Plasma Immersion Ion Implantation System Based on Glow Discharge with Electrostatic Confinement of Electrons

A.S. Metel

State University of Technology STANKIN, Vadkovsky per. 1, Moscow, 127055, Russia,
Phone: 095-972-9558, Fax: 095-973-3866, E-mail: a.metel@mail.ru

Abstract – A glow discharge with electrostatic confinement of electrons (GDECE) is used for plasma production inside a 0.1 m^3 chamber of a plasma immersion ion implantation (PIII) system. At a constant discharge current of ~ 1 A pairs of 30-kV pulses with equal widths are simultaneously applied to an additional anode (positive pulses) and to a substrate (negative pulses). They give rise to 60-μs-wide and ~ 100-A high current pulses in the both circuits. At 25 Hz pulse frequency it results in the dose rate of 2 · 10^{17} ions/cm^2 within one hour. Electrons emitted by the substrate are accelerated in the sheath between the substrate and the plasma up to 60 keV and then decelerated in the sheath between the plasma and the chamber down to 30 keV. Energy of electrons bombarding the chamber walls and the anode is 2 times lower than the 60-keV energy of singly charged ions and 4 times lower than the 120-keV energy of doubly charged ions bombarding the substrate. It ensures a quite low X-ray yield, thus improving the safety.

1. Introduction

In contrast to conventional beamline ion implantation the plasma immersion ion implantation eliminates the need for ion beam extraction, focusing, transport, scanning and other manipulation. The whole surface of any complex-shaped conductive substrate placed in the center of a working vacuum chamber filled with plasma may be simultaneously treated with ions from the plasma if negative high-voltage pulses are applied to the substrate. Due to these advantages the PIII seems to be more productive and cheaper.

Among drawbacks and limitations of the PIII – low efficiency of electric power consumption due to the current of secondary electrons being one order of magnitude higher than the ion current in the circuit of the substrate. We should further mention the need for big-sized working chambers. Width of the sheath near the substrate surface may reach 0.5 m and even for treatment of a small substrate a 1-m-diam chamber is needed. And the most serious obstacle in the way to a wide industrial application of the PIII are dangerous X-rays induced by secondary 50–100 keV electrons bombarding the chamber walls.

Various plasma sources are used in conventional PIII-systems: microwave, RF discharges, cathodic arc, thermionic discharge confined by multipole magnetic field and others [1]. The most part of the treatment time (~ 99%) the plasma has no special effect upon the substrate with the exception of heating it. And only within 20-μs-wide or so high-voltage pulse it is "consumed" by expanding Child-Langmuir sheath, considerable part of the plasma ions being extracted and implanted into the substrate surface. Each pulse results in a decrease of the mean plasma density in the chamber and a recovery time is needed after the pulse, which depends on the type of the plasma source.

A twofold energy decrease of electrons inducing X-rays has been proposed in [2] compared to energy of singly charged ions bombarding the substrate. To achieve the goal a high-voltage pulse applied to the sheath between the plasma and the substrate should be divided into two equal parts, one of which being applied to an additional anode immersed in the plasma, the other part being applied to the substrate. In this case the X-rays are induced through bombardment of the anode by electrons emitted by the chamber and through bombardment of the chamber by electrons emitted by the substrate. To eliminate bombardment of the anode by electrons emitted by the substrate a small grounded screen should be placed between the substrate and the anode [2]. As the electron energy is at least two times lower than the ion energy the X-rays yield may be substantially reduced.

2. Basic Principles of a Discharge with Electrostatic Confinement of Electrons

One of the above parts of the high-voltage pulse may be readily applied to the substrate. But application of a positive high-voltage pulse to an additional anode immersed in the plasma may disable the most part of plasma sources described in [1]. For this reason it was proposed in [2] to use for plasma production a glow discharge with electrostatic confinement of electrons (GDECE), which could be supposed to stand the application of at least 3.75-kV pulses [3]. However nobody could reliably forecast the discharge behavior after 40-kV pulse is applied to the anode. In the earlier research [3] reaction of the discharge to application of up to 4 kV high positive pulses had been studied and the results contributed to elaboration of the following basic principles of the discharge.

The electrostatic trapping consists in rejections of electrons, which enter the positive ion charge sheath surrounding the plasma, by electric field in the sheath after every path through the plasma. They ionize the gas both in the plasma and in the sheath. For this reason there are in the GDECE 3 groups of electrons, which differ from each other with their birth places: at the cathode surface, inside the cathode sheath and in the plasma.

