A 60 kV/ 10A PULSED POWER SUPPLY FOR A PLASMA IMMERSION ION IMPLANTATION EXPERIMENT

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***Abstract* - This paper describes a high voltage pulsed power system for a plasma immersion ion implantation (PIII) experiment. The pulsed power supply consists of a high voltage pulse generator that uses a hard tube switch. The reason for using this type of circuit category in the PIII facility rather than a previously used PFN (pulse forming network) circuit configuration is stated. The experimental results of the application of this device to a glow discharge PIII are also discussed. In order to assess these results, a simple electrical model describes the plasma as a resistive load in parallel with a capacitance taking into account the pulse rise time distortion caused by a long coaxial feeding cable. Plasma parameters for PIII processing, such as implantation ion average current and plasma sheath thickness, are calculated from the experimental results.**

I. INTRODUCTION

Plasma immersion ion implantation (PIII) is a technique developed during the late 80's for surface treatment of metal and polymer materials that consists of applying negative high voltage pulses to a target immersed in plasma. As a negative voltage pulse is applied to the sample a positively charged sheath (non-neutral) region between the plasma and the sample is progressively increased as illustrated schematically in Fig. 1. During the presence of the negative voltage pulse the electrons are repelled from the target on time scale which is relatively short compared to the ion motion. This leaves behind an expanding ion plasma sheath toward the walls of the vacuum chamber and the remaining electric field accelerates the plasma ion in the direction of the target. As a result, the ions are implanted into the target surface from all sides without the necessity of the target manipulation used in the conventional ion implantation methods. Through this technique it is possible to produce relevant modifications of the surface properties of a wide range of materials such as metals, plastics and ceramics. PIII process can be applied to semiconductor fabrication, material synthesis, polymers, anti-corrosion coatings, machine tools, metallurgy and many other items in high technology industries as described elsewhere [1],[2].

However, for a successful implantation certain important requirements should be met for the pulsed power system, which is a vital part of a PIII experiment

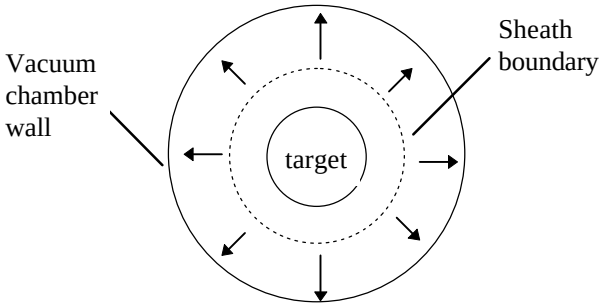

Fig. 1. The expansion of the plasma sheath .

and the main concern of this paper. For instance, the output pulse shape should not depend much on the load impedance and the pulse generator itself should be resistant to short-circuits. Also, it is desirable that the frequency and pulse length can be determined arbitrarily [3]. Although a pulse forming network (PFN) combined with a pulse transformer can be used as a pulse generator for PIII applications [4] this type of circuit exhibits two basic drawbacks. First, it is very difficult to match the plasma load to the output impedance of the PFN circuit. Second, the PFN pulse length is fixed by the number *n* of *LC* cells (where *L* and *C* are respectively the inductance and capacitance of each PFN cell). Therefore, a pulsed power supply of 50 kV/ 10 A built previously for a microwave generator [5] (called gyrotron) in a circuit category of hard tube type was modified and adapted for the PIII experiment in our laboratory. The main objective of this work is to present the modified circuit design of this pulse generator and to discuss the experimental results of its application to a PIII glow discharge. Besides that, a circuit simulator (named PSPICE) is used to predict the experimental result by using a plasma circuit model, which includes the distortion in the pulse rise time produced by the coaxial cable that connects the pulser to the PIII target.

