https://doi.org/10.46813/2023-145-103

STUDY OF VACUUM HIGH-GRADIENT BREAKDOWNS FROM THE ION-MODIFIED SURFACE OF COPPER ELECTRODES

V.A. Baturin, A.Yu. Karpenko, S.O. Lebedynskyi, O.Yu. Roenko, S.O. Eryomin, O.P. Novak, R.I. Kholodov
Institute of Applied Physics NASU, Sumy, Ukraine
E-mail: lebos@nas.gov.ua

The influence on the resistance to high-voltage breakdown of samples irradiated with double-charged copper ions Cu^{2+} with an energy of 300 keV and different irradiation doses was studied. It is experimentally shown that when irradiating a copper electrode with Cu^{2+} ions, the values of breakdown characteristics improve by 17…28% with increasing irradiation dose. A theoretical study of the effect of material defects such as pores on the emission current was carried out. It is shown that the field emission current from the metal surface near nano-objects has a vibrational resonance feature. The resonance condition is determined by the depth of the nanoscale void from the metal surface. If the resonance conditions are not met or if the size of the defects increases, the emission current decreases rapidly.

PACS: 52.80.Mg; 52.80.Vp; 79.70.+q

INTRODUCTION

In recent years, the Institute of Applied Physics of NASU has been studying the possibility of reducing the probability of high-voltage high-vacuum breakdowns in accelerator structures of modern ion/electron accelerators in order to increase their electrical strength at electric field gradients above 100 MV/m. This work involves testing materials used in the production of RF structures, usually high-purity copper. To achieve higher electric field gradients in RF accelerator structures, it is necessary to reduce both the probability of breakdowns and the magnitude of dark currents. Assuming that one of the factors affecting high-vacuum breakdowns is the surface properties of the electrode material, we proposed to consider the possibility of improving the resistance of the electrodes of accelerating structures to high-vacuum breakdowns by modifying their surface. The ways of such modification can be the application of thin-film coatings on the surface of electrodes or irradiation of the surface with ions. The CLIC project being developed at CERN will use high-frequency power supply in the X-band (12 GHz). At this frequency, the skin layer is 0.6 µm, so the proposed thicknesses of the modified layers should not exceed the skin layer thickness.

We consider the possibility of treating materials by ion implantation methods to increase the electrical strength of accelerator structures by developing radiation defects and intermetallic inclusions in the surface layers of the material of accelerator structures in order to significantly reduce the dark current and, consequently, increase the resistance to high-voltage breakdowns.

In this work, we experimentally and theoretically investigate the effect of the development of radiation-induced defects in the surface layers of the material used to process the structural materials of accelerator structures in order to target changes in their surface properties so as to improve their resistance to vacuum breakdowns and at the same time determine the optimal parameters of the required ion-plasma surface treatment of these structures.

1. EXPERIMENTAL STUDY OF THE MODIFIED SURFACE OF COPPER ELECTRODE

The experiments were aimed at studying the effect of surface modification of copper samples, which leads to the formation of radiation-induced defects, on the probability of breakdowns, as well as determining the degree of this modification when a noticeable effect occurs. Samples of copper with a low content of impurities were taken as materials for the experiments. The anode was a copper rod. The surface under study was subjected to mechanical grinding and polishing after the samples were made. Next, the samples were subjected to a cleaning procedure, in the form of high temperature annealing in a vacuum and glow discharge treatment. Irradiation of the samples with ions was carried out in such a way that half of the sample surface was modified, and the other half remained unchanged. This made it possible to determine the effect of ion-beam surface treatment on the probability of breakdowns compared to the surface that was not subjected to such treatment on the same samples.

1.1. ION IMPLANTATION

The samples were processed to study the effect of radiation-induced defects formed in the near-surface layers during ion irradiation of the material on the resistance to vacuum breakdown and on the value of the field emission current using ion implantation.

