RICHARDSON PLOT FOR THE (110) PLANE OF A TUNGSTEN SINGLE CRYSTAL

E. E. Azizov, V. A. Mashtakova, and B. B. Shishkin

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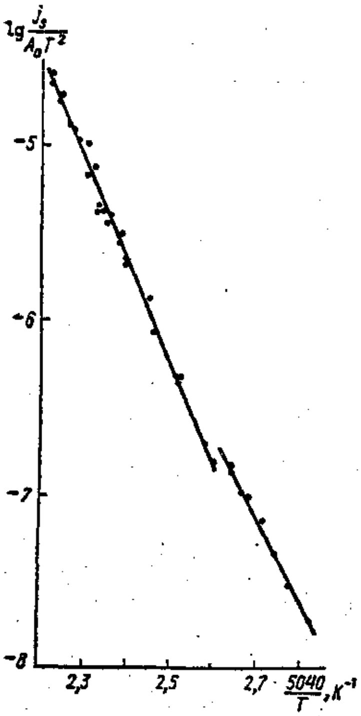
Thermionic emission from the (110) plane of a tungsten single crystal was investigated and it was shown that there is a threshold temperature at which the emission parameters determined from the Richardson plot undergo an increase.

Studies of thermionic emission by atomically pure single crystals of tungsten, molybdenum, and niobium by the plane-parallel diode method described in [1], have revealed that there is a threshold temperature Θ_{te} (the characteristic thermionic emission temperature) whose magnitude is lower by a factor of approximately 2 than the melting point of the metal. When $T \geq \Theta_{te}$, the thermionic emission process differs from Richardson emission by higher emission current density j_s, the appearance of anomalies on the current-voltage characteristics, and oscillations in the diode current [1-3]. Experiments [4] have also shown that the spectra of emitted electrons exhibit a change for $T > \Theta_{te}$.

Recombination emission (RE) was proposed in [1], whereby phenomena observed for $T > \Theta_{te}$ are related to the excitation of electrons by the energy released during the recombination of Frenkel pairs, and the RE current is added to the thermionic current. The recombination energy of Frenkel pairs in the case of tungsten is about 6.3 eV [5] and this is higher by 1.5-2 eV than its work function, which means that electrons excited in a surface layer of depth of the order of the electron mean free path can freely escape from the metal, i.e., RE is a bulk effect. On the close-packed (110) plane of tungsten, the RE effect should be particularly well defined because the work function of this plane is high and therefore the thermionic emission current is low.

We have investigated the thermionic emission from the (110) plane of a tungsten single crystal. The 99.999% pure tungsten was part of a plane-parallel diode [1] mounted in an evacuated chamber. The residual gas pressure did not exceed 10^{-10} torr. Auger analysis of the surface of the single crystal showed that there were small amounts of oxygen and carbon but no other impurities were detected. The anode and cathode surfaces were cleaned up by heating for 15-20 hours at $T \approx 2800$ K. Carbon was removed by the method proposed in [6], whereby the cathode and the anode were roasted in an oxygen atmosphere for 3 hours (partial pressure of oxygen 10^{-8} torr) at 1900 K, and were then heated for 20 min at about 2800 K. The measurements were performed in the temperature range 1400-2500 K.



Richardson plot for the (110) plane
of single-crystal tungsten.

These precautions resulted in reproducible current-voltage characteristics for both increasing and decreasing temperatures. The circulation current was determined to better than 2%, using the standard method and taking the Schottky effect into account [7]. The temperature was measured with the EOP-66 calibrated optical pyrometer to an accuracy of 0.2%. Each Richardson plot was based on a number of series of measurements, with at least 30 points in each series. The figure shows a typical result.

As can be seen, there are two temperature ranges with different Richardson plots, namely, the high temperature region $T > \Theta_{te}$ in which $\Theta_{te} = 1850$ K, and the low temperature region $T < \Theta_{te}$. A least squares fit was obtained for the two regions. Since the two quantities $x = 5040/T$ and $y = \lg j_s/(A_0 T^2)$ were subject to errors (A_0 is the Sommerfeld constant [7]), we minimize the quantity $\Delta x \Delta y/\sqrt{\Delta x^2 + \Delta y^2}$. The resulting values of the emission parameters are listed in Table 1 (A_p is the Richardson constant and ϕ_p the work function). Data for the (111) and (100) planes of tungsten single crystals were taken from [2]. The result $\phi_p = 5.7$ eV is in good agreement with the work function $\phi_p = 5.75 \pm 0.02$ eV reported in [8].

The work function determined by the total current method [7] is related to ϕ_p by the expression $\phi_{tc} = \phi_p + \alpha T$ where α is the temperature coefficient of the work function. If we know the Richardson constant and the work function, we can calculate α from the formula $\alpha = \lg(A_0/A_p)/5040$. The values of α are listed in Table 2. The data for the (100) and (111) planes are taken from [3].

In the low temperature region, α can be either positive or negative, but in the high temperature region it can only be negative, and its magnitude is

Table 1

Plane	φ_p, eV		A_p, $\frac{A}{m^2 \cdot K^2}$	
	$T<\theta_{te}$	$T>\theta_{te}$	$T<\theta_{te}$	$T>\theta_{te}$
(100)	$4,4 \pm 0,2$	$4,76 \pm 0,04$	$2,4^{+4}_{-1} \cdot 10^6$	$2,8^{+0,02}_{-0,6} \cdot 10^7$
(111)	$4,55 \pm 0,05$	$5,52 \pm 0,05$	$1,28^{+0,4}_{-0,3} \cdot 10^6$	$3,9^{+9,8}_{-0,37} \cdot 10^6$
(110)	$5,1 \pm 0,04$	$5,7 \pm 0,04$	$4,03^{+13}_{-2,96} \cdot 10^6$	$75,8^{+103}_{-42} \cdot 10^6$

Table 2

Plane	$\alpha \cdot 10^6 V \cdot K^{-1}$	
	$T<\theta_{te}$	$T>\theta_{te}$
(100)	-4^{-10}_{+5}	-27^{-1}_{+2}
(111)	$-0,5^{-2}_{+2}$	-50^{-3}_{+26}
(110)	$+10^{+3}_{-4}$	-35^{-10}_{+7}

greater than in the low temperature region. This is due to the rapid increase in j_s with increasing temperature for $T > \Theta_{te}$ and, consequently, decreasing Θ_{te}.

These experimental results can be explained in two ways. In the first approach, we assume that our values of ϕ_p and A_p in the two temperature regions correspond to real physical quantities. Consequently, ϕ_p and A_p do actually increase in the high temperature region, and that may be ascribed to, for example, phase transitions at $T = \Theta_{te}$, both in the interior and on the surface of the metal.

The second possible explanation is that the Richardson-Dushman equation, upon which the Richardson plot is based, is incorrect in the high temperature region. The correct version of the equation must take into account the recombination emission. This means that the parameters A_p and ϕ_p obtained in the high temperature region are effective parameters whose physical significance can be revealed only when recombination emission is taken into account.

It is still uncertain which of the two explanations is the correct one, but the second is supported by the following facts: a) the Richardson-Dushman equation was derived for the Maxwellian energy distribution of the emitted electrons, whereas experiment [4] shows that this distribution is not valid in the high temperature range because a fast-electron peak is present on the Maxwellian background, and b) the experimental current-voltage characteristics obtained by the retarding potential method extend to -2 V.

The final answer to these questions will have to await further experiments in which the work function in the high and low temperature regions will be determined by methods other than those employed above.

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