Cathode Material Transformation into Discharge Plasma in Explosive Electron Emission

E.N. Abdullin, G.P. Bazhenov, Yu.P. Bazhenov, A.V. Morozov

Institute of High Current Electronics SB RAS, 4, Akademichesky ave., 634055 Tomsk, Russia
phone 3822-491913, fax 7-3822-492410, abdullin@lhfe.hcei.tsc.ru

Abstract – A mechanism for the direct transformation of the emission center (EC) material into the discharge plasma is suggested. In the condensed state, the EC material is an ion skeleton immersed into a medium of collectivized electrons. The electrical neutrality of the EC material can be violated due to the high current density and the microscopic dimensions of the EC. The Coulomb interaction of excess charges q_+ explodes the EC. The immediate transformation of the EC material into the discharge plasma occurs at the expense of the energy of the Coulomb interaction of the ion skeleton charges on the background of the Joule heating of the material. The Joule heating of the cathode is responsible for the slow decrease in the average charge of the discharge plasma ions with the discharge duration increase.

In the condensed state a cathode matter is electrically neutral. The inter-ion ties are realized through valence electrons being on external atom electronic shells. The least combined electrons are free and can move in the whole volume of a metal. Practically all valence electrons can be considered as free owing to both little width of valence zones and overlapping the ones with the zone of conductivity [1].

The physical properties of the chemical elements are determined by the structure of the atom electronic shells. The data of specific heat of evaporation $A{\cdot}\Delta H_{\text{evapor}}$ of metals versus a number of valence electrons N_{ve} are presented in Fig. 1,a. It is seen that presented values are arranged along a curve with a maximum at $N_{\text{ve}} = 6$. The increase of $A{\cdot}\Delta H_{\text{evapor}}$ at $N_{\text{ve}} = (1–5)$ is related with bonds number increase. The decrease of $A{\cdot}\Delta H_{\text{evapor}}$ is related with presence of detergent orbitals at large N_{ve} values. The metals with $N_{\text{ve}} = 6$ have a large value of the bond energy and belong to number of high strength materials.

The vacuum arc discharge characteristics such as the threshold current I_0, the cathode drop of potential U_{c}, the velocity of d/t_{c} (t_{c} is the commutation time of the discharge gap with the length d), the highest charge of ions recorded in the cathode plasma $n^+_{\max}$ versus N_{ve} have the analogous shape (Fig. 1) [2]. The data for plotting the dependencies were adopted from [3–7]. It is seen that the cathode drop U_{c} is determined not by ionization potentials of a cathode metal in the gas phase but rather its mechanical strength in the solid phase. In contrast to the presented data, the specific erosion of cathode materials in the vacuum arc γ versus N_{ve} (Fig. 1,f) in atom/e (atoms per electron) units has minimum at $N_{\text{ve}} = 6$. Thereupon one can draw a conclusion that all mentioned discharge characteristics are related in a large degree to the properties of the cathode matter in a solid state.

In the report, a scheme of the direct transformation of the cathode material into the discharge plasma is proposed that can be formed under conditions of the excess positive charge in the emission center with high current densities.

Atoms in a solid and liquid metal are ionized, valence electrons of atoms are collectivized. At the distances equal to inter-ion ones there exist intracrystalline fields $E_{\text{in}} \geq 10^8$ V/cm created by ions and collectivized electrons. The potential energy W_{p} of the ion interaction with collectivized electrons compensates forces of mutual electrostatic repulsion of positive ions. At metal temperatures up to the melting ones the kinetic ion energy is $W_{\text{k}} < |W_{\text{p}}|$. Ions having $W_{\text{k}} > |W_{\text{p}}|$ overcome forces of bounding with the metal surface and leave it. The energy $W_{\text{k}} > |W_{\text{p}}|$ can be imparted to ions by means of metal heating, metal surface bombardment with the ions having the energy of $W_{\text{k}} \geq 10$ eV.

