Anti-Reflection Properties of In-Situ Doped Spin-On Film

U. Gangopadhyay, Kyunghae Kim, J. H. Park, S. K. Dhungel, D. Mangalaraj, and J. Yi*
School of Electrical and Computer, Engineering, Sungkyunkwan University, 300 Cheon cheon Dong, Jangan-gu, Suwon, Kyunggi-do 440-746, Korea

H. Saha
Department of Electronics and Tele-communication Engineering, Jadavpur University, Calcutta – 700 032, West Bengal, India

D. W. Kim
Samsung SDI Co. Ltd., Corporate R&D Center, Yongin City, Korea

* E-mail : yi@yurim.skku.ac.kr

(Received 12 June 2003, Accepted 1 October 2003)

Anti-reflection properties of post diffusion doped spin-on source (in-situ AR coating) have been investigated in some detail. A simple experiment for reflectivity study using oblique incidence of light and necessary modification of the theory of minimum reflectivity at oblique incidence has been established. The comparative study of the in-situ AR coating with available spin-on AR film on silicon Solar Cell Surface have been investigated.

Keywords : Solar cell, AR(Anti Reflection), SOD(Silicon On Doping)

1. INTRODUCTION

In order to decrease front surface reflection of a mono-crystalline silicon solar cells, different antireflection coating have been used, from SiO_2 single layers to complex double layer over textured surfaces[1,2]. High efficiency commercial mono-crystalline silicon solar cells, PECVD silicon nitride coating has normally been used in batch process[3], but it is not cost effective. Spin-on doping (SOD) and short time furnace annealing [4-8] directly addresses the issue of fabrication costs by reducing the processing time in comparison with conventional furnace processing using $POCl_3$ source[9,10] without significant loss in the solar cell performance. But, when spin-on source diffusion, a well known diffusion technique for junction fabrication of Solar Cells under low cost consideration is used, the in-situ post diffusion doped spin-on film (same as PSG layer after conventional $POCl_3$ diffusion) can be optimized as an anti-reflective coating for Solar Cell. The comparative properties of this in-situ doped silica AR coating with that formed by the commonly available Titanium silica film "C" (Emulsitone company USA) on Solar cell surface has been investigated in this paper. The AR coating characteristics have been investigated through reflectivity measurement using oblique incidence. The necessary modification of the theory of minimum of reflectivity at oblique incidence has also been carried out and reported in this paper.

The anti-reflection coating on the Solar Cell surface has been formed either by a) Intentional deposition of spin-on Titanium silica film 'C' on silicon surface separately after the formation of n^+ front layer or b) Unintentional coating of doped spin-on silica film for SOD diffusion.

Titanium silica film 'C' (Emulsion) has been spin-on the diffused silicon surface after removing the post-diffused silica film. The spin speed is varied from 2000 r. p. m. to 3000 r. p. m. for fixed 20 seconds duration. The coated wafers are then baked following the usual procedure . The solar cells are then made as described above.

Normally, the measurement of refractive index is carried out by ellipsometeric method[11]. But this method is unsuitable for measurement on rough surface due to possibility of large error in determination of indices, even for small values (5nm) of roughness[12]. Therefore we have used the reflectance spectra as the basis for measurement of refractive indices and thickness of coated AR film, neglecting the absorption of the film. Oblique incidence is used in instead of the usual normal incidence.

The Fresnel reflection co-efficient for oblique light reflected off the j th boundary between the j th and (j + 1)th layers are given by [13].

$$r_{sj} = \frac{n_j \cos\theta_j - n_{j+1}\cos\theta_{j+1}}{n_j \cos\theta_j + n_{j+1}\cos\theta_{j+1}} \tag{1}$$

$$r_{pj} = \frac{n_{j+1} \cos\theta_j - n_j\cos\theta_{j+1}}{n_{j+1} \cos\theta_j + n_j\cos\theta_{j+1}} \tag{2}$$

The subscripts s and p represent the light polarized perpendicular and parallel to the plane of incidence respectively.