Earlier, we showed the possibility of increasing the breakdown voltage on copper cathode samples when they were implanted with gas ions [1]. At this stage, our goal is to study the effect of radiation damage occurring during implantation in the near surface layer on the breakdown resistance of copper samples. The copper samples were irradiated with double-charged copper ions. The ion-beam treatment of the samples was carried out on a high-dose implanter of the IAP NASU, which allows irradiating samples with single or double-charged ions with energies up to 300 keV [2]. To exclude the possibility that the introduction of foreign atoms into the surface layer of the samples could affect their properties, copper ions were chosen as the implanted material, which were implanted into the surface layers of copper samples at three different doses. Subsequently, these samples were further investigated at the breakdown test facility [3]. These samples played the role of cathode in the discharge gap. Copper rods were used as the anode.

Implantation parameters and penetration characteristics for samples

№	Cathode	Anode	Irradiation parameters for samples			The ratio of dark currents I/I_{Cu}	Ratio of the breakdown voltage of coated copper to the breakdown voltage of pure copper: U/U(Cu)		
			Type of ions	Dose D, ions/cm^2	Energy E, keV		Appearance of dark current	Breakdowns occurring	Breakdown
99	Cu	Cu	Cu+	$7\cdot10^{15}$	300	<1	0.75	1.01	1.01
102	Cu	Cu	Cu+	$1.3\cdot10^{16}$	300	~1	1.28	1.06	1.05
103	Cu	Cu	Cu+	$3.5\cdot10^{16}$	300	>1	1.27	1.24	1.09

1.2. EXPERIMENTAL TECHNIQUE

The methodology for conducting experimental studies is described in detail in [4]. In each experiment, the following criteria were used to compare the breakdown resistance of the modified surface of the samples in relation to the unmodified one: the voltage at which the prebreakdown current occurs, the voltage at which microbreakdowns occur, and the voltage of the final breakdown. The dependence of the pre-breakdown current on the voltage was also determined. It is worth noting that the probability of breakdowns is affected by a number of different reasons: the magnitude and type of applied voltage, electrode conditions, residual vacuum, the size of the interelectrode gap, etc. Therefore, the key in these studies is not the absolute values of breakdown voltages, but the comparison of values in the case of modified and unmodified sample surfaces.

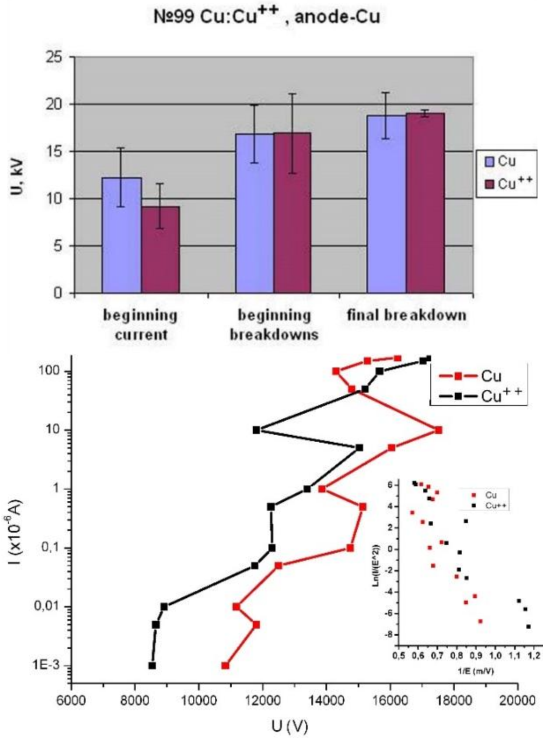


Fig. 1. Breakdown characteristics for samples irradiated with Cu^{2+} ions with an irradiation dose of $D=7\cdot10^{15}$ cm^{-2} in conventional and Fowler-Nordheim coordinates

Therefore, the surface of each prepared sample was divided into two parts. One part of the surface was modified, and the other part was not affected in any way. The experiments were conducted at many points on the surface of the samples to reduce the influence of differences in the degree of processing and surface cleanliness or the presence of local surface defects. Subsequently, the results were averaged separately for the modified and unmodified parts of the surface.