Creation of the external electric field E_{ext} at a metal surface breaks the balance of electrons and ions interaction forces. The field E_{ext} accelerating ions causes field emission of ions from the metal surface. Increase of E_{ext} results in the ion current increase. There exists a critical value E_{ext} at which the ion current increases stepwise by several orders of magnitude and glowing appears near the metal surface. Field emission of ions passes into a stage known as "field evaporation". The field evaporation zone radius is evaluated in the limits of $10^{-7} \div 10^{-6}$ cm. Minimum value of E_{ext} necessary for field evaporation makes up $5{\cdot}10^8$ V/cm [8] and decreases with the metal temperature increase. Surface density of elementary positive charges $\sigma = 5.53{\cdot}10^{14}$ cm^{-2} corresponds to the field $E_{\text{ext}} = 5{\cdot}10^8$ V/cm, forces of ion repulsion are not compensated, metal surface explodes. The electric field E_{ext} accelerating electrons causes field emission of electrons that is finished with the metal surface explosion as well, generation of glowing at a metal surface, transmission of a field emission into explosive electron emission (EEE) [9].

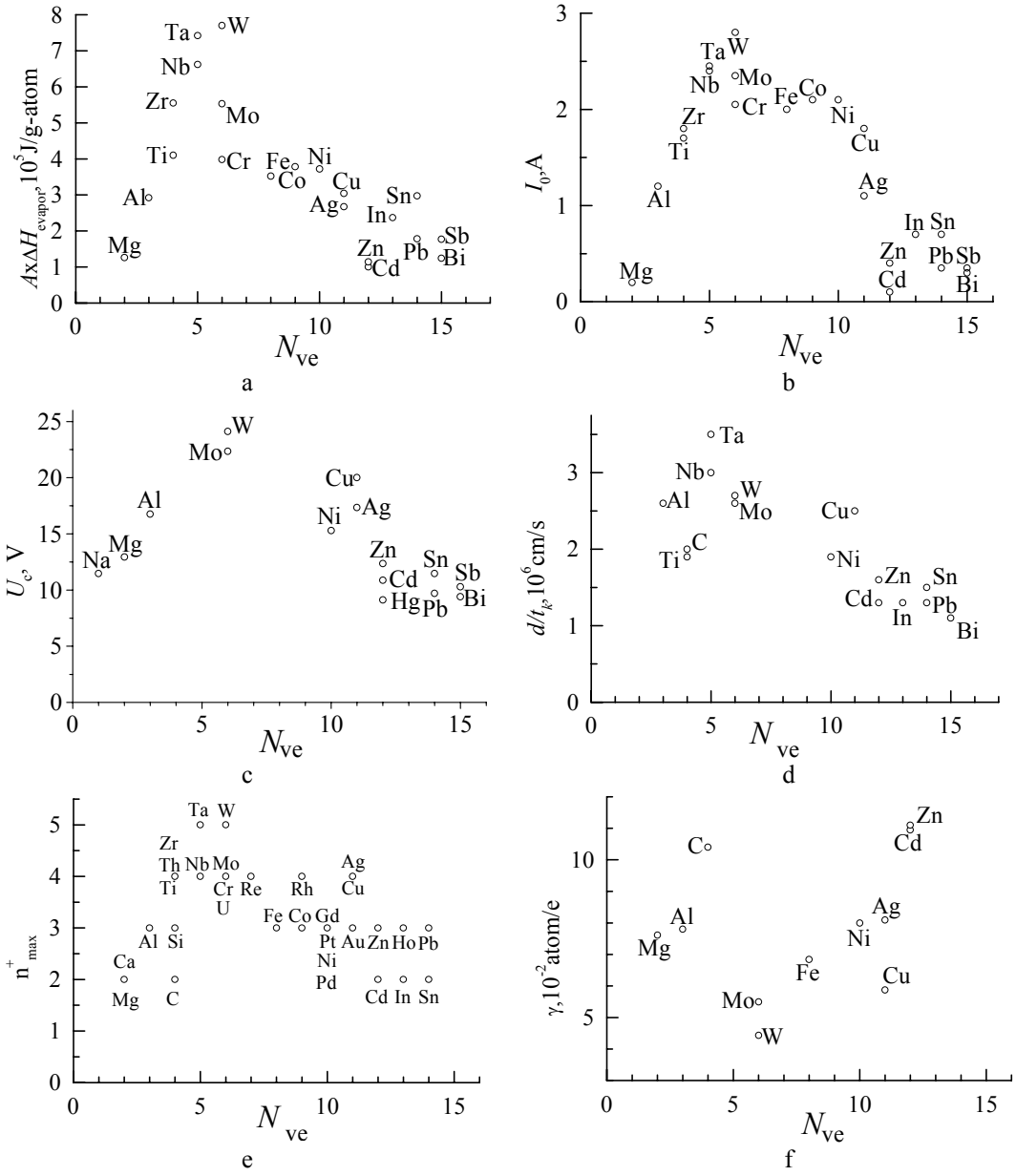

Fig. 1

Field emission current heats a metal, provides thermal activation of EEE. Both field evaporation and EEE are the result of surface explosion of the metal interacting with an electric field.

