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

A.I. Ryabchikov, I.A. Ryabchikov, I.B. Stepanov

Nuclear Physics Institute at Tomsk Polytechnic University, 634034, Russia, Tomsk, Lenina st., 2a, alex@npi.tpu.ru

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 dielectric 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

This is the second part of the paper devoted to investigations of high-frequency metal plasma immersion ion implantation (HFMPI^3) using DC vacuum arc sources. Common regularities of attendant processes and special features of the metal samples treatment using HFMPI^3 were discussed in the first part. In this part the character of HFMPI^3 into dielectric samples and bipolar voltage application for HFMPI^3 are considered.

2. Investigation of HFMPI^3 into Dielectric Materials

In contrast to metallic targets case the character of processes near the target surface changes essentially when dielectric samples are used. It is well-known that DC bias potential application to the holder provides constant electric field near its surface which extracts ions from plasma and accelerates them towards the target. Otherwise, when DC bias potential applied to dielectric samples the acceleration lasts only for short period of time connected with target surface charge process. After that the charge stored on target surface are shielding bias potential of electrode from plasma and acceleration stops. So, the problem of the investigations was to examine the transient processes near the dielectric surface in short period of time after bias potential application on target.

The bias potential amplitude measured on sample surface without plasma flow increases in proportion with applied voltage while voltage pulse duration is about 2 μs. At the same time the bias potential value on dielectric sample surface is below then applied one. Difference is determined by dielectric qualities of the sample and by its thickness and values ranging from several percents to few tens of percents. The rest of voltage drop falls at vacuum gap between surface of the dielectric and wall of the vacuum chamber. The gap size in all experiments was tens of centimeters order of magnitude.

The situation changes distinctly, if dielectric sample is immersed into plasma. The waveforms of potentials measured on the surface of the glassceramic (a) and glass (b) samples for different distances from vacuum arc source output are shown in Fig. 1.

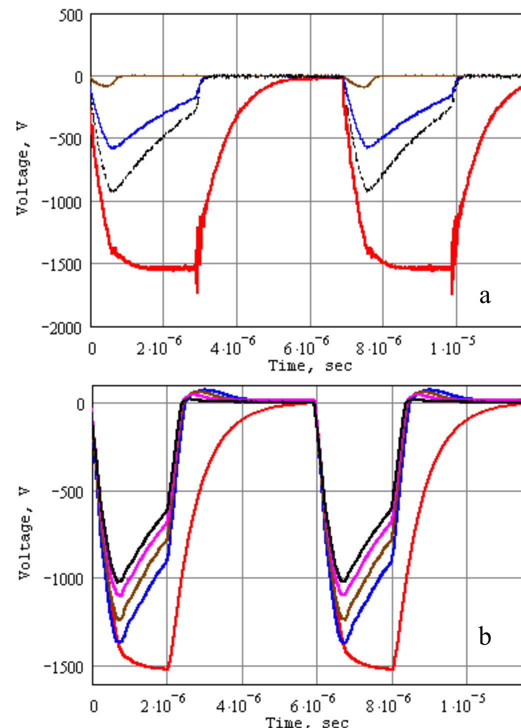

Fig. 1. Surface potential waveforms for glass (a) and glassceramic (b) samples for different plasma concentration values

[1] This work was supported by CRDF grant RR2-1030 and by Ministry of Education RF grant T02-07.5-1838.

The analysis of these data indicates that for ceramic samples with much greater capacity than the capacity of glass one, the potential on the target surface, that determines the accelerating voltage for ions, exists during whole pulse of applied bias potential. The potential of the surface amount to its maximum value during the applied potential rise time. Then the potential goes down steadily because of surface charge by extracted ions.

As evident from Fig. 1,b the same surface potential behavior is observed during the whole pulse for glass samples immersed into low-concentration plasma flow (the sample was placed on the long distance from plasma source output). If the value of the concentration is much greater because of greater ion flow density and the capacity of the dielectric sample is low enough then the surface of the sample charges completely during the pulse of applied voltage and there is no electric field outside of sample. So it's important to choose the proper relation between plasma characteristics and pulse duration and amplitude according to characteristics of given dielectric sample to realize the plasma-immersion ion implantation.

