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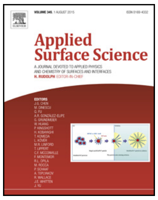

Anti-reflection coatings for silicon solar cells from hydrogenated diamond like carbon

Debajyoti Das*, Amit Banerjee

Nano-Science Group, Energy Research Unit, Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700 032, India

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ABSTRACT

Aiming towards a specific application as antireflection coatings (ARC) in Si solar cells, the growth of hydrogenated diamond like carbon (HDLC) films, by RF magnetron sputtering, has been optimized through comprehensive optical and structural studies. Various physical properties of the films e.g., (I_D/I_G) ratio in the Raman spectra, percentage of sp^3 hybridization in XPS spectra, H-content in the network, etc., have been correlated with different ARC application properties e.g., transmittance, reflectance, optical band gap, refractive index, surface roughness, etc. The ARC properties have been optimized on unheated substrates, through systematic variations of RF power, gas flow rate, gas pressure and finally controlled introduction of hydrogen to the DLC network at its most favorable plasma parameters. The optimum HDLC films possess $(T_{700})_{max} \sim 95.8\%$, $(R_{700})_{min} \sim 3.87\%$, $(n_{700})_{min} \sim 1.62$ along with simultaneous $(E_g)_{max} \sim 2.53$ eV and ~75.6% of sp^3 hybridization in the C-network, corresponding to a bonded H-content of ~23 at.%. Encouraging improvements in the ARC properties over the optimized DLC film were obtained with the controlled addition of hydrogen, and the optimum HDLC films appear quite promising for applications in Si solar cells. Systematic materials development has been performed through comprehensive understanding of the parameter space and its optimization, as elaborately discussed.

1. Introduction

Even after decades of research on various carbon allotropes, there is lack of comprehensive understanding of properties, aiming specific application possibilities. Carbon with its hybridization property is capable of forming single, double and triple bonds with itself or with other suitable elements in the network. Accordingly, carbon has versatile allotropes ranging from diamond, graphite, DLC, amorphous carbon, fullerenes to graphene and carbon nanotubes (CNT). In general, an amorphous carbon can have any mixture of sp^3, sp^2, and even sp^1 sites. The sp^3 phase has only σ states while the sp^2 phase also possess π states. The σ and π bonds have a significantly different behaviour [1]. Hence, the physical property of carbon allotropes has a strong dependence on the ratio of sp^3 (diamond-like) to sp^2 (graphite-like) bonds [2,3]. Diamond like carbon (DLC) has been comprehensively defined as amorphous carbon with a significant amount of sp^3 bonds, as the presence of high sp^3 content gives DLC properties comparable to diamond [1,4]. The DLC films with a good amount (~10–50%) of hydrogen-content are commonly known as hydrogenated DLC (HDLC, a-C:H) films [5].

The DLC films have drawn the interest of the materials scientists as a cheaper alternative to diamond for variety of applications ranging from the microelectronics, optics to tribology industries [2,6]. These are potential candidates for protective and optoelectronic materials owing to its similar advantageous properties to diamond, e.g. excellent mechanical hardness, high heat conduction, wear resistance, high electrical resistance, chemical inertness, low friction coefficient, high transmittance of infrared to ultraviolet light and excellent field emission properties [7,8]. The properties of DLC could be tailored between those of diamond (with dominating sp^3 phase) and graphite (dominating sp^2 phase) by variation of deposition parameters, according to application requirement [9]. The vital aspect of high transmission with reduced reflectance along with brilliant mechanical strength is that it has the capability to maintain enough visibility in the potential field for protective antireflection coatings (ARC) [10]. ARC is a type of optical coating applied to the surface of solar cells, lenses and other optical devices. It helps improving the device performance by increasing the transmitted light through reduction of reflection loss, leading to a significant efficiency (10–20%) improvement in Si-based solar cells [11–13]. Moreover, other than terrestrial applications, DLC films may be successfully used as protective coatings for solar cells against action of radiation (solar wind, γ-quanta) which is one of the key factors for efficiency degradation in space [14].

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* Corresponding author. Tel.: +91 33 2473 4972; Fax: +91 33 2473 2805.
E-mail addresses: erdd@iacs.res.in, profdebajyotidas@gmail.com (D. Das).

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DLC thin films can be grown by using different techniques such as filtered cathodic vacuum arc (FCVA) [15,16], filtered cathodic jet carbon arc (FCJCA) [17], pulse laser deposition [18], radio-frequency sputtering [19], ion-beam sputtering [20], Microwave PECVD (MW-PECVD) [3] and various other methods [21]. Considering application of ARC on the already fabricated top electrode of solar cells, only low temperature process can be used. Hence, the typical process to deposit ARC is sputtering or PECVD, which are used extensively in the manufacture of microelectronic devices owing to their advantages of being low temperature processes. Sputtering is however more preferable considering its low equipment and process cost and large area uniform deposition facilities. In sputtering, plasma is formed by an electric field (DC or RF) that allows growth of films at lower temperature than what would normally require in CVD process. RF-magnetron sputtering is a sophisticated technology for controlled, uniform growth of thin films in high deposition rate. Particularly for insulating materials (e.g., DLC), RF sputtering avoids the charge build up on the cathode (target) by alternating potential. Further effect of magnetron is to increase the ionization of deposition gas (Ar) even at very low chamber pressure (~1 mTorr). Magnetron increases the probability of electron striking the gas molecules by increasing electron path-length and simultaneous (perpendicular) use of electric and magnetic field.