State and velocity of particles obtained by means of evaporation, ion bombardment and metal surface explosion are different. The main part of particles of any metal evaporated or knocked with ion bombardment consists of neutral atoms. Explosion products of any metal are relic plasma of a condensed metal. The velocity of atoms evaporating from the copper surface heated to 1500 K makes up $7.88 \cdot 10^4$ cm/s; the velocity of atoms knocked from the copper surface with Kr^+ ions accelerated to the energy of 900 eV equals to $4.77 \cdot 10^5$ cm/s [10]. The velocity of ions incoming from the copper cathode surface during the EEE process makes up $2.5 \cdot 10^6$ cm/s [5]. The velocity of the ions that are evaporated from the metal surface at its heating or knocked from the metal surface at the accelerated ion bombardment is small. Ions entrain valence electrons providing ion bond with the surface. Electrons recombine with ions and neutral metal ions are formed. Work function of the neutral metal atom φ_A does not exceed 10 eV and is comparable with the work function of the electron φ_e. Work function of the metal ion is $\varphi_e > \varphi_a$.

The field $E_{ext} \geq E_{in}$ withdraws a potential barrier on the metal surface, opens free outlet to metal particles beyond the surface boundaries. The notion of work function loses its sense, the metal "dissolves" in the field E_{ext}. The metal surface isn't uniform. Due to microscopic roughness of the surface the local fields E_{ext}

can differ sufficiently from the average value and owing to defects of a crystal array the local fields E_{in} can also essentially differ from the average value. Therefore, a potential barrier is withdrawn not on the whole surface but only in microscopic parts with the lowest E_{in} and highest E_{ext}. If the field E_{ext} accelerates electrons, then a layer of positively charged ions is formed on the metal surface. Ion field involves into acceleration the next layer electron, forms a new layer of positively charged ions. Simultaneously, layer destruction takes place owing to electrostatic repulsion. EEE excites, a cathode spot (CS) appears. Flowing current heats the cathode, the CS surface state changes. The CS surface state change results in its properties change as well. Three types of CS are distinguished. In a CS I, solid metal transforms into discharge plasma omitting melting, evaporation, ionization of metal vapour. In a CS II, discharge plasma is formed from a melted metal omitting evaporation and vapor ionization. A CS II corresponds to situation when a part of valence electrons is captured with the ions evaporating from the melted surface. The ion charge is decreased but the process has an explosion character since particle scattering velocity is determined by Coulomb repulsion of ions but not the cathode spot temperature. Thermal processes occur in parallel to EEE (Fig. 2).

To sustain EEE, it is necessary to provide constant resumption of a layer of positively charged ions on the metal surface. If a new layer isn't formed instead of the decayed one, then EEE is stopped, a CS dies. The field $E_{ext} \geq E_{in}$ is necessary to form the first layer and to initiate EEE. Each subsequent layer is formed due to the ion field of the previous layer. But this is possible if a discharge circuit is capable to accept electrons leaving the forming layer. The condition of EEE self-maintenance is the circuit capability to transmit threshold current I_0. Electron deficit in decay products of the cathode metal reveals itself with cathode drop of the potential U_0. An important characteristic of EEE is consumption of the cathode matter γ for EEE maintenance.

The range of experimental values of γ is spread from $\sim 10^{-2}$ atom/e to tens of atom/e [7, 11–13]. In conditions of EEE, a CS emits oppositely charged particles that on the whole carry no electric charge (plasma). That means that the cathode emits as many electrons to each ion emitted by a CS as it is necessary for ion neutralization. Then $\gamma \leq 1$. If $\gamma > 1$, then cathode erosion is conditioned by not only EEE but also by evaporation, splashing of liquid metal drops, and ejection of solid microparticles of the cathode material. Lower limit of γ in a quasi-stationary discharge with EEE is defined by the number of valence electrons of metal atoms N_{ve}. A coordination number of the atom on the metal surface is approximately twice less than in the metal volume. Hence, only a half of valence electrons bounds the atom with the metal surface. From here we conclude that $\gamma \geq 2N^{-1}_{ve}$. If $\gamma < 2N^{-1}_{ve}$, then either thermal or field electron emission prevails over EEE. Most often cathode erosion is evaluated in g/C. In these units the values of $\gamma \sim 10^{-4}$ g/C correspond most to EEE.