Each group has its own tasks. The main task of the cathode electrons is production in the sheath of the first generation of fast electrons.

The main task of the sheath electrons is ionization of the gas including production in the sheath of the second, third and further generations of fast electrons, which play more and more important role at higher discharge voltages.

The sheath electrons underlie what people call "the hollow cathode effect", which is in fact a particular case of the effect of electrostatic electron trapping. The latter is based on electron multiplication in the cathode sheath and does not depend on the trap type: multi-rod cathode-labyrinth [4], hollow cathode [5] or cathodes in magnetic field [6].

Initial energy of an electron produced in the sheath corresponds to potential difference between its birth point and the plasma. It may reach a value just a little lower than the cathode electron energy. The sheath electrons normally produce more ions than the cathode electrons.

Initial energy of electrons produced in the plasma is low for a substantial ionization and they are charged with transport properties of the plasma.

Reaction of the discharge to application of a high-voltage pulse should be governed by the ratio Λ/L, where Λ is energy relaxation length of the cathode electrons in inelastic collisions and L is mean length of electron trajectory in a volume V of the electrostatic trap before leaving it through aperture S_a of electron losses. For isotropic electrons [5]

$$L = 4V/S_a. \quad (1)$$

Surface of the mentioned above additional anode is an unavoidable part of the S_a and

$$\Lambda = (eU/W)\lambda_o, \quad (2)$$

where e is the electron charge, U is voltage between the additional anode and the cathode (chamber), W is a mean energy needed for production by fast electrons of one free elementary charge and λ_o is a mean path of cathode electrons between ionizing collisions in the range of their energy decreasing from eU down to W:

$$\lambda_o = \frac{1}{n_o(eU - W)} \int_W^{eU} \frac{d\varepsilon}{\sigma(\varepsilon)}, \quad (3)$$

where n_o is the density of gas molecules and $\sigma(\varepsilon)$ is dependence of ionization cross-section on electron energy ε [2].

In a stationary GDECE Λ is mainly shorter than L. At a typical discharge voltage U of hundreds V λ_o is nearly constant. But at U exceeding several kV λ_o is proportional to U and Λ is rising as U^2. For this reason at acceptable for the PIII gas pressures of ~ 0.1 Pa and less Λ of the cathode electrons as well as of the sheath electrons is several orders of magnitude higher than L and one could expect a low ionization rate within the high-voltage pulse. Λ decreases inversely to the rising gas pressure, but the pressure > 0.1 Pa is unacceptable as the ion free path for the resonant charge exchange should exceed the sheath thickness of dozens cm.

On the other hand, ratio of the number N_s of ions produced at $\Lambda < L$ by the first generation of sheath electrons to the number N_c of ions produced by cathode electrons [7]

$$N_s/N_c = C(U)(d/a)eU/W, \quad (4)$$

where C is a factor, which takes into account increase of ionization probability in the sheath due to electron deceleration and rises just a little slower than U [7], d is the sheath thickness, and a is the mean path of the electrons between rejections in the sheath,

$$a = 4V/S_c, \quad (5)$$

where S_c is the cathode surface area [5]. Even neglecting the rise of d/a we may suppose an N_s/N_c increase of 1000 or more times after the high-voltage pulse application due to the U increase of ~ 100 times. It means that cathode electrons may be released from ionization of a great number of molecules and sheath electrons are able to do it for them. But in any case every cathode electron has to produce in the sheath at least one another to support the discharge.

At $U \sim 2$ kV and higher the further generations of sheath electrons should be taken into account. When a 40-keV electron is decelerated in the sheath down to 100-eV energy σ is two orders of magnitude higher than in the plasma. At $\Lambda >> L$ the cathode electrons spend in the trap volume V a negligible part of their energy. But if their mean free path in the trap for ionizing collisions both in the plasma and in the sheath $\lambda_{p,s} < L$, before leaving the trap each of them produces at least one electron. For the above reason they produce in the sheath more electrons than in the plasma and energy of those electrons is just a little lower than energy of the cathode electrons. The first generation of sheath electrons also produces in the sheath more electrons than in the plasma and energy of the second generation is just a little lower than energy of the first generation. Energy of the third generation is just a little lower than energy of the second generation and so on.

