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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 λ= 835 (DBR1) and 565 nm (DBR2). High reflectance (>90%) for DBR1 and lower value of 70% for DBR2 was measured with bandwidth Δλ=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-SiC:H/a-SiO:H films with high n-contrast. DBR based on PECVD a-SiC:H/a-SiO_2 stacks forming Fabry-Perot microcavity with Er-doped a-SiO:H active light emitting layer resulted in an increase of emission brightness [2].

DBR based on selectively transparent conducting photonic crystal have been reported in [3,4] as rear contact while simultaneously transmitting part of solar energy which can be used for indoor heating and lighting in build integrated photovoltaic with PECVD n-i-p a-Si:H solar cells.

DBR approach could be alternative to or compatible with other light trapping schemes, which have been applied in thin film PV solar cells for harvesting energy of solar spectrum.

This work reports on fabrication, structural, and optical studies of DBR's comprising PECVD alternative Si:H/SiC:H quarter-wavelength layers.

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%SiH_4+90%H_2 mixture and intrinsic SiC:H from CH_4+SiH_4+H_2 mixture. All gases used are semiconductor purity from "Matheson Inc.". Deposition temperature was T_d= 160° 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 Ω 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

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top and on the bottom of the stack, a total number of 13 layers were deposited per DBR.

B. Caracterization methods

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

1) Thickness measruements: 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 cm^2.

2) Optical constant measurements: Spectral dependence of refractive index, n(λ), and extinction coefficient, κ(λ), 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 $I_0 \approx 10$ mW/cm^2 intensity in the wavelength range from λ = 400 nm to 1200 nm with a wavelength resolution Δλ = 3.96 nm.

4) Scanning Electron Microscopy Analysis: A "Scios DualBeam SEM" from "FEI Company" with a superficial resolucion 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 Discusions

A. Spectral dispersion of n(λ), κ(λ)

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(λ) and κ(λ), in Si:H (a) and in SiC:H (b) films.

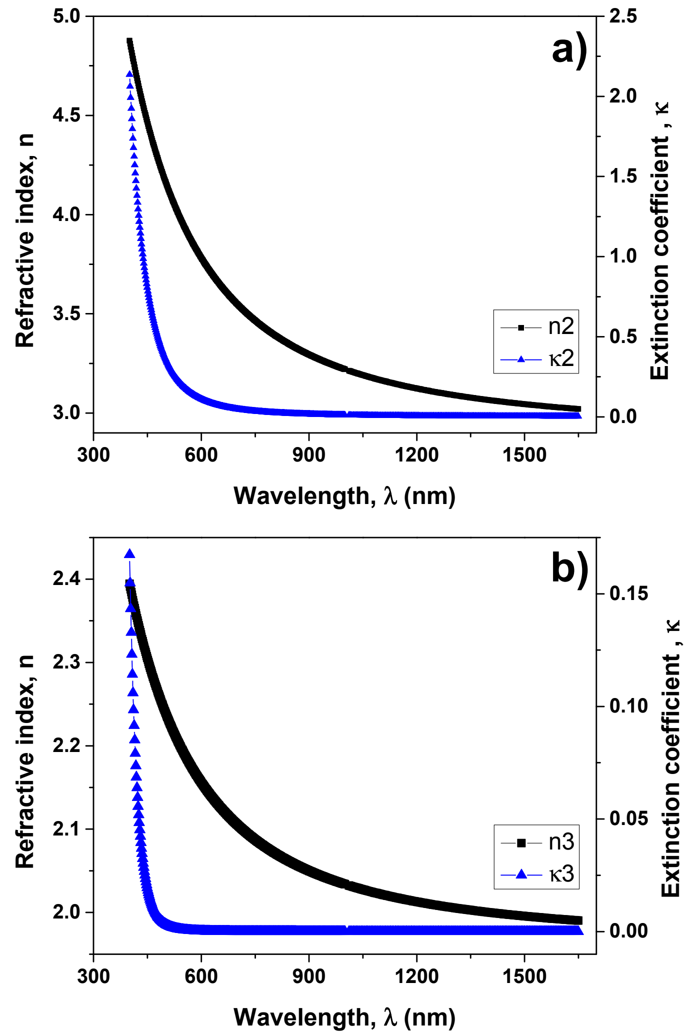

Fig. 1. Dispersions of optical characteristics (refractive index, n(λ) and extinction coefficient, κ(λ)) for a-Si:H (a) and SiC:H films (b).

