Physical section, Faculty of Science, Masaryk University, Brno

PHYSICAL PRACTICUM

Physical practicum 3

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Field of Study: AF **Grade:** II **Semester:** IV **Tested:**

Task No. **2:** **Study of thermal electron emission**

1. Theory

Thermal electron emission is the heat-induced flow of electrons from a surface or over a potential-energy barrier. This occurs because the thermal energy given to the electron overcomes the binding potential, also known as work function of the metal. According to the Richardson-Dushman equation the emitted electron current I is related to the absolute temperature T by the equation:

$$I = BT^2 \mathrm{e}^{\frac{-w}{kT}} \qquad => \qquad \mathtt{ln}\left(\frac{I_{nas}}{T^2}\right) = \mathtt{ln}B - \frac{w}{kT}$$

where w is the work function of the metal, k is the Boltzmann constant and B is constant including area of the cathode. Absolute temperature can be calculated from Ohm's law and from following equation:

$$R_t = \frac{\rho d}{S}(1 + \alpha t),$$

where $\rho = 4,89.10^{-8}\Omega\mathtt{m}$, d is length of fiber, S is cross-sectional area of fiber, $\alpha = 4,83.10^{-3}K^{-1}$ is temperature coefficient of electrical resistance and t is temperature in degrees of Celsius. Schottky effect is a reduction in the energy required to remove an electron from a solid surface in a vacuum when an electric field is applied to the surface. Changes in currents can be expressed by following equations:

$$\mathtt{ln}I'_n = \mathtt{ln}I_n + \frac{w_p}{kT}, \qquad \mathtt{ln}I'_n = \mathtt{ln}I_n + \sqrt{\frac{e^3}{4\pi\epsilon_0 k^2 T^2}} \times \sqrt{E},$$

where e is elementary charge, ϵ_0 is vacuum permittivity, k is the Boltzmann constant, w_p is increase of the work function and E is intensity of electric field near of cathode which is defined as:

$$E = U_a \frac{1}{r\mathtt{ln}(R/r)},$$

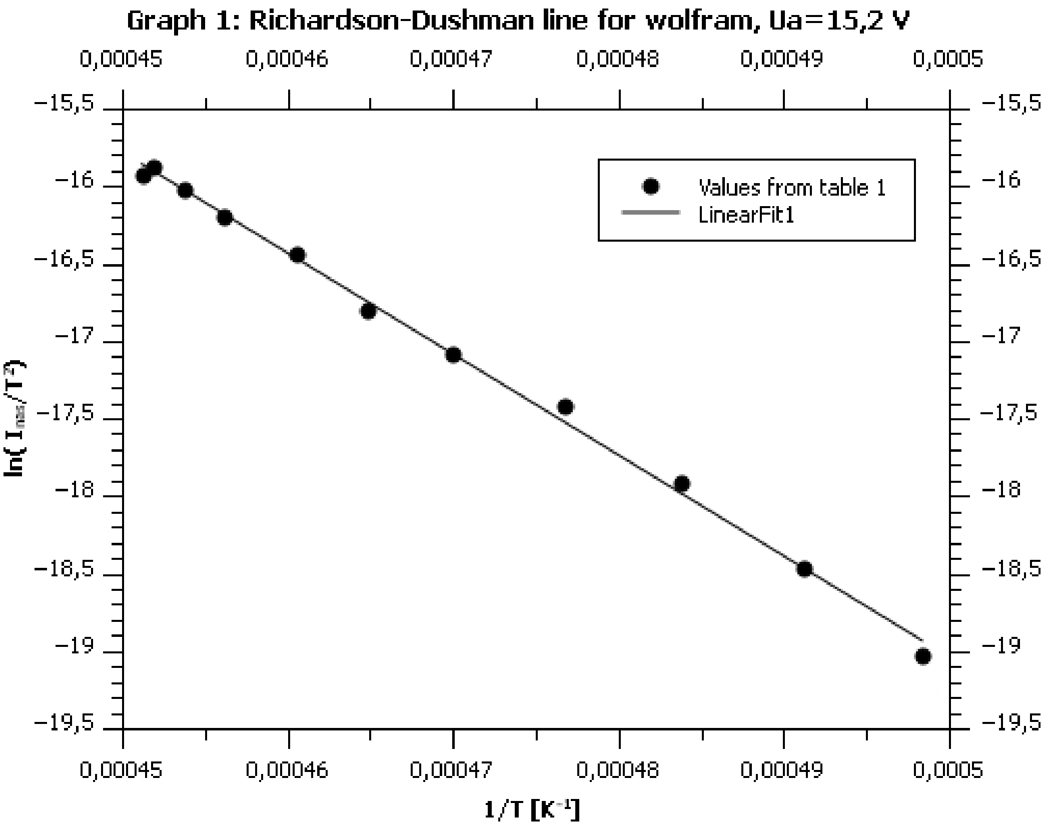
where U_a is voltage of anode, r is the radius of cathode and R is the radius of anode.

