High Voltage Pulsed Power Blumlein Generators for Materials Surface Processing by Plasma Immersion Ion Implantation[+]

J.O. Rossi[†], M. Ueda and J.J. Barroso

National Institute for Space Research
Associated Plasma Laboratory
P.O. Box 515 S.J. Campos-SP Brazil 12201-970

Abstract- **Plasma Immersion ion implantation is a processing technique used for the surface treatment in metallurgical and semiconductor applications. Basically it consists of applying negative high voltage pulses to a target immersed in plasma. Normally, this technique needs a high voltage pulse generator capable of producing pulses ranging between 10 and 300 kV and over a period between 1 to 40 μs depending on the plasma conditions and the target to be treated. However the pulser normally used for this application is based on hard-tube technology, which is expensive because of the high voltage switch required. This is especially a critical factor for implantation of non-conducting materials (such as ceramics, glasses or polymers) since voltages in excess of 100 kV can compensate for the reductions in the implanted energy caused by the insulating work-piece. On the other hand, pulsed power devices (known as Blumlein pulsers) have been used with great success for high voltage pulse generation in the range of nanoseconds. Moreover, they have a simpler construction and are cheaper compared to the hard-tube pulsers. Thus in this paper we are presenting, for the first time, the design of a high voltage Blumlein pulser (150 kV/300 A) for long pulse operation ($\approx$1 μs) to fill the need of cheaper pulsers for surface treatment of non-conducting materials.**

I. INTRODUCTION

Plasma immersion ion implantation is a technique developed during the late 80's for surface treatment of metals and semiconductors that consists of applying negative high voltage pulses to a target immersed in gaseous ionized medium known as plasma (normally nitrogen plasma). As a negative voltage pulse is applied to the sample a positively charged sheath (non-neutral) region between the plasma and the sample increases progressively. During the presence of the negative voltage pulse the electrons are repelled from the target on time scale, which is relatively short, compared with the ion motion scale. 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 conventional ion beam implantation method. Through this technique it is possible to produce relevant modifications of the surface properties of a wide range of materials such as metals, semiconductors and insulators as described elsewhere [1-2]. In the case of electrically insulating materials the implantation process requires a metallic electrode to produce the accelerating electric filed to extract the ions from the surrounding plasma. For metallic implantation, the target-piece also works as the electrode. When implanting non-conducting materials, it is necessary to use an electrode behind the insulating work-piece. For this configuration, the dielectric voltage drop across the insulating work-piece reduces the plasma sheath voltage and, hence, the implantation energy imparted to the process. To compensate for this reduction we could operate with higher voltages in excess of 100 kV. Moreover with higher applied voltages deeper implantation is obtained due to the higher energetic ions extracted. This is particularly important for the case of some oxide-metal deposition on the surface work-piece, which may lead to a plasma sheath voltage reduction.

However for operating voltages above 100 kV serious constraints are imposed to the high voltage hard-tube pulser normally used in this type of surface processing. Because of the high voltage switch required, the construction cost of this device becomes prohibitive. Even the use of a pulse transformer for this case has several drawbacks as its difficult construction due to the high voltage isolation and the increased pulse rise time caused by the parasitic leakage inductance. Alternatively, high voltage special pulsed power devices (Blumlein Pulsers) made of transmission lines are of cheap construction and eliminate the necessity of using the conventional pulse transformer for the high voltage generation. They have been used with success in a great variety of applications such as in lasers, breakdown tests, x-ray generation, etc [3-4]. These devices, capable of generating high voltage pulses of several hundreds of kV in the nanosecond pulse duration with extremely short rise-time on the order of several ns, consist of several stacked Blumlein lines charged in parallel and discharged synchronously in series into the load. For example, Fig. 1 shows a two-stage coaxial pulser structure where a single switch at the lower voltage

[+] Work supported by the Research Assisting Foundation of the State of São Paulo (FAPESP), SP, Brazil.
[†] E-mail: rossi@plasma.inpe.br.