The current oscillogram for glassceramic sample (Fig. 2) indicates the existence of considerable capacitive current during the pulse rise time and practically constant ion current during the whole pulse. During the fall time reverse polarity current appears resulted from parasitic capacities discharge and compensation of stored on the sample surface positive charge by plasma electrons.

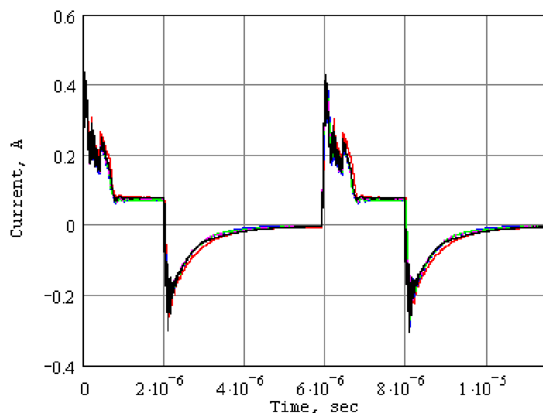

Fig. 2. Current waveforms for glassceramic sample

As the potential on the dielectric surface changes dynamically during the pulse of applied voltage, the energy distribution of ions tends to polyenergetic as opposed to metallic sample. Wholly polyenergetic energy distribution with energies of ions ranging from thermal to maximum, defined by maximum surface potential value and by ion maximum charge state, appears when the sample charging time is less then or equal to pulse duration (see Fig. 1,a).

As well as the width of the ion sheath depends not only on plasma concentration and sort of ions, but also on bias voltage value, the conditions of pure ion implantation into dielectric materials may be provided for different duty factor values ranging from 0.5 to 0.99.

While the potential of the target surface is zero the plasma deposition on sample surface occurs for dielectric samples just as for metallic samples. It means that the coating is deposited. The difference between dielectric and metallic samples in this point of view is the fact that in case of dielectric sample zero potential can occurs on surface even during the bias voltage pulse if the surface is charged, while in the case of metallic sample the potential of the surface defined by generator output voltage completely. Every subsequent bias voltage pulse provides ion mixing of the previously deposited coating.

If the thickness of coating deposited between pulses is approximate to the ion-sputtered during the pulse one the high-concentration ion implantation regime will be realized [20–22]. This regime is characterized by higher efficiency of the implanted doping accumulation in comparison with usual ion implantation.

The increase of duty factor leads to coatings growth rate decrease. Pure ion implantation is realized when pulse repetition rate is so high that pause between pulses is enough for accelerating gap filling by unperturbed plasma only.

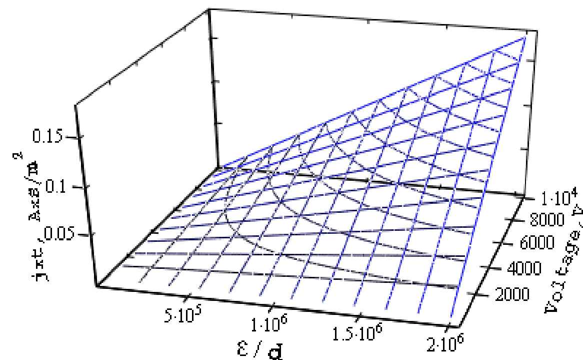

Fig. 3. Application area of HFMPI^3 method for dielectric samples treatment

Figure 3 demonstrates the application area of the HFMPI^3 method as applied to dielectric materials. The area of effective method use lies under the surface, defined by dielectric characteristics (by relation of dielectric permittivity and thickness of the sample), by bias voltage amplitude and by product of ion current density from plasma and pulse duration. The figure indicates that high-density plasma providing ion current density of hundreds of A/cm^2 order of magnitude can be used for modification of properties of dielectric targets with bias voltage pulse duration about tens or hundreds of nanoseconds as well as low-density plasma providing ion current density of tens or hundreds of μA/cm^2 order of magnitude, but pulse duration can be increased up to tens or hundreds of microseconds without efficiency decrease.

3. Investigation of HFMPI^3 Using Bipolar Sinusoidal Bias Potential

The scheme of the experiment is presented on Fig. 4. Investigations show that the processes on both samples are similar. The difference is in the temporal shift on half-cycle.

