Characterization of Hydrogen Plasma used for Introducing Hydrogen into Semiconductors

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This paper reports the investigation result of RF power effects on the RF hydrogen plasma parameters. The hydrogen plasma parameters are measured experimentally in the center of the deposition chamber by means of the cylindrical Langmuir probe. The measurements are done at 0.2 mbar hydrogen gas pressures. The applied discharge powers are between 50 W and 200 W. It is found that the electron and ion densities increase with the RF power. The ion density dependence of the cathode sheath voltage is fitted to $N_i\left(cm^{-3}\right)=-3.5\ 10^{10}+9.2\ 10^{7}\left(V_0-V_{dc}\right)$. The plasma and floating potentials are less sensitive to RF power.

Key words: Hydrogen plasma, RF power, Langmuir probe, Pressure.

I. INTRODUCTION

Hydrogen is a monovalent gas on the one hand and a very aggressive chemical species on the other hand. It is used for characterization of the deep and shallow levels in semiconductors. Moreover its introduction in semiconductor crystal lattice passivite the electrical activity of many deep level and impurity states in elemental and compound semiconductors.

There are four methods used for introducing hydrogen in semiconductors, it can be introduced during material crystal growth, by implantation, by chemical reaction at the surface, or via hydrogen plasma [1]. The last one is most used, but it requires the characterization of hydrogen plasma, in other words, the measurement of the plasma parameters (plasma potential V_0, floating potential V_f, electron temperature T_e, electron density N_e, ion density N_i, etc.). However, several techniques such as Optical emission spectroscopy (OE) [2-5], Self excited electron resonance (SEER) [6], Langmuir probe (LP) [7-13], etc. are available to determine plasma parameters.

The probe technique is an excellent tool and simple means for plasma parameters measurements, it was introduced by Langmuir in the 1920s. But, its use in RF plasma has induced two problems [14 -15]: the RF interference and contamination effect. These problems can be overcome respectively by tuning and applying a

large bias voltage to the probe. Moreover, the experimental data were collected quickly.

In the present work, we have investigated the hydrogen plasma with a single cylindrical Langmuir probe.

II. PROCEDURE EXPERIMENTAL

The plasmas studied are generated in an Alcatel SM 601 reactor constituted of two circular parallel electrodes 5 cm apart. The cathode used as a target is coupled with an RF power generator (13.56 MHz) flexible to 400 W. However, both anode used as a substrate and stainless steel deposition chamber are grounded. The system operates in capacitive mode and the thin films are elaborated by the sputtering of a solid target. The Before the introduction of gas, the vacuum chamber is evacuated up to 10^{-6} Torr.

To carry out the electrical characterization of our plasma, a cylindrical electrostatic probe is used. It is a 0.2 mm diameter, 10 mm length tungsten wire and it is held in a Pyrex tube. The Langmuir probe was inserted through one of the side flanges of the deposition chamber, and was positioned at the centre of the chamber (at 2.5 cm from each electrode).

It is known that in RF plasma, the plasma potential oscillates with the waveform which is applied to generate the plasma. The synchronization in phase and module of bias potential of the probe with that of plasma potential is ensured by a compensation passive system (Fig. 1).

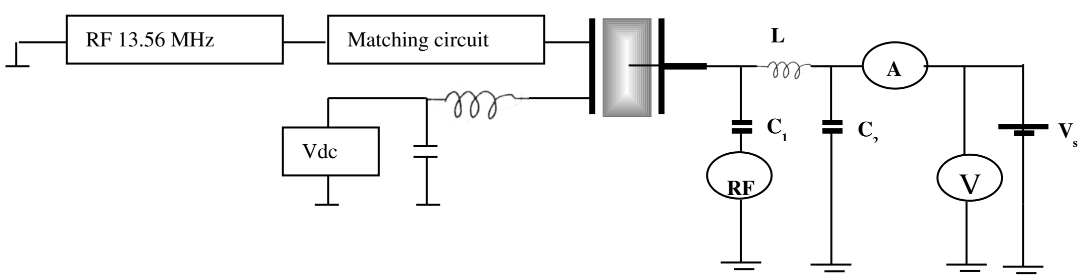

Fig. 1: Schematic representation of the RF sputtering circuit with electrical Langmuir

RF power was applied through a 50 impedance shielded wire; all the applied power was dissipated in the plasma when the impedance of the system target-plasma – substrate and the feeding wire are equal. This situation can be achieved by the matching network (Fig. 1) (for more details see [16]).

For each power, the probe voltage V_p ranges between – 60 V and + 60 V. And for each probe potential V_p, we measure the continuous part of the probe collected current I_p. Before performing a measurement, the probe is highly biased in order to clean it by electron impact. The graphical representation of these currents I_p as a function of the probe bias potential V_p, allows to obtain the

probe characteristic $I_p(V_p)$ (Fig. 2). This characteristic contains three distinct regions; electron saturation region, ion saturation region, and transition region.