For unpolarised light, the total reflectivity is given by

$$R = \frac{r_s r_s^* + r_p r_p^*}{2} \tag{3}$$

Equation (3) leads to

$$R = \frac{1}{2}\left[\left(\frac{r_{1s}^2 + r_{2s}^2 + 2r_{1s}r_{2s}\cos\delta}{1 + r_{1s}^2 r_{2s}^2 + 2r_{1s}r_{2s}\cos\delta}\right) + \left(\frac{r_{1p}^2 + r_{2p}^2 + 2r_{1p}r_{2p}\cos\delta}{1 + r_{1p}^2 r_{2p}^2 + 2r_{1p}r_{2p}\cos\delta}\right)\right] \tag{4}$$

Where $\delta = \frac{4\pi n d \cos\theta}{\lambda}$

r_{1s}, r_{2s} , r_{1p} and r_{2p} can be computed using equation (1) and (2) by putting j =0 and 1. The condition of minimum reflectivity is given by [15].

Where, $\delta = (m+1)\pi$ (5)

and m=0, 1, 2, 3 ….

Thus, we have the reflection minimum for an oblique incidence θ_0 as:

$$R_{min} = \frac{1}{2}\left[\left(\frac{\cos\theta_0\sqrt{(n_2^2 - \sin^2\theta_0)} - n_1^2 + \sin^2\theta_0}{\cos\theta_0\sqrt{(n_2^2 - \sin^2\theta_0)} + n_1^2 - \sin^2\theta_0}\right)^2 + \left(\frac{n_1^4\cos\theta_0\sqrt{(n_2^2 - \sin^2\theta_0)} - n_2^2(n_1^2 - \sin^2\theta_0)}{n_1^4\cos\theta_0\sqrt{(n_2^2 - \sin^2\theta_0)} + n_2^2(n_1^2 - \sin^2\theta_0)}\right)^2\right] \tag{6}$$

Under the minimum reflection condition, the thickness of the coating is also determined by

$$t_c = \frac{\lambda_0}{4(n_1^2 - \sin^2\theta_0)^{1/2}} \tag{7}$$

where λ_o is the wave length of minimum reflectivity.

2. EXPERIMENTAL

The reflectance measurement reported here is similar to the one used by Yeh et al [14]. The schematic diagram of experimental arrangement is shown in Fig. 1.

In this experiment, the samples are placed on prism table of a spectrometer. The reflected beam of light falls on a calibrated Solar Cell acting as a detector of light rays. The parallel beam of light from the collimator is incident on the sample through a fine slit so that the non-specular reflected light intensity has been measured by the same detector in position A and B respectively. The reflected to incident light intensity ratios is the measured reflectivity of the sample. The spectral reflectance under constant photon flux condition has been measured by placing a set of narrow band optical filters in the range between 400 band optical filters (in the range between 400 ~ 1100nm). The variations of reflectance of different AR coated surface with wavelength have been shown in Fig.2 and 3.

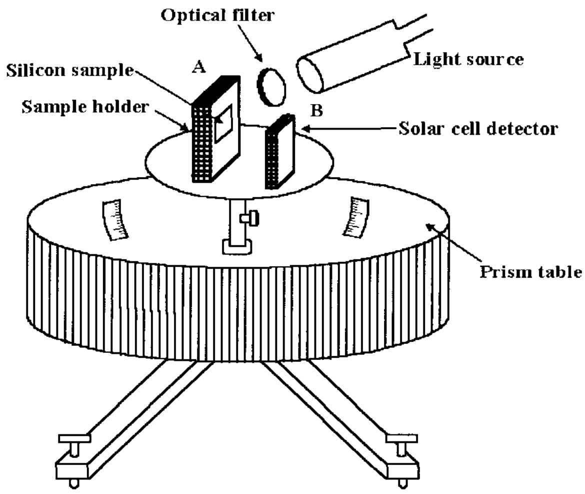

Fig. 1. Schematic diagram of experimental arrangement of reflectivity measurement.

