα, X-ray radiation (λ = 1.5418 Å). The Raman spectra of the films were recorded using a Horiba Jobin Yvon 800 UV Micro-Raman Spectrometer with Ar⁺ laser (Excitation wavelength of 514.5 nm). The film for high resolution transmission electron microscopy (HRTEM) micrographs was obtained by means of a TEM (JEOL JEM-3100F) operating at 300 kV. The optical transmission and reflectance spectra of the films were obtained using a JASCO V570 ultra-violet visible near-infrared (UV–VIS–NIR) spectrophotometer. The XRD and Raman scattering spectroscopy were performed on films deposited on c-Si and quartz substrates while the optical spectroscopy was measured only on the films deposited on the quartz substrate.

3. Results and discussion

Fig. 1 shows the X-ray diffraction (XRD) spectra of films deposited on c-Si and quartz substrates at different rf powers. For the films deposited on c-Si substrate, all the films except for the film deposited at rf power of 25 W show diffraction peaks at 28.4, 47.3 and 56.1° corresponding to c-Si orientations of (111), (220) and (311) planes respectively [6]. The absence of a diffraction peak at 47.3° for the film deposited at rf power of 25 W could be due to less dominance of the c-Si (220) plane contributing to the diffraction. However, for the films deposited on the quartz substrate, there are only small c-Si diffraction peaks appearing at 28.4, 47.3 and 56.1° for the films deposited at rf powers above 25 W. For the films deposited at rf powers below 25 W, there is a very small shoulder at 28.4° appearing from the broad amorphous peak at about 22° suggesting that the presence of very small crystallites embedded within the amorphous matrix for the films. From this observation, we find that there is a difference in the effect of the substrate in inducing the crystallization of the deposited film under variation of rf power. The c-Si substrate as a semiconductor shows a crystalline orientation of c-Si (311) plane in the figure, which induces the crystalline growth in the deposited films with preferred orientation of c-Si (311) plane. Moreover, this crystalline in the deposited film was formed at the lower rf powers. For the quartz substrate as insulator, the crystalline growth behaved naturally in the deposited film with preferred orientation of c-Si (111) plane in highly diluted hydrogen of rf-PECVD deposition [7]. However, this crystalline plane only appears significantly for the films deposited at rf power above 25 W. An increase in rf power increases the intensity of the diffraction peaks for both films deposited on c-Si and quartz substrates indicating the increase in crystallinity of the films. By using the Scherrer’s equation, the crystallites size can be estimated from the relation of \( D = \frac{k\lambda}{\beta\cos\theta} \), where \( k \), \( \lambda \), \( \beta \) and \( \theta \) are the Scherrer’s constant, the wavelength of X-ray, the full width at half maximum (FWHM) and Bragg angle of the diffraction peak respectively [8]. The values of the crystallite sizes for the films deposited on c-Si and quartz substrates are tabulated in Table 1. The variations of the crystallite sizes for the both films are consistent with the XRD spectra as a function of rf power.

Raman scattering spectra of films deposited on c-Si and quartz substrates at different rf powers is shown in Fig. 2. Note that, all the films show appearance of asymmetric Raman peaks in the range of 500–512 cm⁻¹ indicating that the films are mixed phases of nanocrystalline and amorphous structures [9]. However, the films deposited on c-Si substrates at rf powers of 5 and 15 W show appearance of a sharp crystalline TO peak at about 520 cm⁻¹. Due to the thickness of the films (less than 500 nm) and laser wavelength of 514.5 nm used in the measurement, the sharp crystalline TO peak suggests the single c-Si at 520 cm⁻¹ is due to the effect of c-Si substrate [10]. The variation of these Raman peaks demonstrates a similar trend with the XRD diffraction peak intensities as a function of rf power. Moreover, the Raman peaks shifted to a lower wave number from the single c-Si peak at 520 cm⁻¹ agreeing with the XRD result that has been suggested, namely that there are very small crystallites embedded within the amorphous matrix in all the deposited films. From the Raman scattering spectra, it is well known that the Raman peak can be deconvoluted into three components corresponding to amorphous, grain boundaries and nanocrystalline components at around 480, 500 and 515 cm⁻¹ respectively. A typical Raman peak deconvolution into four components for the films deposited on c-Si substrates is shown in Fig. 2(c). The additional component at around 520 cm⁻¹ is

