High-Frequency Short-Pulsed Metal Plasma-Immersion Ion Implantation Using Filtered DC Vacuum-Arc Plasma (Part I)[1]

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Abstract – An innovative concept in the development of advanced coating deposition and ion implantation method including an application of filtered DC metal plasma source and high-frequency short-pulsed negative bias voltage with a duty factor in the range 10÷99% are considered. The regularities of ion implantation and metal plasma deposition for metal samples are theoretically and experimentally investigated.

Experimentally has been shown that metal plasma based ion implantation as well as high-concentration metal plasma ion implantation with compensation of ion surface sputtering by metal plasma deposition as well as ion-assisted coating deposition can be realized by variation of bias potential ranging from 0 V to 4 kV, pulse repetition rate smoothly adjusted in the range (2÷4.4)·10^5 pps and pulse duration ranging from 0.5 to 2 μs. Special features of the material treatment method depending on plasma concentration, pulse repetition rate and duty factor has been examined.

1. Introduction

Plasma-immersion ion implantation (PI^3) using gas-discharge plasma was proposed in the works [1, 2] and investigated in detail in many other works for both pulsed and continuous plasma generation modes [3–9]. Much less amount of works are devoted to investigations of metal plasma immersion ion implantation (MPI^3) [10–19]. The regularities of attendant processes for high-concentration ion implantation regime with surface ion sputtering compensation by plasma deposition were investigated in [20–22]. The arc discharge was pulsed with duration from 50 up to 400 μs. Ion implantation was provided by DC voltage source and bias potential pulse duration was less than plasma generation pulse duration to realize the high-concentration ion implantation regime. Works [10, 20, 23] are devoted to various metal plasma deposition methods with repetitively-pulsed vacuum arc and negative bias potential application. Bias potential pulse duration was less than vacuum arc pulse duration (several microseconds order of magnitude). The treatment opportunity for internal surfaces of tubes with vacuum arc source and PI^3 application was demonstrated in [24]. It is shown that distribution of ion energy depends on pulse duration greatly.

The possibility of effective MPI^3 regimes application for coating deposition using DC vacuum arc was demonstrated in [25] for the case of relatively long-pulse repetitively-pulsed bias potential application (τ = 200 μs with repetition rate up to 200 pps).

Use of continuous metal plasma flows, especially cleaned of microparticles, for materials properties modification and coatings deposition with ion mixing is of the great interest of high-performance ion implantation and ion-assisted coating deposition methods development.

This work is devoted to investigation and development of ion streams formation processes, dynamics of near-electrode sheath alternation and ion power distribution modification, effect of bias potential pulse form, amplitude and duration on characteristics of ion stream formed during high-frequency metal plasma immersion ion implantation (HFMPI^3). Taking into account the opportunity of realization of high-concentration ion implantation and ion-assisted coating deposition on dielectric substrates, this work includes the consideration of processes accompanying the application of short-pulsed negative bias voltage with high repetition rate.

2. Physical Model of HFMPI^3

It is proposed, that plasma flow, formed by DC vacuum arc discharge, moves orderly towards sample holder with velocity $V = 2\cdot10^4$ m/s. Dielectric, semiconducting and conductive samples to be treated are set on metal holder. The physics of the processes, providing ion streams forming, differs for conductive and dielectric materials. When metallic samples are used, the load of pulsed bias potential generator has both capacitive and active components. Capacitive component has a place only at a period of transition, when accelerating gap enlarges up to stationary state defined by Child-Langmuir limit or by fixed distance between samples and plasma emission boundary (in case of plasma emission boundary limitation by grid electrode). Immersion ion implantation from metal plasma into metallic substrates, taking into account an active constituent of pulse generator load and the existence of plasma flow direct velocity, could be realized using DC, long-pulsed and short-pulsed bias potential at the holder and accordingly on the samples surface.

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There are two typical stages of accelerating gap evaluation near potential electrode immersed into plasma. First stage concerned with much greater electrons mobility in comparison with ions and lies in forming of "quick" sheath of electrode potential shielding from plasma by ion space charge. The ions are practically static during this stage. During the second stage the concentration of ions accelerated in near-electrode electric field are redistributing along the speed direction of ions. As a result the ion sheath width rises up to some stationary value determined by Child-Langmuir law. After the second stage completion the load current of generator is determined by ion emission current from plasma.

