A Specially Designed PLC-Based High-Voltage Pulse Modulator for Plasma Immersion Ion Implantation

Zongtao Zhu, Chunzhi Gong, Zhijian Wang, Xiubo Tian, *Member, IEEE*, Yi Li, Shiqin Yang, Ricky K. Y. Fu, and Paul K. Chu, *Fellow, IEEE*

***Abstract*—A novel high-voltage pulse power system based on a programmable logic controller (PLC) is developed for plasma immersion ion implantation (PIII). The PLC unit with strong anti-interference ability is utilized to optimize both electrical parameters and ion-implantation processes with manual or/and procedure modes. Specially designed periphery circuits are developed to realize the arbitrary adjustment of pulsing frequency and width which is impossible for conventional PLC systems. The electrical protection can also work rapidly in the case of a sudden short circuit. In the main power circuit, a tetrode hard tube is employed to switch the dc high voltage. In order to reduce the rise time of the pulse as much as possible, the potentials on the tetrode grids are optimized. A closed-loop system is also designed to ensure implantation voltage not to depend on the plasma load during the PIII processes. With the help of numerical calculation or simulation, the expected ion energy-number spectrum can be easily obtained.**

***Index Terms*—Ion implantation, plasma sheath, programmable logic controller (PLC), pulse modulator.**

I. Introduction

PLASMA immersion ion implantation (PIII) [1] is a well-established technique for surface modification. The samples are immersed in a plasma generated by an independent plasma source and biased to a high negative potential. Consequently, ions in the plasma are accelerated and implanted into the samples, resulting in surface mixing, modification, and even thin-film formation under certain conditions [2]–[4]. This technique presents several significant advantages such as high ion flux, high throughput, capability of treating irregular targets, and simpler instrumentation compared to conventional beam-line ion implantation [5]–[7]. However, successful implantation requires a pulsed power unit, which is a vital part of a PIII system. The application of a pulsed high voltage instead of a dc voltage is essential to the proper control of the thermal load to the samples and sometimes to reduction of the risk of electrical arcing which can otherwise damage the samples. This is usually achieved by varying either the repetition frequency or the pulse duration of the applied high-voltage pulses. The output pulse shape should be quasi-rectangular and relatively independent of the load impedance, and the power modulator itself should be resistant to short circuits [8]. Moreover, it is desirable that the frequency and pulsewidth can be adjusted arbitrarily. Consequently, in complex PIII processes, an intelligent control system is usually preferred.

In this paper, a novel programmable logic controller (PLC)-based high-voltage pulse modulator with a maximum pulse voltage of 40 kV is described. In the power system, a tetrode serves as a hard tube to switch the dc high voltage directly, and the control system is based on a PLC unit (Panasonic FPX-C30T) which provides anti-interference capability and flexibility. Specially designed periphery circuits are developed so that the frequency and pulsewidth can be adjusted arbitrarily through the PLC system. The voltage of the control grid is optimized to obtain pulse rise time as short as possible. The modulator can protect itself when a sudden arc or short circuit occurs. Automatic constant voltage is accomplished to avoid the fluctuation of the output voltage induced by plasma load variation. The parameters can be set on a touch screen (WEINVIEW MT510TV5). To be mentioned, certain ion projection depth profiles can be easily obtained by running a preset time-dependent voltage program.

II. Hardware

A. Main Power Circuit

The schematic of the PLC-based high-voltage pulse modulator is shown in Fig. 1. To obtain a high-voltage pulse, a tetrode hard tube T (TM-702F) is employed to switch the dc high voltage [9], [10]. The dc high-voltage unit charges the high-voltage capacitor C $(0.5\ \mu\text{F}/40\ \text{kV})$ through resistor R_1 and high-voltage silicon heap D. The transient charging current is limited by resistor R_1 (20–40 kΩ). When the tetrode is triggered, the capacitor discharges through the tetrode in series with the plasma load. Resistor R_2 (of several tens of ohms) is utilized to protect the power system against a sudden short circuit. A hollow inductance T is utilized to limit the peak current caused by the steeper rising rate of the voltage (du/dt)

Manuscript received January 31, 2010; revised April 20, 2010; accepted May 11, 2010. Date of publication July 8, 2010; date of current version November 10, 2010. This work was supported in part by the National Natural Science Foundation of China under Grants 10905013, 50773015, and 10775036 and in part by Hong Kong Research Grants Council Special Equipment Grant SEG CityU05.