input side of the device makes the commutation of the Blumlein lines. The line commutation converts, after one line propagation delay time δ, the initially opposed voltages to equally phased voltages that add to give a larger resultant (as indicated in Fig. 1), which persists twice the line propagation time. Ideally, the voltage gain should be equal to 2nV for open end or nV for a matched load, where V is the initial charging voltage and n is the number of stacked Blumlein lines. Unfortunately, in this type of circuit the voltage gain is reduced by the presence of parasitic lines formed by the coaxial line outer conductors and the ground plane (see the secondary mode line impedance Z_2 in Fig. 1), which can never be fully eliminated. A way of improving the gain efficiency is to increase the parasitic line impedance Z_2 by winding the pulser transmission lines. In this case the gain loss effect of the parasitic lines is reduced and the voltage gain is attained to its ideal value equal to n since $Z_2 >> Z_B = 2Z_0$, where Z_B and Z_0 are respectively the Blumlein impedance and the coaxial cable characteristic impedance. This makes coaxial cables more suitable than strip lines for this configuration. Moreover, for long pulse operation above 1 μs (required for applications in plasma immersion ion implantation) coaxial cable windings are more compact than long straight strip lines. Thus in this paper we are proposing the construction of a coaxial Blumlein with five stages to operate with long pulses (≈1μs) at output voltage levels above 100 kV. For the pulser design, we limit the charging voltage to 30 kV due to safety reasons of coaxial cable breakdown, which means a maximum output voltage of 150 kV into a matched load of 500 Ω. Other main pulser characteristic is the expected operation at a repetition frequency of 100 Hz, taking into account the power supply charge rate. In particular, for our application in material processing by plasma immersion the main problem is the impedance matching between the output generator and the plasma. As the plasma resistance varies, voltage reflection could damage some devices such as the switch tube and also decrease the generator efficiency. The analysis of this problem when the pulse generator operates under a variable and non-linear plasma resistance will be presented in section III. Despite this problem, it will be shown that it is possible to use this type of pulse generator in plasma processing applications. The next section will give more details about the design of the pulser to be built.

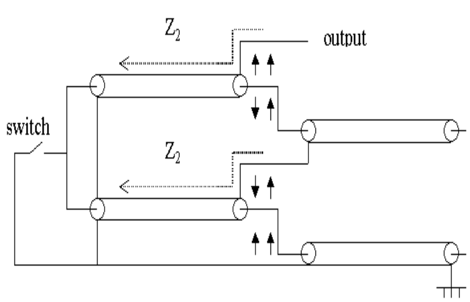

Fig. 1. A two-stage stacked Blumlein pulser.

II. PULSER DESIGN

The pulser design consists of a Blumlein device with five stages made of ten coaxial cables URM 67 with equal lengths of 100 m. The reason for using a 100 m cable length is to produce a pulse with long duration of 1 μs considering a double transit time of 10 ns/m for the cable dielectric. To reduce the device dimensions and to increase its efficiency the coaxial lines will be wound around polyethylene tubes as shown by the cross section view of one pulser stage in Fig. 2. In this view the wound bottom cable represents the line in which the pulse inversion occurs (active) and the wounded top cable represents the charge storing passive line of the first Blumlein stage. All the supporting tube axes of the wounded passive and active lines may lie in the same plane, but this would increase too much the horizontal dimension of the support structure. The choice of the structure layout shown in Fig. 3 is to provide the same value of the secondary mode impedance for all active lines in the stack. Using this structure layout we may calculate the secondary mode impedance for each active line such as [5]

$$Z_2 = \frac{129 \boldsymbol{p} N r_L}{l} \sqrt{m_r \log\left(\frac{2h}{r_c}\right)} \qquad (1)$$

where m_r is the relative magnetic permittivity of the coil core medium, h is the distance between the outer part of the coaxial winding and the ground plane, l is the winding length, r_L and r_c are respectively the winding mean and outer radii and N is the number of turns. Using a length L=100 m of coaxial cable wound on a polyethylene support tube with radius a=0.2 m gives an estimated number of turns N= 80 ($L/2\pi a$). Since the outside diameter of the coaxial cable URM 67 is 10 mm a winding length of about 0.8 m is obtained. Thus making the approximation a»r_L»r_c (since the cable outside diameter is much smaller compared to the support tube radius) and knowing the parameter h=0.5 m obtains from (1) that Z_2 is on the order of 7 kΩ. The estimate of this parameter in the pulser design is necessary to assure that $Z_2 >> 2Z_0$, which keeps the gain device for a matched load nearly equal to the number of stacked Blumlein lines.