These processes are mixed for real pulses with finite pulse rise time. The electron component of ion current density is determined by plasma-emission boundary velocity during the rise of bias voltage:

$$j_{\mathrm{e}} = \bar{z} \cdot e \cdot n \cdot V_{\mathrm{bound}} \,,$$

where $\bar{z}$ – average ion charge state in plasma, e – electron charge, n – plasma concentration, V_{bound} – ion plasma-emission boundary velocity (the velocity of near potential electrode sheath expansion in plasma). The full current is determined by sum of electron displacement current, ion current and secondary-emission current:

$$j_{\Sigma} = \bar{z} \cdot e \cdot n \cdot (V_{\mathrm{pl}} + k \cdot V_{\mathrm{pl}} + V_{\mathrm{bound}}) \,,$$

where V_{pl} – the projection of plasma flow velocity on normal to potential electrode surface, k – the coefficient taking into account the secondary ion-electron and other types of emission. And the measurable value of current is

$$I_{\mathrm{mes}} = I_{\Sigma} + I_{\mathrm{c}} \,,$$

where I_{c} – the current of parasitic capacitances charge.

The situation changes when dielectric samples are used. If dielectric sample fully covers sample holder than active component of load is completely excluded and ion accelerating processes are determined by capacitive component only.

It is obvious that electric fields arising near the surface of dielectric when negative bias potential is applied to holder are determined by thickness and permittivity of dielectric, by dynamics of ions accumulation on the surface of the sample as well as by plasma and bias potential pulse parameters. If bias potential pulse is long and plasma density is relatively high than charging of dielectric can complete quick enough and all electric field will be concentrated only inside of capacitor composed of dielectric charged surface and potential electrode (holder). After that it will be no electric field outside of this capacitor, so it is unsuitable to use bias potential pulses with duration greater than dielectric surface charging time. Hence it is important to determine the parameters of plasma, dielectric sample and bias potential pulse required to realize energy-optimal regimes of PI^3 using DC vacuum-arc source generated metal plasma.

If plasma flow is continuous than electric field arise between plasma and charged surface of dielectric sample after switching off bias potential on holder. As a result not ions, but electrons are extracted from plasma. The current of electrons and their mobility are much greater then current and mobility of ions, so the surface charge compensation will happen almost instantly. Estimations show that charge compensation time does not exceed a few nanoseconds. This compensation time is of great importance since it is practically determine the allowable pulse duty factor for HFMPI^3 regimes realization. Use the microsecond duration pulses and possible pause duration, for example, allows to increase the pulse duty factor up to unity. On the other hand it means that for high $f\tau$ value (close to 1) not only plasma deposition using PI^3, but ordinary and high-concentration ion implantation may be realized.

3. The Experimental Installation and Investigation Technique

The scheme of experimental installation is shown in Fig. 1. Vacuum-arc evaporator (8) equipped with titanium cathode was used for continuous metal

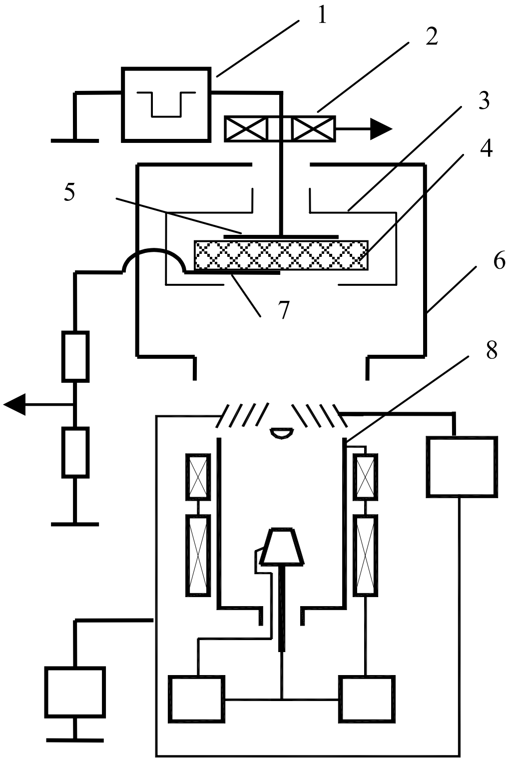


Fig. 1. The scheme of experimental installation: 1 – short-pulsed bias potential generator, 2 – Rogovsky coil, 3 – shield, 4 – target sample, 5 – potential electrode (sample holder), 6 – vacuum chamber, 7 – potentiometer, 8 – vacuum-arc plasma source equipped with shutter-type plasma filter

plasma flow generation. Shutter-type plasma filter [26] was used to remove microparticles from metal plasma flow. The glassceramic plates a one millimeter thick, window glass plates a four millimeter thick and metallic plates was used as samples. The samples were located at metallic holder (5). The generator (1) with pulse duration smoothly adjusted in the range 0.5÷2.5 μs, negative bias voltage amplitude from 0 V up to 3 kV and pulse duty factor smoothly adjusted in the range 0.2÷0.66 was used for bias potential supply on holder.