1.3. IRRADIATION BY Cu^{2+} IONS

To study the effect of radiation-induced defects in the surface layers of copper on its resistance to vacuum breakdown, copper samples were irradiated with two-charged copper ions at three different irradiation doses. The use of copper ions eliminated the influence of impurity atoms that can be introduced during irradiation and made it possible to study the effect of only the degree of defectiveness of the surface layers on the breakdown characteristics. Table shows the irradiation modes of the samples and the parameters of their penetration characteristics.

The study of copper samples for resistance to breakdowns when irradiated with Cu^{2+} ions with an irradiation dose of $D=7\cdot10^{15}$ cm^{-2} showed (Fig. 1) that the voltages at which breakdowns occur and the final breakdown voltage are comparable to those on pure copper, and the voltages at which breakdown currents occur are worse than for pure copper.

For the pre-breakdown current curves, the curve on the implanted samples has worse performance than on pure copper, and only at currents corresponding to tens of milliamperes does the curve shift to a hundred times higher voltage at equal currents, compared to the curve for pure copper.

An increase in the irradiation dose with copper ions to $D=1.3\cdot10^{16}$ cm^{-2} led to an increase in the voltage at which pre-breakdown currents occur, the voltage of breakdown appearance and the voltage of final breakdown on the irradiated surface, compared to pure copper. Fig. 2 shows the pre-breakdown current curves become comparable on implanted and non-implanted surfaces.

As a result of increasing the irradiation dose to $D=3.5\cdot10^{16}$ cm^{-2}, only the ratio of pre-breakdown currents changed. Fig. 3 shows the dark current curve on the irradiated surface was directed towards higher voltages.

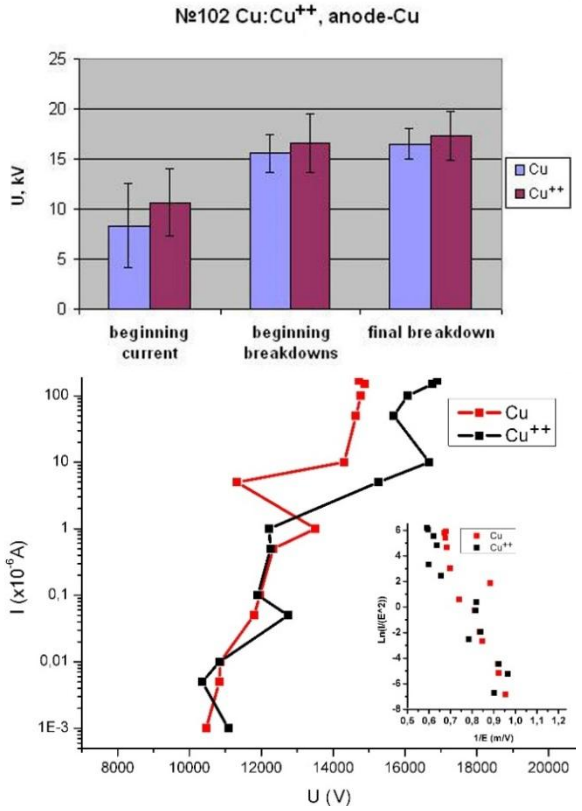


Fig. 2. Breakdown characteristics for samples irradiated with Cu^{2+} ions with an irradiation dose of $D=1.3\cdot10^{16}$ cm^{-2} in conventional and Fowler-Nordheim coordinates

