Concerning Electrical Breakdown in Vacuum

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Abstract – Material characteristics versus the number of electrons in the valence atom shell not used in the previously published papers are presented here. The electric field interaction with the collective electrons and the ion skeletons of the electrode material result in the initiation of the plasma formation (ecton) on the surface of one of the electrodes and the breakdown of the interelectrode gap.

Material characteristics versus the number of electrons in valence atom shells not used in the papers published earlier are presented here.

The result of the electric field interaction with collective electrons and ion frames of electrode material atoms in vacuum is appearance of a plasma formation (ecton) on the surface of one of the electrodes and breakdown of an interelectrode gap.

Connections of thermophysical characteristics of metals, arc discharge characteristics in vacuum, characteristics of discharge cathode plasma with the number of electrons in valence shells of the cathode metal atoms N_{VE} are presented in [1, 2]. In [1, 2] there were used the data for polycrystalline metals. Results from different sources are presented widely. Hence, we present a possibility for specialists to be convinced if necessary in the objectivity of the data stated in [1, 2], to exclude possible misrepresentations of information. In this paper, we adhere to the analogous approach.

Connection of a static breakdown voltage UBR with N_{VE} for different electrode materials is shown in Fig. 1. Values of U_{BR} were obtained in a uniform field created by polycrystalline material electrodes [3]. Materials with the crystals consisting of sheet structures (C) or primitive three-dimensional arrays (Sn, In, Bi) have low U_{BR}. Spread in values of U_{BR} in materials with the same N_{VE} is stipulated by not only the difference of the crystalline structures but also by electron configuration of valence atom shells forming a crystal. Hence, C and Ti, Sn and Pb differ simultaneously both in a crystalline structure and electron configuration of valence atom shells. But Ta and Nb, W and Mo have a body-centered cubic lattice while Zn and Cd have face-centered close-packed crystalline lattices and differ only by electron configurations of valence atom shells. The significance of configuration of valence atom shells of a cathode material in a bimetallic effect is demonstrated in [4].

Figure 2 presents the work function of cathode matter atoms φ_a versus N_{VE} for more than 50 metals.

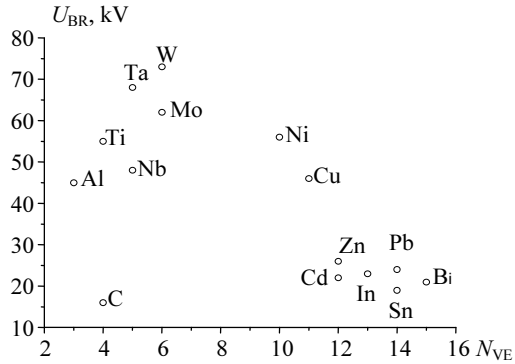

Fig. 1. Static break-down voltage in vacuum with the cathodes made of materials with different number of electrons in valence shells

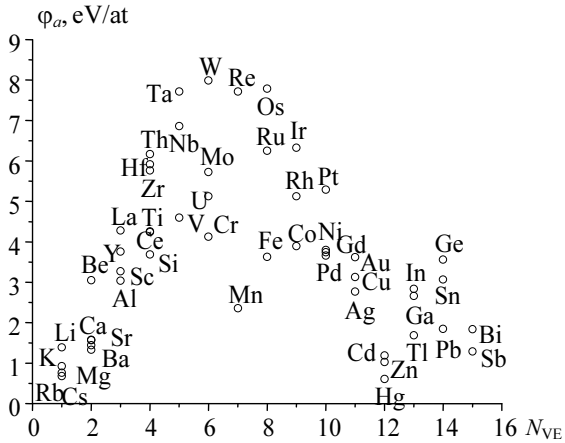

Fig. 2. Work function of atoms of materials with different number of electrons in valence shells

Values of energy necessary to eliminate one atom from the metal surface are taken as φ. Fig. 3 shows the dependence of the electron work function φ_e of metals with different N_{VE} [5]. Dependence φ_e (N_{VE}) differs from dependence φ_a (N_{VE}). Fig. 4 presents the ratio φ_e/φ_a of metals with the same N_{VE}. Metals settled below a dotted line in Fig. 4 both in pure form and in the form of compounds are used, as a rule, as hot cathodes. The number of atoms in the unit of volume of these metals n_a is larger than that of the metals placed upper the dotted line (Fig. 5).

