Surface & Coatings Technology 228 (2013) S433–S436

Contents lists available at SciVerse ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

VHF SiH_4/H_2 plasma characteristics with negative ions

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ARTICLE INFO

Available online 18 May 2012

Keywords:
VHF plasma
Negative ion
Sheath potential
Solar cell

ABSTRACT

A VHF SiH_4/H_2 plasma was produced using a multi rod electrode and the plasma parameters were measured using a heated Langmuir probe, where the frequency of the power source was 80 MHz. The Langmuir probe characteristics indicated that when the concentration of SiH_4/H_2 is increased, negative ions appear and at the same time the electron temperature increases.

1. Introduction

Microcrystalline silicon has been widely investigated to reduce production costs of solar cells [1], where a large area deposition ($>1\ m^2$) is also required. Usually VHF plasmas have been used to increase the deposition rate of microcrystalline silicon because of the high electron density. Recently, it was found that a higher deposition rate of microcrystalline silicon is achieved by a short gap discharge at a high pressure [2–4]. Microcrystalline silicon is deposited by introducing a small amount of SiH_4 gas into H_2 plasmas. As well known, negative ions are produced in SiH_4 plasma [5]. The cross section of electron attachment is much lower than that of ionization. However, negative ions are confined in plasma without diffusing to electrodes, leading to high negative ion density. Thus, it is an important subject in solar cell development to investigate the parameters of SiH_4/H_2 plasma including negative ions. The simplest method to estimate negative ion density is to use Langmuir probe characteristics. When there are negative ions, the electron saturation current of the I–V curve decreases. Thus, the negative ion density n_- normalized to the ion density n_i is in the following:

$$n_-/n_i = 1 - I_e/I_{e0} \tag{1}$$

where I_e and I_{e0} are the electron saturation currents with negative ions and without negative ions, respectively. Thus, the negative ion density is easily estimated from the reduction of the electron saturation current. Note that this method includes the assumption that the ion density is kept constant even when negative ions increase [6].

The sheath potential is one of the key parameters in plasma CVD because it corresponds to the ion bombardment energy. According to the Langmuir probe theory [7], the sheath potential V_w is in the following:

$$V_w \approx \frac{\kappa T_e}{2q} \ln\left(\frac{2m_i}{\pi m_e}\right). \tag{2}$$

Here κ, q, m_e and m_i are the Boltzmann constant, electron charge, electron mass and ion mass, respectively. As seen from Eq. (2), the sheath potential is estimated from the electron temperature Te if there are no negative ions. That is, the comparison between the measured sheath potentials and those calculated using Eq. (2) provides information about the existence of negative ions.

In this paper, we measured the parameters of VHF SiH_4/H_2 plasma with a heated Langmuir probe and discussed the VHF SiH_4/H_2 plasma characteristics from the Langmuir probe I–V curve.

2. Experimental

The experimental apparatus (height: 600 mm, width: 600 mm, depth: 400 mm) consisted of a vacuum chamber, a multi rod electrode of 422 mm × 422 mm and a VHF power source [8,9]. A VHF plasma was produced using the multi rod electrode which consists of many stainless steel thin rods. VHF power with a frequency of 80 MHz was supplied to the power feeding points on the multi rod electrode through an impedance matching box to generate a VHF plasma between the multi rod electrode and the substrate. The forward and reflected VHF powers were measured with a power meter. In order to carry out the experiment under the same conditions as those in plasma CVD, a Corning 7059 glass substrate (300 mm × 300 mm) was placed on the substrate heater, which was electrically grounded. The discharge gap was 55 mm. The used gas was SiH_4/H_2 with the flow rate of (50–100) sccm. The experiments were carried out at the pressure of 70 mTorr. To achieve a uniform

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doi:10.1016/j.surfcoat.2012.05.036

gas flow, the gas was spouted from several holes in the tubes, which were positioned behind the multi rod electrode. The plasma parameters were measured with a heated Langmuir probe to obtain correct I–V curves [9]. A heated tungsten wire (diameter = 1 mm and length = 2.7 mm) was used as the heated Langmuir probe. The probe was positioned at a distance of 41 mm from the multi rod electrode. The reliability of the heated probe was confirmed from I–V characteristics of pure Ar and H_2 plasma using an ordinary (not heated) Langmuir probe.

3. Experimental results

At first we examined the sheath potential that is defined by the potential difference between the plasma potential V_s and the floating potential V_f as a function of concentration of SiH_4/H_2 for different VHF powers. The floating potential V_f is the potential at which the ion current is equal to the electron current (the probe current I = 0). In this experiment, a tungsten wire was used as the probe, that is, a cylindrical probe was used, so that its accuracy of the plasma potential may be reduced due to the variation of current with voltage in the electron saturation region compared with the plane probe. Here the plasma potential V_s was determined by finding the intersection of the straight line used to estimate the electron temperature and the linear extrapolation of the electron saturation current on the semilogarithmic plot of the probe I–V curves. Fig. 1(A) is a typical semilogarithmic plot of the probe I–V curve. The sheath potential V_w was estimated from V_s obtained using the semilogarithmic plot and V_f. Fig. 1(B) shows that measured sheath potentials agree with those calculated using Eq. (2), where H^+ and SiH_3^+ were assumed for the concentration of 0% and those larger than 4% as dominant ions, respectively [10]. Here the curves were plotted to fit the experimental results using the least-squares analysis. In addition, as shown in Fig. 2, the electron saturation current density I_{es} increases with increasing the concentration of SiH_4/H_2, that is, the electron density increases when the concentration is increased. These results indicate no indication of negative ions. In this case, the electron temperature was 2–3 eV for the concentration lower than 10%.