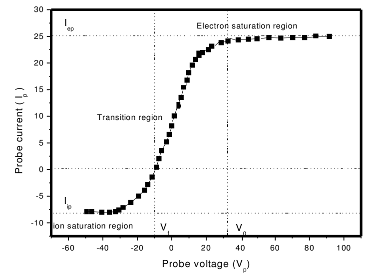

Fig. 2: Langmuir probe characteristic $I_p(V_p)$

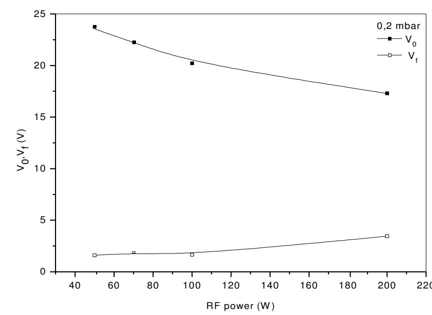

Fig.3: The variation of the plasma potential V_o (full symbol) and floating

III. EXPRESSION OF DATA ANALYSIS

When emission of secondary electron from the probe, the probe etching and the bombardment of the probe by high energy electron are disregarded, the evolution of current versus the probe bias potential in each region is given by the following equations [17]:

1. Electron saturation region

$$I_p = |I_e| = A_p N_e e \left(\frac{K_B T_e}{2\pi m_e}\right)^{1/2} \frac{2}{\sqrt{\pi}} \left(1 + \frac{e(V_p - V_0)}{K_B T_e}\right)^{1/2} \quad (1)$$

2. Ion saturation region

$$I = |I_i| = A_p N_i e \left(\frac{K_B T_e}{2\pi m_i}\right)^{1/2} \frac{2}{\sqrt{\pi}} \left(1 + \frac{e|V_p - V_0|}{K_B T_e}\right)^{1/2} \quad (2)$$

3. Transition region

$$I_p = A_p N_e e \left(\frac{K_B T_e}{2\pi m_e}\right)^{1/2} \exp\left(-e\frac{|V_p - V_0|}{K_B T_e}\right) \quad (3)$$

Where I_e and I_i are respectively the electron and ion current, A_p is the probe area, m_e and m_i are respectively the electron and ion masses, V_0 and V_p are respectively the plasma potential and probe bias voltage, *e* is the elementary charge and K_B is the Boultzmann factor.

Regarding to the theoretical expressions (Eqs. 1, 2 and 3) and the probe characteristic, the plasma parameters can be determined as follows:

The floating potential corresponds to the potential for which the probe current is zero. The plotting of $I_p^2(V_p)$ respectively in the electron saturation region (ion saturation region) gives a straight line with a slope p_e (p_i) proportional respectively to N_e^2 (N_i^2).

The plasma potential was defined by the intersection point of the slopes in the electron saturation region and the transition region [17]. To determine electron temperature T_e, we plot on a semi-logarithmic scale the probe characteristic in the transition region, the slope of the

$LnI_p(V_p)$ in this region gives the following relationship

$$\frac{1}{T_e}\alpha\frac{\partial\, Ln(I_p)}{\partial V_p} \quad (4)$$

IV. EXPERIMENTAL RESULTS AND DISCUSSION

In hydrogen plasma, the electrons mean free path for 0.2 mbar pressure is equal to 2.8 mm [18-19]. Thus, the electrons mean free path is greater than the probe ray ($r_p = 0.09\ mm$). The variations of the plasma potential V_0 and floating potential V_f as function of the RF power for 0.2 mbar hydrogen pressure are reported in Fig. 3. This figure shows that with increasing RF power from 50 W to 200 W, the plasma and floating potentials vary respectively from 23 to 17 V and 5 to 7 V.

From these figures we note a quasilinear increase of the electron density with the RF power. On the other hand, for RF power higher than 100 W, the ion density became less sensitive to the RF power. The increase of the electron and ion densities with RF power is due on one hand; to the raise of the cathode sheath voltage V_{cs} ($V_{cs} = V_0 - V_{dc}$, where V_0 and V_{dc} are respectively the plasma and self bias voltages) (Fig. 6), the cathode sheath voltage is proportional to the acceleration energy of electrons to the plasma core and ions to the target respectively. On the other hand, the sheaths oscillation thicknesses, sheaths amplitudes and target secondary emission increase with the RF power [20-21], this implies an increase in the number of the electrons arriving at from the plasma core, towards the sheath edge and which will return towards the plasma to cause ionization (by Surf effect).