2. Measurement

Radius of cathode $r = 0,05$ mm
Radius of anode $R = 0,7$ mm
Length of cathode $d = 15$ mm

Table 1: Measured values for Richardson-Dushman equation (Ua = 15,193 V):

n	U_f [V]	I_f [A]	I_a [A]	R [Ω]	T [K]	$1/T$ [K^{-1}]	$\ln(I_n/T^2)$
1	0,945	1,004	0,004	0,941	1880	0,000532	-20,6
2	1,035	1,053	0,002	0,983	1971	0,000507	-21,4
3	1,100	1,102	0,022	1,000	2007	0,000498	-19,0
4	1,127	1,114	0,039	1,012	2036	0,000491	-18,5
5	1,158	1,129	0,071	1,026	2067	0,000484	-17,9
6	1,188	1,143	0,120	1,040	2098	0,000477	-17,4
7	1,214	1,153	0,173	1,053	2128	0,000470	-17,1
8	1,237	1,163	0,233	1,064	2151	0,000465	-16,8
9	1,259	1,173	0,341	1,073	2171	0,000461	-16,4
10	1,280	1,183	0,442	1,082	2192	0,000456	-16,2
11	1,292	1,188	0,533	1,087	2204	0,000454	-16,0
12	1,301	1,192	0,623	1,092	2213	0,000452	-15,9
13	1,301	1,190	0,597	1,093	2216	0,000451	-15,9



Results of linear fit from the 1st graph ($y(x) = a * x + b$):
$a = (\ -65200 \pm 1200\ )$ K $b = (\ 13.56 \pm 0.55\ )$