Useful information concerning electrical breakdown can be obtained from the results of investigations of the secondary ion emission of metals being subjected to the ion beam bombardment. At the ion bombardment of metals the cathode sputtering of its surface occurs. The sputtering products are neutral atoms and ions [6, 7].

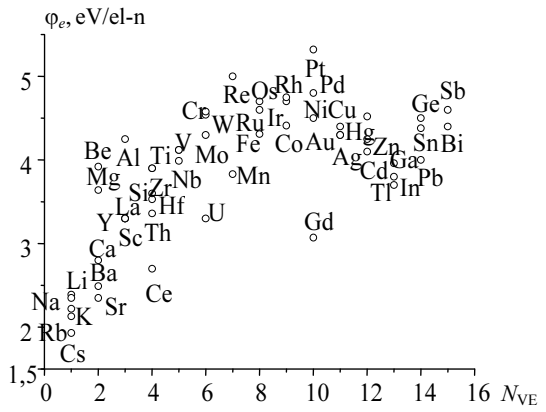

Fig. 3. Work functions of an electron from the surface of materials with different number of electrons in valence shells

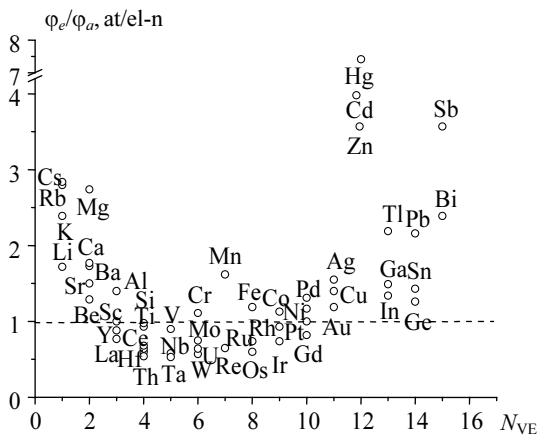

Fig. 4. Ratio of the work function of electrons to the work function of atoms of different materials

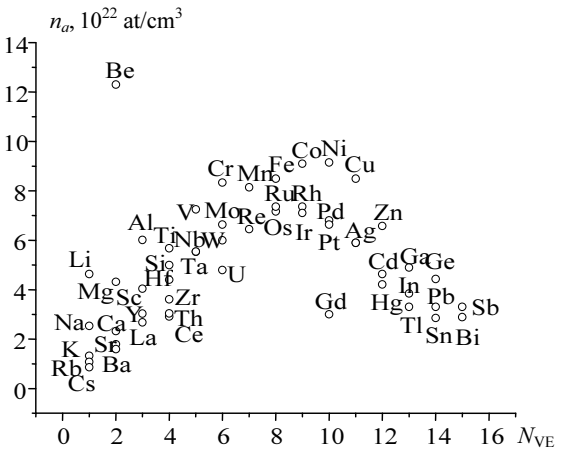

Fig. 5. Number of atoms (ions) in a unit value of materials versus the number of electrons in valence shells

The degree of ionization of the sputtering products α depends on N_{VE} of the atoms of the sputtered material [6]. Fig. 6 is plotted by the data presented in [7]. In difference with the author [7] who tried to connect α with ($U_i - \varphi_e$) and failed to find a correlation between these values (U_i is the atom ionization potential), connection of α with N_{VE} is obvious. Comparison of Figs. 3 and 6 clearly shows that the degree of ionization of the metal sputtering products drops at the ion bombardment at the increase of φ_e. The ionization potential U_i has no essential importance in the degree of ionizations of the sputtering products α. The reason is that even in the initial state a metal consists of a system of positively charged ions, the system stability being provided by collectivized electrons [8].

