Anomalous volt-ampere characteristics of vacuum diodes with metallic single-crystal electrodes

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(Submitted 17 April, 1979; resubmitted 18 June 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **30**, No. 2, 99–102 (20 July 1979)

Anomalies have been found on the initial portion of the volt-ampere (V-A) characteristic of a diode with a single-crystal tungsten cathode. The anomalies appear on the V-A characteristic, starting at some threshold value of the cathode temperature $T = \Theta_{TE}$, Θ_{TE} which is the characteristic thermal emission temperature. It is assumed that the effect is caused by the emission of electrons formed during the recombination of thermal defects.

PACS numbers: 85.10. – n

1. A planar-geometry symmetrical vacuum diode (Fig. 1) was designed and built for studying the thermionic emission of the differential crystallographic planes (faces) of metallic single crystals. The specific design of the device was chosen as the result of a numerical calculation of the distribution of fields in such a manner that the deviations from a uniform electrostatic field between the cathode and anode would not exceed 0.1–1%. The cathode and anode were identical faces of the same single crystal. The experimental results for the tungsten (100) face are presented below. The purity of the specimen was 99.999 mass%. The accuracy of the determination of the faces (~30′) was checked by means of Laue patterns. The cathode temperature was measured with a standard EOP-66 pyrometer. The measurement error was ± 5 K within the 1600–2200 interval.

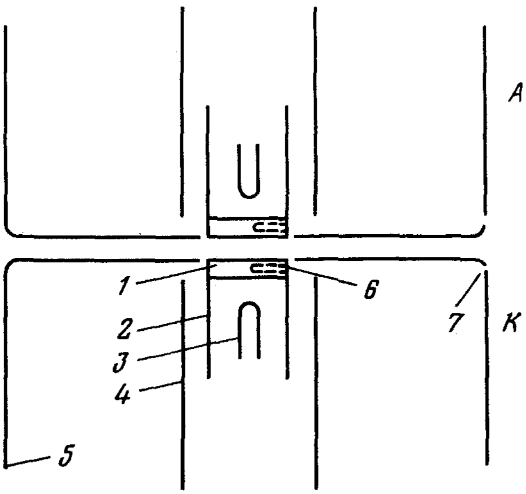

FIG. 1. Symmetrical planar diode. *A*, *K* are anode and cathode assemblies. 1—cathode; 6 mm diameter, ~1 mm thick; 2—cathode base; 3—heater (bifilar spiral); 4—guard cylinder; 5—guard ring; 6—"blackbody" model; 7—opening for making pyrometer readings.

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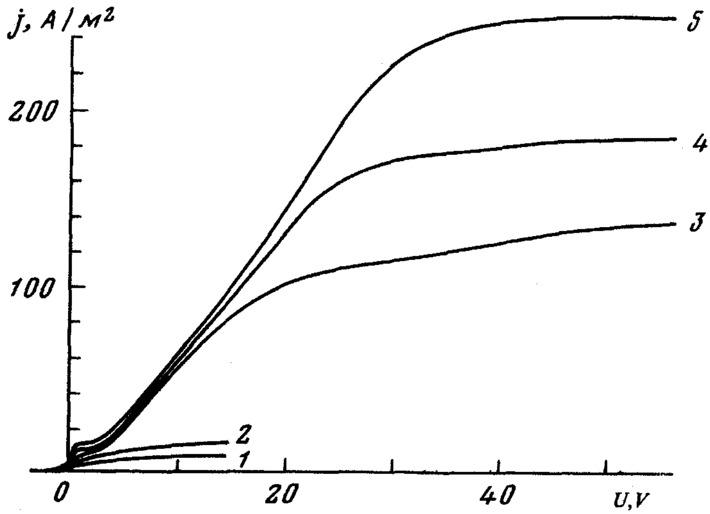

FIG. 2. V-A characteristics of diode. Curve parameter is the cathode T °K: 1—1708; 2—1783; 3—1920; 4—1; 5—1996.

The diodes were mounted in a dismountable metal vacuum chamber with an oil-free pumping system. The limiting vacuum in the chamber was 5×10^{-11} torr; the residual gas pressure during the V-A characteristic measurements did not exceed 5×10^{-9} torr with the cathode hot. The V-A characteristic was traced by means of PDS-021 and "Watanabe" *x-y* recorders. Typical curves are shown in Fig. 2. Figure 3 shows the initial portions of the V-A characteristics at an enlarged scale.