Table 1 presents results of experimental test of γ [12], I_0 [3], d/t_C [5], n^+_{max} [6] allowing evaluating the cathode surface square S_E emitting plasma and the current density in a cathode spot. In a solid metal $n_I = \rho N_A/A$. The velocity of plasma ejection out the cathode $\mu = n_I v_I/4$. From the other side, $\mu = \gamma I_0/eS_E$. Equating the two expressions for μ, we find $S_E = 4\gamma I_0/n_I v_I$ and current density $j_e = I_0/S_E$. The calculated values are presented in the Table 1. Average values of the inter-ion distance $a = (n_I)^{-1/3}$ are presented in the Table 1 for comparison too. The j_e values are large enough and correspond to high plasma concentration. Assuming that heat-excited electrons in the zone of conductivity take part in the current transfer only, the current density corresponding to appearance of positive charged region in a metal can be of $a \sim 10^9$ A/cm^2 [14]. Some materials such as halfmetals (Bi, C) have relatively small number of free electrons and can have less current density in comparison with values in Table 1.

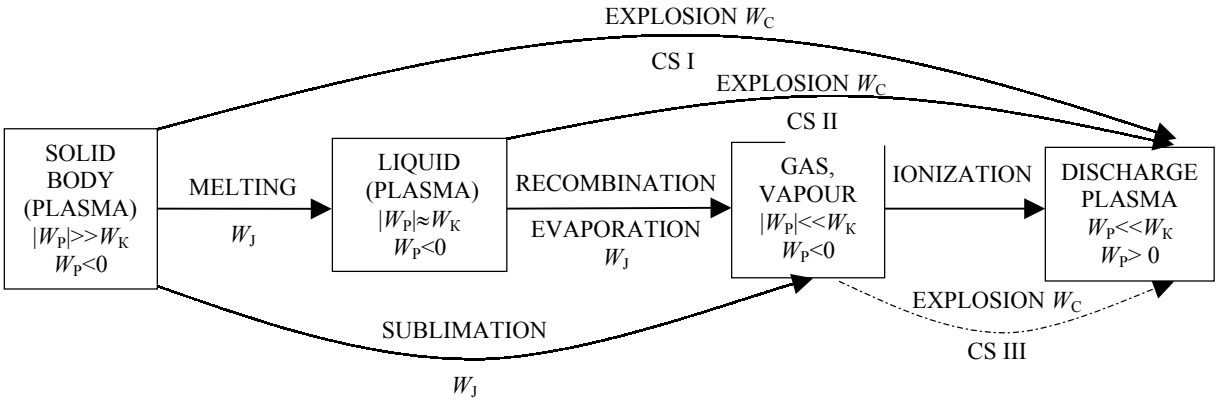

Fig. 2

Table 1

	γ, atom/e	d/t_C, 10^6 cm/s	I_0, A	n^+_{max}	m_I, 10^{-26} kg/atom	n_I, 10^{22} cm^{-3}	a, 10^{-8} cm	S_E, 10^{-11} cm^2	j_e, 10^{10} A/cm^2
Sn	0.441	1.5	0.7	+2	19.7	2.96	3.23	17	0.41
Bi	0.597	1.1	0.3	–	34.7	2.82	3.29	14.4	0.21
Cd	0.366	1.3	0.1	+2	18.7	4.64	2.78	1.52	0.65
Zn	0.294	1.6	0.4	+3	10.9	6.58	2.48	2.8	1.42
Al	0.233	2.6	1.2	+3	4.5	6.02	2.55	4.46	2.69
Cu	0.137	2.5	1.8	+4	10.6	8.5	2.27	2.9	6.21
Ni	0.177	1.9	2.1	+3	9.7	9.15	2.22	5.3	3.96
Ti	0.105	1.9	1.7	+4	8.0	5.68	2.6	4.13	4.11
Nb	0.045	3.0	2.4	+4	15.4	5.54	2.62	1.62	14.8
Mo	0.039	2.6	2.35	+4	15.9	6.64	2.47	1.33	17.7
Ta	0.038	3.5	2.45	+5	30.0	5.55	2.62	1.2	20.4
W	0.037	2.7	2.8	+5	30.5	6.0	2.55	1.6	17.5
C	0.169	2.0	0.1	+2	2.0	9.76	2.8	0.22	4.55
Pb	–	1.3	0.35	+3	34.42	3.31	3.1	–	–
In	–	1.3	0.7	+2	19.07	3.94	2.94	–	–