Taking into account such an ionization cascade in the sheath and an increase of the sheath thickness d after the high-voltage pulse is applied one may suppose that even at $\Lambda >> L$ the multiplication of fast electrons in the sheath may result in a rapid growth of the plasma density instead of the decrease. The most reliable way to find out what will happen in reality is an experiment.

3. Experimental Set-up

Figure 1 presents a photograph of an experimental PIII-system. Walls and two doors of a cylindrical 50-cm-diam to 50-cm-long vacuum chamber are covered with water-cooled and isolated from the chamber targets made of 2-mm-thick titanium sheets. The targets form a hollow cathode. In the hollow cathode there are an anode of stationary discharge connected with the grounded chamber, a substrate holder near the bottom and an additional anode near the top screened with a titanium band, all the three being inserted into the hollow cathode through the holes in the cylindrical target.

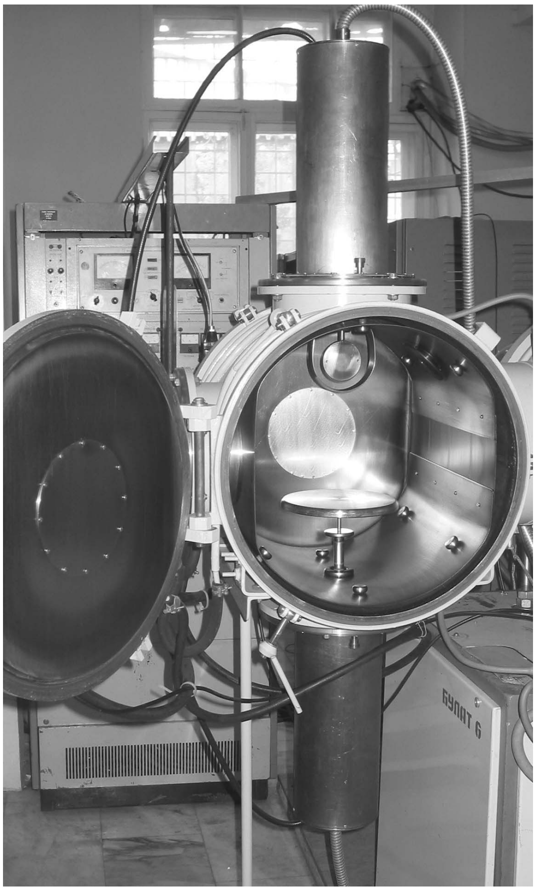

Fig. 1. Photograph of the experimental PIII-system

Electrical diagram is presented in the Fig. 2. Glow discharge with a constant current of ~ 1 A between the anode 1 and the hollow cathode 2 is being supported at argon pressure 0.05–0.5 Pa by the rectifier 3 with a capacitive filter connected through the resistor 4 of ~ 500-O resistance to the cathode 2. Capacitors 5 and 6 each of 0.05 μF are being charged through the resistors 7 of 75-kO resistance, the diodes 8 and through the resistors 9 of 700-O resistance from the high-voltage transformers 10.

When the voltage at the capacitor 6 reaches the breakdown value for one of two gaps of the three-electrode spark switch 11 connected to the capacitors 5 and 6 through solenoids 12 each of 8-mH inductance the current pulse of the capacitor 6 discharge induces a pulse of negative voltage drop through the resistor 9. Through a cable and a feed-through at the bottom of the chamber the pulse is applied to the substrate holder 13. Amplitude of the pulse may be adjusted by means of the gap width variation of the spark switch 11. Frequency may be adjusted by means of output voltage variation of the transformer 10. The maximum pulse frequency amounted to 25 Hz.

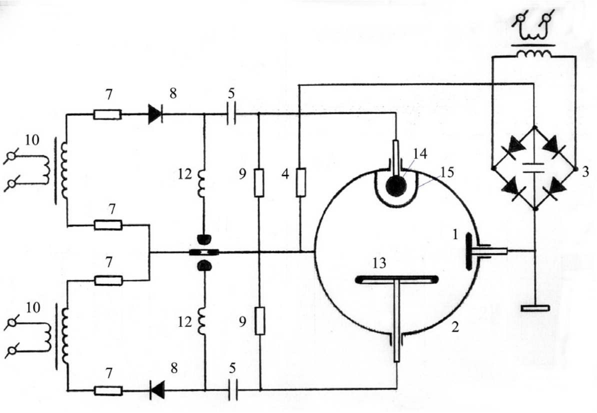

Fig. 2. Electrical diagram of the system: 1 – anode; 2 – hollow cathode; 3 – rectifier; 4, 7, 9 – resistors; 5, 6 – capacitors; 8 – diodes; 10 – high-voltage transformers; 11 – three-electrode spark switch; 12 – solenoids; 13 – substrate holder; 14 – additional anode; 15 – screen