Z. Zhu, C. Gong, Z. Wang, X. Tian, Y. Li, and S. Yang are with the State Key Laboratory of Advanced Welding Production Technology, School of Material Science and Engineering, Harbin Institute of Technology, Harbin 150001, China (e-mail: xiubotian@163.com).

R. K. Y. Fu and P. K. Chu are with the Department of Physics and Materials Science, City University of Hong Kong, Kowloon, Hong Kong.

Digital Object Identifier 10.1109/TPS.2010.2051166

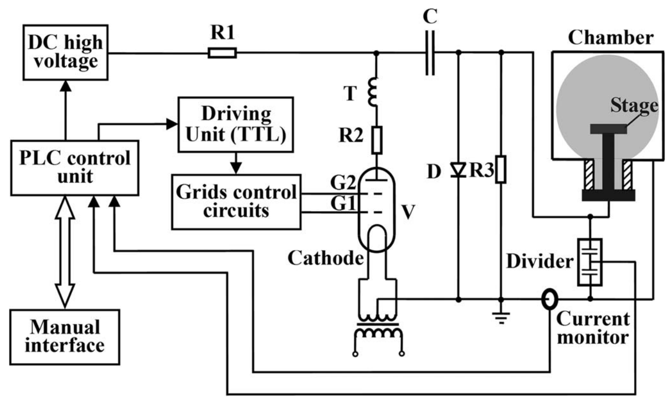


Fig. 1. Schematic of the PLC-based high-voltage pulse modulator.

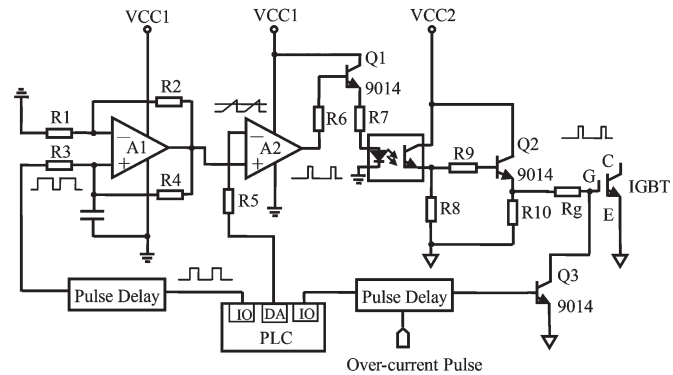


Fig. 2. PLC-based driving circuit.

at the beginning of the pulse. The cathode and grids of the tetrode tube are controlled by independent circuits. According to the cutoff curve of the tetrode provided by the manufacturer, the potential on grid G_2 ranges from $+1500$ to $+2500$ V. In order to ensure that the tetrode completely closes, the potential on the tetrode control grid G_1 must be below -750 V. In our power system, the potential on control grid G_2 is $+1700$ V. The potential on grid G_1 is controlled by a TTL driving unit based on PLC. When the triggering signal takes effect, the potential on control grid G_1 increases from -840 (closing potential) to $+200$ V (opening potential). The tetrode remains switched on as long as the TTL pulse is present. The output voltage and current are detected by the capacitance divider and current monitor, respectively.

A pulse rise time that is as short as possible is preferred to achieve uniform PIII [11]. The potential on control grid G_1 has to be optimized. It is $+200$ V in our system, and the rise time of the pulse is about 1 μs. A larger G_1 potential may lead to deleterious electrical oscillation. The potential on grid G_2 has a slight influence on the rise time of the pulse, and no obvious difference is observed with the G_2 potential changing from $+1500$ to $+1900$ V. Due to the capacitance of the plasma load and cable, a long fall time is induced after the tetrode shuts down. This will lead to the energy nonuniformity of incident ions, and surface sputtering of treated samples may happen. This fall time may last several hundreds of microseconds due to the high resistance of the plasma sheath. The hard tube or series solid-state switch (e.g., IGBTs) can be utilized to discharge the equivalent capacitor rapidly. A fall time of less than 1 μs has been reported [12]. However, this method may make the circuit of the modulator more complex and bring extra hardware cost. Therefore, a pull-down resistor is frequently utilized in practical circuits, although power consumption is needed. In our system, the fall time of the pulse is controlled by pull-down resistor R_3 of 20–30 kΩ.