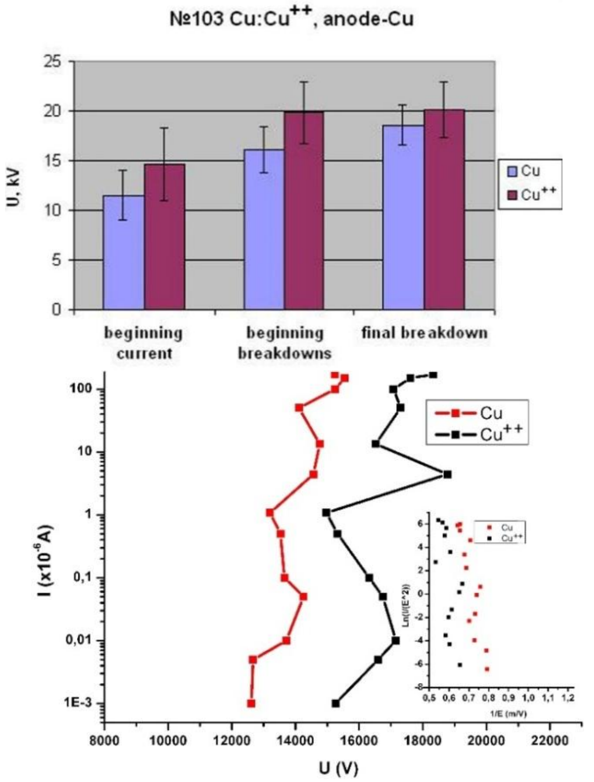
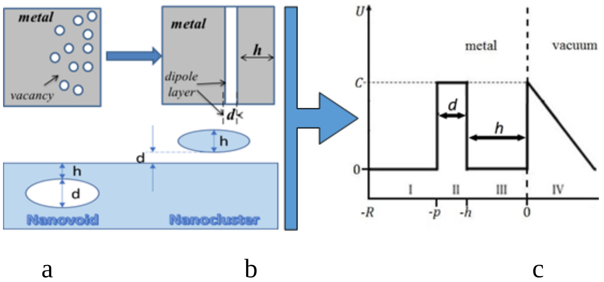


Fig. 3. Breakdown characteristics for samples irradiated with Cu^{2+} ions with an irradiation dose of $D=3.5\cdot10^{16}$ cm^{-2} in conventional and Fowler-Nordheim coordinates

Thus, the irradiation of the copper surface with two-charged copper ions for the development of radiation defects showed the following. For experiments with a copper anode, at low doses of irradiation, the characteristics of pre-breakdown currents deteriorate, and the voltage of pre-breakdown currents becomes lower. With an increase in the irradiation dose, and hence an increase in the number of accumulated defects in the near-surface layers of the samples, these values become appropriate and, with a further increase in the dose, significantly improve on the irradiated surface. The final breakdown voltage also increases.

2. THEORETICAL STUDIES OF THE INFLUENCE OF PORES IN THE METAL SURFACE LAYER ON THE FIELD EMISSION CURRENT DENSITY

One of the types of radiation defects formed during irradiation is pores. That is why we have conducted theoretical studies of the effect of such defects on the field electron emission current, which is one of the initial factors of high-voltage breakdowns When considering defects in the near-surface layer of a metal electrode, it is advisable to use two-barrier potential models. Fig. 4,a schematically depicts pores that arise as a result of surface modification, for example, under the influence of ion irradiation. This potential barrier model also allows us to take into account another class of defects: nanoclusters of several nanometers in size on the surface of a metal electrode. If there is a nanoscale void in the metal surface layer, the model represents h as the distance from the metal-vacuum interface to the location of the nanoscale void in the metal surface layer, and d as the diameter of the nanoscale void. If the nanocluster is located on the metal surface, then the barrier parameters can be explained as h is the size of the nanocluster, and d is the thickness of the dipole layer of the metal-metal contact. In the following, for convenience, we will consider pores in the near-surface layer, but all calculations will be valid for nanoclusters as well.



a b c

Fig. 4. Model of formation of nanoscale defects in the metal surface layer: a – nanopores in the surface layer; b – nanoclusters on the surface; c – scheme of a double potential barrier describing these defects

In Fig. 4,c, region I is the internal region of the metal, regions II and III are the regions of metal modification, and region IV is the potential barrier at the metal-vacuum interface. The effect on the current density of field emission of vacancies and pores of angstrom sizes formed during irradiation of the metal surface is taken into account by introducing the effective thickness of the dipole layer d, which is the sum of the volumes of all formed defects and voids of the modified surface (see Fig. 4,a,b).