The circuit current was measured between sample holder and generator output by Rogovsky coil (2). The measurement of sample surface facing to vacuum-arc source output was realized by high-resistance divider (7) used as potentiometer.

The ion current on target in researches was controlled by sample holder move along plasma source axis and accordingly by variation of the distance between target and plasma filter output. The experimentally measured target ion current density, depending on filter output – sample surface distance, is shown in Fig. 2 for bias potential amplitude ranging from 100 to 500 V.

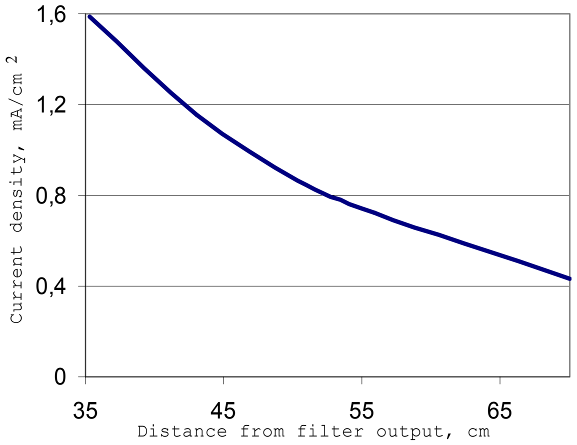


Fig. 2. Target ion current density depending on distance between target surface and plasma filter output

A number of experiments were carried out without plasma filter to get approximately twice plasma concentration and correspondingly twice target ion current density.

All investigations were made with pressure in vacuum chamber in the range (1÷5)·10^{-3} Pa.

The registration of current and voltage signals was made by 6-channel Le Croy oscilloscope.

4. Investigation of HFMPI^3 into Conductive Materials

Figure 3 shows bias potential waveforms for three different pulse durations. As follows from figure the rise and fall time does not depend on pulse duration. Fig. 4 demonstrates the waveform change for three different bias voltage amplitudes when potential electrode is immersed into plasma flow. Comparison of Figs. 3 and 4 points out some increase in pulse rise time for case of plasma-immersed potential electrode. It is connected with fast electron vacation of the near-electrode sheath with bias potential pulse application to the metallic target. The value of electron displacement current is big enough. It is congruent with output current of the generator and it result in the pulse rise time increase.

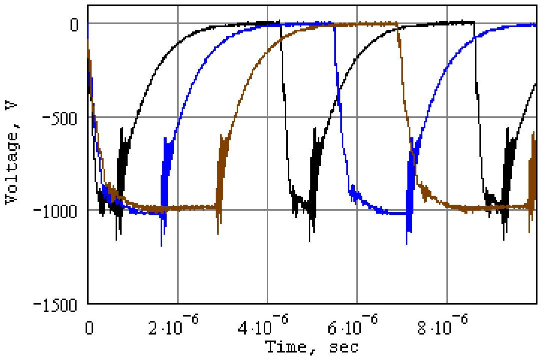


Fig. 3. Bias voltage waveforms for three different pulse duration

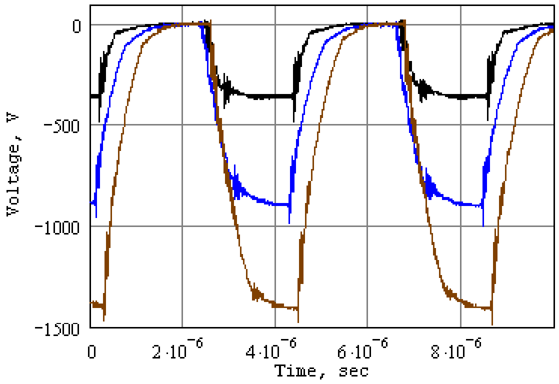
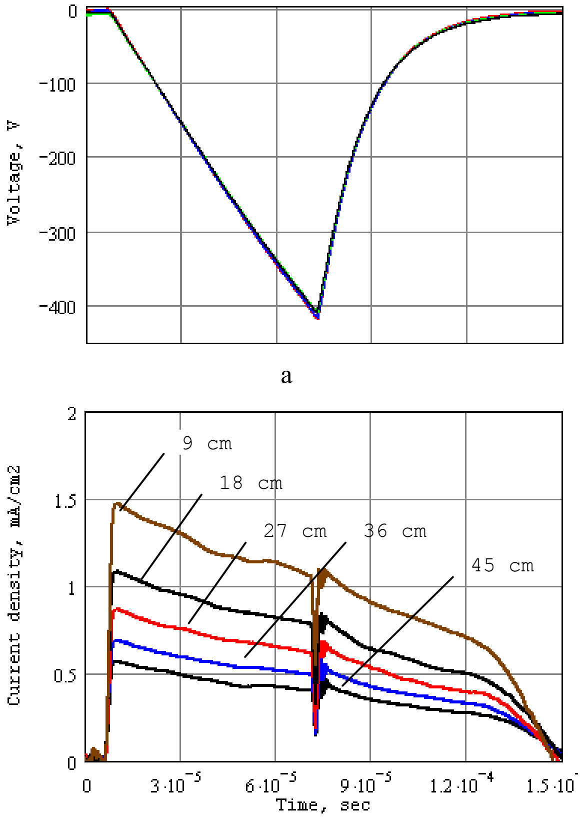