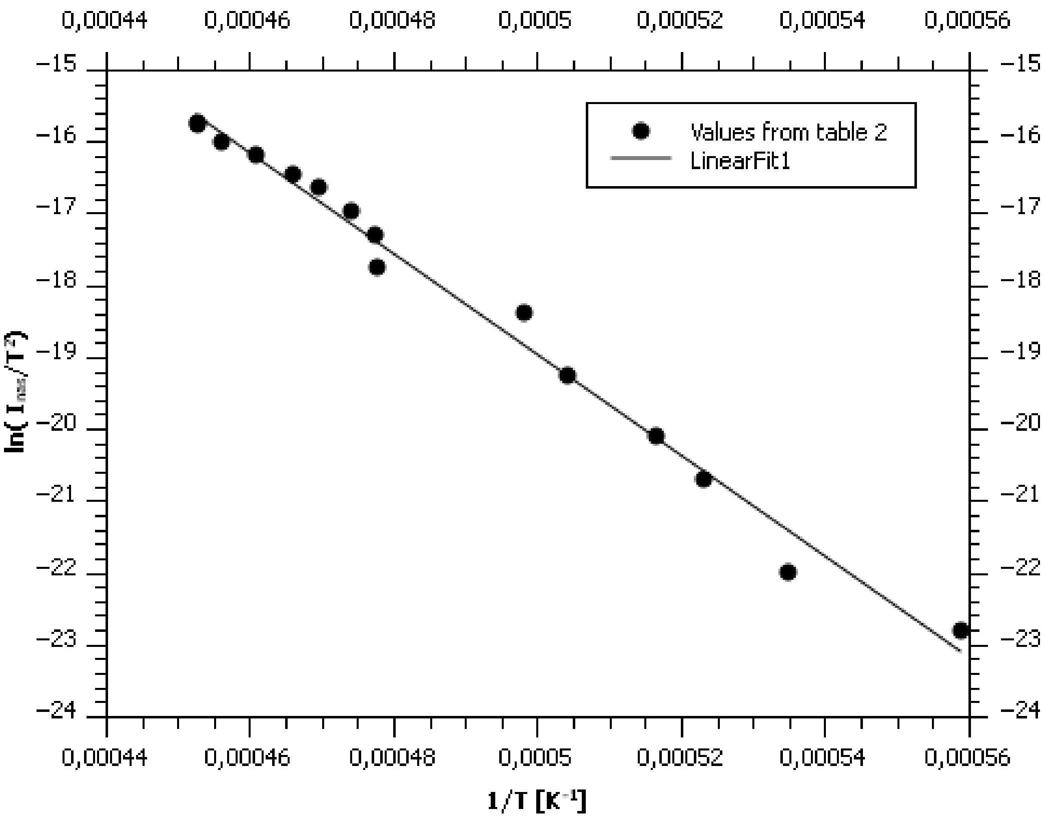
Work function of wolfram: $w = -ak = (\ 9.00 \pm 0.17\ ) \times 10^{-19}$ J $= (\ 5,62 \pm 0.10\ )$ eV $\delta_r = 1.8\%$

Constant $B = \exp(b) = (\ 775000 \pm 31000\ )$ $\delta_r = 4.1\%$

Table 2: Measured values for Richardson-Dushman equation (Ua = 30,084 V):

n	U_f [V]	I_f [A]	I_a [A]	R [Ω]	T [K]	$1/T$ [K^{-1}]	$\ln(I_n/T^2)$
1	0,906	1,006	0,0004	0,901	1789	0,000559	-22,8
2	0,977	1,043	0,0010	0,937	1870	0,000535	-22,0
3	1,015	1,062	0,0038	0,956	1912	0,000523	-20,7
4	1,036	1,072	0,0070	0,967	1936	0,000516	-20,1
5	1,079	1,092	0,0174	0,988	1984	0,000504	-19,2
6	1,111	1,112	0,0418	1,000	2008	0,000498	-18,4
7	1,174	1,131	0,0876	1,038	2094	0,000478	-17,7
8	1,187	1,143	0,1366	1,038	2095	0,000477	-17,3
9	1,205	1,153	0,1926	1,045	2110	0,000474	-17,0
10	1,227	1,163	0,2696	1,055	2131	0,000469	-16,6
11	1,243	1,170	0,3284	1,062	2147	0,000466	-16,5
12	1,264	1,178	0,4396	1,073	2171	0,000461	-16,2
13	1,283	1,185	0,5474	1,083	2193	0,000456	-16,0
14	1,301	1,193	0,6954	1,090	2210	0,000453	-15,8
15	1,301	1,194	0,7296	1,090	2209	0,000453	-15,7

