Capacitance of High-Voltage Coaxial Cable in Plasma Immersion Ion Implantation

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[Manuscript received April 25, 2000]

Plasma immersion ion implantation (PIII) is an excellent technique for the surface modification of complex-shaped components. Owing to pulsed operation mode of the high voltage and large slew rate, the capacitance on the high-voltage coaxial cable can be detrimental to the process and cannot be ignored. In fact, a significant portion of the rise-time/fall-time of the implantation voltage pulse and big initial current can be attributed to the coaxial cable.

1. Introduction

Plasma immersion ion implantation (PIII) has been proven to be an effective surface modification method[1,2] and is particularly suitable for large targets with an irregular geometry as no sample manipulation or rotation is required.

PIII is conducted in a pulsed high-voltage mode, and an equivalent capacitance is naturally induced on the coaxial cable supplying the voltage to the sample stage from the power modulator. The capacitance can degrade the shape of the voltage pulse, and in this paper, we investigate the phenomenon of the high-voltage coaxial cable.

2. Voltage/Current Configuration

Figure 1 shows the simplified circuit of our PIII pulse power supply[3] and Fig.2 depicts the typical experimental current/voltage waveforms. The voltage waveform is characterized by a finite rise-time and fall-time. This is mainly caused by the equivalent capacitance on the cable. In Eq.(1), time $t_1$ represents the charging time of the cable, vacuum chamber and plasma capacitance through the series impedance:

$$t_1 = R_{\text{series}}*(C_{\text{cable}} + C_{\text{chamber}} + C_{\text{plasma}})$$ (1)

The fall time of the pulse $t_3$ is given by the resistance-capacitance $(RC)$ constant of the cable (and plasma) and the series and pulldown impedance. The voltage is determined by:

$$V \approx V_0 e^{-(t/\tau_3)}$$ (2)

where

$$\tau_3 = (C_{\text{cable}}+C_{\text{chamber}}+C_{\text{plasma}})*(R_{\text{pulldown}}//R_{\text{plasma}}).$$

It is evident that the plasma load induces a large initial current peak that gradually decreases as time elapses. Note that the current peak in Fig.2 is reinforced by the charging current of the cable capacitance or displacement current, $I_d$. The displacement current can be measured without plasma. As shown in Fig.3, the displacement current measured using the same voltage as that in Fig.2 is quite big. Comparison of the displacement and implantation currents indicates that the initial part of the implantation current is mainly the displacement current. As recommended by Shamim et al.[4], the effective current can be obtained by subtracting the displacement current from the implantation current[5]. As shown in Fig.4, the displacement current is generally 2.5 times that of the effective peak current in typical experimental conditions. That is to say, a large portion of the current provided by the modulator is dissipated in the high-voltage cable, and attention must be paid to this phenomenon when designing PIII equipment.

3. Power Dissipation

As aforementioned, a part of the electrical power
supplied by the pulse modulator is wasted by the charging and discharging of the high-voltage cable. Therefore, the cable capacitance can be a major source of inefficiency in the PIII system. The power lost to repetitively charge and discharge the cable can be calculated by:

\[ P = 2fE = fCV^2 \]  

For example, the dissipated power in a 6 ft. long coaxial cable at 100 kV/5 kHz is about 9000 W. This results in overloading of the power modulator.

4. Implantation Energy

The voltage pulse rise-time resulting from the cable capacitance has a large influence on the ion implantation energy. According to Child-Langmuir law and the work of R.A.Stewart, et al.:

\[ \delta = 0.7368 \left( \frac{t_r}{t} - 0.6t_r \right)^{\frac{1}{2}} \]  

where \( t_r \) is the rise-time, \( t \) is the pulse duration, and \( \delta \) represents the fraction of implanted ions with energies \( W < W_0 \) assuming that every ion entering the sheath receives the full energy. The different values of \( \delta \) as a function of the rise time \( t_r \) are displayed in Fig.5.

Although the dissipated energy in the cable is small compared to that of the implantation process itself, it impacts the energy distribution considerably. For a voltage pulse with a rise-time of 2 \( \mu \)s and pulse width of 40 \( \mu \)s, 27\% of the ions receive an energy less than \( eV_0 \). When the rise-time increases, the fraction of the ions with energies less than \( eV_0 \) will go up even more. Therefore, the cable capacitance that determines the time-constant of the circuit affects the implantation energy significantly.

5. Conclusion

Plasma immersion ion implantation features high voltage and high \( dv/dt \) leading to a high capacitance effect in the coaxial cable between the sample holder and power modulator. This capacitance induces a big initial current (displacement current) which is sometimes several times the implantation current, consequently increasing the burden on the modulator. It also increases the time-constant of the circuit leading to a long voltage rise-time thereby reducing the average implantation energy. Since it is impossible to eliminate the cable, minimizing the cable length or prolonging the pulse width with a lower repetition frequency may mitigate the effects.

Acknowledgement

The work was supported by the Hong Kong RGC Earmarked Grants 9040344 and 9040412 as well as RGC Germany Joint Scheme 9050084.

REFERENCES