II. THE PULSE GENERATOR

Fig. 2 describes the schematic diagram of the pulsed power supply used for the PIII experiment. The circuit consists basically of capacitor bank C (2.0 μF/ 100 kV) which discharges through a tetrode tube TH5188 in series with the plasma load. A dc high voltage power supply

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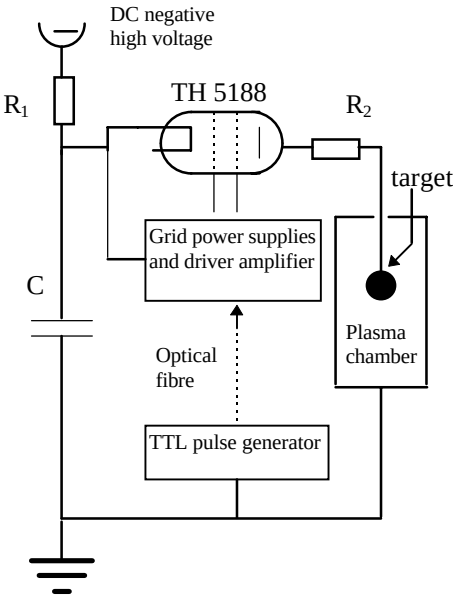

Fig. 2. Schematic diagram of the pulsed power supply for the PIII experiment**.**

(100 kV/50 mA) is used to charge the capacitor bank and the resistor R_1 of 60 kΩ limits the transient charging current. The tetrode operates as a fast on-off switch and the TTL pulse generator located on ground at the panel rack controls the pulse length. The tube remains switched on as long as the TTL pulse is present. Whenever this external triggering occurs, the potential on the tetrode control grid is increased from -300 V (cut off condition) to a few volts above the tetrode cathode potential leading the tube into saturation. As the tube and its driver amplifier are located on the high voltage floating deck an optical fibre transmits the TTL signal via optical interface units. A second resistor R_2 of 6 kΩ in series with the tetrode and the plasma load protects the system against the risk of short-circuits. Since the current capability of the tetrode is of the order of 10 A in the case of a short-circuit, the limit of the charging voltage is up to a maximum of 60 kV. The pulsed system has a maximum capability of operating at a repetition frequency of about 1 kHz with a duty cycle of the order of 5 %. This means a maximum pulse duration of about 50 μs for the operation condition described above. For operation of the pulsed system at frequencies above 100 Hz, it is necessary to install fans to avoid excessive ohmic heating in the resistors R_1 and R_2 .

III. TESTS AND MODELLING

The high voltage pulse generator was connected to the plasma chamber of the PIII facility as described in Fig. 2. The target immersed in a nitrogen plasma consisted of a stainless steel support with an approximate cylindrical shape with a diameter of 50 mm and length of 100 mm. Silicon and stainless steel samples with a diameter of 5 mm and thickness of 1 mm were distributed along the surface of this support. A glow discharge between a small electrode located inside the chamber and ground produced the plasma. For this a DC power supply of 600 V/ 1A was used. A Langmuir probe measured the plasma parameters such as electron density n_e and temperature T_e. For the experimental test these plasma parameters were: n_e = 4.0×10^{10} cm^{-3} and T_e = 5.0 eV. Fig. 3 shows the applied voltage (top curve) and the respective current (bottom curve) to the target during the process of implantation. From the voltage and current wave forms in Fig. 3 the plasma resistance in the stationary state can be calculated by dividing the peak voltage by the respective peak current, which gives a value of about 15 kΩ. Observe in these curves that the long rise and fall times are due to both the plasma sheath capacitance C_s and the coaxial cable capacitance C_d . In this case the inclusion of the cable distortion is necessary since a long length of the coaxial cable RG-213 (about 30 m) was used to connect the pulsed power supply output to the PIII sample. The operation frequency for the pulsed system during the implantation process was about 700 Hz with total exposure time up to 60 minutes. The capacitor was charged up to a voltage of approximately 20 kV as described by the flat top of the tetrode anode voltage in Fig. 4. Observe in Fig. 4 that the flat top of the pulse represents the capacitor bank voltage as the tetrode switch is closed with its conduction resistance being practically zero. Also note that pulse droop rate is negligible since the switch closure time of 50 μs is much lower than the bank discharge time constant of the order of 400 ms (approximately $(R_2 + R_p)C$ if the sum of the plasma sheath capacitance and the coaxial cable capacitance C_d compared to C is neglected). Again note the presence of capacitance effect due to C_s and C_d in the tail of the output voltage of the pulsed system shown in Fig. 4.

