High Contrast Distributed Bragg Reflectors Based on Si:H/SiC:H PECVD Multilayer Structure

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Abstract—In this work we study the high contrast distributed Bragg reflectors (DBRs) based on plasma deposited Si:H/SiC:H films. Optical constants of these materials were measured by means of spectral ellipsometry and used in theoretical calculations of spectral transmittance and reflectance. The stacks consisted of 13 layers of the films were designed to provide stop band center at \( \lambda = 835 \) nm (DBR1) and 565 nm (DBR2). High reflectance (>90%) for DBR1 and lower value of 70% for DBR2 was measured with bandwidth \( \Delta \lambda = 260 \) nm. The properties of DBR1 are of promise as back reflector in PECVD PV solar cells because of his stop band characteristics and complete compatibility with solar cell fabrication. While DBR2 structure shows worse filter properties suggesting significant effect of light absorption in Si:H layers.

Keywords—Optical properties; Interference; Distributed Bragg reflectors; Si:H; SiC:H;

I. INTRODUCTION

Plasma enhanced chemical vapor deposition (PECVD) is rather mature technology employed in fabrication of commercial devices such as e.g. displays (active-matrix liquid-crystal display, AM LCD), photovoltaic (PV) solar cells, sensors, etc. This technique allows fabrication of multilayered structures consisting of various materials with different optical characteristics enabling selectively transparent (reflective) elements based on constructive light interference. This approach is also known as Distributed Bragg Reflectors (DBR) or 1D photonic band gap materials. DBRs formed from plasma deposited layers have been widely studied. For example polarization effect on the stop band have been reported in [1] in the stack of PECVD a-Si:H/a-SiO:H films with high n-contrast. DBR based on PECVD a-Si:H/a-

II. EXPERIMENTAL

A. Fabrication process

The multilayer structures were fabricated in a cluster tool system with 3 deposition chambers from “MVSyst. Inc.”. In order to reduce effect of ambient exposition loading/un-loading samples was via load-lock chamber. Intrinsic Si:H was deposited from 10%SiH4+90%H2 mixture and intrinsic SiC:H from CH4+SiH4+H2 mixture. All gases used are semiconductor purity from “Matheson Inc.”. Deposition temperature was \( T_d = 160^\circ \) C. RF discharge is excited at frequency \( f = 13.56 \) MHz and power \( W = 5W \). Substrates of “Corning 1737” glass and boron doped c-Si (1-10 \( \Omega \) cm) are used for optical and SIMS/SEM analysis, respectively.

A multilayer stack of quarter-wavelength Si:H/SiC:H layers was deposited in such way that Si:H films were placed on the
top and on the bottom of the stack, a total number of 13 layers were deposited per DBR.

### B. Characterization methods

The experimental DBR structures are characterized by the measurements as follow:

1) **Thickness measurements**: Steps on the films and on the stacks were utilized to measure thickness with a “Dektak XT” profilometer. A minimum of 5 measurements were performed to determine thickness. Uniformity of thickness was ± 5 % over area of 6 cm².

2) **Optical constant measurements**: Spectral dependence of refractive index, \( n(\lambda) \), and extinction coefficient, \( \kappa(\lambda) \), of the separate layers for the DBRs were determined by the spectral ellipsometer “J.A. Woollam Co., Inc. model M-2000”.

3) **Spectral transmittion measurements**: A “Triax320” monochromator, calibrated with a thermopile sensor mod. 71938 from “Thermo Oriel Instruments Inc.”, a “Keithley 6517A” electrometer, as well as, a 300 W Xenon lamp with a “Newport Power Supply 69911” with a feedback system were used for the experimental setup. During the spectral measurements the samples were illuminated with monochromatic light \( I_0 \approx 10 \text{ mW/cm}^2 \) intensity in the wavelength range from \( \lambda = 400 \text{ nm} \) to 1200 nm with a wavelength resolution \( \Delta\lambda = 3.96 \text{ nm} \).

4) **Scanning Electron Microscopy Analysis**: A “Scios DualBeam SEM” from “FEI Company” with a superficial resolution of 1 nm is used to take transversal images of the samples. Transversal preparation is made in situ by the SEM system.

5) **SIMS analysis**: Solid content in the samples studied is determined by Secondary Ion Mass Spectroscopy technique. A time of flight TOF-SIMS-5 instrument from “ION TOF GmbH” was used for depth profiling with a double beam (Bi⁺ ions for analysis and Cs⁺ ions for sputtering) regime of analysis.

### III. Results and Discussions

#### A. Spectral dispersion of \( n(\lambda) \), \( \kappa(\lambda) \)

Spectral dependence of refractive index and extinction coefficient of the PECVD fabricated Si:H and SiC:H films were calculated from spectral ellipsometry measurements. Fig. 1 shows experimental results for \( n(\lambda) \) and \( \kappa(\lambda) \), in Si:H (a) and in SiC:H (b) films.

