

MOTIVATION

Electron emission from cathodes occurs when electrons in the conduction band of the cathode overcome a certain potential barrier. Depending on the physical conditions enabling the release of electrons from the cathode, the mechanisms of electron emission are categorized as resulting from individual events (ion bombardment) or collective effect (high temperature in the cathode, high electric field on the cathode surface). Collective effects characterize the arc regime of operation of electric discharges that are relevant to cathodic arcs, electric arcs in switching devices as examples of application fields.

COMPUTATIONAL METHOD

Electron emission from a metal surface at a temperature T_c in the presence of electric field F

$$J_{em} = e \int_{-\infty}^{\infty} \int_{W_a}^E T(F, W) \mathcal{N}(T_c, \phi, E) dW dE$$

The supply function according to the Sommerfeld theory and Fermi-Dirac statistics

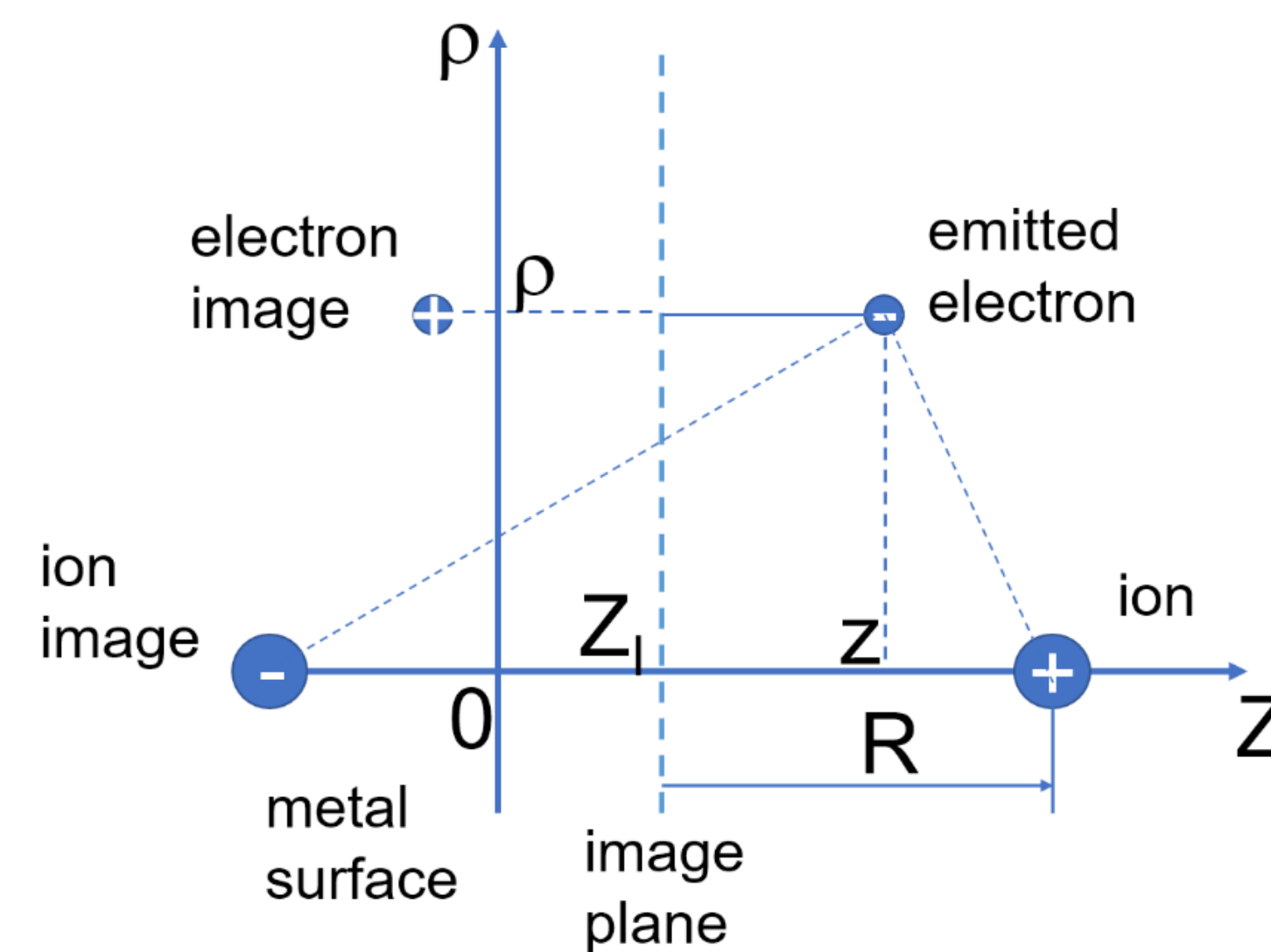
$$\mathcal{N}(T_c, \phi, E) = \frac{4\pi m_e}{h^3} \left(\exp\left(\frac{E+\phi}{k_B T_c}\right) + 1 \right)^{-1}, E_F \approx -\phi$$