Discharge in the second gap of the spark switch 11 is ignited by plasma penetrating from the first gap of the switch 11 through a hole in its central electrode connected to the hollow cathode 2. For this reason positive pulses are applied to the additional anode 14 when voltage at the capacitor 5 reaches only 70% of that at the capacitor 6. However the positive pulse delay amounts in this case dozens μs. After the ratio of the voltages exceeds 90% the delay is less than 1 μs. Two high-voltage pulses of equal amplitude and width are applied to the substrate holder (hatch curve 1 in the Fig. 4,a) and to the additional anode (hatch curve 2 in the Fig. 4,a) simultaneously.

4. Experimental Results

Application to the disc-shaped additional anode (Fig. 1) immersed in the plasma of 1-A stationary discharge in nitrogen at $p \sim 0.1$ Pa of positive 35-kV pulses results in sinusoidal ~ 100-A current pulses in the circuit of the additional anode. This current value and voltage between the anode 14 and the cathode 2 not exceeding several kV nearly correspond to a short L-C circuit. It means that at the surface area $S_a = 80\ \text{cm}^2$ of the anode 14 (Fig. 2) plasma density may rise faster than the current in the short L-C circuit. This fact first proves the above suggestion concerning the cascade multiplication of fast electrons in the sheath at $\Lambda > L$ and secondly makes the high-energy ion implantation impossible.

To solve the problem it is needed to increase the ratio Λ/L. For this purpose the disc-shaped additional anode has been replaced with rectangular 40-cm-long anode made of 2-mm-thick titanium strip parallel to the chamber axis. Another 3-cm-wide to 48-cm-long strip electrically connected to the hollow cathode has been placed under the anode, which should exclude bombardment of the additional anode by high-energy electrons emitted by the substrate. Hatch curves in the Fig. 3 present waveforms of the current in the anode circuit and full curves – of the voltage at the anode when high-voltage pulses are applied at nitrogen pressure 0.2 Pa. They correspond to anodes differing from each other with their width and area $S_a = 80$ cm^2 (1), 200 cm^2 (2), 400 cm^2 (3) and 800 cm^2 (4). For comparison the chain curve presents the waveform of voltage drop induced with discharge current of the capacitor 5 through the resistor 9 before the stationary discharge is ignited. Tenfold increase of the anode surface leads to tenfold rise of Λ/L and results in a decrease of the current amplitude from 90 A down to 50 A and in an increase of the voltage amplitude from ~ 3 kV up to 28 kV.

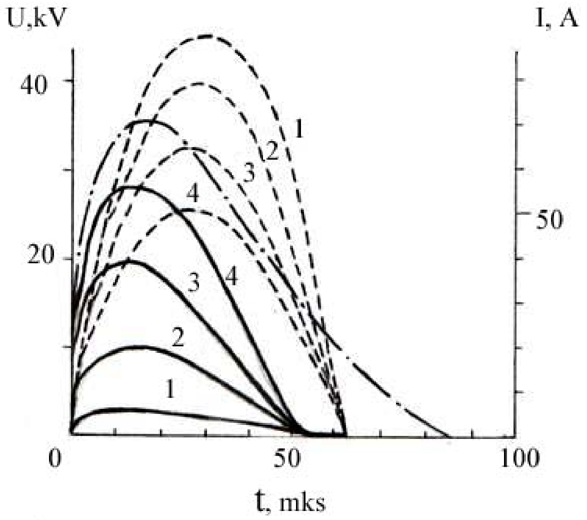

Fig. 3. Waveforms of the additional anode potential U and (full curves) and of the current I in its circuit (hatch curves) at nitrogen pressure 0.2 Pa and at additional anode area S_a = 80 (1), 200 (2), 400 (3) and 800 cm^2 (4)

In Fig. 4,a full curves present waveforms of the voltage pulses at the substrate holder (1) and at the additional anode (2) for $p = 0.2$ Pa and $S_a = 800$ cm^2 when both capacitors 5 and 6 are in operation. For comparison the hatch curves present the waveforms of voltage drops induced with discharge currents of the capacitors 5 and 6 through the resistors 9 before the stationary discharge is ignited. Waveforms in Fig. 4,b demonstrate reaction of the stationary low-density plasma to application of both voltage pulses. Within 20 µs current in the circuit of additional anode is rising from 1 A up to 50 A. Due to corresponding increase of plasma density and due to emission of secondary electrons current in the circuit of the substrate holder reaches 20 A. This value corresponds to ~ 10 mA/cm^2 current density of ions bombarding the holder with surface area of 700 cm^2.