B. PLC Control Unit

A PLC system (Panasonic FPX-C30T) is utilized to control the power supply and PIII processes. PLC possesses powerful functions such as logic, sequencing, timing, counting, etc. Here, the PLC unit is expected to control the PIII processes and deliver the pulse to control grids G_1 and G_2. However, the I/O ports of the Panasonic FPX-C30T can generate a pulse with a variable frequency but only a fixed duty cycle or a pulse with a variable duty cycle but a fixed frequency. It is difficult for the PLC to generate a pulse with arbitrarily changing pulsewidths and frequencies. In order to solve this problem, a peripheral circuit based on PLC is designed to obtain the driving pulse required by PIII. Fig. 2 shows the schematic of the circuit. One of the PLC I/O ports delivers a pulse with a duty circle of 20% and an arbitrarily adjustable frequency between 10 and 1000 Hz. This pulse is delayed to generate a new synchronous pulse with a width of 320 μs and subsequently changed into a sawtooth wave by an integrated circuit. The sawtooth wave is leveled by the dc signal from the D/A module of the PLC to produce a square wave as the original driving pulse source. After optical isolation and amplification, the pulse can be used as the driving signal to switch the IGBT. The length and frequency of the pulse can be accurately controlled by the PLC. This system based on PLC can deliver pulses with widths ranging from 10 to 300 μs and frequencies from 10 to 1000 Hz with a maximum duty circle of 1%.

During PIII, the plasma load is generally dependent of the plasma density, specimen materials, gas pressure, etc. Therefore, the output pulse voltage may change due to different plasma resistances, leading to variations in the implantation energy. In our power modulator, a closed-loop control-system-based PLC unit is developed and employed. As shown in Fig. 1, when the voltage detected by the PLC changes, the control signal will be delivered to adjust the dc high-voltage unit to ensure a constant output voltage. Fig. 3 shows the voltage and average current on the condition of different load resistances with and without control of constant voltage. Evidently, the output voltage decreases with a smaller plasma load, which is not expected in practical applications.

Touch screen WEINVIEW MT510TV5 is used as the user interface. Communication between the touch screen and PLC unit is maintained via an RS-232 port. All the parameters are set on the interface, and both "manual" and "procedure" modes are provided, as shown in Fig. 4. The manual mode is recommended for simple PIII processes so that the parameters can be manually changed in time.

In the procedure mode, the parameters may be automatically adjusted according to procedures designed for different PIII

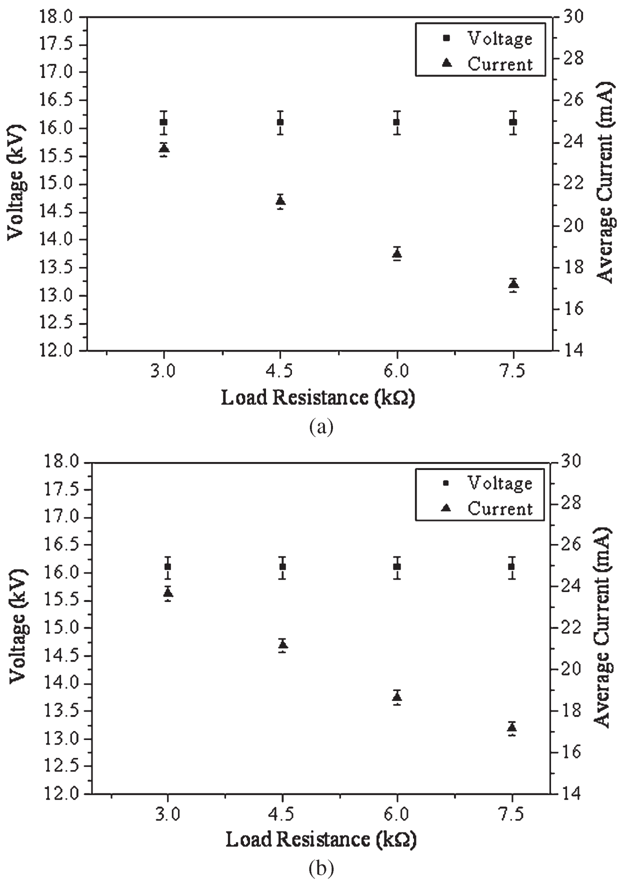


Fig. 3. Characteristic curves of output voltage and average current: (a) Without and (b) with constant-voltage control.

