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Investigation on growth behavior of multiphase silicon carbon film for front contact layer in a Si thin film solar cell

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ABSTRACT

Boron doped hydrogenated multiphase silicon–carbon (multiphase silicon–carbon) film has been grown by a plasma enhanced chemical vapour deposition (PECVD) method to obtain the properties of high conductivity and a low absorption coefficient. It consists of amorphous carbon, amorphous silicon and a crystalline silicon-like clustering phase. It has the advantage of reducing optical loss due to the wider band gap of amorphous carbon compared to amorphous silicon carbide. The film was fabricated in conditions of low power density with a high hydrogen flow rate to increase the ratio of the amorphous carbon. This result is able to be achieved because the reaction of Si-based and C-based radicals is suppressed by the deposition condition of low electron temperature (T_e) of the plasma and the short residence time of the gases. The multiphase silicon–carbon showed high electrical conductivity and a low optical absorption coefficient in the short wavelength region. Applying it for use as a front contact layer in a Si thin film solar cell, it showed an improvement in the conversion efficiency due to the increase in the quantum efficiency in the short wavelength region.

1. Introduction

Hydrogenated silicon–carbon alloys have received considerable attention in many optoelectronic application fields due to the superior optical properties of having a wide band gap [1–3]. Wide band gap materials have the advantage of low optical absorption loss. Recently, the properties of high conductivity as well as a wide band gap have been required in order to enhance device performance, even though an increase in the band gap is related to a decrease in the electrical conductivity. The significance of this material is that its electrical and optical properties can be controlled by the carbon, silicon, and hydrogen composition of the film [4].

The hydrogenated amorphous silicon carbide (a-SiC:H) has a restricted application due to its low electric conductivity. It has been shown that hydrogenated microcrystalline silicon carbide (μc-SiC:H) with crystallites of a few nm in size in an amorphous matrix has a high conductivity and high optical transmittance [5]. However, it is very hard to use it in industry for mass production because it is mainly deposited by the methods of electron–cyclotron resonance chemical vapor deposition (ECR CVD), hot wire CVD, and photo-CVD [6–8]. With these methods, it is difficult to control the uniformity of the deposition in large area. Even though some researchers had introduced μc-SiC:H grown by the plasma enhanced chemical vapor deposition (PECVD) method with high power density due to the excellent uniformity of deposition achieved for a large area [9,10], it also can damage either the substrate or the interface of devices by highly energetic ions and electrons in high power density [11].

In order to overcome the above mentioned problems, the authors have introduced a boron doped hydrogenated multiphase silicon–carbon (multiphase silicon–carbon) film, consisting of hydrogenated amorphous silicon (a-Si:H), hydrogenated amorphous carbon (a-C:H) and a hydrogenated microcrystalline (μc-Si:H) phase in previous work [12]. The carbon atoms mainly exist as a-C:H phase with a C–C bond in its film. The film is able to reduce a greater amount of optical absorption loss than an a-SiC:H phase with C–Si bonds because the optical band gap of a-C:H (2.84 eV) is wider than that of a-SiC:H (2.1–2.58 eV) [13]. Furthermore, the formation of the microcrystalline silicon phase is favorable for obtaining a high level of conductivity [14].

In this paper, we have analyzed the growth behavior of multiphase silicon–carbon film grown by the PECVD method, which is easy to obtain superior uniformity in large area. The structural, optical and electrical properties of hydrogenated silicon–carbon alloy films have been investigated for deposition conditions of

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various power densities and hydrogen (H_2) flow rates, related with electron temperature (T_e) in plasma. Thus, authors have tried to maximize the ratio of the C–C bonds to C–Si bonds to fabricate the multiphase silicon–carbon film. The film is able to reduce the optical absorption loss while keeping a high electrical conductivity of film.

The multiphase silicon–carbon film was also applied as a front contact layer in a triple-junction (a-Si:H/a-SiGe:H/μc-Si:H) Si thin film solar cell in order to verify its superior properties with low optical absorption loss and high electrical conductivity. The front contact layer in the Si thin film solar cell is required to possess the property of high conductivity to enable tunneling transport between the transparent conductive oxide (TCO) with its n-type character and the p layer [15]. Furthermore, it is very important to obtain the property of a wide band gap to reduce the optical absorption loss as well. The quantum efficiency in the short wavelength region is significantly affected by the optical absorption of the window layer [16].

2. Experimental

The hydrogenated silicon–carbon alloy films on soda lime glass substrate were grown by capacitively coupled radio frequency PECVD, operated at a radio frequency of 13.56 MHz, with a gaseous mixture of hydrogen (H_2), methane (CH_4), and diborane (B_2H_6) diluted to 0.5% in H_2 and silane (SiH_4) as the source gases. The deposition conditions of the PECVD system are as follows: a working pressure of 266.6 Pa, a H_2/SiH_4 gas flow ratio of 300, a CH_4/SiH_4 gas flow ratio of 0.2, and a B_2H_6/SiH_4 gas flow ratio of 0.01, a H_2 flow rate of 2–3 slm and a power density of 53–173 mW/cm^2. All films are about 40 nm in thickness.

