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Plasma diagnostic studies of S bend filtered cathodic vacuum arc system for the deposition of tetrahedral amorphous carbon films

O S Panwar, Mohd Alim Khan, P N Dixit, B S Satyanarayana*, R Bhattacharyya†, Sushil Kumar & C M S Rauthan

Plasma Processed Materials Group, National Physical Laboratory, Dr K S Krishnan Road, New Delhi 110 012

*MIT Innovation Center and Electronics & Communication Department, Manipal Institute of Technology, Manipal 579 104.

†Emeritus Scientist, National Physical Laboratory, New Delhi 110 012

E-mail:ospanwar@mail.nplindia.ernet.in

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The plasma parameters obtained using Langmuir probe of the vacuum arc generated in the outer region of an S bend filtered cathodic vacuum arc system developed for the deposition of tetrahedral amorphous carbon (ta-C) film and also hydrogen and nitrogen incorporated ta-C films have been reported. The effects of varying arc current and the magnetic field have been studied on the plasma parameters of the vacuum arc used in depositing ta-C, ta-C:H and ta-C:N films at different hydrogen and nitrogen partial pressures. The values of ion-saturation current (I_{is}), electron temperature (T_e) and electron density (n_e) are found to be in the range 1.50×10^{-7}-2.63×10^{-6}A, 1.90-2.29 eV and 3.6×10^{9}-7.4×10^{10} cm^{-3}, respectively, of the vacuum arc generated for the deposition of as grown ta-C films. Hydrogen and nitrogen incorporation of the precursors are found to reduce the values of I_{is}, T_e and n_e of the arc generated. The presence of magnetic field is found to increase the values of I_{is} and n_e and reduce those of T_e in depositing as grown ta-C films whereas hydrogen and nitrogen incorporation of the precursors decrease the values of I_{is} and n_e and enhances those of T_e. The properties of ta-C film so grown are also briefly summarized and found to have some novel features.

Keywords:Plasma diagnostic, Langmuir probe, Filtered cathodic vacuum arc, Tetrahedral amorphous carbon film

1 Introduction

Amorphous carbon films having considerably high sp^3 bonded carbon content referred as tetrahedral amorphous carbon with and without hydrogen and nitrogen have been used in electronics, optoelectronics, micro electro mechanical systems and sensors besides its use in tribological application especially as protective coatings for hard disc drives[1-6]. These ta-C films were grown using a wide variety of processes including filtered cathodic vacuum arc (FCVA)-direct and pulsed source, pulsed laser ablation, mass selected ion beam deposition and electron cyclotron wave resonance processes and there are many good reviews covering the same in the literature[2-4,7]. Among the successful methods for the preparation of ta-C films, the FCVA technique was particularly useful for industrial applications because it provided highly ionized plasma of energetic carbon ions, from which dense films of amorphous carbon could be grown at reasonable deposition rates[8]. The cathodic vacuum arc is a relatively low voltage process with high current density of discharge. However, due to the extreme conditions in the cathode arc spot, macroscopic fragments of the cathode material are also emitted. The incorporation of these macro particles in the film not only causes morphological imperfections but also degrade the electronic and optical properties. Electromagnetic deflection of the plasma through L bend (90°) using a curved solenoid was first used to remove the macro particle from the carbon plasma by Aksenov *et al*[9]. The macro particle filter, on the other hand, has limited transport efficiency and tends to collimate the plasma leading to a restricted area of deposition. The efficiency of the removal of macro particles could also be improved using an S bend magnetic filter sacrificing the deposition rates due to the reduction in ion transport efficiency[10-15]. The pulsed mode of the plasma also allowed better filtering of the macro particle in the plasma process since the ions tended to be extracted in the plasma beam during the pulse fall out of the plasma when the beam was stopped[16-22]. All these processes mentioned above are highly energetic processes and the control of ion energy leads to the variation in the material properties. Further, the high rate of ionization and the option to vary the ion energy and ion density, under optimum conditions can lead to creation of momentary pseudo thermo dynamic conditions of high temperature, on the surface of film, leading to nano-structured carbons[21,22]. Thus, very subtle variation in the process parameters leads to the variation in the material properties. However, there seems to be reports only from a few groups on the properties of carbon thin films deposited by filtered cathodic vacuum arc process using an S bend magnetic filter. One of the first systematic reflectance and photoluminescence related study has been published by this group[23], on as grown ta-C films by varying negative *dc* substrate bias and hydrogen and nitrogen incorporated ta-C (ta-C:H and ta-C:N) films deposited at comparatively high substrate bias of –300 V using an S bend FCVA process to understand their luminescence behaviour.