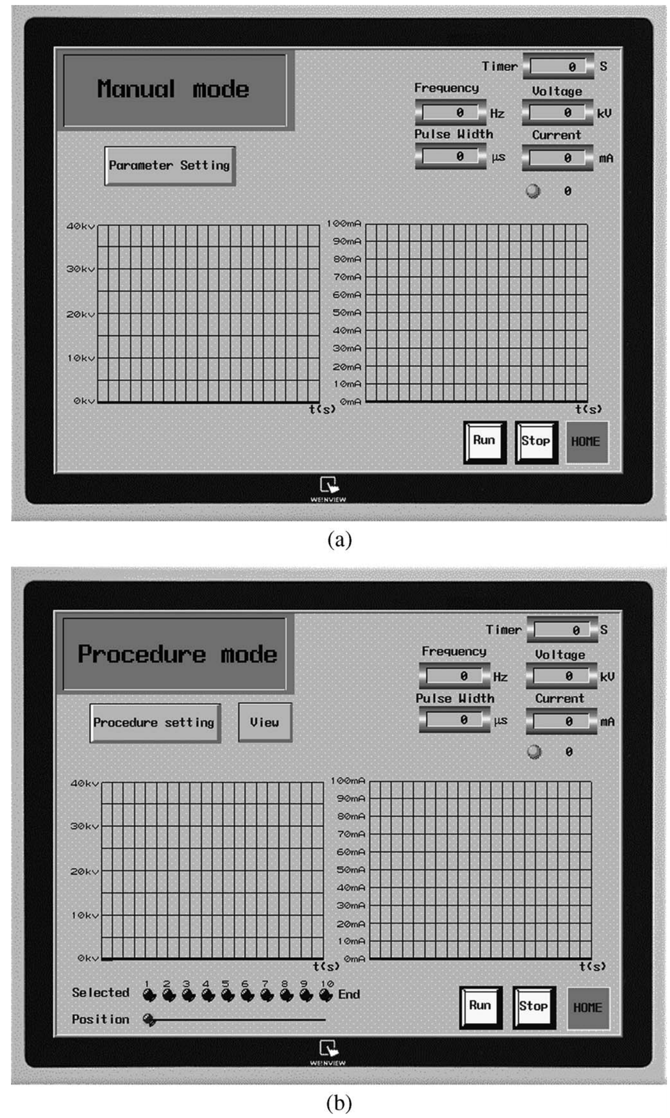


Fig. 4. Interface as shown on the touch screen: (a) Manual mode and (b) procedure mode.

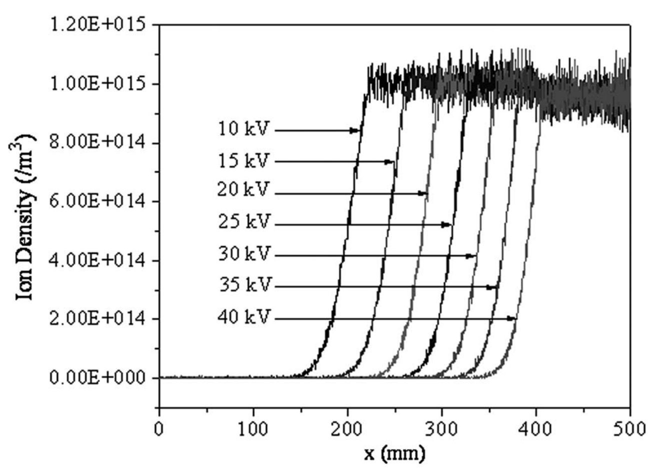


Fig. 5. Voltage-dependent plasma sheath configuration at the end of a 10-μs pulse.