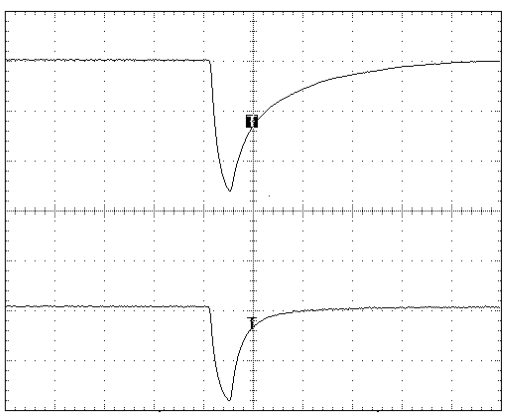

Fig. 3. The applied voltage (top curve) and respective current (bottom curve) to the target during the implantation process. Vertical scale: 5 kV/div (top curve) and 0.5 A/div (bottom curve). Horizontal scale: 100 μs/div.

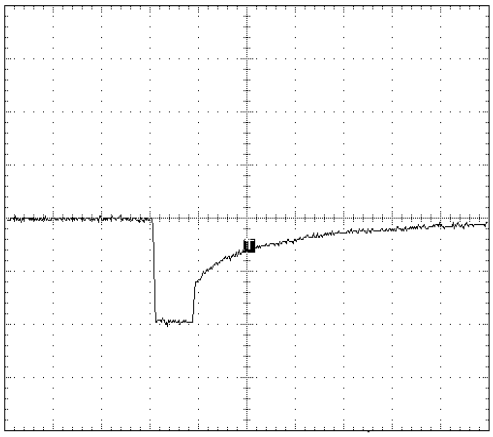

Fig. 4. The tetrode anode voltage during the implantation process. Vertical scale: 10 kV/div. Horizontal scale: 50 µs/div.

A good approximation for modelling this phenomenon is illustrated by the plasma circuit model described in Fig. 5, which includes the coaxial cable distortion in the rise time. In this case the plasma is modelled as resistive load (i.e. the plasma resistance in the stationary state) in parallel with the plasma sheath capacitance C_s. The coaxial cable distortion is given by the inclusion of the total distributed capacitance C_d of the coaxial cable in parallel with the plasma sheath capacitance as shown in Fig. 5. This distributed capacitance can be calculated as $C_d = L \times C_d' = 3$ nF, where $L = 30$ m is the total coaxial cable length and $C_d' = 100$pF/m is the distributed capacitance per unit length for the coaxial cable RG-213. Using a circuit simulator programme (such as the PSPICE) it is possible to estimate the value of the plasma sheath capacitance of the order of 2 nF. For example, Fig. 6 shows the simulated curve of the tetrode anode voltage using the plasma circuit model. Once more observe in this figure the RC discharge in the tail of the curve, after the opening of the tetrode switch as described by the plasma circuit model of Fig. 5. By using the calculated plasma sheath capacitance it is possible to determine the implanted dose of ions on the target in terms of average ion current per pulse as [3], [6]:

$$I_{ion} = C_s U/t_{pulse} , \qquad (1)$$

where I_{ion} is the average ion current, U is the maximum applied voltage to the target and t_{pulse} is the pulse length. Setting $C_s = 2$ nF, $U = 13$ kV and $t_{pulse} = 50$ µs gives a value of approximately 0.5 A for the average ion current per pulse during the process of implantation. Also it is important to know the plasma sheath thickness during the process of implantation since this parameter is used for the evaluation of the plasma sheath capacitance. The plasma sheath capacitance can be calculated by multiplying the sheath volume V by the ion charge density en_i and dividing this product by the applied voltage U, that is [3]:

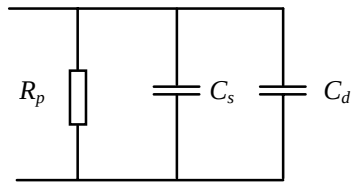

Fig.5 The plasma circuit model including the coaxial cable capacitance.