Fig. 4. Bias voltage waveforms for three different voltage amplitude

Attention should be drawn on the fact that ion current to the target exists within full pulse duration in spite of the negative signal presence in current oscillogram. Ion energy distribution was simulated in the work [27]. It was shown that ion energies are determined by waveform and weakly depend on transient processes in ion sheath for metallic target and pulse duration essentially exceeding the ion sheath expansion time (several microseconds order of magnitude).

The investigation of contribution of electron displacement current accompanying ion sheath evaluation was made using negative sawtooth voltage generator. The voltage and current waveforms for five different plasma concentration values are presented on Fig. 5,a,b. Plasma concentration was modified by variation of distance between filter output and potential electrode.

Current oscillograms are shown after deduction of parasitic capacities charge current which was measured for the same system without plasma flow. As evident from data presented in Fig. 2 the value of measured current with DC bias potential ranging from –100 V up to –500 V is constant while Fig. 5,b is demonstrated target current decrease with potential rise.



a

b

Fig. 5. Sawtooth bias voltage (a) and full diode current (b) waveforms for different distances from filter output (plasma concentration values)

On the other hand, there is no electron current spike during the rise time in this case. The current of electron displacement, of course, exists in this case too, but it is spaced alone whole pulse. The existence of this displacement current explains the decrease of full current on target with potential rise. It is connected with the fact that ion sheath width is approximately determined by Child-Langmuir law for constant ion current in concerned time scales:

$$h = \frac{U^{3/4}}{\sqrt{9\pi \cdot j_i}} \cdot \sqrt[4]{\frac{2 \cdot \bar{z} \cdot e}{m_i}}.$$

Here j_i is the current of ion extraction from plasma, m_i – ion mass, $\bar{z}$ – average ion charge state in plasma. The electron current contribution to the full current will decrease with voltage rise, as evident from the next formula:

$$j_e = \bar{z} \cdot e \cdot n \cdot V_{bound} = \bar{z} \cdot e \cdot n \cdot \frac{dh}{dt} = \\ = \frac{3 \cdot \bar{z} \cdot e \cdot n \cdot U_0}{4 \cdot \sqrt{9\pi \cdot j_i}} \cdot \sqrt[4]{\frac{2 \cdot \bar{z} \cdot e}{U \cdot m_i}}.$$

It is supposed that voltage rises linearly and can be expressed through the rise factor by formula

$$U(t) = U_0 \cdot t \Rightarrow \frac{dU}{dt} = U_0.$$

Given data allows to make a conclusion of the electron displacement current value control opportunity by variation of bias voltage pulse rise time.

The contribution of secondary ion-electron emission current to the full current can be estimated from data presented in Fig. 6. The curve is demonstrated smooth increase of measured ion current density from 1.58 to 2.3 mA/cm^2 with bias potential increase from 500 V to 2 kV.

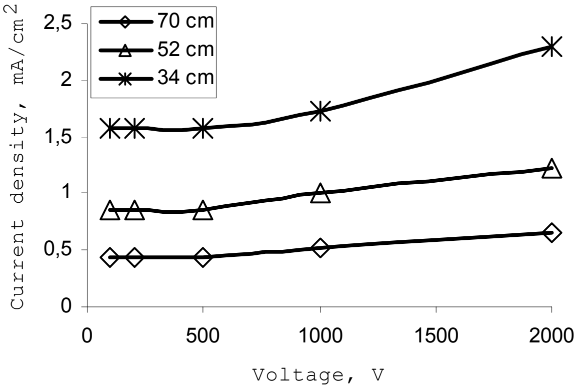


Fig. 6. Current density depending on bias potential applied

References

See the second part of the paper.