Graph 2: Richardson-Dushman line for wolfram, Ua=30,1 V



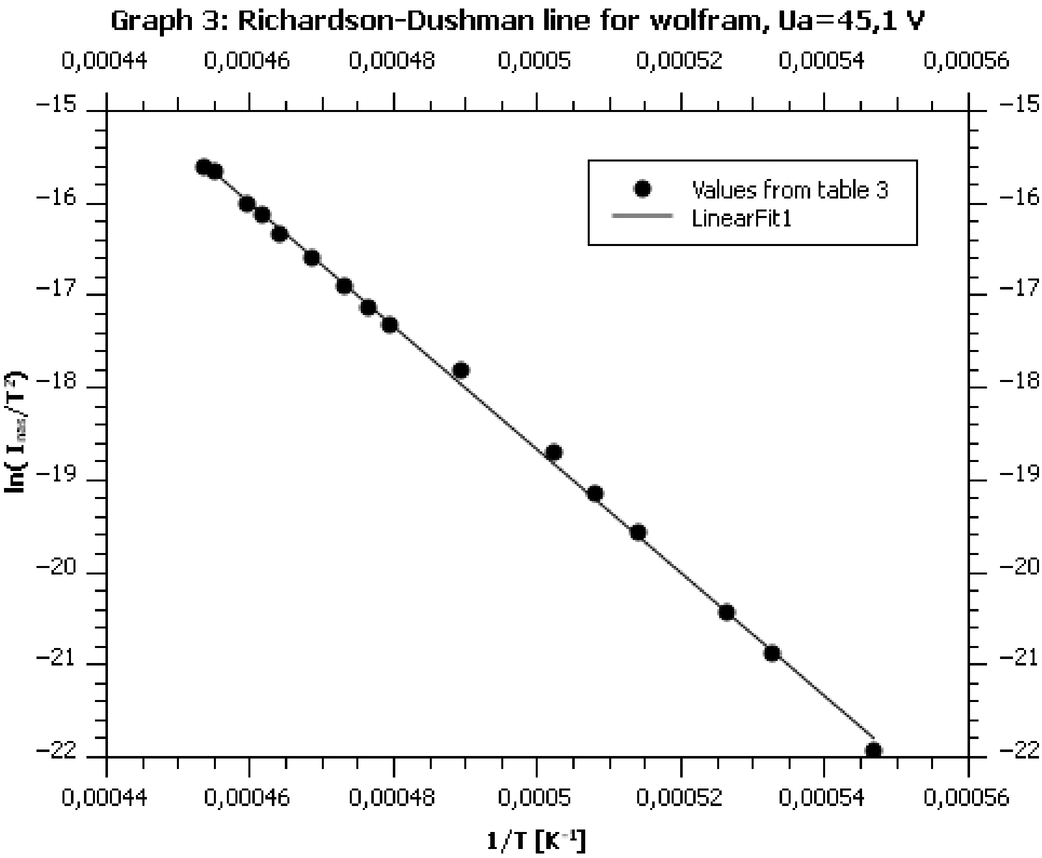
Results of linear fit from the 2nd graph ($y(x) = a_2 * x + b_2$):
$a_2 = (\ -70200 \pm 2100\ )$ K $\qquad b_2 = (\ 16.1 \pm 1,0\ )$

Work function of wolfram: $w_2 = -a_2 k = (\ 9.69 \pm 0.29\ ) \times 10^{-19}$ J $= (\ 6,05 \pm 0.18\ )$ eV $\qquad \delta_r = 3.0\%$

Constant $B_2 = \exp(b_2) = 9 \times 10^6$

Table 3: Measured values for Richardson-Dushman equation (Ua = 45,072 V):

n	U_f [V]	I_f [A]	I_a [A]	R [Ω]	T [K]	$1/T$ [K^{-1}]	$\ln(I_n/T^2)$
1	0,947	1,031	0,001	0,918	1828	0,000547	-21,9
2	0,990	1,053	0,003	0,940	1877	0,000533	-20,9
3	1,009	1,062	0,005	0,950	1900	0,000526	-20,4
4	1,051	1,082	0,012	0,971	1946	0,000514	-19,6
5	1,072	1,092	0,019	0,981	1969	0,000508	-19,1
6	1,093	1,102	0,030	0,991	1991	0,000502	-18,7
7	1,143	1,126	0,076	1,015	2043	0,000489	-17,8
8	1,180	1,141	0,132	1,034	2086	0,000479	-17,3
9	1,193	1,146	0,159	1,041	2100	0,000476	-17,1
10	1,207	1,153	0,204	1,047	2114	0,000473	-16,9
11	1,228	1,163	0,283	1,056	2134	0,000469	-16,6
12	1,250	1,173	0,371	1,065	2155	0,000464	-16,3
13	1,261	1,178	0,463	1,070	2165	0,000462	-16,1
14	1,272	1,183	0,526	1,075	2176	0,000460	-16,0
15	1,296	1,195	0,767	1,085	2198	0,000455	-15,7
15	1,301	1,196	0,800	1,088	2204	0,000454	-15,6