This paper supplements our earlier report[23] by undertaking plasma diagnostic studies with the help of Langmuir probe in the outer region of an S bend FCVA system. The study also includes the effect of hydrogen and nitrogen incorporation of the precursors and estimates the electron temperature and electron density as a function of experimental variables of the vacuum arc generated. The properties of the ta-C films deposited are also briefly summarized.

2 Experimental Details

The electrical connection of a Langmuir Probe is shown in Fig. 1(a) which is placed where the deposition of films were carried out. The arc is initiated by a mechanical striker of high purity (99.999%) graphite rod of 7 mm dia. (anode) to high purity (99.999%) graphite rod of 50 mm dia. used as cathode of a custom designed and indigenously developed double bend (S bend) FCVA system[24]. The FCVA system consists of (a) water cooled cathode and anode, (b) an S bend magnetic filter over a 6 inch duct to remove the macro particles and neutrals and (c) a 8 inch SS cross deposition chamber with a provision of biasing the substrate. Two turbo molecular pumps backed by two rotary pumps evacuate the system. Typically, a vacuum better than 10^{-6} mbar is achieved in the system. The magnetic filters are energized using three different *dc* power supplies and a magnetic field of ~350 G is achieved inside the duct. The diagnostic system consists of the Langmuir probe and its power supply and a digital storage oscilloscope (Yokogawa, 100 MHz, DL1520). This facility[25] was provided by M/s Facilitation Centre of Industrial Plasma Technologies (FCIPT), Gandhinagar, India. This circuit as shown in Fig. 1(a), consists of a ramp generator that generates a ramp voltage of + 40 V to - 60V with a frequency of 50 Hz. This ramp voltage is given to the probe along with a *dc* shift of –1.2 V to –40 V. As is well known, when a probe is immersed in plasma, it acquires a potential known as floating potential (V_f). During such a situation it does not draw any net current. Langmuir probe starts drawing ion current according to the positive or negative probe potential applied with respect to V_f. *dc* shift can be adjusted to get the

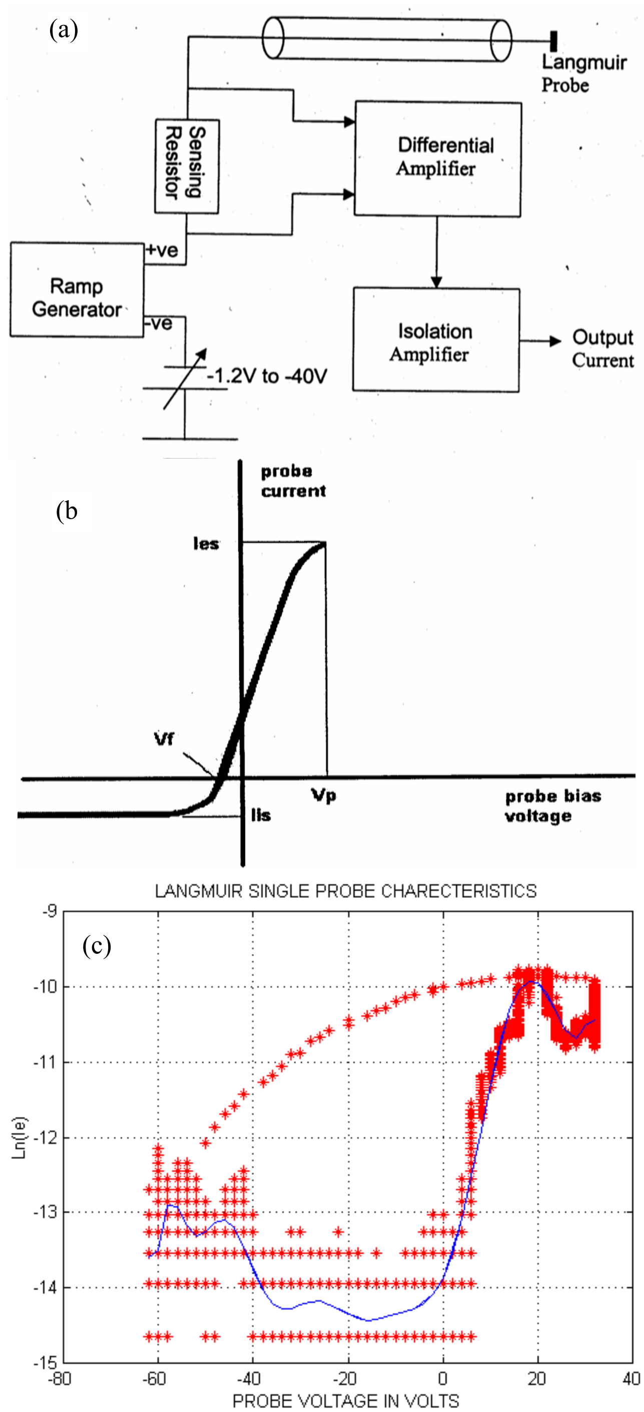

Fig. 1 — (a) shows the electrical connection of a Langmuir Probe, (b) typical *I-V* characteristics drawn and (c) actual *I-V* characteristics recorded.