In general, the formula for finding the current density of field electron emission is as follows:

$$j = \int_0^{\mu} N(W)D(W)dW, \tag{1}$$

where $N(W)$ is the number of electrons falling on the surface of a unit area per unit time with kinetic energy W normal to the surface, $D(W)$ coefficient of electron tunneling through the potential barrier. In the case of a perfectly smooth surface, this current was found by Fowler and Nordheim [5] and is equal to:

$$j_{F\_N} = A(eE)^2 \exp\left(-\frac{B}{eE}\right), \tag{2}$$

where A and B constants depending on metal properties.

To find the field electron emission current taking into account nanoscale defects in the near-surface metal layer j_{mod}, we found the electron tunneling coefficient through the potential barrier shown in Fig. 4,c. The tunneling coefficient in the case of a double potential barrier is

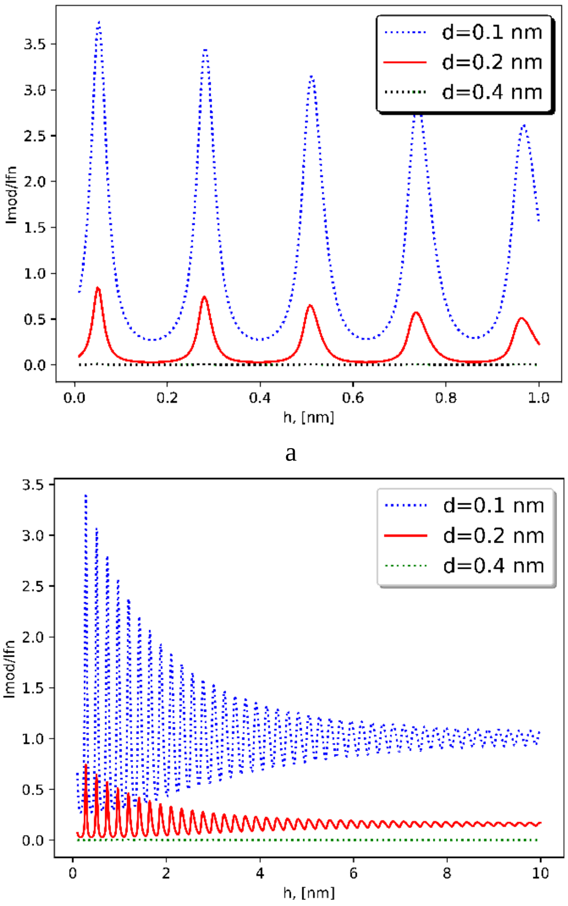
$$D = \frac{16(C-W)^{3/2}W^{3/2}e^{-\frac{4k(C-W)^{3/2}}{3eE}}e^{-2k\sqrt{C-W}d}}{C\left(2\sqrt{W}\sqrt{C-W}cos(k\sqrt{W}h)+(C-2W)sin(k\sqrt{W}h)\right)^2}, \tag{3}$$

where C is a height of the potential barrier, W is an electron energy, $-e$ is an electron charge, E is an electric field strength, m is an electron mass, $k = \frac{\sqrt{2m}}{\hbar}$. From expression (3), it can be seen that the current will have a resonant character. The condition of the tunneling coefficient maximum [6] is

$$h = \frac{\lambda_B}{4}(2n+1), n = 0,1,2,..., \tag{4}$$

where $\lambda_B = \frac{\sqrt{2}\pi\hbar}{\sqrt{mW}}$ is the de Broglie wavelength for the electron. It is also evident from formula (3) that the current should decay exponentially with increasing defect size d. In the case of no defects ($d = h = 0$), expression (3) takes the form of the known tunneling coefficient from a smooth metal surface [5].