With \( n(\lambda) \) data measured by ellipsometry in the Si:H and SiC:H films utilized in multilayered DBR structures, theoretical calculations of transmission \( T(\lambda) \) and reflection \( R(\lambda) \) have been performed with centers at different wave lengths depending on thicknesses of the films and number of layers. Table 1 summarizes the theoretical parameters for two DBRs, where \( n2 \) and \( t2 \) are the refractive index and the thickness for Si:H film; while \( n3 \) and \( t3 \) are the similar parameters for the SiC:H film.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Band center (nm)</th>
<th>( n2 )</th>
<th>( t2 ) (nm)</th>
<th>( n3 )</th>
<th>( t3 ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBR1</td>
<td>835</td>
<td>3.3</td>
<td>63.3</td>
<td>2.07</td>
<td>100.9</td>
</tr>
<tr>
<td>DBR2</td>
<td>565</td>
<td>3.55</td>
<td>39.9</td>
<td>2.17</td>
<td>65.2</td>
</tr>
</tbody>
</table>

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*Fig. 1. Dispersions of optical characteristics (refractive index, \( n(\lambda) \) and extinction coefficient, \( \kappa(\lambda) \)) for a-Si:H (a) and SiC:H films (b).*

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The optical losses as function of wavelength in the DBR were calculated from $\kappa(\lambda)$ data. Optical absorbance $A(\lambda)$ is determined from Beer-Lambert law as follows:

$$A(\lambda) = 1 - e^{-\frac{7t_{SiH} + 4\pi \kappa(\lambda)}{\lambda} * e^{6t_{SiC:H} + 4\pi \kappa(\lambda)}}$$  \hspace{1cm} (1)$$

Thicknesses of the films ($t_{SiH,SiC:H}$) in the absorbance calculation are those measured from step profile measurements in the Si:H and SiC:H films prepared for $n(\lambda)$ and $\kappa(\lambda)$ measurements. The numbers 7 and 6 in (1) are the number of Si:H and SiC:H layers, respectively.

### B. SEM profile and SIMS analysis

After fabrication of the stack structures a transversal image of DBR1 is taken by SEM and it is presented in fig. 2a. To estimate one period comprising two layers (Si:H/SiC:H), intensity profile of the SEM image is shown for cross section notified by the dashed line in Fig. 2b. This period has an estimated value of 215±15 nm. The SIMS profile of DBR1 is presented in Fig. 2c aligned with the SEM image to match cross section profile.

According to fig. 2c silicon content is constant $[Si]=5.1+0.1 \times 10^{22}$ atoms/cm$^3$. It can be clearly identified the 13 films forming the DBR 1 structure. Main contaminant given by SIMS profile is oxygen showing practically constant concentration of $(2.03+0.15) \times 10^{19}$ atoms/cm$^3$ over entire profiling depth. From the profile, there is estimated a transition region of $9.8\pm2.7$ nm between Si:H and SiC:H layers. The width of these regions depends on the deposition parameters and the technical characteristics of the deposition system (changing of material type growth was realized by switching off/on RF power).

### C. Reflectance and transmittance for distributed Bragg reflector DBR 1 (centered at $\lambda=835$ nm)

A DBR1 centered at $\lambda=835$ nm was fabricated as described before. Fig. 3 presents the theoretical and experimental optical transmittance $T(\lambda)$ of the DBR. Optical transmittance of DBR1 shows a center wavelength at $\lambda=835$ nm in a good agreement with theoretical calculation (without taking into account absorption), for a DBR centered at $\lambda=835$ nm. Reflectance $R(\lambda)$ of the filter is calculated from the measured transmittance and the stack absorbance from (1) and plotted in Fig. 3.

Both $T(\lambda)$ and $R(\lambda)$ measured are in a good agreement for long part and center, while short wavelength part shows some discrepancy. Origin of that and also appearance of small peak in the band are still not clear. Nevertheless both $T(\lambda)$ and $R(\lambda)$ curves show proper stop gap in the range from $\lambda=700$ to 1050 nm behavior promising in device applications.

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Fig. 2. Data on SEM profile and SIMS analysis in DBR1 sample: a) Transversal SEM image, the dashed line indicates a position of the intensity profile, b) Intensity profile of SEM image, c) Atomic content profile as function of etching depth.
Two types of distributed Bragg reflectors (DBRs) utilizing plasma deposited Si:H/SiC:H films have been fabricated. Central wavelength in T(\(\lambda\)) and R(\(\lambda\)) spectra of these filters are located at \(\lambda=835\) nm and \(\lambda=565\) nm for DBR 1 and DBR 2, respectively. High reflectance (>90%) for DBR1 and lower value of 70% for DBR2 was measured with bandwidth \(\Delta\lambda=260\) nm. The properties of DBR1 are of promise as back reflector in PECVD PV solar cells because of his stop band characteristics and complete compatibility with solar cell fabrication. While DBR2 structure shows worse filter properties suggesting significant effect of light absorption in Si:H layers. The latter means a need for further study of PECVD materials with wider bandgap and higher n-contrast for DBRs in shortwave lengths.

IV. SUMMARY AND CONCLUSIONS

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