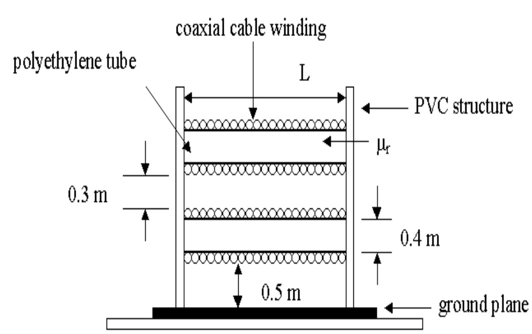

Fig. 2. Cross sectional view of the Blumlein line pulser structure.

In order to charge the Blumlein coaxial structure we need a charging high voltage power supply with maximum output voltage of 35 kV. Note that the maximum charging voltage is kept below the maximum dc operational voltage of the cable URM 67 of 40 kV to avoid dielectric breakdown. We have selected a compact charging power supply that is based on high frequency switching power conversion with a constant charge capability rate of 8 kJ/s. Since the distributed cable capacitance is of the order of 100 pF/m the total Blumlein structure capacitance is calculated as 100 m×10×100 pF/m = 100 nF. For the charge rate of 8 kJ/s and the total energy of 80 J ($W=CV^2/2$) stored in the Blumlein structure capacitance C=100 nF at an operational charge voltage V=30 kV, we expect a maximum pulse repetition rate of 100 Hz. Ideally in this case the pulser should be capable of producing a pulse of 150 kV/300 A across a 500 Ω test dummy load, but the pulse voltage amplitude in the real case is reduced because of the output current draining into the secondary mode impedance of each generator stage. As the Blumlein generator acts as step up pulse transformer with transformation ratio of 1:5, the current through the pulser switch is on the order of 1.5 kA. Taking into account the pulser repetition rate of 100 Hz and the voltage and current parameters (30 kV/1.5 kA) at the input side we have opted for a thyratron tube switch from EEV (model CX 1722) with maximum voltage and current capabilities of 35 kV and 5 kA. This switch is a glass envelope single gap tube that conducts in the reverse direction (hollow anode version). This is an important switch characteristic in applications (such as plasma immersion ion implantation) where a huge load variation leads to reversal reflected voltages at the generator input. To switch this tube the best option is to use a driver unit (TT-G1/G2 Northstar) responsible for triggering first the thyratron grid G1 (1.0 kV) followed by the second grid G2 after a fixed time interval (usually between 0.5 and 1.5 μs). For the high voltage tests, we are designing a liquid load resistance with a solution of sodium sulfate to have a value of about 500 Ω.

III. PULSER OPERATION ASSESSMENT

During the implantation process the plasma resistance tends to increase as the sheath expands. Moreover, the plasma resistance depends on other factors such as applied voltage, ion mass, target area, etc. As described elsewhere [6] for a target with planar geometry the plasma resistance R_{pl} is given by

$$R_{pl} = \frac{9}{4\varepsilon_o}\frac{[s(t)]^2}{A(\gamma+1)}\sqrt{\frac{M}{2eV(t)}} \tag{2}$$

where A is the target area, γ is the electron secondary emission coefficient, M is the ion mass, $V(t)$ is the applied voltage, e is the ion charge and $s(t)$ is the plasma sheath thickness. In practice the applied target voltage is increased to the full voltage V_0 over a finite long rise time t_r, that is $V(t)=V_0 t/t_r$, and using the model proposed by Stewart and Lieberman [7] the plasma expanding sheath $s(t)$ is calculated as

$$s(t) = s_o\left(\frac{4}{15}\right)^{1/3}\frac{(\omega_{pi}t)^{5/6}}{(\omega_{pi}t_r)^{1/2}} \qquad \text{for } t \le t_r \tag{3}$$

$$s(t) = s_o\left[\frac{2}{3}\omega_{pi}\left(t-\frac{3}{5}t_r\right)\right]^{1/3} \qquad \text{for } t \ge t_r \tag{4}$$

where ω_{pi} is the ion plasma frequency and s_0 is the initial ion matrix sheath expressed as

$$\omega_{pi} = \sqrt{\frac{ne^2}{\varepsilon_o M}} \tag{5}$$

$$s_o = \sqrt{\frac{2\varepsilon_o V_o}{en}} \tag{6}$$

where n is the plasma density and $\varepsilon_0 = 8.9\times10^{-12}$ F/m is the electric permittivity of free space. Assuming that the rise time of the applied pulse voltage is sufficiently long (so that t_r is on the order of the pulse duration of 1μs) simplifies the plasma calculation. For example, in this case using only (3) gives the plasma sheath thickness as shown in Fig. 3, assuming a nitrogen plasma N_2^+ ($M = 4.68\times10^{-26}$ kg) with average density $n = 1.0\times10^{16}$ cm^{-3}, full voltage V_0 =150 kV and t_r=1μs. Putting $s(t)$ into (2) gives the temporal plasma resistance variation shown in Fig. 4 for a target area A=0.3 m^2 with secondary emission coefficient γ=9. This result shows that the plasma resistance can be approximated by a linear variation (in the range of range 0-500 Ω) during the pulse time interval of 1μs as indicated by the dotted line seen in Fig. 4.

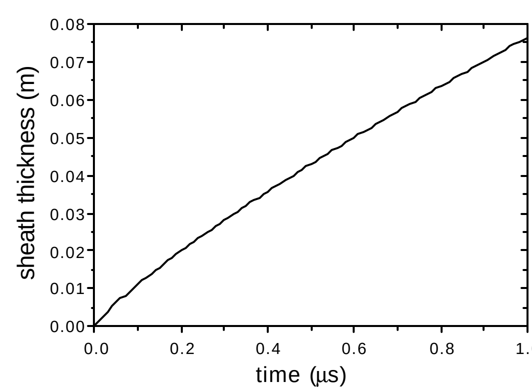

Fig. 3. Plasma sheath thickness as a function of time.

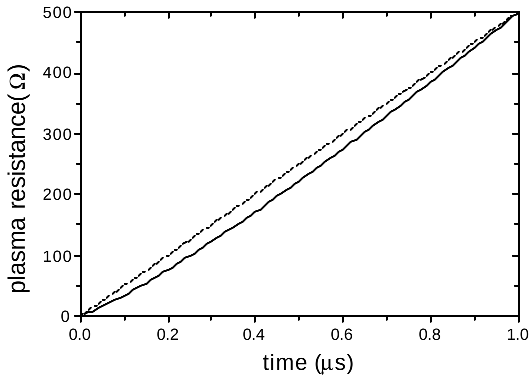

Fig.4. Plasma resistance as a function of time.

A detailed analysis of matching impedance condition between the pulse generator and the plasma is made by means of a circuit simulator (PSPICE). As shown in Fig. 5 an LC pulse forming network (PFN), composed of 10 sections (L=25 μH and C=100 pF) with characteristic impedance equal to the pulser output impedance (500 Ω) and propagation delay time of 500 ns, represents the pulse generator. The PFN delay time is equal to the propagation delay time of the pulser coaxial lines and the influence of the parasitic lines in the pulser modeling are neglected since Z_2>>$2Z_0$. The opening of the normally closed switches (S_1-S_{10}) in parallel with 50 Ω resistors as indicated in Fig. 5 simulates approximately the linear plasma load variation by means of an increasing step function. In the simulation the pulse is produced as soon as the switch S_0 is closed. As the charge voltage of the coaxial lines is on the order of 30 kV the PFN initial charge voltage in the simulation is set at a 300kV. For this initial condition one obtains a 150 kV/300 A pulse into a matched load, which persists for twice the line propagation time (i.e. pulse duration t_p=1μs).

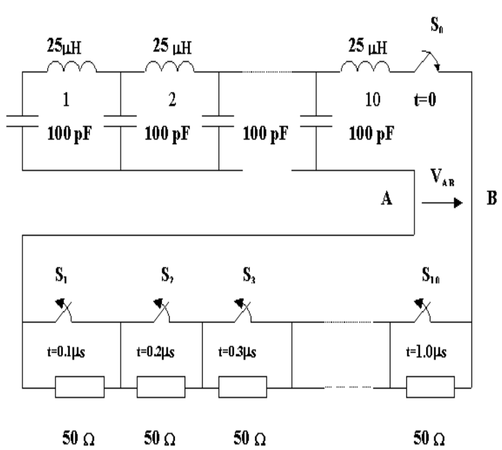

Fig. 5. Electrical scheme used for the PSPICE simulation.

Figs. 6 and 7 show respectively the applied voltage and implantation current obtained in the simulation. The plasma current waveform in Fig. 7 demonstrates that the impedance mismatch is attenuated if the plasma resistance equals the output generator impedance (see the decreasing current variation in the range of 600-300 A). The explanation for this current decrease is that during the pulse wave front the plasma impedance is too low and, thus, basically only the output generator impedance limits the implantation current, producing a peak current on the order of 600 A. When the plasma resistance equals the output generator impedance the current decreases to 300 A as shown in Fig 7. However, the mismatch introduces reflections of shorter duration as shown by the inverted peaks in the tail of the pulse shown in Figs. 6 and 7. Moreover the temporal linear variation of the plasma load increases the rise time t_r of the applied pulse voltage so that t_r=t_p=1μs, as assumed initially for the calculation of the plasma resistance. Nevertheless, some loss in the voltage gain is observed due to impedance mismatch since the voltage peak in Fig. 7 is slightly lower than 150 kV.

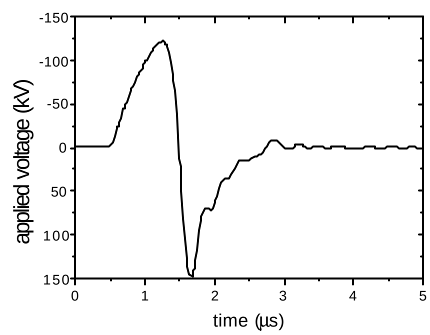

Fig. 6. The applied pulse voltage V_{AB} across the target.

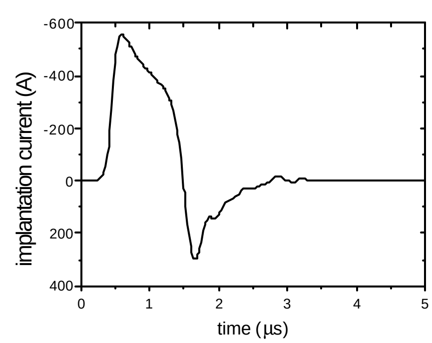

Fig. 7. The correspondent implantation current.

IV. DISCUSSION

We have suggested, for the first time, the application of Blumlein Pulsers in surface treatment of polymers by using plasma immersion ion implantation. In this paper we present the design of a 150 kV/300 A coaxial Blumlein generator for pulses with long duration of 1μs. In the design, the coaxial lines are wound on support tubes to minimize the effect of the parasitic secondary mode impedance of the pulser structure. As a result, the device voltage gain using a matched resistive load can be given approximately by the number of stacked Blumlein lines. The main problem in the design is the impedance matching between the plasma and the pulser for ion implantation processes. As the plasma resistance varies linearly during the pulse application (predicted by the plasma modeling) the performance generator deteriorates because of the impedance mismatch. The main consequences are the gain drop and long rise time of the applied voltage pulse, the implantation current decrease (instead of flat top pulse) and the presence of voltage and current reflections. Despite this, the pulse generator operation for plasma processing is possible since the most part of the energy is spent into the load as seen by the respective voltage and current waveforms shown in Figs. 6 and 7. Moreover, high current rates varying between 600 and 300 A provide sufficient implantation current for the surface plasma processing. The reason for that is the shorter pulse duration of the reflections compared with the pulse time interval. Also because of the current inversion we have opted for a hollow anode version of the switch tube (model CX 1722) that is capable of conducting in both directions. Possible damages to the pulser caused by excessive voltage above the coaxial cable breakdown are avoided.

In this case, as the voltage reflection coefficient is negative (the plasma resistance is lower than the output generator impedance during the pulse application) the reflected voltage has an inverse polarity to the incident voltage, keeping the voltage across the coaxial cable dielectric less than the initial charging voltage. For safety reasons this value in the pulser design is kept below the dielectric breakdown voltage on the order of 40 kV.

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