We have numerically calculated the field emission current density from the modified metal surface j_{mod} using formula (1). A comparison of the values of the field emission current density from the surface with nanocavities in the near-surface layer of the metal j_{mod} and the current from the idealized metal surface j_{F-N} is shown in Fig. 5. It shows the ratio of the current from the modified surface to the current from the ideal surface for different defect sizes d and their depth h at a constant value of the local electric field strength $E_{loc} = 5\,{}^{GV}\!/_{m}$. This value was chosen as the average value of the local intensity during high-vacuum breakdown experiments, since the planned intensity of the CLIC accelerator is $E = 100\,{}^{MV}\!/_{m}$, and the field gain is usually in the range of $\beta = 30 \ldots 140$ [7]. Fig. 5,a shows the current ratio in the case of pores located at a depth of 0 to 1 nm. Fig. 5,b shows a similar dependence for h in the range from 0 to 10 nm. From these figures, the current density from the modified surface has a resonant character. The maximum current density j_{mod} is more than 3 times higher than j_{F-N}. It can also be concluded that with an increase in h, the current density fluctuations decrease. The largest value of the current density as a function of h has the first maximum at the point $h = \frac{\lambda_B}{4}$, which is like the method of applying an anti-reflective coating to optical lenses [8]. However, in non-resonant regions, the current density from the modified surface decreases to almost zero. Also, the current density decreases significantly with increasing pore diameter d and increasing h.



a

b

Fig. 5. Comparison of the values of the field emission current density j_{mod} and j_{F-N} depending on d and h: a – for h=0…1 nm; b – for h=0…10 nm

Fig. 6 shows a color map of the dependence of the current from the modified surface expressed in units of Fowler-Nordheim current as a function of the size of the vacuum gap d and the thickness of the metal layer h at a constant value of the local electric field strength

$$E_{loc} = 5\,{}^{GV}\!/_{m}.$$

From the figure, it can be concluded that the current does indeed have a resonant periodic character that does not depend on the size of the defect d. The maximum values of the current, which is amplified up to 3.5 times, as well as in the case of the maximums of the tunneling coefficient (4), are repeated with a period corresponding to the de Broglie wavelength (5).

It is also worth noting that in the case when the size of the defects (or their effective size) is $d > 0.2\,nm$, a decrease in the field electron emission current from the modified surface should be observed, regardless of their depth. Therefore, surface modification, which leads to the formation of nanopores in the near-surface layer of the material, may indeed be one of the ways to increase the resistance of materials of accelerator structures to breakdowns.

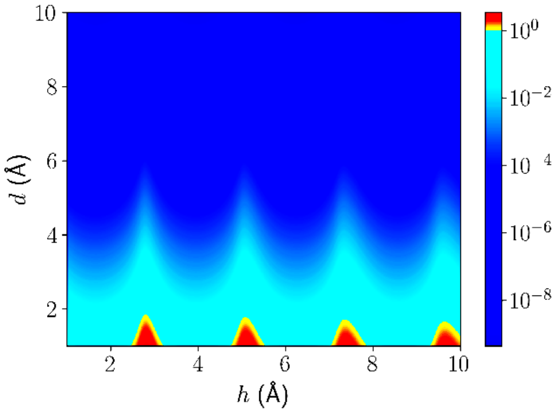


Fig. 6. Graphical dependences of the current from the modified surface as a function of pore size d and metal layer thickness h

SUMMARY

The influence of radiation-induced defects on the resistance to vacuum breakdowns was experimentally investigated. The main parameters of the breakdown characteristics studied for these samples were determined, which include the voltages between the electrodes at which dark currents appear, the voltages at which micro breakdowns occur, and the voltages at which the final breakdown occurs. These parameters are averaged values for a set of experimental points on the sample and are determined for two types of sample surfaces: modified and unmodified copper sample surfaces.

Irradiation with Cu^{2+} ions has shown that with an increase in the irradiation dose, and hence an increase in the number of developed defects in the near-surface layers of the samples, various values of the breakdown characteristics improve by 17…28%.