Current variation in the circuit of the inductance in 60 µs results in the polarity change of the additional anode potential. Plasma potential is after that close to ground potential of the anode 1 (Fig. 2) and a reversed current of ~ 10-keV ions bombarding the additional anode and of secondary electrons reaches maximum value of ~ 8 A. In this stage the rest of energy is dissipated, which amounts to ~ 12% of the energy stored in the capacitor. The dashed curve in Fig. 4,a presents a dependence of potential difference between the plasma and the substrate holder on the time t.

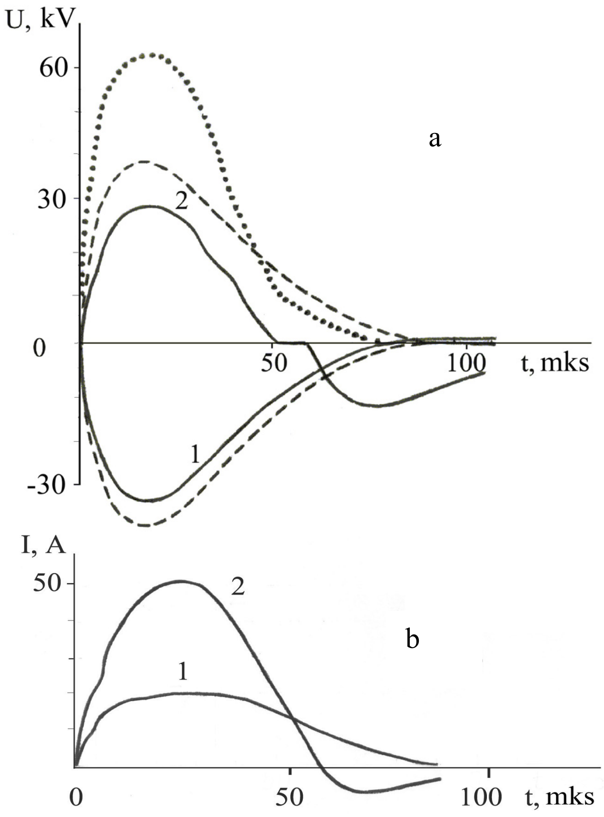

Fig. 4. a – waveforms of the substrate holder potential (1) and of the additional anode potential (2) at nitrogen pressure 0.2 Pa after stationary discharge is ignited (full curves) and before the ignition (hatch curves) as well as of the plasma-to-substrate potential (dashed curve); b – current waveforms in the circuits of the holder (1) and of the additional anode (2)

It shows that in the interval between 5 µs and 35 µs energy of singly charged ions bombarding the holder amounts to ~ 60 keV. The product of the 25-Hz pulse frequency and of the $3 \cdot 10^{-5}$ s interval shows that the total exposition time of the holder to 60-keV ions amounts to 3 seconds within 1 hour (3600 s). As the ion current density of 10 mA/cm^2 corresponds to implantation of $6 \cdot 10^{16}$ ions/cm^2 within 1 second it results in the dose rate of ~ $2 \cdot 10^{17}$ ions/cm^2 within one hour.

Estimates of the Child-Langmuir sheath near the substrate holder during the pulse result in the sheath width not exceeding several cm. For this reason there is no special need for big-sized chambers and also one order of magnitude higher gas pressure is acceptable in contrast to conventional PIII-systems.

As the substrate is only 3 seconds within one hour exposed to dense flows of high-energy particles and the rest of time is immersed in low-density plasma it is possible to treat the substrate at low temperature.

5. Conclusions

The above results experimentally proved possibility of a PIII-system development, which ensures a low level of X-rays yield. From technical, economical and ecological points of view they are indicative of the development expediency.

Multiplication of fast electrons in the cathode sheath plays a leading role in the high-voltage glow discharge with electrostatic confinement of electrons and is the reason of a rapid growth of plasma density, which may be regulated through variation of the anode area.

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