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CATHODE DROP OF THE POTENTIAL OF A VACUUM ARC OF METALS

G. V. Markov

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The basic mechanisms of ionization in the cathode spot of a vacuum arc are considered. It is shown that the singly charged positive ions formed here are a result of the collision ionization of the evaporated atoms of a metal by electrons. On this basis the assumption is made that the cathode drop of the potential of the vacuum arc of metals is determined by the energy of ionizing electrons at which the ionization section attains its maximum.

A vacuum arc represents a tool for transfer of an electric arc in vacuum (the pressure of residual gases is no more than $1\cdot10^{-1}$ Pa) between a cathode and an anode [1] when between them a certain potential difference $U = U_c + U_a$ exists. Usually $U \sim 10$–30 V and $U_c \sim 10$–30 V while $U_a \sim 0.5$–1 V [1]. This is attributed to the fact that all basic physical processes leading to initiation of a vacuum arc and its existence proceed in its cathode spot and are localized near the cathode surface. Purely visually the cathode spot is perceived as a luminous point that traverses over the cathode surface.

The classical picture of the physical processes in the cathode spot of a vacuum arc of metals [1–10] includes the evaporation of metal atoms from the cathode surface at a temperature close to the boiling point T_{liq} of the metal and the thermoautoelectronic emission of electrons from this surface. Next, the spread of the vapor and the acceleration of the electrons in an electric field U_c are observed. Here the electrons begin to efficiently ionize the evaporated atoms and a plasma cloud is formed from positive ions and electrons with a degree of ionization of 0.5–0.95. Most of the positive ions formed [7] return, under the action of the field U_c, into a cathode spot on the cathode surface, thus heating this surface up to temperatures close to the boiling point. A lesser portion of the ions propagates into a vacuum chamber and, due to gasdynamic acceleration [8], acquires energies of 20–120 eV [1, 5, 9], which substantially exceeds the value of eU_c [1].

As is evident from the results of the experimental studies of the ionic composition of a plasma of the vacuum arc of metals [10], for the overwhelming majority of the latter the plasma constitution also includes, in addition to the singly charged ions, doubly-, triply- and even quintuply charged ions. Since the energy of double- and higher-order collision ionization by the electrons of metal atoms substantially exceeds eU_c, this is indicative of the possibility of participation of several mechanisms of formation of positive ions in the cathode spot [11].

Ionization of Atoms in the Cathode Spot. Ionization of the evaporated ions in the cathode spot occurs as a result of collisions with the electrons accelerated in the field U_c and, most likely, by two mechanisms. The first mechanism is the direct collision ionization, where an atom collides with an electron e, whose kinetic energy is higher than the ionization energy of atom E_i, and electron e is knocked out of atom A: $A + e \rightarrow A^+ + 2e$. The second mechanism is the step ionization, where atom A collides sequentially with several electrons that possess energy $E < E_i$. As a result of such collisions, atom A can accumulate an energy sufficient to pass to the self-ionization level A^* and to undergo nonradiative decay with subsequent electron

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TABLE 1. Dependence of the Excitation and Ionization Sections and Rates of Al and Cu on the Electron Energy E

Sections and rates of excitation and ionization	Element	E, eV								
		5	7	9	11	13	15	17	19	21
$\sigma\cdot 10^{16}$, cm^2	Al	1.24	2.32	2.48	2.46	2.41	2.34	2.32	2.30	2.25
	Cu	–	2.10	2.41	2.49	2.50	2.46	2.41	2.36	2.31
$\sigma^+\cdot 10^{16}$, cm^2	Al	–	1.30	3.80	5.20	5.90	6.23	6.26	6.20	6.14
	Cu	–	–	0.30	0.90	1.20	1.40	1.55	1.58	1.59
$v\sigma\cdot 10^7$, cm^3/sec	Al	0.31	0.37	0.44	0.48	0.51	0.53	0.55	0.58	0.59
	Cu	–	0.37	0.42	0.48	0.53	0.56	0.57	0.58	0.58
$v\sigma^+\cdot 10^7$, cm^3/sec	Al	–	0.40	0.50	0.57	0.62	0.66	0.69	0.70	0.70
	Cu	–	–	0.18	0.22	0.24	0.26	0.28	0.29	0.30

emission: $A \to A^* \to A^+ + e$. It is rather difficult to determine which of the mechanisms of ionization prevails in the cathode spot of a vacuum arc [2, 4].