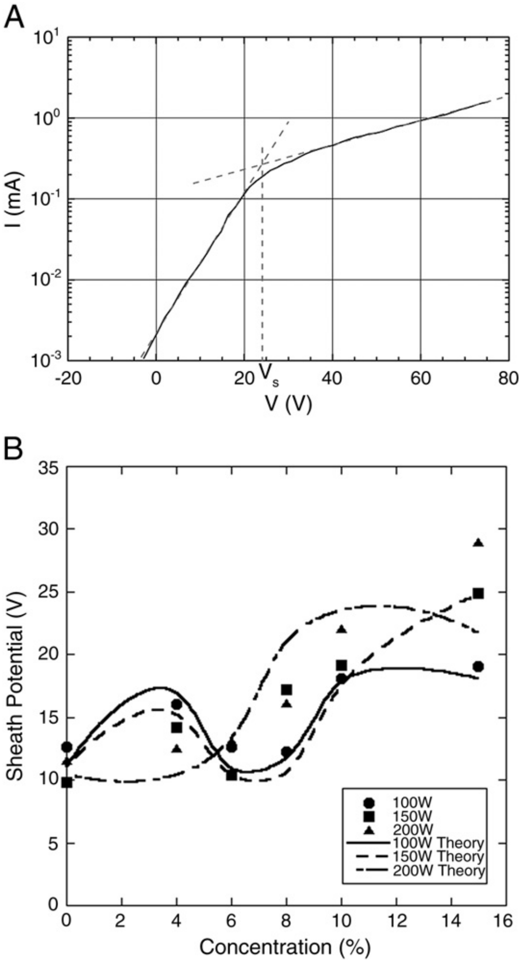

Fig. 1. (A) A typical semilogarithmic plot of the probe I–V curve in the H_2 plasma, where the power and the pressure are 150 W and 120 mTorr, respectively. (B) Dependence of the sheath potential on the concentrations of SiH_4/H_2 for different VHF powers. Here the pressure and the gas flow rate were 70 mTorr and 100 sccm, respectively.

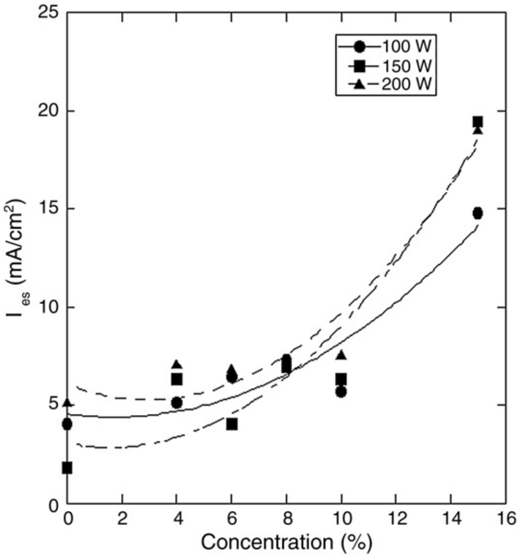

Fig. 2. Dependence of the electron saturation current density I_{es} on the concentrations for different VHF powers. Here the pressure and the gas flow rate were 70 mTorr and 100 sccm, respectively.

Then, we increased the concentration up to 30% and measured the plasma parameters as a function of VHF power at 70 mTorr. Fig. 3 shows that measured sheath potentials are lower than the calculated ones for 30%. Here SiH_3^+ was assumed as the dominant ions in the plasma. The reduction of the sheath potential for 30% is considered to be due to the existence of negative ions [11–15]. In fact, as shown in Fig. 4, when VHF powers are increased, the electron saturation current density I_{es} increases for 0% except at 200 W and 10% while I_{es} is almost constant for 30%, that is, the electron density does not increase with increasing VHF power for 30%. On the other hand, as shown in Fig. 5, the ion saturation current density I_{is} increases independently of the concentration with increasing VHF powers, that is, when VHF powers are increased, the ion density increases. Thus, we conclude from Figs. 3–5 that there are a lot of negative ions for the concentration of 30%.

The electron temperature is one of the key parameters in PECVD and lower electron temperatures are required because as described in Eq. (2), the ion bombardment energy is proportional to the electron temperature. As well known, when negative ions are produced, the electron temperature tends to increase. We measured the electron temperature Te as a function of power for different concentrations. Fig. 6 indicates that Te is (4–4.5) eV for 30% while Te is (2–3) eV for 0% and 10%. This result supports the existence of negative ions at 30%.

It is well known that when there are negative ions in the plasma, the sheath potential decreases [11–15]. According to Amemiya [11], the sheath potential in the presence of negative ions is given as follows:

$$V_w \approx \frac{\kappa T_e}{2q} \ln\left(\frac{m_i}{2\pi m_e}\right) + \frac{\kappa T_e}{q} \ln(1-\alpha) \tag{3}$$