processes. PIII is a relatively complex process. The energy of ions is related to many factors such as the rise and fall times of the high-voltage pulse, voltage amplitude, pulse duration, etc. In order to get an optimal modification effect, the implantation voltage (energy) may need time-dependent change in a single PIII process to achieve the expected ion depth profile. In our work, the energy-number distribution of implanted ions has been calculated using 1-D PIC simulation. The analytical model has been described in details elsewhere [13]. The plasma density is $1 \times 10^9/\text{cm}^3$, and the total pulsewidth of the high voltage is 10 μs with a rise time of 1.2 μs and a fall time of 4 μs. The flat voltage of the pulse varies from 10 to 40 kV with a voltage interval of 5 kV. The simulation results have demonstrated that the plasma sheath configuration is much dependent on the applied voltage, as shown in Fig. 5. The thickness of the plasma sheath is more sensitive to the bias when a lower voltage is applied. Fig. 6 shows the energy-number distribution of ions for a single pulse with different voltage amplitudes. During each pulse, the ions with low energy occupy less than 1% of ions with high energy. Therefore, the ions with low energy may be neglected in the calculation, and a quasi-continuous energy-number spectrum of ions for any shape can be obtained by changing the time of each step preset through the touch screen in the procedure mode. Fig. 7 shows the calculation results of the energy-number spectrums of implanted ions for processes A and B, respectively. In this case, the frequency of the high-voltage pulse is 100 Hz, and the voltage waveform shape is described previously. The voltage amplitude and the time of each step are shown in the small chart in Fig. 7. The number of

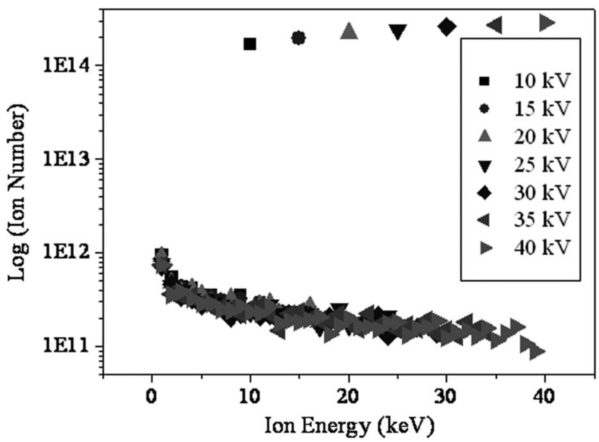


Fig. 6. Energy-number spectrum of ions for a 10-μs pulse.

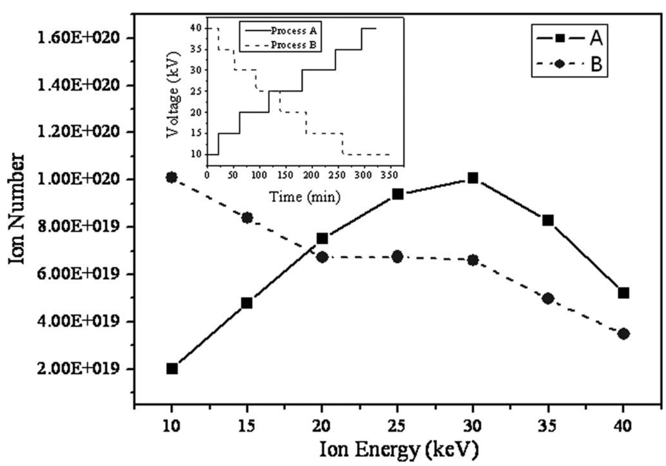


Fig. 7. Energy-number spectrum of incident ions for processes A and B, respectively.

ions with a certain energy is equal to the ion number per pulse times the total number of pulses within the whole processing time. In fact, the time-dependent voltage cannot only change step by step but also change continuously as a certain function of time for optimal surface properties.

III. Experimental Results

During PIII, sudden electrical arcing can happen. In this case, the G_1 driving pulse is switched off immediately for several hundreds of microseconds to protect the power system and reduce material damage from arcing. If the overcurrent signal lasts for a long time (e.g., 5 s), the PLC will deliver a signal to shut down the main power. Fig. 8 shows the waveform when a short circuit happens. The response time is relatively short to protect consequently the power system and components.

Fig. 9 shows the waveforms with different pulse amplitudes and pulsewidths with a resistor load of 100 kΩ. The high-voltage pulse has a small rise time, and the amplitude of the pulse voltage is very stable. The maximum voltage can be turned up to as high as 40 kV. The fall time is about 40 μs controlled by a 24-kΩ resistor. The pulsewidth and frequency can be set arbitrarily by the PLC.