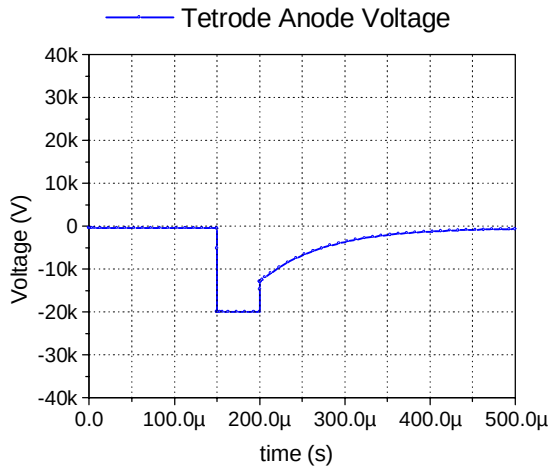

Fig. 6. The PSPICE simulation of the tetrode anode voltage.

$$C_s = e\, n_i\, V/U , \qquad (2)$$

where the sheath volume V is calculated as:

$$V = \pi (r_2^2 - r_1^2)L = \pi(2r_1 + w)wL , \qquad (3)$$

where r_2 is the plasma sheath radius, r_1 is the target radius, L is the target length and w is the plasma sheath thickness given by the difference $r_2 - r_1$. By using Eq. (2) a quadratic expression for w is obtained as:

$$C_s U/(\pi\, e\, n_i\, L) = 2r_1\, w + w^2 \qquad (4)$$

As the measured electron density is of the order $n_e \cong n_i = 4.0\times10^{10}$ cm^{-3} and the electron charge $e = 1.6\times10^{-19}$ C the solution of Eq. (4) (with $U = 13$ kV, $L = 10$ cm and $r_1 = 2.5$ cm) yields a value for the plasma sheath thickness of approximately 9.15 cm.

IV. Conclusions

In this paper we discussed the experimental results of a pulsed power supply built in a circuit category of hard tube type applied to a glow PIII discharge. It was shown that the long rise and fall times of the order of tens of µs of output pulse applied to the target are due to the plasma

sheath capacitance and to the distributed capacitance of the coaxial cable used to connect the pulsed system to the PIII experiment. For instance, to minimise the pulse rise time the protecting resistor of 6 kΩ can be eliminated by putting a thyratron tube between the output and ground to protect the system in the case of a short-circuit. In this new circuit layout the pulse rise time constant RC decreases since R depends only on the resistance of the connections whose value is of the order of hundreds of mΩ. Another way to reduce the pulse rise time to less than 1 μs is to use one side of the switch at ground potential as described in [3]. In this circuit configuration it is not necessary to add a protection system (such as the thyratron tube) since in this case the risk of arcs in the load is greatly reduced. This is because the tube cathode current mostly flows to the grids as the anode potential drops below the tube screen grid voltage during the occurrence of an arc in the load. As a result, this reduces the voltage of the grids, which decreases the cathode current and reduces the risk of tube damage during the arc. The advantage of our present pulse generator compared to this system is that it eliminates completely the risk of a short-circuit damage in the tube, but at the cost of high value of pulse rise time of the order of 50 μs. The use of a shorter length of coaxial cable to make the output connection could also help to minimise the pulse rise and fall times due to the reduced cable capacitance. For this, the pulsed power supply should be placed closer as much as possible to the PIII experiment.

Another important contribution of this work is the calculation of the plasma sheath capacitance using a plasma circuit model, which takes into account the pulse rise time distortion caused by the coaxial cable connection. To make this calculation a PSPICE circuit simulator was used. Finally this paper showed that it is possible to calculate from this result (that is, the plasma sheath capacitance) important parameters of the implantation process, such as the dose of implanted ions in terms of an average current per pulse and the thickness of the plasma sheath.

V. References

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