2. The major experimental results consist of the following. A characteristic thermal emission temperature $T=\Theta_{\rm TE}$ exists for the cathode, which divides the family V-A characteristics into two qualitatively different types. The low-temperature V-A characteristics, measured for $T<\Theta_{\rm TE}$ (1,2 in Fig. 2 and 1,2,3 in Fig. 3), form a fan of

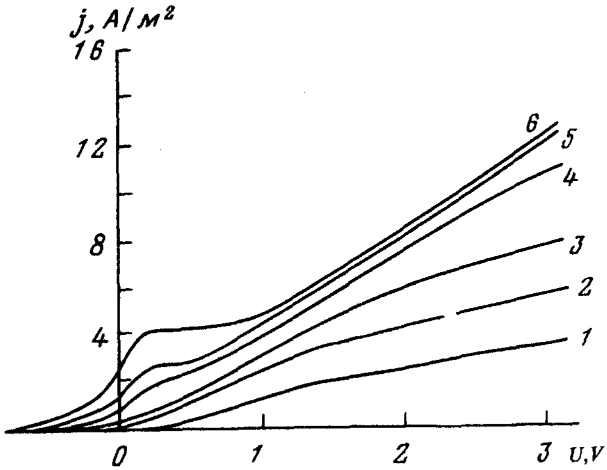

FIG. 3. Initial portions of V-A characteristics. The curve parameter is the cathode temperature T °K: 1—1708; 2—1728; 31783; 4—1836; 5—1883; 6—2000.

curves that diverge from approximately the origin, are continuous at each point and have continuous first derivatives. The high-temperature V-A characteristics, measured for $T > \Theta_{TE}$ (3,4,5 in Fig. 2), have clearly evident regions caused by the electron space charge. In these regions the V-A characteristics nearly merge. In the initial portions of the high-temperature V-A characteristics (3,4,5 in Fig. 2 and 4,5,6 in Fig. 3) anomalies- "steps" appear. The anomalies become more prominent with the increase in the cathode temperature. For the (100) face of the tungsten single crystal the temperature $\Theta_{TE} = 1810 \pm 5$ K; for the tungsten (111) face $\Theta_{TE} = 1860 \pm 5$ K.

The causes of the described anomalies of the V-A characterstics may be associated with the changes in the properties of the tungsten single crystals due to the temperature or to unique features of the diode electron plasma. Control experiments were performed in order to resolve this alternative. In the first series of control experiments the V-A characteristics were measured for diodes with different cathode-anode spacings. The major results are quite repeatable and do not depend on the cathode-anode spacing as it varies from 0.7 to 1.8 mm. In the second series of control experiments the V-A characteristics were measured for diodes with single-crystal anode and high-efficiency tungsten-barium thermocathodes. No anomalies of the V-A characteristics were observed in these diodes.

Thus, *it can be assumed that for* $T \gtrsim \Theta_{TE}$ *the state of the tungsten single crsytal is altered*. As a result of this change, electrons are generated in the single crystal at $T \gtrsim \Theta_{TE}$ that are fast compared with thermal electrons; the V-A characteristics in Fig. 3 extend to 1 V in the retarding voltage region.

3. Let us consider a possible physical picture of the phenomena leading to the observed anomalies. It is known that with an increase in the temperature to the melting point high-temperature corrections, in particular corrections caused by thermal defects (TD) of crystals,[1] make an every greater contribution to the equation of state of the transition metals and alloys. The present-day concepts of TD as localized objects, to all appearances, are valid up to some temperature $T \sim \Theta_{TE}$. If this is so, then recombination of the TD is possible in the high-temperature region $T > \Theta_{TE}$.

Let us assume that the excess energy, released during the recombination of a pair of TD, is transferred to an electron. Simple estimates show that in such a process the electron should be raised to an energy level lying above the vacuum level. In fact, twice the TD formation energy in tungsten amounts to[2] 6.3 eV, while the work function of the (100) face is equal to 4.5 eV according to our measurements.

Consequently, in addition to the usual thermoelectrons the transition metals at $T \gtrsim \Theta_{TE}$ can emit electrons that are formed in the recombination of thermal defects. To all appearances, this mechanism explains the observed anomalies of the V-A characteristics.

The anisotropy of the recombination electron emission phenomenon is directly related to the work function anisotropy.

The authors wish to thank the participants and leaders of the seminars of Professor N. B. Brandt and Professor A. A. Rukhadze for their well-intentioned criticism and interest in this work.

[1]V.N. Zharkov and V.A. Kalinin, Uravneniya sostoyaniya tverdykh tel pri vysokikh davleniyakh i temperaturakh (Equations of State of Solids at High Pressures and Temperatures), Nauka, Moscow, 1968.
[2]Ya. A. Kraftmakher and P.G. Strelkov, Fiz. Tverd. Tela (Leningrad **4**, 2271 (1962) [Sov. Phys. Solid State **4**, 1662 (1962–3)].