The refractive indices, the thickness of AR coated film under different experimental conditions and the consequent short circuit current densities are shown in Table 1 and 2.

Table 1. Post diffusion spin-on doped film.

No	Speed (rpm)	Gas (N_2:O_2)	n	t (nm)	J_{SC} (mA/cm^2)
S1	4000	1:2	1.48	120.2	27.73
S2	4000	1:1	1.885	72.9	30.33
S3	3500	1:1	1.82	119.2	29.0
S4	4000	Only O_2	1.427	136.1	27.0

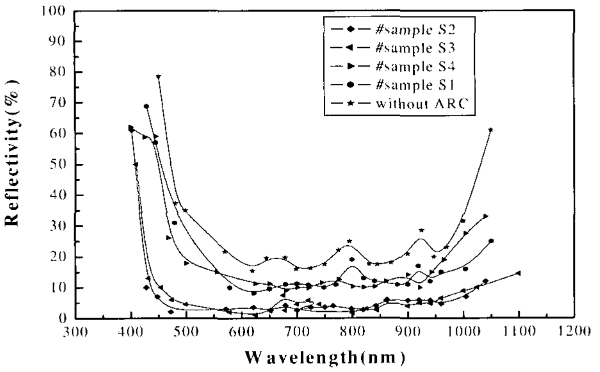

Fig. 2. Reflectance of different in-situ spin-on doped coated samples along with and without AR coated sample. (Ref. Table 1).

The spectral response is measured by placing a set of narrow band optical filters (in the range between 400 ~ 1100 nm) against an intense parallel beam obtained with a 500watt tungsten lamp in conjunction with reflector lens system and water filter. The radiations of different wavelengths, emerging through the filters are adjusted to be of constant photon flux. The spectral variation of the short-circuit current of different AR coated silicon solar cell are shown in Fig. 4 and 5.

3. RESULTS AND DISCUSSION

From Fig. 2 and Fig. 3 one notes that the overall reflectivity of both post diffusion spin-on doped silicon film (in-situ coated doped spin-on film) and commercial Titanium silica AR film coated surfaces are reduced considerably as compared with textured mono-crystalline silicon. The characteristics of the various spin-on in-situ film surfaces used in the reflectivity measurement curve are shown in Table 1 and in Fig. 2. Similarly the characteristics of Titanium silica film 'C' coated surfaces used in the measurement of reflectivity are also shown in Table 2 and Fig. 3.

From Fig. 2, it is observed that the overall reflectivity, the value and position of minimum reflection corresponding to different in-situ films are varying with diffusion ambient i. e. gas mixture (N_2 and O_2) proportion used. Thus, one notes from Table 1 that the refractive indices of these films vary from 1.48 to 1.855 depending upon the gas mixture ratio, but do not depend on the spin speed. On the other hand, the effective film thickness depends on both gas mixture ratio and spin speed. The reasons of these variations may be ascribed to the growth of a doped complex silicon oxide film. The value of refractive index of ideal single layer AR coating is about 78 nm. Therefore, the refractive index 1.855 of post diffusion doped spin-on film (in-situ silica film) is very close to ideal value 1.96. Fig. 4 shows that the spectral response of the short circuit current of the silicon solar cells fabricated with these films improve significantly particularly in the visible region. More specifically Table 1 indicates that the short circuit current density increases from 26 mA/cm^2 for the non – AR coated cell to 30.3 mA/cm^2 for the optimized in-situ AR coating on silicon solar cell surface by these films.

Figure 3 indicates the reflectance of the Titanium silica film 'C' on silicon surface. The optimized refractive index value of the spin-on film is 2.18 which is also very closed to ideal value (~ 1.96). The short circuit current density for the optimized spin speed increases to 29.4 mA/cm^2 from 26 mA/cm^2 in this case.