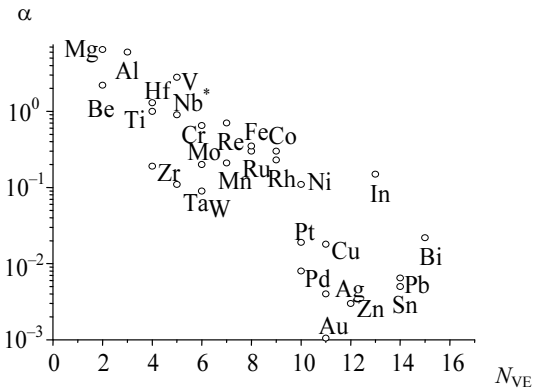

Fig. 6. Degree of ionization of the cathode sputtering products versus the number of electrons in valence shells of sputtered materials. In [7], Fig. 1.21, Ni is presented by two values of α. This is, evidently, a misprint. Nb corresponds to the larger value of α (judging by the difference of $u_i - \varphi_e$)

However, current flowing disturbs the system stability. In a closed dc electric circuit of high density, Schwarz observed a displacement of the conductor material from anode to cathode up to the circuit break near the anode [9]. The authors [10] observed a directed drift of ions, boundaries of crystal grains and dislocations at the high-density current flowing. The papers devoted to isotope separation at the dc transmission through liquid metals are well known as well [11]. In case the electrons binding the ion at a metal surface with neighboring ions are eliminated, a coulomb explosion will occur. The ion will be ejected from the metal surface wit the rate corresponding to the temperature of $10^5 \div 10^6$ K. But such temperatures of the discharge gap electrons have not been found out. Thermal evaporation occurs owing to the fact that temperature rise results in increase of the ion oscillation amplitude in the crystal lattice points. The distance x between the ions increases. At $x \to x_{cr}$ some bounds between the ions break down and binding electrons are released. The value of x_{cr} becomes equal to the order of a double constant lattice. At $x \geq x_{cr}$ the number of broken ties exceeds the number of the unbroken ones. If metal heating is made in the electric field accelerating the electrons, then thermoemission current reaches an inadmissible large value and the cathode is destroyed.

Figure 7 presents the fragments of conditional crystal lattices of the anode and cathode metal in a prebreakdown state. Under the field influence the

length of the bonds between ions increases till the greater part of the bonds exceeds x_{cr}. This will occur when the external field E_{ex} reaches the value higher than the intracrystalline field E_{ic}. Electrons released during the bonds breakdown will rush toward the anode. The ion that lost the bonds with the neighboring ions will rush towards the anode as well. The electrons are moving in the accelerating field. The ion is moving in a braking field under the influence of a pulse obtained from the ions that are still hold by the cathode. This is the way of ecton origin. If a formed ecton becomes able for self-reproducing, then the gap breakdown takes place. For a formed ecton $en_iv_i = 4\gamma j_0$. This ratio results from the experimental data.

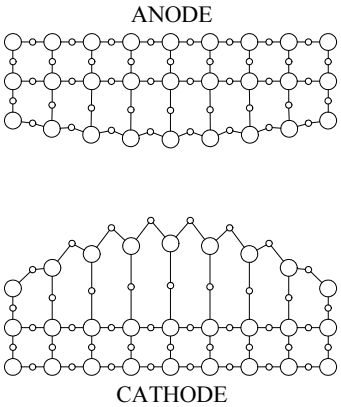

Fig. 7. To the mechanism of appearance of cathode and anode ectons, ∘ – electron; ○ – ion

A polycrystalline electrode consists of many fine chaotically oriented grains. Planes of various crystallographic orientations and with various density of atomic (ion) packing appear on the electrode surface. The most close-packed are the planes with small Miller indices but not always with the least ones [12]. These planes have the highest work function φ_e, the shortest distance between ions, the least transparency for the external field E_{ex}, the highest strength of the intracrystalline field E_{ic}. An ecton is generated at the crystallographic planes having the minimum packing density. All boundary parts of the electrode surface are formed by crystallographic planes with higher packing density, higher work function φ_e, and higher E_{ic}. Hence, ecton yielding outside the boundary of the plane on which it was initially formed is impossible without increasing E_{ex}. In the presence of the formed ecton the role of E_{ex} is realized via cathode decline in potential U_c. Ecton transition from one crystallographic plane to another is depicted at the oscillograms of U_c in the form of potential oscillations.

Anode ectons are formed in the fields of E_{ex} having larger strength than the cathode ones. Therefore, anode ectons appear only in nonunifom fields that are created in the gaps with the anode in the form of a point and a flat or hemispherical cathode. Minimal value of the field E_{ex}, strength necessary to excite the anode ecton at a room temperature is approximately equal to $5 \cdot 10^8$ V/cm. Appearance of the anode ecton is most probable at the crystallographic planes with a small E_{ic}. For example, according to the packing density, the planes of Mo are disposed in the following order: (111), (112), (100), (110) [7]. Ecton appearance is most probable at the facet (111). Here, the facets made of Mo are emitting four-charge ions [13].