![Fig. 1. XRD spectra of nc-Si:H thin films deposited on (a) c-Si and (b) quartz substrates at different rf powers.](image-url)
contributed by the signal from c-Si substrate. The crystalline volume fraction, $X$, of the films was estimated using the relation of $X = \frac{I_b + I_c}{a I_a + I_b + I_c}$, where $I_a$, $I_b$ and $I_c$ are integrated intensities of the Raman peaks corresponding to amorphous, grain boundaries and nanocrystalline components respectively. The factor $a$ is generally equal to 1 for nc-Si films [11]. Also, the crystallite size of the nanocrystallites in the films can be estimated using the relation of $d = \frac{2 \pi \sqrt{B}}{\Delta \nu}$, where $B$ is 2.24 cm$^{-1}$ nm$^2$ for Si and $\Delta \nu$ is the value of shift nanocrystalline component to single crystal Si peak located at 521 cm$^{-1}$ [12]. The values of the estimated crystalline volume fraction and crystallite size for the films deposited on c-Si and quartz substrates are tabulated in Table 1.

As can be seen from the table, the values of crystalline volume fraction are higher for the films deposited on c-Si and quartz substrates at higher rf powers (60 and 80 W). However, the values of crystalline volume fraction for the films deposited on c-Si

<table>
<thead>
<tr>
<th>rf Power (W)</th>
<th>XRD</th>
<th>Raman</th>
<th>Optical</th>
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<tbody>
<tr>
<td></td>
<td>Crystalline size, $D_c$ (nm)</td>
<td>Crystalline size, $D_q$ (nm)</td>
<td>Crystallite size, $D_c$ (nm)</td>
</tr>
<tr>
<td>5 W</td>
<td>3.4</td>
<td>2.5</td>
<td>27</td>
</tr>
<tr>
<td>15 W</td>
<td>3.7</td>
<td>3.2</td>
<td>28</td>
</tr>
<tr>
<td>25 W</td>
<td>3.7</td>
<td>3.1</td>
<td>25</td>
</tr>
<tr>
<td>60 W</td>
<td>5.7</td>
<td>5.1</td>
<td>51</td>
</tr>
<tr>
<td>80 W</td>
<td>6.8</td>
<td>6.6</td>
<td>55</td>
</tr>
</tbody>
</table>

$D_c$, $D_q$ and $X_c$ represent the estimated crystallite size from XRD, crystallite size from Raman and crystalline volume fraction from Raman respectively. $t$ – c and q represent the parameters of the films that deposited on c-Si and quartz substrate respectively.

Fig. 2. Raman scattering spectra of nc-Si:H thin films deposited on (a) c-Si and (b) quartz substrates at different rf powers. (c) A typical of Raman peak deconvoluted into four components for the films deposited on c-Si substrates. The fitted components labelled as a, b, c and d represents the amorphous, intermediate, nc-Si and c-Si components respectively. The light grey line indicates the sum of the all components.
substrate are higher as compared to the films deposited on a quartz substrate. On the other hand, the crystallite size increases with increase in rf power for the films deposited on both the substrates. This shows good agreement with the XRD results. An increase in the crystallite size of nc-Si depending on the deposition conditions is compatible with previous observations [13–15]. In this case, pre-hydrogen plasma treatment about 10 min before the deposition created a lot of energetic atomic hydrogen removing the oxide contaminants on the substrate surface, which then leads to the creation of the dangling bonds. These dangling bonds provide preferable growth sites for crystallization at the early stage of the film growth. During the deposition, an increase in rf power produces more atomic hydrogen from the dissociation of SiH₄ and H₂ molecules. The presence of atomic hydrogen plays an important role in the creation of nucleation sites on the surface by breaking weak bonds and forming rigid bonds after the abstraction. Along with the local heating induced by this process, this leads to an increment in crystallite size and density of the crystalline regions that formed during the deposition and it can even enhance the agglomeration of adjacent nc-Si during growth. Thus, for this deposition condition bigger nc-Si with a higher crystalline volume fraction are formed at higher rf powers, however, the crystallization is more significant for the films deposited on c-Si substrate.

Fig. 3 shows a HRTEM image of the nc-Si:H thin films deposited at rf power of 80 W. In the figure, the image demonstrates a homogeneous amorphous network with a presence of small crystalline grains surrounding the amorphous matrix. From the rough estimation on the image, the diameter of the crystalline grain is about 5 nm. This crystallite size is about the same with the average crystallite sizes that was estimated from XRD and Raman scattering spectra for the films deposited on c-Si and quartz substrates at the same rf power. The estimated lattice spacing is about 0.31 nm which corresponds to the c-Si (111) plane. This supports the preferred orientation of c-Si (111) plane that was shown by the XRD results. The inserted figure labelled (a) showed that the crystalline grains in the amorphous matrix are clustering together forming spherical nanoparticles with the average particle diameter being about 23 nm. The corresponding electron diffraction pattern as shown in the inserted figure labelled as (a) shows the evidence of the crystallinity of the film. The weak electron diffraction signal could be due to small amounts of crystalline grains present in this scanning spot. Besides, the crystalline volume fraction in the film is considered low (43%) for the weak electron diffraction signal.

Fig. 4 shows the optical reflectance and transmittance spectra of the films deposited at different rf powers. In Fig. 4(a), the reflectance spectra exhibits interference patterns at the wavelength above 400 nm due to the effects of coherent multiple reflections on the films. On the other hand, the end point of the interference fringe of the reflectance spectrum shifted significantly towards a longer wavelength from 390 to 540 nm with increase in rf power. In addition, appearance of clear peaks at 274 nm in the UV region of the reflectance spectra for all the films suggests that the films are crystalline in structure which has been indicated by previous works [6,16]. In Fig. 4(b), the transmittance spectra show interference fringes at the wavelength above 400 nm which is similar to the interference fringes of the reflectance spectra. These spectra present a good transparency in the near-infrared region. However, this transparency degrades in the visible region which can be explained by the optical absorption characteristics of the films. Generally, the region of 400–600 nm, where the transmittance decreases gradually to zero indicates the absorption edge of the optical energy gap. In Fig. 4(b), the absorption edge shifted to a longer wavelength with increase in rf power. This is similar with the shift of the end point of the interference fringe in the reflection spectrum with increase in rf power. Therefore, these changes in the reflectance and transmittance spectra suggest that the optical energy gap decreases with increase in rf power.
The thicknesses of the films were determined from interference fringes of the reflectance and transmittance spectra in Fig. 4, using the conventional optical expressions which have been employed by Manifacier et al. [17] and Swanepoel [18] since 1980. The calculated thicknesses of the films are tabulated in Table 1. The film thickness increases with increase in rf power. This is consistent with increase of the number of interference fringes of the reflectance and transmittance spectra against rf power which is usually used as an indication of the film thickness. Generally, increase in rf power enhances the dissociation and ionization of silane radicals and thus a resulting increase of the flux of depositing precursors to the substrate surface. This has contributed to the increase of the deposition rate [19–21].

From the obtained data of the reflectance, R and transmittance, T, the n versus ë plots of the films can be obtained by fitting the n values obtained at the extreme points of the interference fringes to the Cauchy relation [22] of

\[ n = n_0 + \left( k_0 / \lambda^2 \right) \]

where \( n_0 \) is the static refractive index of the film and \( k_0 \) is a constant fitting parameter. The values of static refractive index of the films are in the range between 2.5 and 3.

Also, the data of reflectance, R and transmittance, T, can be used to determine absorption coefficient, \( \alpha \) of the films using the relation [23]

\[ \alpha = (1/t)\ln(1 - R)/t \]

where \( t \) is film thickness. The calculated \( \alpha \) was plotted against the photon energy, \( E \) to determine the Urbach energy, \( E_U \) using the relation [24]

\[ \alpha(E) = \alpha_0 \exp\left( (E - E_U) / (E_C) \right) \]

where \( \alpha_0 \) is a constant and \( E \) is the onset of the band tail. The figure of the variation of \( \alpha \) against photon energy of the films deposited at different rf powers is not shown. The calculated \( \alpha \) in the region of the absorption edge was substituted into the Tauc relation [25]

\[ \alpha(E) = B^2(E - E_C)^2 \]

where the \( E_C \) is optical energy gap which is determined from the extrapolation of the linear region of the Tauc plot of \( (\alpha E)^{1/2} \) versus \( E \) from the Tauc relation, the \( B \) is proportional to the slope of the band edge and \( E \) is photon energy. The region of the energy (1.8–3.0 eV) was selected due to the region of density of states of nc-Si:H thin film where the absorption edge occurs. Fig. 5 shows the Tauc’s plots of the films deposited at different rf powers. In the figure, it clearly shows that the absorption edge shifted to lower photon energy with increase in rf power. Also, the absorption intensity increases with increase in rf power. These are agreeable with the observation in Fig. 4(b). Variation of the optical energy gap with rf power will be discussed in the next part of the text.

Variations of the Urbach energy, \( E_U \) and Tauc slope, \( B \) of the films with rf power are shown in Fig. 6. \( E_U \) also called Urbach tail band width defines the width of the exponential tail of density of states, which extends into the band gap. Usually, the exponential tail of the density of states was referring to the localized states which are an indication of structure disorder, where a higher value indicates higher disorder [26]. As in \( E_U \), \( B \) is an indicator of the structural order, however, it is inversely proportional to the structural disorder where a high value of \( B \) indicates a more ordered film structure with a large band edge width [27]. The \( B \) decreases gradually at lower rf powers (5 W–25 W) and is nearly constant at low values with further increase in rf power. However, the \( E_U \) showed an opposite trend as compared to the \( B \). These trends indicate that the films are more ordered at lower rf powers and decreased in structural order with further increase in rf power. Generally, the films are more disordered in nature due to the increase in the deposition rate with increase in rf power [7]. In this work, the increase in the crystallite size and simultaneous increase in crystalline volume fraction with increasing rf power, as observed from XRD and Raman scattering spectroscopy studies respectively, confirm the formation of an increasing number of nc-Si grains at higher rf power. So, the increase of the band edge width with increasing rf power signifies the growth of defects and disorder [23] which may be correlated with the increasing number of nc-Si grains and the associated grain boundaries which are known to be normally highly defective [21].

The dispersion curve obtained from the Cauchy relation was described above and can be used to determine the dispersion energy, \( E_d \) and single oscillator energy, \( E_o \) using the Wemple and DiDenomico relation [28,29] of

\[ n^2 - 1 = E_d / (E_o^2 - E^2) \]

where \( E_o \) and \( E_d \) are the single oscillator energy and photon energy respectively. Furthermore, the obtained values of \( n_o \), \( E_o \) and \( E_d \) were substituted into Bhattacharya relation [30] of

\[ \beta = E_d / (E_o(n^2 - 1)) \]

to estimate the ionic constant, \( \beta \) of the films. The value of \( \beta \) is dependent on the chemical bonding character of the material. Fig. 7 shows the variations of the dispersion energy, \( E_d \) and ionic constant, \( \beta \) of the films with rf power. Generally, the \( E_d \) is a measure of the strength of the inter-band optical transitions which indicates the characteristics of electronic transition from valence band to conduction band in the film. The value of \( E_d \) is related to the structural disorder in the film [31] and the structural disorder of nc-Si:H films were mainly contributed by the grain boundaries of nanocrystallites embedded within the amorphous matrix [31]. As can be seen from the figure, the \( E_d \) increases with increase in rf power indicates that the films are more disordered at higher rf
powers. The $E_d$ agrees with the $B$ and $E_u$ under the same variation of rf power. The values of single oscillator energy, $E_{oo}$, are nearly constant for all the deposited films. The values of $\beta$ are in the range of 0.2–0.27 for all the deposited films indicate the atomic bonds in the films have ionic characteristics [32]. This also suggests that all the films containing the same anions species. From previous report [28], the $\beta$ increased with the crystallinity of the ionic solids which contained a single anion species. Therefore, the trend of $\beta$ with rf power for all the deposited films suggests that high values of $\beta$ could be an indication of the crystallinity in the films. This agrees with the crystalline volume fraction of the films as tabulated in Table 1. The inset of the figure showed the same trend occurs to the $X_C$ under the same variation of rf power which agrees with the prediction above.

In addition, the dispersion energy, $E_d$ can be related to hydrogen content, $C_H$ using the following relation [33] of $C_H(\%) = (1/3)/(n_e/n_v)(4 - \sqrt{E_d}/2.8)$, where $n_e$ is the electron density of c-Si taken as $2 \times 10^{23}$ electrons cm$^{-3}$, and $n_v$ is the valence electron density in the film which is determined using the following relation [34] of $n_v = 0.0143E_d^{3/2}/(\varepsilon(0) - 1) \times 10^{22}$ electrons cm$^{-3}$, where $\varepsilon(0)$ is taken as $n_o$ which is the long-wavelength limit of the refractive index [32]. The variations of the optical energy gap, $E_G$, and hydrogen content, $C_H$, of the films with rf power is shown in Fig. 8(a). $E_G$ decreases gradually with increase in rf power to 60 W and showed nearly no change with further increase in rf power up to 80 W. On the other hand, the $C_H$ shows no significant variation with the rf power. In general, the variation of $E_G$ in nc-Si:H thin films has been reported as dependent on the hydrogen content, $C_H$ [35], the structural disorder [36] or the crystallite size of nc-Si. In a-Si:H films, the optical energy gap is known to increase nearly proportional to the hydrogen content [35]. The values as high as 2–2.5 eV have been reported at ~40% hydrogen content [37]. The values of optical energy gap measured in our nc-Si:H films are in the range of 1.82–2.27 eV with hydrogen content about 34–39%. However, the optical energy gap of nc-Si:H films showed no dependence on the hydrogen content indicating that the hydrogen could be accumulated in the amorphous phase. By neglecting of the role of the hydrogen content, the variation of the optical energy gap could be due to the structural disorder and the crystallite size of nc-Si. The results from the variations of the $E_G$, $B$, and $E_d$ with rf power as described above explains that the highly disordered film structure narrows the optical band gap for the films deposited at higher rf powers. This is supported by previous work which studied the relation of the optical energy gap with the structural disorder in the nc-Si:H thin films [27].