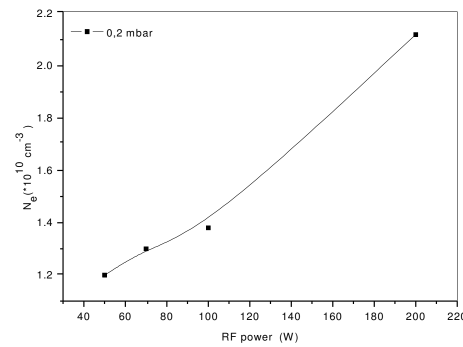

Fig. 4: The variation of the electron density versus the RF power

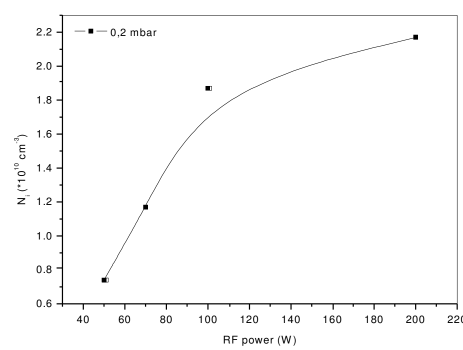

Fig. 5: The variation of ion density versus the RF power

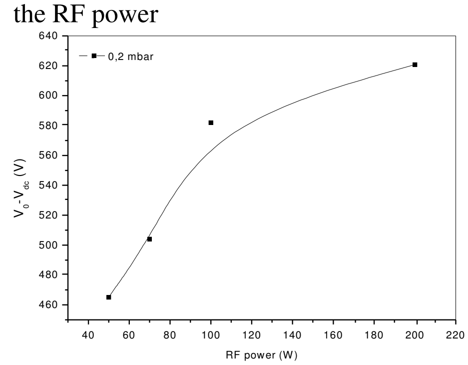

Fig. 6: The variation of the cathode sheath potential versus the RF power

This result indicates that RF power has only a little influence on the plasma and floating potentials, thus it influence more the cathode sheath thickness and self bias potential.
The curves of the electron and ion densities versus the RF power in pure hydrogen plasma are shown respectively in Figs. 4 and 5. In other words, the increase of the voltage, the thickness and the oscillations of the cathodic sheath and cathode secondary emission create a high number of energetic electrons, which leads to an increase of the ionization rate. For RF powers less than 100 W, the behavior of N_i and N_e is almost similar. This can be explained by the fact that the hydrogen ions are created mainly by the direct ionization process ($H + e \rightarrow H^{+} + 2e$).
As can be seen in Figs. 5 and 6, the pace of the ion density and cathode sheath voltage are similar. The ion density changes linearly as the cathode sheath voltage (Fig. 7). Using a linear fit of the Fig. 7, we have established an empirical formula describing the dependence of ion density on the cathode sheath voltage. This formula can be expressed as

$$N_i\left(cm^{-3}\right) = -3.5\ 10^{10} + 9.2\ 10^{7}\left(V_0 - V_{dc}\right) \quad (6)$$

(V_0 and V_{dc} are in volt).

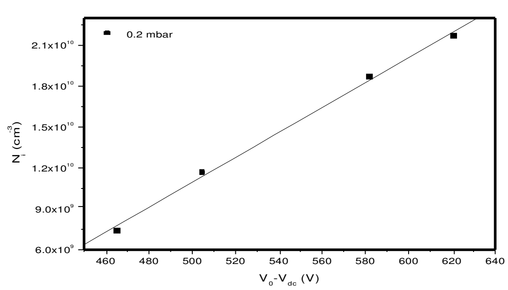

Fig. 7: The variation of ion density N_i versus the sheath potential (V_0 – V_{dc}), where V_0 and V are respectively the plasma and self bias

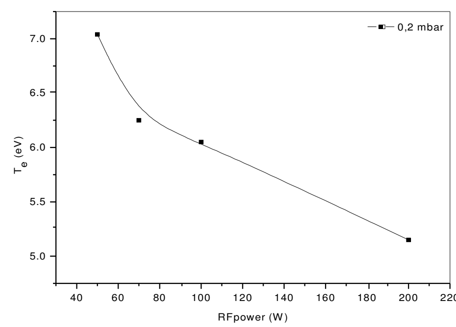

Fig. 8: The variation of the electron temperature versus the RF power

Fig. 8 reports the evolution of the electron temperature T_e as a function of the RF power for 0.2 mbar pressure.
From this figure we note, when RF power ranging between 50 W and 200 W, the electron temperature varies from 7 to 5 eV. Thus, in the core of hydrogen plasma, the electron temperature is unaffected by the RF power.

V. CONCLUSION

The hydrogen plasma is investigated with a cylindrical Langmuir probe. We found that, in the hydrogen plasma core, the RF power plays an important role in the electrical parameters. The electron and ion densities are respectively linearly related to the RF power and cathode sheath voltage. It was also found that, in the hydrogen plasma core the electron temperature, plasma potential and floating potential are less sensitive to RF power.

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