Table 2. Spin on Titanium silicon film 'C'.

No.	Speed (rpm)	n	t (nm)	J_{SC} (mA/cm^2)
S5	2500	2.18	90.9	28.4
S6	3000	2.18	84.9	29.0
S7	3500	2.18	78.8	29.4

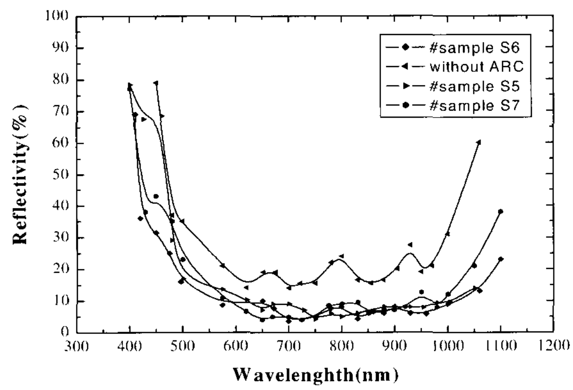

Fig. 3. Reflectance of different 'Titanium silica film C' spin-on doped coated samples along with without AR coated sample. (Ref. Table 2)

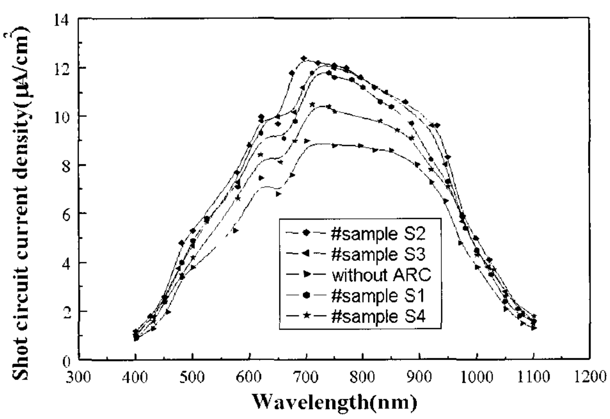

Fig. 4. Variation of short circuit current density with wavelength of different in-situ spin-on doped coated samples along with without AR coated sample. (Ref. Table 1)

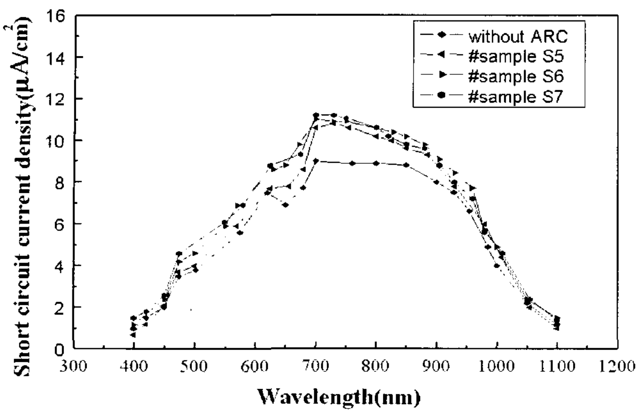

Fig. 5. Variation of short circuit current density with wavelength of different 'Titanium silica film C' spin-on doped coated samples along with without AR coated sample. (Ref. Table 2)

This is also clear from Fig. 5 showing the spectral response of Titanium coated silicon solar cell. Thus from the points of view of technology and cost, one can conclude that the use of post diffusion doped spin-on film (in-situ AR film) as an AR coating film has an advantage over the commercial Titanium spin-on AR film for silicon solar cells.