In this connection, the excitation and ionization sections and rates were calculated for Al and Cu by semiempirical and sufficiently verified formulas [12, 13]. For evaluation of the excitation section σ and rate $v\sigma$, these formulas have the form

$$\sigma = 14.52\pi a^2 f(0, 1)\,(\mathrm{Ry}/E_n)^2\,\gamma(x)/(x+1)\,, \tag{1}$$

$$v\sigma = 3.2\cdot 10^{-7} f(0, 1)\,(\mathrm{Ry}/E_n)^{3/2} \exp(-y)\, y^{0.5}\,\rho(y)\,, \tag{2}$$

while for the section σ^+ and for the rate $v\sigma^+$ of single collision ionization:

$$\sigma^+ = [\pi am/(2l_0+1)]\,\left|\mathrm{Ry}/E_\mathrm{i}\right|^2 [\beta/(\beta+1)]^{3/2}\, C/(\beta+F)\,, \tag{3}$$

$$v\sigma^+ = 1\cdot 10^{-8}\, m/(2l_0+1)\,\left|\mathrm{Ry}/E_\mathrm{i}\right| \exp(-\alpha)\, B\alpha^{0.5}/[(\alpha+1)^{0.5}(\alpha+D)]\,. \tag{4}$$

Results of the Analysis. We consider the following transitions of excitation: ($3^2P_{1/2}$–$4^2S_{1/2}$) for Al and ($4^2S_{1/2}$–$4^2P_{1/2}$) for Cu. These transitions were chosen so that after double collision with electrons the atoms of these metals had the possibility of passing to a self-ionization level followed by decay into a positive ion and an electron.

Results of the calculation of σ, σ^+, $v\sigma$, and $v\sigma^+$ are presented in Table 1. As follows from these results, the excitation and collision ionization sections and the rates of these processes are quantities of the same order. This is indicative of the equiprobability of both mechanisms of ionization proceeding in the cathode spot of Al and Cu. However, since the step ionization requires a higher frequency of collisions of atoms with electrons than in the collision ionization, the mechanism of the latter appears to be more preferable in the formation of singly charged ions. Therefore it is quite reasonable to assume that the process of single ionization in the cathode spot of the vacuum arc is based on the mechanism of direct collision ionization: $A + e \to A^+ + 2e$. In the case of formation of multiply charged ions, the step ionization plays a decisive role.

Cathode Drop of the Potential. If formula (3) is used to calculate the section of single collision ionization by electrons σ^+ of atoms of the metals Mg, Ti, V, Cr, Fe, Co, Ni, Zr, Nb, Mo, Ta, W, Pb, Zn, In, Bi, and Cd, then for all the metals we obtain the same form of the dependence $\sigma^+(E)$ (see Fig. 1). As is seen, σ^+ rapidly increases with the electron energy, attains its maximum within the range 7–25 eV, and slightly decreases with subsequent increase in the energy of an ionizing electron. In Table 2, for some pure metals

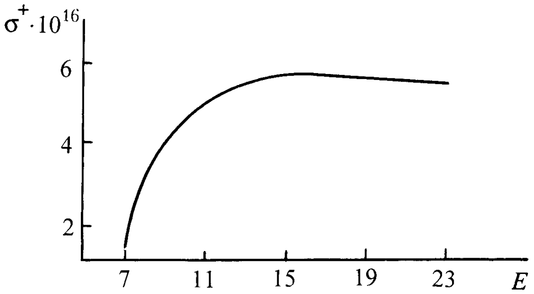

Fig. 1. Dependence of the single collision ionization section of metal atoms on the energy of ionizing electrons. σ^+, cm^2; E, eV.

TABLE 2. Values of the Cathode Drop of the Potential U_c of a Vacuum Arc

Element	Mo	Ta	Zr	Cu	Al	Fe	W	Ti	Ni
E_m, eV	19.0	21.4	18.9	21.0	17.0	21.5	21.7	20.0	20.9
eU_c, eV [1]	24	24.5	22	21.5	16.7	20.5	26	20.5	20
eU_c, eV [4]	–	–	–	16	15.5	17	17	–	16
eU_c, eV [14]	17.2	21.4	18.5	15.4	18.6	18	22.6	17.6	17.3

TABLE 3. Dependence log p of the Vapor Pressure of Al, Mg, Pb, Bi, and In on the Temperature T

Element	T, K					
	1000	1200	1400	1600	1800	2000
Al	–7.3	–4.6	–2.6	–1.2	–0.11	0.76
Mg	1.0	2.16	–	–	–	–
Pb	–1.9	–0.32	0.82	2.33	–	–
Bi	–1.83	–0.2	0.95	1.82	2.47	–
In	–4.14	–2.08	–0.65	0.49	1.34	2.02

the values of energy E_m are given at which the dependences $\sigma^+(E)$ attain their maximum. Here, the values of the cathode drop of the potential taken from different works are presented (see the figure). As a comparison of the E_m and eU_c values reveals, their numerical values are close for a great number of the pure metals indicated above. The differences do not exceed 10–20%. Therefore the assumption can be made that the cathode drop of the potential of a vacuum arc of the pure metals is determined by the energy of the atom-ionizing electrons at which the section of single collision ionization of metal atoms attains its maximum.