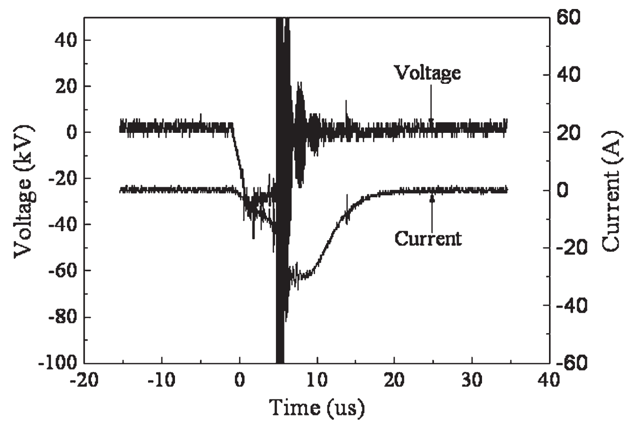


Fig. 8. Waveforms of voltage and current when a short circuit happens.

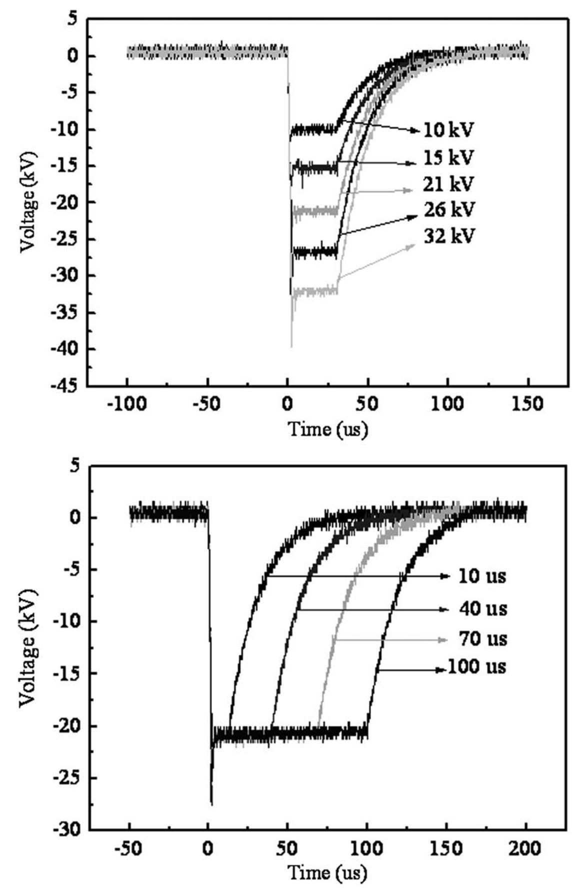


Fig. 9. Waveforms with different pulse amplitudes and pulsewidths.

IV. Conclusion

A novel high-voltage power modulator based on PLC has been developed for PIII. The pulselength can be varied from 10 to 300 μs and the frequency from 10 to 1000 Hz. The PLC system can control the PIII processes and pulse parameters in a flexible manner. In particular, a circuit has been developed to realize the exact control of the frequency and pulsewidth of the pulser. More importantly, the energy-number spectrum of incident ions can be arbitrarily set using the procedure mode combined with numerical calculation or simulation. The power system has robust protection against overcurrent and short circuits.

References

[1] J. R. Conrad, J. L. Radtke, R. A. Dodd, F. J. Worzala, and N. C. Tran, "Plasma source ion-implantation technique for surface modification of materials," *J. Appl. Phys.*, vol. 62, no. 11, pp. 4591–4596, Dec. 1987.

[2] W. Ensinger, "Correlations between process parameters and film properties of diamond-like carbon films formed by hydrocarbon plasma immersion ion implantation," *Surf. Coat. Technol.*, vol. 203, no. 17/18, pp. 2721–2726, Jun. 2009.

[3] J. Wang, N. Huang, P. Yang, Y. X. Leng, H. Sun, Z. Y. Liu, and P. K. Chu, "The effects of amorphous carbon films deposited on polyethylene terephthalate on bacterial adhesion," *Biomaterials*, vol. 25, no. 16, pp. 3163–3170, Sep. 2004.