The realization degree of the described mechanism is most high under conditions of increasing current in the circuit as well as presence of the plasma in the interelectrode gap providing the electron beam charge compensation at the extraction of a high density electron current. In our opinion, the mechanism of obtaining high current densities in the emissive center is roughly similar to the one of the current increase in a vacuum diode under conditions of unstable current extraction [15]. As it is well known, the current in the diode in the initial stage of the current flowing is determined by the cathode plasma emissivity and the conductivity of the cathode-anode gap. When at the plasma expansion the vacuum gap allows passing more current than emissive ability of the cathode plasma supplies, the rupture of the plasma can take place. The emergent plasmoid obtains positive potential that results in increase of the electrical field on the cathode and conductivity of the interelectrode gap. The resulting positive charge in the gap allows compensating the spatial charge of the electron beam with much higher current density. If the special efforts are not used, the current in the gap increases quickly right up to short circuit current of the power supply. In a similar way, the current density increase in the emissive centers can take place right up to appearance of the uncompensated charge regions in the metal. In this case the plasma formed at the explosion of the previous emissive center fulfils a role of the plasmoid being under potential.

References

[1] A.P. Cracknell, K.C. Wong, *The Fermi Surface*, Oxford, Clarendon Press, 1973, translation from English, Moscow, Atomizdat, pp. 200–201, 1978 (in Russian).

[2] E.N. Abdullin, G.P. Bazhenov, Yu.P. Bazhenov, A.V. Morozov, *in: Proc. of 4th Int. Conf. Plasma Physics and Plasma Technology* **1**, 2003, pp. 96–99.

[3] S.A. Krat'ko, *Synopsis of thesis for a phys.-math. sci. candidates's degree,* Minsk, Belgosuniversity, 1981 (in Russian).

[4] M.P. Reece. Nature **181**, 475 (1958).

[5] Ya.Ya. Yurike, Izv. VUZov. Fizika **11**, 140 (1974) (in Russian).

[6] A.A. Anders, *in: Proc. of 19th Int. Symp. on Discharges and Electrical Insulation in Vacuum,* 2000, pp. 66–67.

[7] J.E. Daalder. J. Appl. Phys. **44**, 3074 (1973).

[8] E. Myuller, T. Zohn, *Field-ion microscopy (principles and application)*, Moscow, Metallurgy, 1972 (in Russian).

[9] G.A. Mesyats**,** *Ectons in a vacuum discharge: breakdown, spark, arc*, Moscow, Science, 2000 (in Russian).

[10] N.V. Pleshivtsev, *Cathode sputtering*, Moscow, Atomizdat, 1968 (in Russian).

[11] I.S. Taev. *Electrical apparatus. General theory,* Moscow, Energy, 1977 (in Russian).

[12] I.I. Aksenov, V.M. Khoroshikh, *Particle flows and mass transfer in a vacuum arc*, Moscow, CSRI Atominform, 1984 (in Russian).

[13] A.I. Vasin, V.A. Petrosov, *in: Low-temperature plasma generators (abstracts)*, Novosibirsk, p. II, 1989, pp. 56–57.

[14] A.F. Nastoyashchii, I.N. Morozov, N.B. Rodionov, *in: Proc. of 17th Int. Symp. on Discharges and Electrical Insulation in Vacuum*, 1996, pp. 774–777.

[15] E.N.Abdullin G.P.Bazhenov, S.M.Chesnokov G.P.Erokhin, V.N.Kiselev, O.B.Ladyzhensky, Izv. VUZov. Fizika. **3**, 83 (1994) (in Russian).