The atomic concentration and chemical bond structure of these films were studied by means of x-ray photoelectron spectroscopy (XPS). Raman spectroscopy is used to analyze the crystalline fraction in the film. The conductivity was measured by the coplanar method with two parallel Ag electrodes separated by a 0.1 mm gap on the film. The absorption coefficient and thickness of the films were obtained by use of a spectroscopic ellipsometer. In addition, optical emission spectroscopy (OES) measurements were used to investigate the electron temperature of the plasma according to the deposition condition. The microstructure of the films was observed by high resolution transmission electron microscopy (HR-TEM) and conductive atomic force microscopy (C-AFM). The films were investigated with a vertical mean current measured by C-AFM if it was vertically conductive. The sample for C-AFM measurement was prepared on conductive aluminum doped zinc oxide (ZnO:Al) coated glass.

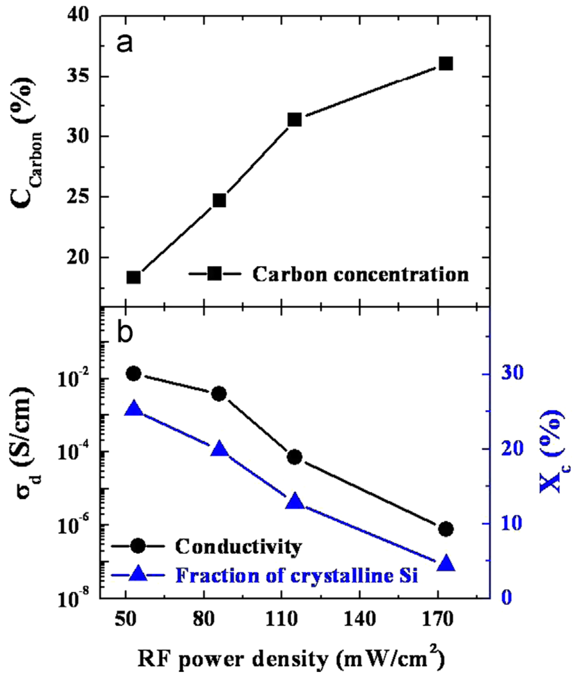

Fig. 1. Single layer properties of hydrogenated silicon–carbon alloy films as a function of the RF power density: (a) carbon concentration, and (b) conductivity and fraction of crystalline Si.

In order to investigate the effect of front contact layer, triple junction Si thin film solar cells with three absorbing layers (a-Si:H/a-SiGe:H/μc-Si:H) were fabricated on transparent front electrode, which was a textured ZnO:Al layer. The solar cells were characterized by current density–voltage measurements under AM 1.5 illumination with a 100 mW/cm^2 light intensity at a 25 °C temperature. The external quantum efficiency (EQE) of each absorbing layers was measured with a spectrally filtered bias light in a wavelength range from 300 to 1200 nm in order to determine the top, middle and bottom cell EQEs separately. The measurements were carried out in a cell with a defined 1 cm^2 with a back contact electrode of silver (Ag).

3. Results and discussion

3.1. Growth behavior of multiphase silicon–carbon film

3.1.1. Properties of hydrogenated silicon–carbon alloy films as a function of RF power density

Fig. 1(a) shows the carbon concentration as a function of the RF power density which was calculated from the XPS survey spectra. Within it exist mainly two element peaks, that of carbon and silicon. The carbon concentration in the film increases as the power density increases. It is understood that the dissociation of CH_4 molecules increases at high power density.

In general, the conductivity is strongly related to the crystalline fraction in the film. As shown in Fig. 1(b), the conductivity and the crystalline fraction decreases as the RF power density increases, even though the crystalline fraction increases as the RF power density increases in microcrystalline silicon film without carbon [17]. This means that the increased carbons obstruct the crystallization of Si in the silicon carbon alloy film. It is known that carbon injected into SiH_4 plasma inhibits the crystallization process of Si [18,19].

Fig. 2 shows the absorption coefficient of the films measured by a spectroscopic ellipsometer in a wavelength range from 390 to 580 nm. The optical property of a wide band gap is important in the short wavelength region because it is mainly used for the window layer in the device. As the power density increases, the absorption coefficient decreases at short wavelength region due to the increase of carbon concentration.

Although the absorption coefficient can be reduced at high power density, the film is insufficient to use it at various application fields due to its low electric conductivity and possibility of interface damage in device fabrication.

3.1.2. Properties of hydrogenated silicon–carbon alloy films as a function of the plasma condition

As mentioned in Section 3.1.1, a method for the reduction of the absorption coefficient is needs while maintaining a high conductivity in the film. Therefore, an OES system was used to investigate the correlation between the growth behavior and the plasma condition. An optical emission-intensity ratio of $I_{H\beta}$ to $I_{H\alpha}$ shows a good correspondence to the electron temperature measured by