It has been shown that the field emission current from the metal surface near nanopores has an oscillatory resonance feature. The resonance condition is determined by the depth of the nanoscale void from the metal surface, which is a multiple of $h = \frac{\lambda_B}{4}$.

It is found that when the resonance conditions are met, the density of the field emission current from the copper surface increases by more than 3 times compared to the current from the unmodified surface. In the case of failure to fulfill the resonance conditions or an increase in the diameter of the nanopores, the current density decreases to almost zero.

ACKNOWLEDGEMENTS

The work was performed within the framework of the Targeted Research Program of the National Academy of Sciences of Ukraine “Participation in the latest international projects in high-energy and nuclear physics” for 2021-2023, grant No. II-48-21.

REFERENCES

1. V.A. Baturin, A.Yu. Karpenko, V.E. Storizhko, V.A. Shutko. Investigation of Coper Samples with Ion-Plasma treatment on High Voltage Breakdowns // *Problems of Atomic Science and Technology.* 2018, №4(116), p. 298-301.
2. V.A. Baturin, S.A. Yeryomin, S.A. Pustovoytov, et al. Generation and Formation of Metal Ion Beams on High-Dose Ion Implanter // *Problems of Atomic Science and Technology. Series “Physics of Radiation Effect and Radiation Materials Science”.* 2015, №2(96), p. 204-209.
3. V.A. Baturin, O.Yu. Karpenko, Ia.V. Profatilova, S.O. Pustovoitov, V.I. Miroshnichenko. The experimental setup for high voltage breakdown studies in the high vacuum // *Problems of Atomic Science and Technology.* 2015, №4(98), p. 294-297.
4. V.A. Baturin, A.Yu. Karpenko, S.A. Yeryomin. Development and experimental studies of methods for increasing the stability of materials of accelerating structures to high vacuum electrical discharges // *Problems of Atomic Science and Technology.* 2019, №6(124), p. 23-26.
5. R.H. Fowler, L. Nordheim. Electron emission in intense electric fields // *Proceedings of the Royal Society of London. Series A.* 1928, v. 119, №781, p. 173-181.
6. I.I. Musiienko, S.O. Lebedynskyi, R.I. Kholodov. Nanoclusters and nanoscale voids as possible sources of increasing dark current in high-gradient vacuum breakdown // *The European Physical Journal D.* 2022, v. 76(4), p. 1-10.
7. A. Descoeudres, Y. Levinsen, S. Calatroni, M. Taborelli, W. Wuensch. Investigation of the dc vacuum breakdown mechanism // *Phys. Rev. ST Accel. Beams.* 2009, v. 12, №9, p. 092001-0920011.
8. G.S. Landsberg. Elementary-textbook on physics // *Atomic and Nuclear Physics.* 1989, v. 3.

Article received 18.04.2023

ДОСЛІДЖЕННЯ ВАКУУМНИХ ВИСОКОГРАДІЄНТНИХ ПРОБОЇВ З ІОННО-МОДИФІКОВАНОЇ ПОВЕРХНІ МІДНИХ ЕЛЕКТРОДІВ

В.А. Батурін, О.Ю. Карпенко, С.О. Лебединський, О.Ю. Роєнко, С.О. Єрьомін, О.П. Новак, Р.І. Холодов

Проведено дослідження впливу на стійкість до високовольтних пробоїв зразків, опромінених двозарядними іонами міді Cu^{2+} з енергією 300 кеВ та різною дозою опромінення. Експериментально показано, що при опроміненні мідного електроду іонами Cu^{2+} при збільшенні дози опромінення значення характеристик пробою покращуються на 17…28%. Проведено теоретичне дослідження впливу таких дефектів матеріалу, як пори на емісійний струм. Показано, що польовий емісійний струм з поверхні металу поблизу нанооб'єктів має коливально-резонансну особливість. Умова резонансу визначається глибиною нанорозмірної пустоти від поверхні металу. У випадку невиконання резонансних умов або збільшення розмірів дефектів емісійний струм стрімко зменшується.