4. CONCLUSION

We have investigated the antireflective properties of post diffusion doped spin-on film in detail in this paper. In this paper we have also developed a simple experiment for reflectivity study using oblique incidence of light and necessary modification of the theory of minimum reflectivity at oblique incidence. We have obtained the refractive index of post diffusion doped spin–on film (in-situ silica film) is very close to ideal value of refractive index of ARC 1.96. The comparative study of the in-situ AR coating with standard Titanium silica film 'C' has been made. Moreover, it has been showed that the short circuit current density increases from $26mA/cm^2$ for the non-AR coated cell to $30.3mA/cm^2$ for the optimized in-situ AR coated cell. Thus from the points of view of technology and cost, one can conclude that the use of post diffusion doped spin-on film (in-situ AR film) as an AR coating film has an advantage over the commercial Titanium spin-on AR film for silicon solar cells.

REFERENCES

[1] Martin A. Green, "Solar Cells – Operating Principles, Technology, and System Applications", Prentice-Hall, p. 164, 1982.

[2] J. Zhao and M. A. Green, "Optimized antireflection coating for high efficiency silicon solar cells", IEEE Trans. Electron Dev., Vol. 38, No. 8, p. 1925, 1991.

[3] Armin G. Aberle, "Overview on SiN surface passivation of crystalline silicon solar cells", Solar Energy Materials and Solar Cells, Vol. 65, No. 1-4, p. 239, 2001.

[4] L. Pirozzi, G. Arabito, F. Artuso, V. Barbarossa, U. Bessi-Vetrella, S. Loreti, P. Mangiapane, and E. Salza, "Selective emitters in buried contact silicon solar cells: Some low cost solutions", Solar Energy Materials and Solar Cells, Vol. 65, No. 1-4, p. 287, 2001.

[5] S. Bourdais, G. Beaucarne, A. Slaoui, J. Poortmans, B. Semmache, and C. Dubois, "Comparative study of rapid and classical thermal phosphorus diffusion on polycrystalline silicon thin films", Solar Energy Materials and Solar Cells, Vol. 65, No. 1-4, p. 487, 2001.

[6] U. Gangopadhyay, H. Saha, and S. K. Lahiri, "Spin-on diffusion for silicon solar cell fabrication", J.IETE, Vol. 36, No. 6, p. 450, 1998.

[7] A. Rohatgi, Z. Chen, P. Doshi, T. Pham and D. Ruby, "High efficiency silicon solar cells by RTP", Appl. Phys. Lett., Vol. 65, No. 16, p. 2087, 1994.

[8] L. Ventura, A. Slaoui, B. Hartiti, J. C. Muller, F. Stuck, and P. Siffert "Shallow-junction formation by rapid thermal diffusion into silicon from doped spin-on glass films", Proc. 1994 Materials Research Society symposia, Vol. 342, p. 345, 1994.

[9] F. C. Marques, J. Urdanivia, and I. Chambouleyron, "A simple technology to improve crystalline silicon solar cell efficiency", Solar Energy Materials and Solar Cells, Vol. 52, No. 3-4, p. 285, 1998.

[10] Anzhong Lin, Xuejian Wong, Youxin Li, and Liande Chou, "Passivation and gettering of defective crystalline silicon solar cell", Solar Energy Materials and Solar Cells, Vol. 62, No. 1-2, p. 149, 2000.

[11] Paul H. Smith, "A theoretical and experimental analysis of the ellipsometer", Surface Science, Vol. 16, p. 34, 1969.

[12] Carl A. Fenstermaker and Frank L. McCrackin, "Errors arising from surface roughness in ellipsometric measurement of the refractive index of a surface", Vol. 16, p. 85, 1969.

[13] G. E. Jellison Jr. and R. F. Wood, "Antireflection coatings for planar silicon solar cells", Solar Energy Materials and Solar Cells, Vol. 18, No. 2, p. 93, 1986.

[14] Y. C. M Yeh, F. P. Ernest, and R. J. Stirn, "Practical antireflection coatings for metal-semiconductor solar cells", J.Appl. Phys., Vol. 47, p. 4107, 1976.