[4] J. X. Liao, W. M. Liu, T. Xu, and Q. J. Xue, "Characteristics of carbon films prepared by plasma-based ion implantation," *Carbon*, vol. 42, no. 2, pp. 387–393, Nov. 2004.

[5] C. Yu and N. W. Cheung, "Trench doping conformality by plasma immersion ion implantation (PIII)," *IEEE Electron Device Lett.*, vol. 15, no. 6, pp. 196–198, Jun. 1994.

[6] P. K. Chu, "Enhancement of surface properties of biomaterials using plasma-based technologies," *Surf. Coat. Technol.*, vol. 201, no. 19/20, pp. 8076–8082, Aug. 2007.

[7] R. H. Wei, T. Booker, C. Rincon, and J. Arps, "Metal plasma immersion ion implantation and deposition (MPIII and D) using a metal plasma electron evaporation source (MPEES)," *Surf. Coat. Technol.*, vol. 200, no. 1–4, pp. 579–583, Oct. 2005.

[8] J. Brutscher, "A 100 kV 10 A high-voltage pulse generator for plasma immersion ion implantation," *Rev. Sci. Instrum.*, vol. 67, no. 7, pp. 2621–2625, Apr. 1996.

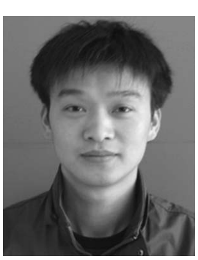
[9] R. Günzel, A. I. Rogozin, M. Demski, S. N. Rukin, J. Brutscher, and T. H. G. G. Weise, "Generation of high voltage pulses for PBII devices," *Surf. Coat. Technol.*, vol. 156, no. 1–3, pp. 54–60, Jul. 2002.

[10] J. O. Rossi, M. Ueda, J. J. Barroso, and V. A. Spassov, "A hard-tube pulser of 60 kV, 10 A for experiment and modeling in plasma immersion ion implantation," *IEEE Trans. Plasma Sci.*, vol. 28, no. 5, pp. 1392–1396, Oct. 2000.

[11] D. T. K. Kwok, M. M. M. Bilek, D. R. McKenzie, and P. K. Chu, "The importance of bias pulse rise time for determining shallow implanted dose in plasma immersion ion implantation," *Appl. Phys. Lett.*, vol. 82, no. 12, pp. 1827–1829, Mar. 2003.

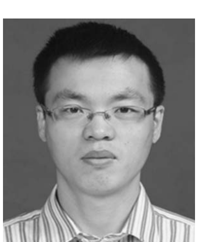
[12] J. O. Rossi, M. Ueda, and J. J. Barroso, "Plasma immersion ion implantation experiments with long and short rise time pulses using high voltage hard tube pulser," *Surf. Coat. Technol.*, vol. 136, no. 1–3, pp. 43–46, Feb. 2001.

[13] D. T. K. Kwok, P. K. Chu, and C. Chan, "Ion dose uniformity for planar sample plasma immersion ion implantation," *IEEE Trans. Plasma Sci.*, vol. 26, no. 6, pp. 1669–1679, Dec. 1998.



Zongtao Zhu was born in Anhui, China, in 1983. He received the B.S. degree in materials science and engineering from Jilin University, Changchun, China, in 2005 and the M.S. degree in materials science and engineering from the Harbin Institute of Technology, Harbin, China, in 2007, where he is currently working toward the Ph.D. degree.

His current research interests include development of modulators for ion implantation and deposition, pulsed power technology, and fabrication of functional films.



Chunzhi Gong was born in Heilongjiang, China, in 1979. He received the B.S., M.S., and Ph.D. degrees in materials science and engineering from the Harbin Institute of Technology, Harbin, China, in 2002, 2004, and 2008, respectively.

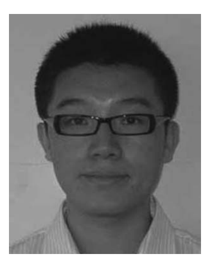
He is currently an Assistant Researcher with the State Key Laboratory of Advanced Welding Production Technology, School of Material Science and Engineering, Harbin Institute of Technology. His research interests include modulators for ion implantation and deposition, numerical simulation of plasma processing, and plasma sources and applications.