required electron or ion current. The biasing voltage to the Langmuir probe is applied via a variable sensing resistor. This resistor can be varied from 1 K to 10 K depending on the plasma density. This resistor develops the required potential drop for the differential amplifier circuit depending on the current drawn by the probe. The voltage drop across the sensing resistor is fed to the input of the differential amplifier circuit. This circuit measures the potential difference across the sensing resistor and gives an output that is proportional to the current drawn by the probe corresponding to the applied voltage. To measure this current with oscilloscope, it is isolated using isolation amplifier circuit signal which oscillates the current signal to be measured by the oscilloscope from the floating circuit.

The hydrogen and nitrogen gas of high purity was introduced into the vacuum system with the help of a needle valve and the mass flow controller, near to the cathode for depositing ta-C:H and ta-C:N films, respectively. The current voltage (*I*-*V*) characteristics were recorded by varying the arc Off voltage and at two different hydrogen and nitrogen partial pressures. Films were also grown under the same conditions but at a fixed arc Off voltage and characterized. The effect of varying magnetic field was then investigated during the deposition of these films, at two different partial pressures of hydrogen and nitrogen, at a fixed arc voltage.

3 Results and Discussion

3.1 Langmuir probe

The typical and actual *I*-*V* characteristics using Langmuir probe of the vacuum arc generated in an S bend FCVA system have been recorded at the place where substrates are normally kept for the deposition of the films which are shown in [Fig. 1(b and c)], respectively. The current drawn by the probe from the plasma is positive, when the probe bias is much negative with respect to the plasma potential, V_p. It is well understood and documented that the electric field around the probe, confined to ion sheath will prevent all but the most energetic electrons from reaching the probe, effectively reducing the electron current to zero. The current collected by the probe will then be entirely due to positive ions, since these encounter only an attracting field. This point is called the ion-saturation current (I_{is}), which is given by[25]:

$$I_{is} = 0.6\, n_i\, e\, A\, v_s \qquad \ldots(1)$$

where n_i is the ion density at the sheath edge, where the plasma is assumed to be unperturbed by the probe, v_s is the velocity with which the ions enter the ion sheath and A is the collecting area of the probe. The ion density can be calculated using Eq. (1).

As the probe bias is made more positive, the number of electrons, which are able to overcome the repulsive electric field, increases exponentially for plasma with Maxwell Boltzmann distribution. This contributes a negative current reducing the overall current collected by the probe. Eventually, the electron current collected is equal to $-I_{is,}$ so that the total current is zero. The potential at which this happens is called the floating potential (V_f). The floating potential is negative with respect to the sheath potential (V_s) which is given by [25]:

$$V_f = V_s - (kT_e/2e) \ln [2m_i/ \pi m_e] \qquad \ldots(2)$$

One may also note that an electrode immersed in the plasma, but electrically floating with very high impedance to the ground will collect a zero current. Hence, such an electrode will automatically require the floating potential. m_e and m_i are the masses of the electron and ion, respectively.

Further, increase of the probe bias to V_P allows the electron current to totally dominate the ion current. This current is given by[25]:

$$I_e = n_e\, e\, A\, v_e \exp[e\,(V_p - V_s)/kT_e] \qquad \ldots(3)$$

where n_e is the electron density. The electron thermal velocity v_e is given by[25]:

$$v_e = (k\, T_e/2\pi m_e)^{1/2} \qquad \ldots(4)$$

This implies that the negative bias on the probe with respect to the plasma potential is making the probe into a retarding potential analyzer. The slope of the graph between the logarithm of the current and the potential on the probe will have a slope giving the electron temperature, T_e by[25]:

$$T_e = \frac{\mathrm{d}V}{\mathrm{d}\,(\ell n\, I_e)} \qquad \ldots(5)$$

At V_s, electrons are unrestricted from being collected by the probe. Any further increase in bias will simply add energy to the electrons, not the current drawn. Hence, the term ‘electron-saturation current’ I_{es} is given by[25]: