An All Solid-State Pulsed Power Generator for Plasma Immersion Ion Implantation (PIII)

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One of the key technologies in the plasma Immersion ion implantation (PIII) is the delivery of high-voltage pulsed power to the plasma chamber to accelerate the ion toward the target. This paper describes an all solid-state pulsed power generator for PIII. The high-voltage pulsed power system is based on Marx circuit configuration and semiconductor switches, which has many advantages compared with the conventional circuit category, tube-based technologies such as gridded vacuum tubes, thyratrons, pulse forming network and transformer, in repetition frequency and pulse width modulation and lifetime. Operation for PIII at pulse repetition frequencies of between 50pps and 500pps, has been achieved at pulse voltage amplitude from 2kV to 60kV, at pulse duration of between 20 μs and 100 μs. The high-voltage pulsed generator and its performance concerning experimental results is described in detail when driving a plasma ion implantation chamber.

1. Introduction

Plasma immersion ion implantation (PIII) has been paid attention all the while since the late 1980s. The major interest in PIII processing originates from its flexibility in ion energy and the capability to efficiently treat, or deposit on, large areas, and (within limits) to process non-flat, three-dimensional workpieces, including forming and modifying metastable phases and nanostructures. The PIII can be used for surface treatment of metallic, semiconductor fabrication, polymers material. More recently, the rapidly growing field of biomaterial synthesis makes use of PIII and PIII to alter surfaces of or produce coatings on surgical implants and other biomedical devices. With limitations, also nonconducting materials such as plastic sheets can be treated [1].

In the PIII process, the plasma is produced by a RF and then accelerated by the high-voltage pulsed power generator which provides a negative voltage pulses. The electrons are repelled from the target and leaves behind an ion plasma sheath that expand toward the wall of the vacuum chamber. The remaining electric field accelerates the ion toward the target. An ideal high–voltage pulsed power generator with fast rise and fall times and flat-top pulse voltage independent of the load impedance are required to achieve consistent PIII results. Also, it is desirable that the pulse generator itself should be resistant to short circuit, and the frequency and pulse width can be adjustable. All these take a challenge to the pulsed power technology. Until now, there are several pulsed power technologies have been implemented such as a pulse forming network (PFN) combined with a pulse transformer [2], hard-tube pulser [3] and solid-state modulator with IGBT switches in series [4]. These pulsed power sources have their advantages and disadvantages. The pulse forming network circuit have two intrinsic drawbacks, it is very difficult to match the plasma load to the output impedance of the PFN circuit and the PFN pulse length is fixed by the number of LC sections and LC electrical parameters. The pulse voltage waveforms provided by hard-tube pulser is not ideal flat-top ones for PIII the rise and fall time is about tens of microsecond due to the conduction time of gas switch. Solid-state modulator with IGBT switches in series overcomes the drawbacks above two circuits with arbitrary pulse width control. But many in series IBGT modules operating in high voltage have high risk of breakdown and are more expensive than hard-tube switch. A balanced voltage and reliable protection circuit is very important for this circuit configuration. Therefore a new type of pulsed power generator of 60kV/3A based on Marx circuit configuration has been built for PIII. This paper is to describe the working principle and performance and present the experimental results with resistance load and plasma load to a glow discharge PIII. Furthermore, with a simplified circuit model is used to discuss the distortion effect by the circuitry parameters and plasma load.

2. Operating principle

The schematic diagram of the solid-state pulsed power generator for PIII is shown in Fig.1.The circuit comprises a set of charging power supply with high frequency resonant converter (3kV/20kHz), a inductor for insulation the charging circuit from the high voltage output, a Marx circuit including 20 sets of IGBT modules, capacitors and high power diodes, and control and protection circuit.

The principle of a conventional Marx generator with spark gap is that the capacitors is charged in parallel and discharged in series. In charging mode, the primary power source charge the in parallel capacitors through the resistors, and in discharging mode, firing all the gap switches simultaneously is necessary to provide the load with voltage adder. The efficiency and the frequency are limited by the presence of the resistors and gap switches. However, recently developed Marx generators using semiconductor components as their key switches overcome the deficiency of conventional Marx generator [5]. Such novel Marx circuit take advantage of solid-state semiconductor modules and achieve high voltage output. It can operate as both opening and closing switches, providing extensive flexibility in pulse width and repetition. In addition, reliability, long lifetime and small size are available. With careful design, short circuit load and protect itself from over current damage with fast response time can be achieved, so it is desirable for PIII.

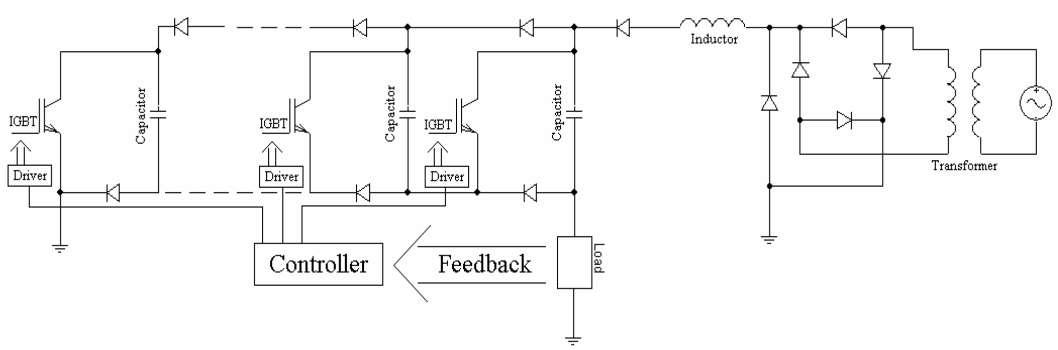

Fig.1 A schematic diagram of all solid-state Marx generator

The pulse power generator work in two modes of charging and Discharge as follow. First, the pulse transformer passes the energy to the secondary winds from a generator of high repetition rates sine voltage. Via the large inductor and diodes, the 20 sets of capacitors in parallel are charged to 3kV by the high voltage and high frequency rectified bridge. The large inductor acts as a current limiter. In this mode, IGBTs are at off-state, and, hence, there is no voltage across the load. When the capacitors are charged to the preset voltage, the circuit transfers the second mode, that is, IGBTs turning on simultaneously. Consequently, the capacitors are connected in series by those on-mode IGBTs. Thus, the load could acquire a negative high voltage of 60kV which is the sum of the voltage of capacitors. Diodes take place of resistors as the isolator in conventional Marx generator. As a result of the absence of resistors, the system has a much shorter charge time and is of great efficiency.

3. Design of the proposed circuit

3.1 Capacitor

The capacitor in the all solid-state Marx generator is determined by the pulse width τ, the total output voltage V_0, the voltage drop of the output pulse voltage ΔV_0, and the load resistance Rload. That is, the capacitor value should meet the following equation,

$$\frac{C_n}{n} \geq \frac{Q}{\Delta V_0} = \frac{\tau}{\Delta V_0}(I_{in} + I_{load}) \qquad (1)$$

3.2 Inductor

The inductor in the circuit has double functions. At the phase of the capacitors is charged, the inductor limits the charging current and acts as a ripple filter. During the discharging mode, the inductor isolates the high voltage pulse from the charging power source due to the bypass effect by the diode in parallel charging source. Under the condition of time constant of $T = \pi\sqrt{LC_n / n}$ is much shorter than pulse width τ, the maximum current in the inductor is,

$$I_{in} \approx \frac{V_0 \tau}{L} \qquad (2)$$

In fact there are (n-1) sets of capacitors in series with inductor forms a loop circuit to provide the current in inductor. This current in parallel to the load current follows the IGBT switches. Once the IGBT switches opened, the residual current re-charges the capacitors. The voltage insulation design of the inductor should be higher than the total output voltage.

3.3 IGBT switch and driver

The switch is the key component for the pulsed power generator. Recently innovations in solid-state power electronics makes it possible to achieve a flexible pulse voltage generator, which operate both opening and closing switches, providing extensive flexibility in pulse width and frequency control and very fast fault protection.

The voltage choice is dependent on the charged voltage at the capacitor. Some over-voltage capacity should be considered. The current option should include both current flowing through in inductor and load current.

$$i = i_{inductor} + i_{load} = \frac{V_0 \tau}{L} + \frac{V_0}{R_{load}} \quad (3)$$

IGBTs need isolation driver power and signal. In this paper the isolation voltage with 60kV insulation level is implemented using optical fiber. Self-powered IGBT drivers are employed here, because of the narrow pulse width compared with the period. Control signals are transmitted by optic fibre. The relatively high voltage is transformed to the nominal potentials of drivers efficiently by the DC-DC circuit. With the help this negative voltage, the driver would turn off the IGBT faster, more reliably and more efficiently.

3.4 Short circuit protection

It is likely that the plasma load would turn to short circuit. Therefore, arc detection and protection are required. The isolation of signal and synchronized signal can be simply implemented by sending the signal from serially connected optic transmitter. A small current limiting resistor is added in the load loop, to keep the short-circuit current not to excess the rating of IGBT. Secondly, a hall sensor monitors the load current and, if abnormal situation is detected, the sensor feedback over-current signals to block the control signal with response time less than 1μs. Over voltage protection is implemented by a voltage divider network across the load. The capacitor-resistors divider network measures output pulse voltage and feedback it to the control system of charge source. The charge source would be stopped if over voltage of the load is detected and, then the voltage of the capacitor would decrease.

4. Experimental results

4.1 Resistor as load

In order to test the performance of solid-state Marx generator, a resistor with a resistance of 20k Ω as load is used for experiment. The voltage waveforms with different amplitude as shown in Fig.2 show a rectangular shape with a rise time of 0.8 μs and with a droop at the flat top being less than 20%. The rise time is determined mainly by the conduction time of solid-state switches. The fall time is dependent on both the opening time and load characteristic.

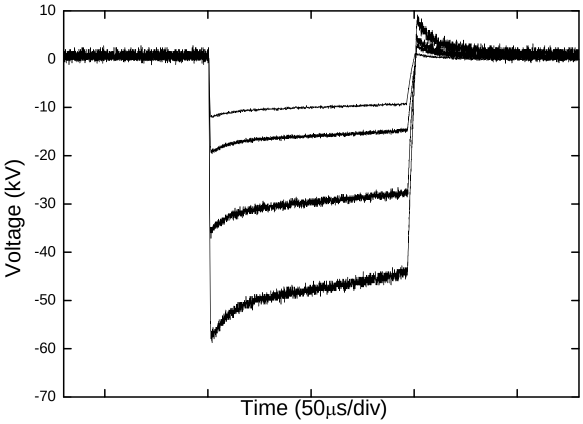

Fig.2 Waveforms of voltage with different amplitude applied to a resistor load

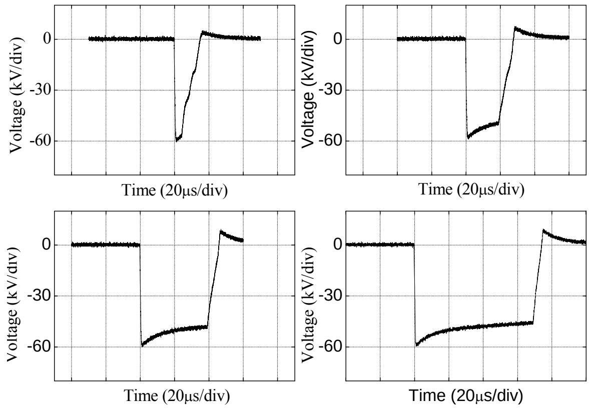

Fig.3 Waveforms of voltage with different pulse width

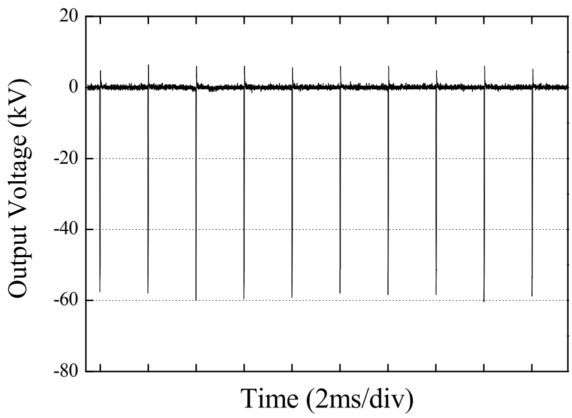

Fig.4 60kV Voltage output at 500Hz operating frequency

Fig.3 and Fig.4 show waveforms of different pulse width and 500Hz repetitive operation. it is seen that the pulsed power generator is flexible and suitable for different operating condition.

4.2 Plasma as load

Fig.5 shows the waveforms of the applied voltage and current for a disk target, which was immersed in plasma. The applied voltage was 20kV with a negative polarity. From the current waveform it is noticed that there is a peak at the initial stage, which is caused by the presence of stray capacitance between the target and the ground chamber and ion sheath capacitance [6], at the same time, the rise time of the voltage waveform changes to a degree. In order to investigate the effect of parameters in the pulsed power generator on the rise time, the voltage waveforms in load in three operating state are compared as shown in Fig.6. The curve 1 is the voltage without any load, the curve 2 is the voltage with resistance load, and curve 3 is the voltage with plasma discharge load. From the comparison, we can see that cable inductance and resistance has a little

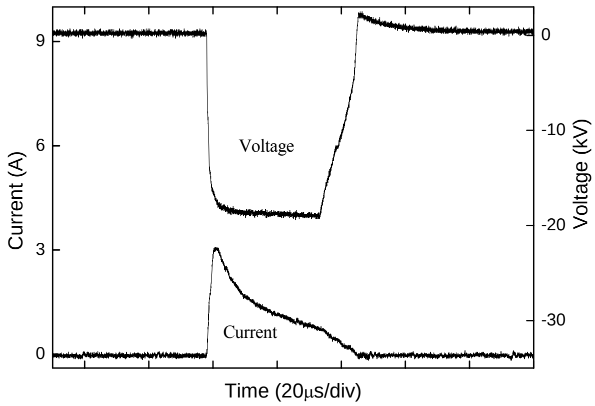

Fig.5 Waveforms of voltage and current in plasma load

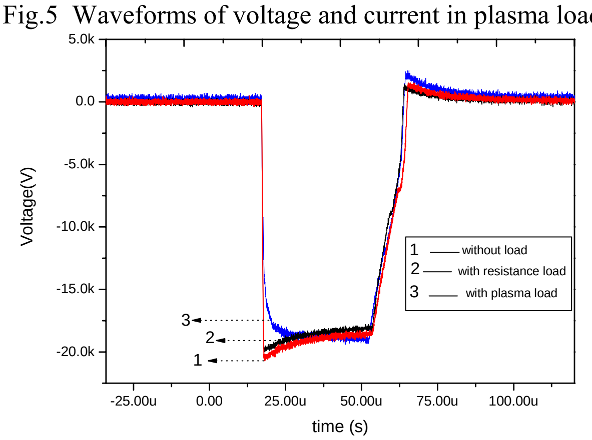

Fig.6 Waveforms of voltage with different load

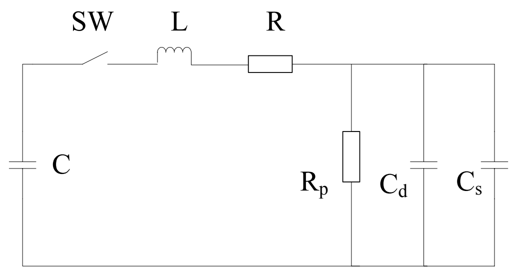

Fig.7 An equivalent plasma model circuit

influence on the rise times and voltage amplitude of plasma load. Due to the presence of capacitance in the plasma load, the rise time of voltage in the plasma load becomes large. At the same time, the fall time is almost not changed by the plasma load. This result is consistent with the paper [6]. For An equivalent plasma circuit model is built as shown in Fig.7. The charged capacitor in series is expressed by C, which can be considered a voltage source. The cable for connecting the generator output and plasma discharge chamber becomes inductance L and resistance R. the ion sheath can be shown as a parallel connection of capacitor C_d and R_p. The stray capacitance is expressed by C_s. From the circuit model, it is seen that the rise time in plasma load is determined by the closing time of solid-state switch (which can be neglected) and inductance in the circuit and capacitance in the plasma load. The fall time is dependent on the opening time of the switch and the time constant of the plasma load. Reducing the inductance in the circuit is helpful for lowering the rise time and fall time.

5. Summary

An all solid-state pulsed power generator based on Marx circuit configuration has been designed for PIII. The primary experiments with resistance load of 60kV/500Hz with 20 μs to 100 μs and PIII experiments of 20kV/ 500Hz demonstrated that it has flexibility in pulse width, voltage amplitude and operating frequency. The system operates reliably for plasma arc fault protection. The experiments and circuit analysis showed that the rise time and fall time is determined mainly by the plasma load.

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7. References

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