According to the model that has been described by Santana et al. [38], the presence of nc-Si embedded within the amorphous matrix enhanced the quantum confinement effect which is responsible for the widening of the band gap. The model of the quantum confinement effect follows the relation of $E_G = E_c + (c/a^2)$, where $c$ is the confinement constant, $E_c$ is the bulk silicon band gap and $a$ is the diameter of crystallite. From this relation, it clearly indicates that the optical energy gap, $E_G$ depends on crystallite size of nc-Si embedded within the amorphous matrix. Moreover, the crystallite size of the nc-Si must be smaller than 10 nm in order to enhance the quantum confinement effect. Fig. 8(b) shows the variation of $E_G$ against the crystallite size of the nc-Si in the films. The values of crystallite sizes plotted in the figure, refers to the crystallite sizes that were determined from the XRD and micro-Raman scattering spectra for the films deposited on quartz substrates. This is to ensure the consistency of the results which can be understood that the values of $E_G$ were determined from the films deposited on quartz substrates. From the figure, a decrease of crystallite size of nc-Si shows gradual increase in $E_G$ which shows good agreement with the confinement model as described above. At least, these crystallite sizes of nc-Si could be responsible for the quantum confinement effect which narrows the optical band gap of nc-Si:H thin films at higher rf powers.
Table 2 tabulates the summary results of the various deposition methods, their deposition conditions and film properties. The result in this work shows almost similar with the work reported by Badran et al. [39]. Higher deposition pressure generally produced similar results with the work reported by Deyan et al. [40]. Higher hydrogen dilution ratios was carried out by Badran et al. [39]. Higher deposition pressure generally produced similar results with the work reported by Deyan et al. [40].

### Table 2

<table>
<thead>
<tr>
<th>Deposition methods</th>
<th>Deposition conditions</th>
<th>Crystallite size and crystalline volume fraction</th>
<th>Optical energy gap</th>
<th>Reported works</th>
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<tr>
<td>rf-PECVD (1)</td>
<td>Power density $= 179-2857 \text{ mW/cm}^2$ (5–80 W), $T_s = 250 \degree C$, Pressure $= 0.8$ mbar, Hydrogen dilution, $R = F_{H}/F_{SiH_4} = 50$</td>
<td>$d = \sim 2.0-6.6 \text{ nm}$ $X_C = 7-43%$</td>
<td>$E_g \sim 1.86-1.95$ eV</td>
<td>This work</td>
</tr>
<tr>
<td>rf-PECVD (2)</td>
<td>Power $= 10-45 \text{ W}$, $T_s = 220 \degree C$, Pressure $= 1.2$ mbar, Hydrogen dilution, $R = F_{H}/F_{SiH_4} = 50$</td>
<td>$d = \sim 3.6-13 \text{ nm}$ $X_C = 22-58%$</td>
<td>$E_g \sim 1.85-1.88$ eV</td>
<td>Deyan et al. (Ref. [40])</td>
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<tr>
<td>rf-PECVD (3)</td>
<td>Power density $= 340 \text{ mW/cm}^2$, $T_s = 250 \degree C$, Pressure $= 1.33$ mbar, Hydrogen dilution, $R = F_{H}/F_{SiH_4} = 100-300$</td>
<td>$d = \sim 2.5-6 \text{ nm}$ $X_C = 10-54%$</td>
<td>$E_g \sim 1.7-2$ eV</td>
<td>Jadkar et al. (Ref. [42])</td>
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<td>rf Magnetron Sputtering</td>
<td>Power $= 80 \text{ W}$, $T_s = 400 \degree C$, Pressure $= 0.003$ mbar, Hydrogen flow-rate, $F_H = 0.002$ mbar</td>
<td>$d = \sim 1.7-2$ eV $X_C = 54%$</td>
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<tr>
<td>HWCD</td>
<td>Power $= 200 \text{ W}$, Pressure $= 0.013-0.067$ mbar, Hydrogen dilution, $R = F_{H}/F_{SiH_4} = 15$</td>
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</table>

* Only power is shown in the table for the deposition conditions where the geometry of electrode is not provided.

**References**