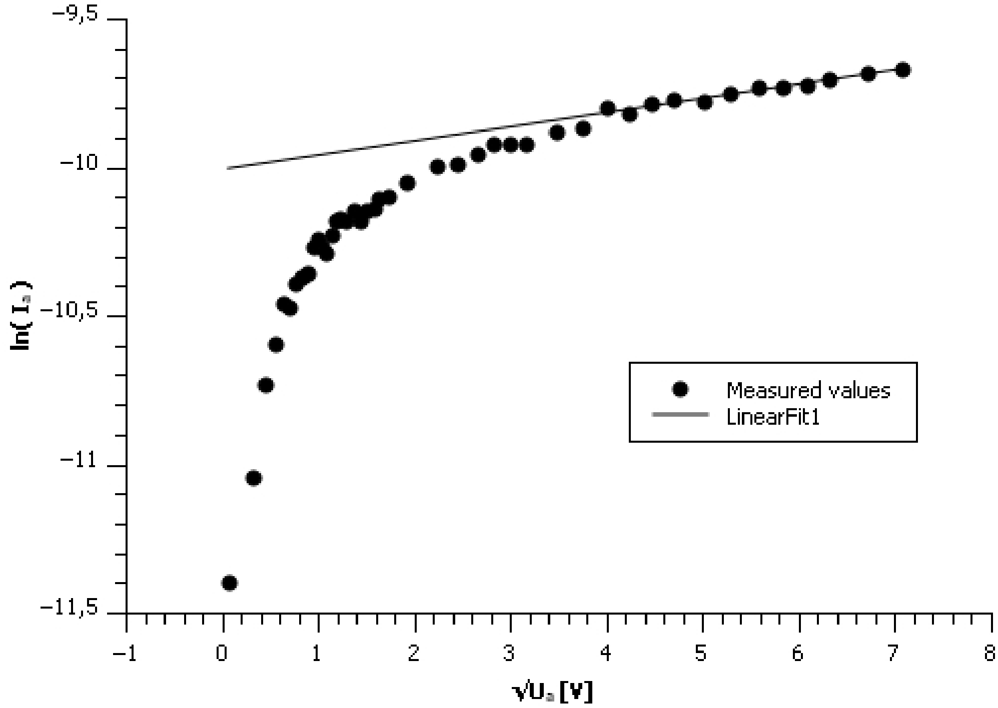
Results of linear fit from the 3rd graph ($y(x) = a_3 * x + b_3$):
$a_3 = (-66730 \pm 610)$ K $\qquad b_3 = (14,69 \pm 0,30)$

Work function of wolfram: $w_3 = -a_3 k = (9.213 \pm 0.084) \times 10^{-19}$ J $= (5,750 \pm 0.053)$ eV, $\delta_r = 0.9\%$

Constant $B_3 = \exp(b_3) = 2.4 \times 10^6$

Theoretical intensity of electric field (for $U_a = 150$V): $E = 1137$ kV/m
The increase of work function: $w_p = 1.498 \times 10^{-20}$ J $= 0.093$ eV
Used cathode current and voltage: $I_f = 1.1177$ A, $U_f = 0.975$ V
Temperature of cathode: $T = 1730$ K
Theoretical increase of saturated current: $_\triangle I_n = BT^2 \mathrm{e}^{\frac{-w}{kT}} (\mathrm{e}^{\frac{w_p}{kT}} - 1) = 85\ \mu$A

Graph 4: Dependence of logarithm of anode current on square root of anode voltage and linear fit of schottky line.