Zhijian Wang was born in Anhui, China, in 1982. He received the B.S. degree in materials science and engineering from the Harbin University of Science and Technology, Harbin, China, in 2004 and the M.S. degree in materials science and engineering from the Harbin Institute of Technology, Harbin, in 2006, where he is currently working toward the Ph.D. degree.

His current research interests include ion implantation and the numerical simulation of plasma processing.

Xiubo Tian (M'01) was born in 1969. He received the B.S. and M.S. degrees in materials science and engineering from the Harbin Institute of Technology, Harbin, China, in 1990 and 1993, respectively, and the Ph.D. degree in physics and materials science from the City University of Hong Kong, Kowloon, Hong Kong, in 2002.

From 1993 to 1998, he was with the State Key Laboratory of Advanced Welding Production Technology, School of Material Science and Engineering, Harbin Institute of Technology, where he is currently a Professor with the School of Material Science and Engineering and the Vice Director of the State Key Laboratory of Advanced Welding Production Technology. From 1998 to 2002, he was with the Plasma Laboratory, City University of Hong Kong. He has authored/coauthored over 100 articles. His research interests include plasma ion implantation, nitriding, hybrid processes, numerical simulation of plasma processing, and plasma sources and applications.



Yi Li was born in Heilongjiang, China, in 1984. He received the B.S. degree in materials science and engineering from Jilin University, Changchun, China, in 2007 and the M.S. degree in materials science and engineering from the Harbin Institute of Technology, Harbin, China, in 2009.

He is currently with the State Key Laboratory of Advanced Welding Production Technology, School of Material Science and Engineering, Harbin Institute of Technology. His research interests include development of intelligent control systems of equipment.

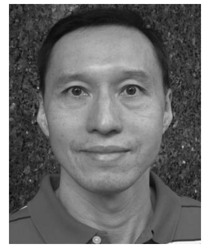
Shiqin Yang received the B.S. degree in materials science and engineering from the Harbin Institute of Technology, Harbin, China, in 1961.

Since 1961, he has been with the Harbin Institute of Technology, where he was the President from 1985 to 2002. From 1980 to 1982, he was a Visiting Scholar with the University of Wisconsin, Madison. He has authored/coauthored over 100 publications. His research interests include ultrasonic equipment and processes for welding applications, plasma welding, plasma ion implantation/nitriding, and surface engineering.

Ricky K. Y. Fu received the B.S. degree in materials science and technology and the M.S. and Ph.D. degrees in plasma physics from the City University of Hong Kong, Kowloon, Hong Kong, in 2000, 2002, and 2005, respectively.

In 2006, he joined the director board in Plasma Technology, Ltd., Hong Kong. He is currently a Researcher with the Department of Physics and Materials Science, City University of Hong Kong. His current research interests include plasma processing and ion implantation, material surface modification, PVD, and plasma-related techniques, including filtered cathodic arc discharge, microarc oxidation, and magnetron sputtering, as well as high-voltage and high-power pulse power supply study and applications. He is the author/coauthor of over 130 publications and several book chapters.

Dr. Fu was the recipient of the Excellent Young Scientist Award from the Chinese Materials Research Society, Beijing, China, in 2004.



Paul K. Chu (F'03) received the B.S. degree in mathematics from The Ohio State University, Columbus, in 1977 and the M.S. and Ph.D. degrees in chemistry from Cornell University, Ithaca, NY, in 1979 and 1982, respectively.

He is currently a Chair Professor of materials engineering with the Department of Physics and Materials Science, City University of Hong Kong, Kowloon, Hong Kong. His research activities are quite diverse, encompassing plasma surface engineering and various types of materials and nanotechnology. He is a Coeditor of six books on plasma science, biomedical engineering, and nanotechnology, has coauthored more than 20 book chapters, 800 journal papers, and 750 conference papers, and is the holder of 15 U.S., European, and Chinese patents.

Dr. Chu is a Fellow of APS, AVS, and the Hong Kong Institution of Engineers. He is a member of the Plasma-Based Ion Implantation International Committee, the Ion Implantation Technology International Committee, and the IEEE NPSS Fellow Evaluation Committee. He is a Senior Editor of the IEEE TRANSACTIONS ON PLASMA SCIENCE and an Associate Editor of *Materials Science and Engineering Reports* and the *International Journal of Plasma Science and Engineering*. He has won a number of awards, including the 2007 IEEE NPSS Merit Award.