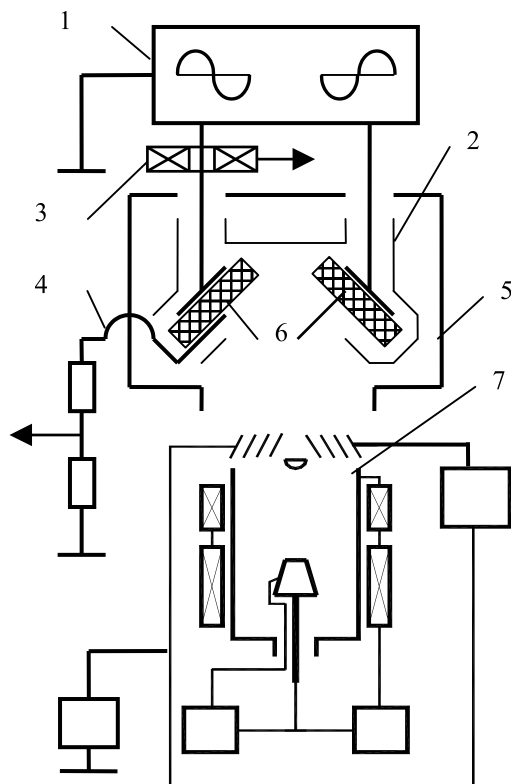

Fig. 4. The scheme of experimental installation: 1 – bipolar sinusoidal bias potential generator, 2 – shield, 3 – Rogovsky coil, 4 – potentiometer, 5 – vacuum chamber, 6 – target samples, 7 – vacuum-arc plasma source equipped with shutter-type plasma filter

The waveforms of generator output voltage and potential on surface of glassceramic target are shown in Fig. 5. As evident from figure the potential of the target surface is very similar to applied one during negative half-wave and has non-zero value during corresponding half-cycle. The amplitude of the surface potential is proportionate to applied bias voltage. Some deviations are resulted from special features of generator volt-ampere characteristic.

The experiments carried out using plasma filter in passive, magnetic-active and electromagnetic-active modes (different modes provides plasma concentrations differing in several times) didn't reveal any dependence between the surface potential waveform and plasma concentration.

The oscillograms of the target current reveal no appreciable current increase during the pulse rise time. It confirms the opportunity of full current amplitude control by bias potential waveform modification.

During the positive half-wave the potential of the surface was much lower than applied one. It can be described by high mobility of the plasma electrons.

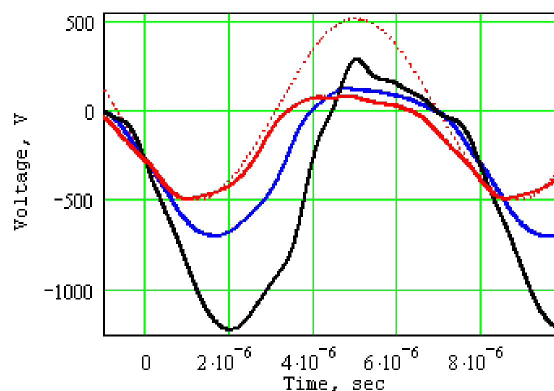

Fig. 5. Waveforms of the dielectric sample surface potential for different applied voltage amplitude and applied voltage waveform with amplitude 500 V (dot curve)

So, between two plasma-immersed samples the accelerating gap (ion sheath) forming by turns near the sample affected by negative half-wave.

On the whole the results of the investigations shows the opportunity of bipolar pulses application for HFMPI^3 into dielectric and conductive materials.

4. Conclusion

As a result of the HFMPI^3 investigation complex carried out using different generator types and sample materials following conclusions can be made:

1. HFMPI^3 can be realized into conductive and dielectric materials equally.
2. Short-pulsed bias potential provides accelerating gap formation near the surface of dielectric. The voltage drop falling at this gap are congruent with applied one.
3. The charge stored on dielectric surface is compensated by plasma electrons after applied potential falls. It creates the necessary prerequisites for development of methods of nonconducting and conductive coatings deposition.
4. Unipolar and bipolar bias potential pulses and particularly high frequency alternative voltage can equally be used to realize HFMPI^3 into metallic and dielectric samples.
5. The value of the full current to the target can be controlled by the bias voltage pulse rise rate variation for the case of metallic target as well as for the case of dielectric one.
6. Energy distribution of ions tends to the polyenergetic type for dielectric targets.
7. Variation of duty factor allows to realize different regimes of material treatment:

a) plasma deposition with ion mixing;

b) high-concentration ion implantation with compensation of ion sputtering by metal plasma deposition;

c) usual polyenergetic ion implantation.