The aim of present work is the development of ARC grade HDLC films at a low temperature by RF-magnetron sputtering, for applications in Si solar cells. The HDLC films are deposited by sputtering of an inexpensive a-C target in Ar atmosphere optimally diluted by hydrogenation, in order to maximize the sp^3 carbon bonding configuration with superior ARC properties, through suitable optimization of growth parameters.

2. ARC theory

To enhance the efficiency in single junction solar cells, it is desirable to increase the collection of light-generated carriers and reduce the optical loses. The light absorption may be increased by: (i) making the cells sufficiently thick or (ii) increasing the optical path-length in the cell by a combination of surface texturing and light trapping. Whereas, the reflection loss may be reduced by: (i) use of ARCs or (ii) by surface texturing. Bare silicon has a high surface reflection of over 30% which costs havoc on the efficiency [14,22]. However considering the process complexities of surface texturing, ARC is a relatively cheaper and easier option to effectively reduce the surface reflection in devices. ARC may also help in inducing light trapping features to increase absorption. Light trapping is usually achieved by changing the angle at which light travels in the solar cell by having it incident on an angled surface or by refractive index engineering by ARC, that light bounces back and forth within the cell many times by total internal reflection.

ARCs on solar cells are a thin layer of dielectric material with definite refractive index and thickness. The light wave reflected from the ARC top surface is out of phase with the same reflected from the semiconductor surface and destructively interferes with one another, resulting in zero net reflected energy. In order to meet the requirement of destructive interference, the product of refractive index and thickness of the ARC happens to be one quarter the wavelength of the incoming wave [23], following:

$$d_1 = \frac{\lambda_0}{4n_1} \tag{1}$$

Considering the peak of the solar spectrum at around 700 nm, λ_0 = 700 nm = 0.70 μm, d_1: thickness of ARC = 70 nm = 0.07 μm, the optimum ARC properties for silicon solar cell requires n_1: refractive index of ARC material = 2.5.

Reflection is further minimized [14] for optimal antireflection effect, if the refractive index of the anti-reflection coating is the geometric mean of those of the materials on either side:

$$n_1 = \sqrt{n_0 n_2} \tag{2}$$

where n_0: refractive index of air = 1, n_2: a refractive index of semiconductor = 3.5 (considering the ARC to be placed on top of the p-type nc-Si layer), and hence n_1: refractive index of ARC material = 1.8708 (from Eq. (1)).

Now the coefficient of reflection with ARC is defined as:

$$\rho = \frac{(n_0 - n_1)}{(n_0 + n_1)}$$

Then reflectivity (Fresnel's law for normal incidence)

$$R(\%) = \rho^2 = \frac{I_R}{I_0} = \frac{(n_0 - n_1)^2}{(n_0 + n_1)^2} \tag{3}$$

where I_R = reflected intensity, I_0 = incident intensity. Considering n_0 = 1, n_1 = 1.87 (from Eq. (1)), the reflectivity R (n_1 = 1.87) = 9.2%. Hence, for single layer of ARC with refractive index (n_1) as above may have a theoretical reflectance (R) = 9.2%. For higher n_1, reflectance increases. Hence it is desirable to keep the ARC refractive index as lower as possible, however keeping the $(n_0 - n_1)^2$ value the lowest.

However, for a multilayer configuration (air/ARC/semiconductor), the scenario is little complex. For the reflectance at normal incidence, a series of parameters may be defined as follows:

$$\rho_1 = \frac{(n_0 - n_1)}{(n_0 + n_1)}$$

$$\rho_2 = \frac{(n_1 - n_2)}{(n_1 + n_2)}$$

$$\theta = \frac{2\pi n_1 d_1}{\lambda_0}$$

Then, reflectivity [22]

$$R(\%) = \rho^2 = \frac{\rho_1^2 + \rho_2^2 + 2\rho_1\rho_2\cos(2\theta)}{1 + \rho_1^2 + \rho_2^2 + 2\rho_1\rho_2\cos(2\theta)} \tag{4}$$

For n_0 = 1, n_1 = 1.87, n_2 = 3.5, considering the peak of the solar spectrum at around 700 nm, λ_0 = 700 nm = 0.70 μm, d_1: thickness of ARC = 70 nm = 0.07 μm,

$$R(\%) = \rho^2 = 2.32\%$$

Hence for n_1 = 1.87, reflectance could come down to R ~ 2.32%. As stated earlier also, for higher n_1, reflectance (R) increases and hence is not desirable.

To achieve efficient transmission of a normally incident light, refractive index grading at the interface of two materials is required to implement anti-reflecting effect. Thus, ARC, when used on the glass surface of a 'solar cell on glass system', should have a refractive index that is intermediate between that of glass (n = 1.55) and air (n = 1). It is evident from Eq. (3) that lower n leads to lower reflectance. However, theoretically [24], n = 1.25 minimizes the reflectance when a layer is in contact with glass (n = 1.55). For instance, pure SiO_2 with n = 1.4 is expected to show the highest transmittance because it is nearest the ideal value. However, the films with SiO_2 coat may have a poor transmittance due to the fact that SiO_2 adhere poorly to glass so intermittent voids may form at the ARC/glass interface [25].

Hence a desirable material, suitable for the ARC application on the glass surface of a 'Si solar cell on glass system', should be one