With n(λ) data measured by ellipsometry in the Si:H and SiC:H films utilized in multilayered DBR structures, theoretical calculations of transmission T(λ) and reflection R(λ) 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 I. THICKNESS CALCULATION FOR TRANSMISSION FILTER BANDS

Sample	**Band center** (nm)	**n2**	**t2** (nm)	**n3**	**t3** (nm)
DBR1	835	3.3	63.3	2.07	100.9
DBR2	565	3.55	39.9	2.17	65.2

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

$$A(\lambda) = 1 - e^{7t_{Si:H}*4\pi\kappa(\lambda)/\lambda} * e^{6t_{SiC:H}*4\pi\kappa(\lambda)/\lambda} \quad (1)$$

Thicknesses of the films ($t_{Si:H/SiC:H}$) in the absorbance calculation are those measured from step profile measurements in the Si:H and SiC:H films prepared for n(λ) and κ(λ) 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+0.1x10^{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)x10^{19} atoms/cm^3 over entire profiling depth. From the profile, there is estimated a transition region of 9.8±2.7 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 λ=835 nm)

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

Both T(λ) and R(λ) 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(λ) and R(λ) curves show proper stop gap in the range from λ= 700 to 1050 nm behavior promising in device applications.

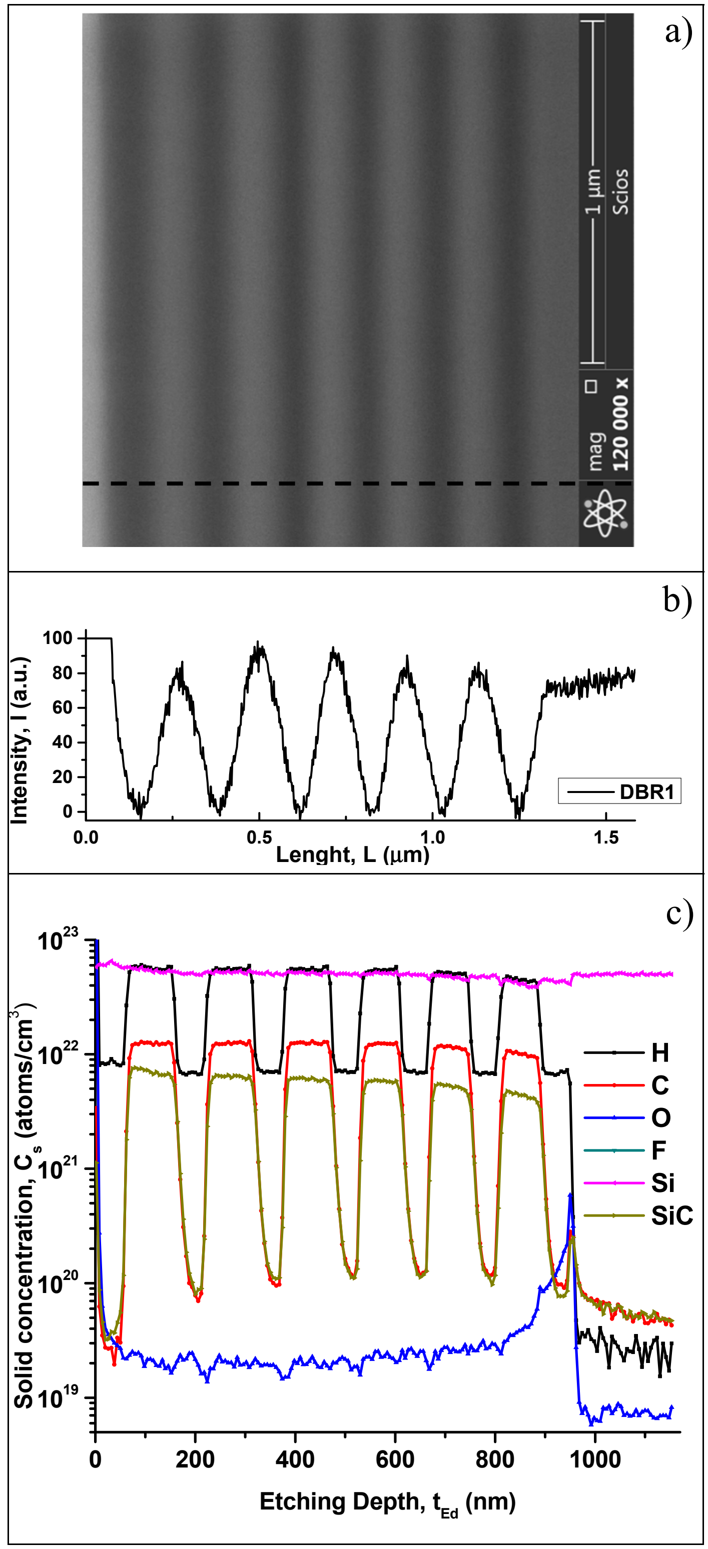

Fig. 2. Data on SEM profile and SIMS analysis in DBR1 sample: a) Transversal SEM image, the dashed line indicates a position of the intensity profile, b) Intensity profile of SEM image, c) Atomic content profile as fuction of etching depth.