It is possible to reach the anode ecton excitation by increasing the metal temperature by means of external heating at a fixed sufficiently high interelectrode potential (thermostimulated excitation of ecton) or by a potential increase up to a certain threshold value U_{cr}. In both cases, ecton appearance is accompanied by the ion current step to a several orders of magnitude and self-heating of the emitter is observed [14]. After ecton excitation, current rise corresponds to the potential increase exceeding U_{cr}. The potential can be decreased to $U_{min} < U_{cr}$. Below U_{min} ecton ceases its functioning. At $U_{min} < U < U_{cr}$, potential decrease up to zero and its subsequent recovery up to the former value on the expiry of the time 10^{-8} s do not result in the emission renewing [15].

The authors [16] first used the potential inversion for cathode ecton excitation and subsequent extraction and acceleration of ions from this ecton. In [17] this method was used to obtain ions in the gap with a liquid-metal capillary filled with Ga-In-Sn alloy. It is shown that ecton keeps its ability to self-reproduction during an interval between the pulse exciting the ecton and the pulse extracting ions from it ranging from 0 ns (as in [16]) to 180 ns. Here, the charge transferred by the ions can exceed by an order of magnitude the charge transferred by electrons at the ecton excitation. Solely cathode or solely anode ectons are unable to provide the breakdown development into a spark and then into an arc stage. This is possible only at the appearance of both cathode and anode ectons.

References

[1] E.N. Abdullin, G.P. Bazhenov. Yu.P. Bazhenov, and A.V. Morozov, *in Proc. 13th Int. Symp. on High Current Electronics*, 2004, pp. 105–108.

[2] E.N. Abdullin, G.P. Bazhenov, Yu.P. Bazhenov, and A.V. Morozov, *in Proc. 8th Int. Conf. on Plasma Physics and Plasma Technology* **1**, 2003, pp. 96–99.

[3] G.A. Mesyats, *Ectons in a vacuum discharge: breakdown, spark*, Moscow, Nauka, 2000, p. 41.

[4] E.N. Abdullin, G.P. Bazhenov. Yu.P. Bazhenov, and A.V. Morozov, *in Proc. 13th Int. Symp. on High Current Electronics*, 2006, pp. 86–88.

[5] R. Shampe, *Physics and techniques of electrovacuum devices*, Vol. 2, Moscow–Leningrad, Energiya, 1964, p. 62.

[6] N.V. Pleshivtsev, *Cathode sputtering*, Moscow, Atomizdat, 1968, p. 113.

[7] V.I. Veksler, *Secondary ion emission of metals*, Moscow, Nauka, 1978, p. 178.
[8] N.B. Brandt and S.M. Chudinov, *Electrons and phonons in metals*, Moscow, Publishing house of Moscow State Univ., 1990, p. 11.
[9] H. Schwarz, Cit. by N.I. Lazarenko, *Electric-spark metal treatment*, Moscow, Publishing house of AS USSR, 1957, p.74.
[10] A.M. Ionov, U.V. Kopetsky, and L.K. Fionova, Physics of metals and metal research **42**, 710 (1976).
[11] S.E. Breslerand G.E. Pikus, Zh. Tekh. Fiz. **26**, 109 (1956).
[12] I.V. Radchenko, *Molecular physics*, Moscow, Nauka, 1965, p. 267.
[13] D. Woodrough and T. Delcher, *Modern methods of surface research*, Moscow, Mir, 1989, 444 pp.
[14] M.D. Gabovich, Uspekhi Fiz. Nauk **140**, 138 (1983).
[15] M.D. Gabovich, A.S. Zyuzya, Yu.N. Kozyrev, and M.B. Fenik, *in Proc. 4th All-Union Symp. on High Current Electronics* (abstracts of papers) 1986, 1, pp. 17–19.
[16] E.I. Logachev, G.E. Remnev, and Yu.P. Usov, Pis'ma Zh. Tekh. Fiz. **6**, 1404 (1980).
[17] M.A. Polyakov, G.N. Fursey, and L.A. Shirochin, *in Proc. 7th All-Union Symp. on High Current Electronics* **2** (abstracts of papers), 1988, pp. 272–274.