8. Ion implantation into dielectrics is accompanied by stored charge compensation after every bias potential pulse.

References

[1] J. Conrad, J. Appl. Phys. **62**, 777 (1987).
[2] J.R. Conrad, R.A. Dodd, F.J. Worzala, X. Qiu, Surf. Coat. Technol. **36**, 927 (1988).
[3] T. Sheng, S.B. Felch, C.B. Cooper, J. Vac. Sci. Technol. **B12**, 969 (1994).
[4] J.B. Liu, S.S. Iyer, R. Gronsky, C. Hu, N.W. Cheung, Appl. Phys. Lett. **67**, 2361 (1995).
[5] M. Nastasi, A.A. Elmoursi, R.J. Faehl et al., *Mater. Res. Soc. Symp. Proc.* **396**, 455 (1996).
[6] K. Holmberg, A. Matthews, *Coatings Tribology: Properties, Techniques and Applications in Surface Engeneering*, Amsterdam, Elsevier, 1994, p. 53.
[7] S.-H. Lin, B.J. Feldman, D. Li, Appl. Phys. Lett. **69**, 2373 (1996).
[8] K.C. Walter, M. Nastasi, N.P. Baker et al., Surf. Coat. Technol. **103–104**, 205 (1998).
[9] R. Günzel, J. Brutscher, S. Mändl, W. Möller, Surf. Coat. Technol. **96**, 16 (1997).
[10] I.G. Brown, A. Anders, M.R. Dickinson, R.A. MacGill, O.R. Monteiro, Surf. Coat. Technol. **112**, 271 (1999).
[11] I.G. Brown, X. Godechot, K.M. Yu, Appl. Phys. Lett. **58**, 1392 (1991).
[12] A. Anders, Surf. Coat. Technol. **93**, 157 (1997).
[13] H. Wang, S.P. Wong, W.Q. Li, M.F. Chiah, C.Y. Poon, W.Y. Cheung, N. Ke, Thin Solid Films **405**, 304 (2002).
[14] M. Sano, K. Yukimura, T. Maruyama et al., Nucl. Instr. and Meth. in Phys. Res. **B 148**, 37 (1999).
[15] Weidong Yu, Lifang Xia, Yue Sun et al., Surf. Coat. Technol. **128–129**, 240 (2000).
[16] Z.M. Zeng, T. Zhang, B.Y. Tang, X.B. Tian, P.K. Chu, Surf. Coat. Technol. **115**, 234 (1999).
[17] H.H. Tong, O.R. Monteiro, R.A. MacGill, I.G. Brown, G.F. Yin, J.M. Luo, Curr. Appl. Phys. **1**, 197 (2001).
[18] Bin Liu, B.Y. Jiang, Y. Fu, D.J. Cheng, X.F. Wu, S.Z. Yang, Thin Solid Films **349**, 110 (1999).
[19] David M. Sanders, André Anders, Surf. Coat. Technol. **133–134**, 78 (2000).
[20] A.I. Ryabchikov, R.A. Nasyrov, Nucl. Instr. and Meth. in Phys. Res. **B61**, 48 (1991).
[21] A.I. Ryabchikov, R.A. Nasyrov, Poverhnost **3**, 98 (1992) (Russian).
[22] A.I. Ryabchikov, S.V. Dektyarev, I.B. Stepanov, Izvestia Vuzov Physics **2**, 82 (1994) (Russian).
[23] T. Zhang, B.Y. Tang, Z.M. Zeng et al, *Surf. Coat. Technol.* **128–129**, 231 (2000).
[24] A.I. Ryabchikov, *Diss. Doct. Ph.-Mat. Sc.*, Tomsk, Russia, 1993.
[25] A.I. Ryabchikov, Surf. Coat. Technol. **96**, 9 (1997).
[26] A.I. Ryabchikov, I.B. Stepanov et al., *in: Proc. of the 5th Conf. on Modif. of Mat. with Part. Beams and Plasma Flows,* Tomsk, Russia, 2000, pp. 460–463.
[27] A.I. Ryabchikov, I.A. Ryabchikov, *in: Proc. of the 6th International Conference on Modification of Materials with Partical Beams and Plasma Flows. Proc.,* 2002, pp. 578–582.