The picture is slightly different for such metals as Zn, In, Cd, Bi, Mg, and Pb, which have low melting and boiling points. For these metals the difference between the quantities E_m and eU_c attains 100%, and this is apparently related to the low boiling points. In Table 3, the dependences of the logarithm of the vapor pressure log $p(T)$ of Mg, Pb, Bi, and In on temperature [15] and, for comparison, of the log $p(T)$ for Al are given. As is seen, the pressure of the aluminum vapor is two to three orders of magnitude smaller at the same temperatures than the vapor pressure of Mg, Pb, Bi, and In, for which it is characteristic to have a boiling temperature lower than ~2000 K. This results in the fact that for these metals, even if the temperature of the cathode surface in the cathode spot is equal to the boiling temperature, the number of evaporating atoms is one to two orders of magnitude higher than the number of electrons emitted from that surface [11]. Therefore, it may be suggested than the decisive part in the formation of singly charged ions in the cathode spot of the vacuum arc of these metals is played by the step ionization rather than by the direct collision ionization. Here, the value of the cathode drop of the potential is likely to be determined by the energy which must be imparted to a metal atom in collisions with electrons for its transition to the self-ionization level with subsequent decay into an ion and an electron.

Thus, for pure metals with a boiling point higher than ~2000 K it may be assumed that the cathode drop of the potential of a vacuum arc is determined by the energy at which the section of single collision ionization of a metal atom by an electron attains its maximum.

NOTATION

U_a and U_c, anode and cathode drop of the potential, respectively, V; Ry = 13.6 eV, Rydberg number; $a = 0.529\cdot10^{-8}$ cm^2; E, electron energy, eV; E_n and E_i, energy of the transition $0 \to 1$ and of single collision ionization, respectively, eV; $f(0, 1)$, force of the transition $0 \to 1$; $\gamma(x)$, $\rho(y)$, tabulated functions; l_0, orbital moment of an optical electron in the initial state; m, quantity of electrons in the shell l_0^m; α, β, F, B, C, and D, constants; e, electron charge; p, vapor pressure, mm Hg. Subscripts: 0, initial state; a, anode; c, cathode; m, maximum.

REFERENCES

1. I. G. Kessaev, *Cathode Processes of an Electric Arc* [in Russian], Moscow (1968).
2. J. M. Lafferty (ed.), *Vacuum Arcs* [Russian translation], Moscow (1982).
3. G. A. Lyubimov and V. I. Rakhovskii, *Usp. Fiz. Nauk*, **125**, No. 4, 665–706 (1978).
4. V. I. Rakhovskii, *Physical Principles of Commutation of Electric Current in Vacuum* [in Russian], Moscow (1970).
5. I. I. Beilis, M. P. Zektser, and G. A. Lyubimov, *Zh. Tekh. Fiz.*, **58**, No. 10, 1861–1870 (1988).
6. P. J. Martin, R. P. Netterfield, and D. R. McKenzie, *Thin Solid Films*, **153**, 91–102 (1987).
7. V. A. Nemchinskii, *Zh. Tekh. Fiz.*, **52**, No. 9, 1748–1755 (1982).
8. V. A. Nemchinskii, *Zh. Tekh. Fiz.*, **55**, No. 1, 60–66 (1985).
9. B. Ya. Moizhes and V. A. Nemchinskii, *Zh. Tekh. Fiz.*, **52**, No. 4, 684–689 (1982).
10. R. L. Boxman, D. M. Sanders, and P. J. Martin, *Handbook of Vacuum Arc Science and Technology*, New York (1995).
11. G. V. Markov and B. A. Éizner, *Vopr. Atomn. Nauki Tekh.* (Kharkov), Issue 4–5, 149–151 (1998).
12. L. A. Vainshtein, I. I. Sobel’man, and E. A. Yukov, *Excitation Cross Sections of Atoms and Ions by Electrons* [in Russian], Moscow (1973).
13. L. A. Vainshtein and V. P. Shevel’ko, *Structure and Characteristics of Ions in Hot Plasma* [in Russian], Moscow (1986).
14. V. E. Grakov, *Zh. Tekh. Fiz.*, **37**, No. 2, 396–401 (1967).
15. C. J. Smithells, *Metals Reference Book* [Russian translation], Moscow (1980).