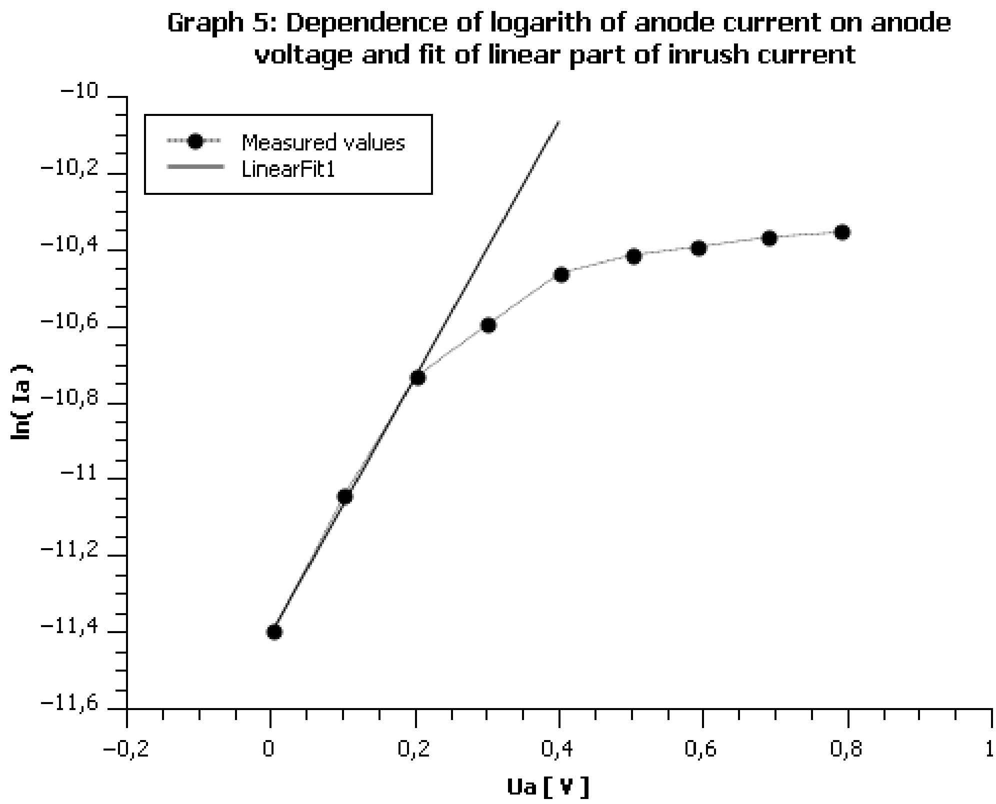


Results of linear fit from the 4th graph ($y(x) = a * x + b$):
$a = (\ 0.0479 \pm 0.0030\ )$ $\qquad b = (\ -10,008 \pm 0,017\ )$

Measured increase of work function:

$$w_{p,m} = a\sqrt{U_a}kT = (\ 1.401 \pm 0.088\ ) \times 10^{-20}\ \mathrm{J} = (\ 0.0875 \pm 0.0055\ )\ \mathrm{eV}$$

Measured increase of saturated current: $_\triangle I_{n,m} = \mathrm{e}^b(\mathrm{e}^{a\sqrt{U_a}} - 1) = (\ 35.9 \pm 3.6\ )\ \mu$A $\qquad \delta_r = 10\%$



Results of linear fit from the 5th graph ($y(x) = a * x + b$):
$a = (\ 3.35 \pm 0.15\ )$ $b = (\ -11,407 \pm 0,020\ )$

Measured temperature of electrons: $T_e = \frac{e}{ka} = (\ 3460 \pm 160\ )$ K

3. Conclusion

In this practicum was determined intensity of electrical field near of cathode $E = 1137$ kV/m (for anode voltage U_a=150V), increase of saturated current in this field $I_{n,m} = 35.9 \pm 3.6$ μA (theoretical value is $I_n = 85\mu$A), measured temperature of electrons $T_e = 3460 \pm 160$ K (temperatures calculated from Ohm's law were above 1730 K) and the work function of wolfram $w = 5.62 \pm 0.10$ eV, which table value is $w_T = 4.5$ eV.