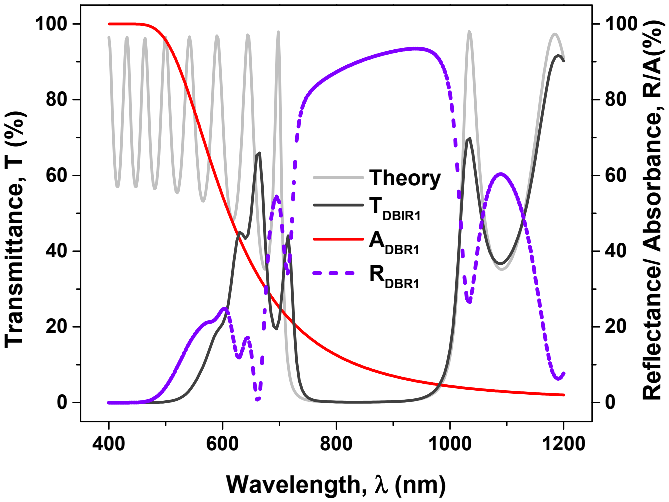

Fig. 3. Spectral dependence of transmittance T(λ) and reflectance R(λ) of DBR1 showing a center at λ=835 nm in comparison with theoretical calculation for a DBR centered at λ=835 nm. Bandwidth of Δλ=265 nm vs the calculated Δλ=285 nm. Calculated A(λ) is also plotted.

D. Reflectance and transmittance for distributed Bragg reflector DBR 2 (centered at λ=565 nm)

DBR2 was fabricated with T- and R-band centered at λ=565 nm. Fig. 4 shows the theoretical transmittance and the measured one. Again, reflection of the filter is calculated from the measured transmittance and the absorbance of the stack of films composing DBR2. This configuration shows worse T(λ), R(λ) DBR properties indicating practically no potential for applications. It is evident that for short wave length DBR materials with wider band gap and higher n-contrast should be found.

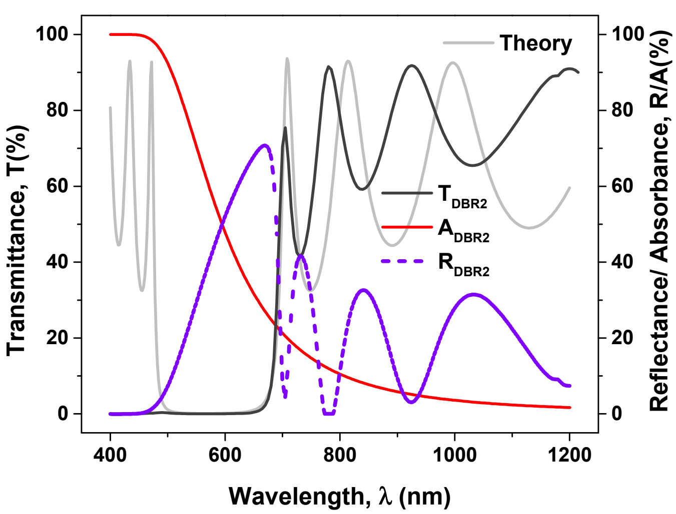

Fig. 4. Spectral dependence of optical transmittance T(λ) and optical reflectance R(λ) of DBR2 centered at λ=565 nm in comparison with theoretical calculation for a DBR centered at λ=565 nm. Bandwidth of Δλ=260 nm vs the calculated Δλ=240 nm. Calculated A(λ) is also plotted.

IV. SUMMARRY AND CONCLUSIONS

Two types of distributed Bragg reflectors (DBRs) utilizing plasma deposited Si:H/SiC:H films have been fabricated. Central wavelength in T(λ) and R(λ) spectra of these filters are located at λ=835 nm and λ=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 Δλ=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.

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