$T(F, W)$ – transmission probability

W - electron energy for the motion on z

E - electron kinetic energy

The transfer matrix method (TMM) is used to obtain $T(F, W)$ [1].



Potential experienced by an emitted electron

$$V(\rho, z) = V_1(z) + V_2(z)$$

- External electric field F

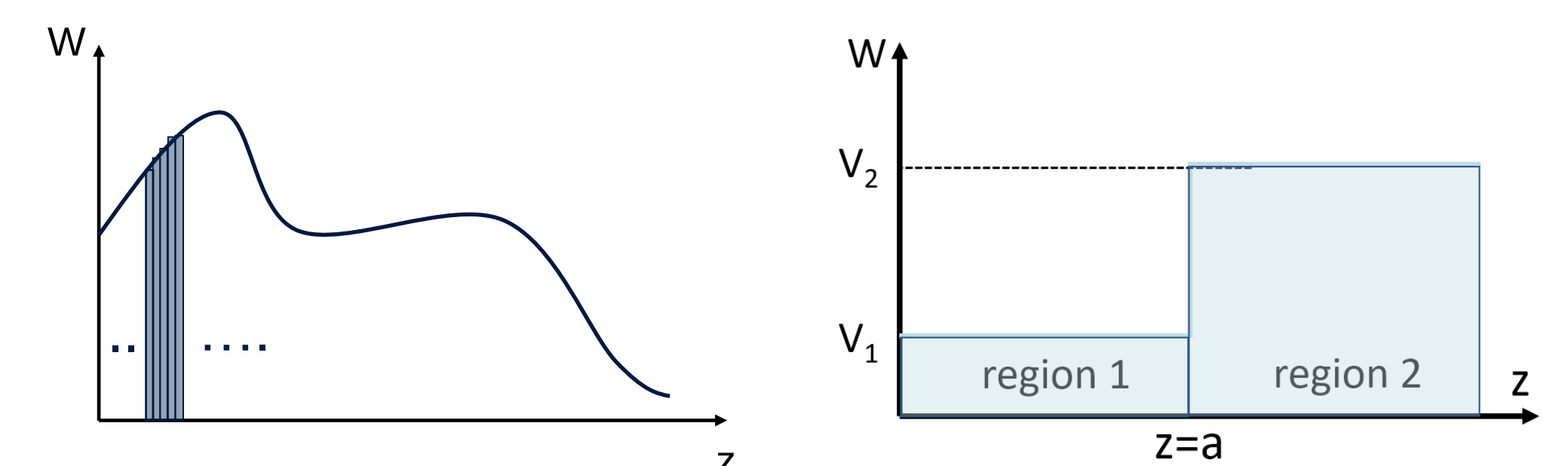
$$V_1(z) = -Fz, \text{ if } z \geq 0$$

- Force of the electron image on the electron

$$V_2(z) = \begin{cases} -\frac{V_0/e}{A \exp[B(z-Z_I)] + 1}, & \text{if } z \leq Z_I \\ -\frac{e}{4\pi\epsilon_0} \frac{1 - \exp[-\lambda(z-Z_I)]}{4(z-Z_I)}, & \text{if } z > Z_I \end{cases}$$

Stationary one-dimensional Schrödinger equation for electron of energy W facing a potential barrier $V(z)$

$$\frac{d^2 \psi(z)}{dz^2} = -\frac{2m_e}{\hbar^2} (W - V(z)) \psi(z)$$



$$\psi(z) = \begin{cases} A_1 \psi_1(z) + B_1 \psi_2(z), & \text{if } z \leq a \\ A_2 \psi_1(z) + B_2 \psi_2(z), & \text{if } z \geq a \end{cases} \quad \begin{pmatrix} A_1 \\ B_1 \end{pmatrix} = T_{12} \begin{pmatrix} A_2 \\ B_2 \end{pmatrix}$$

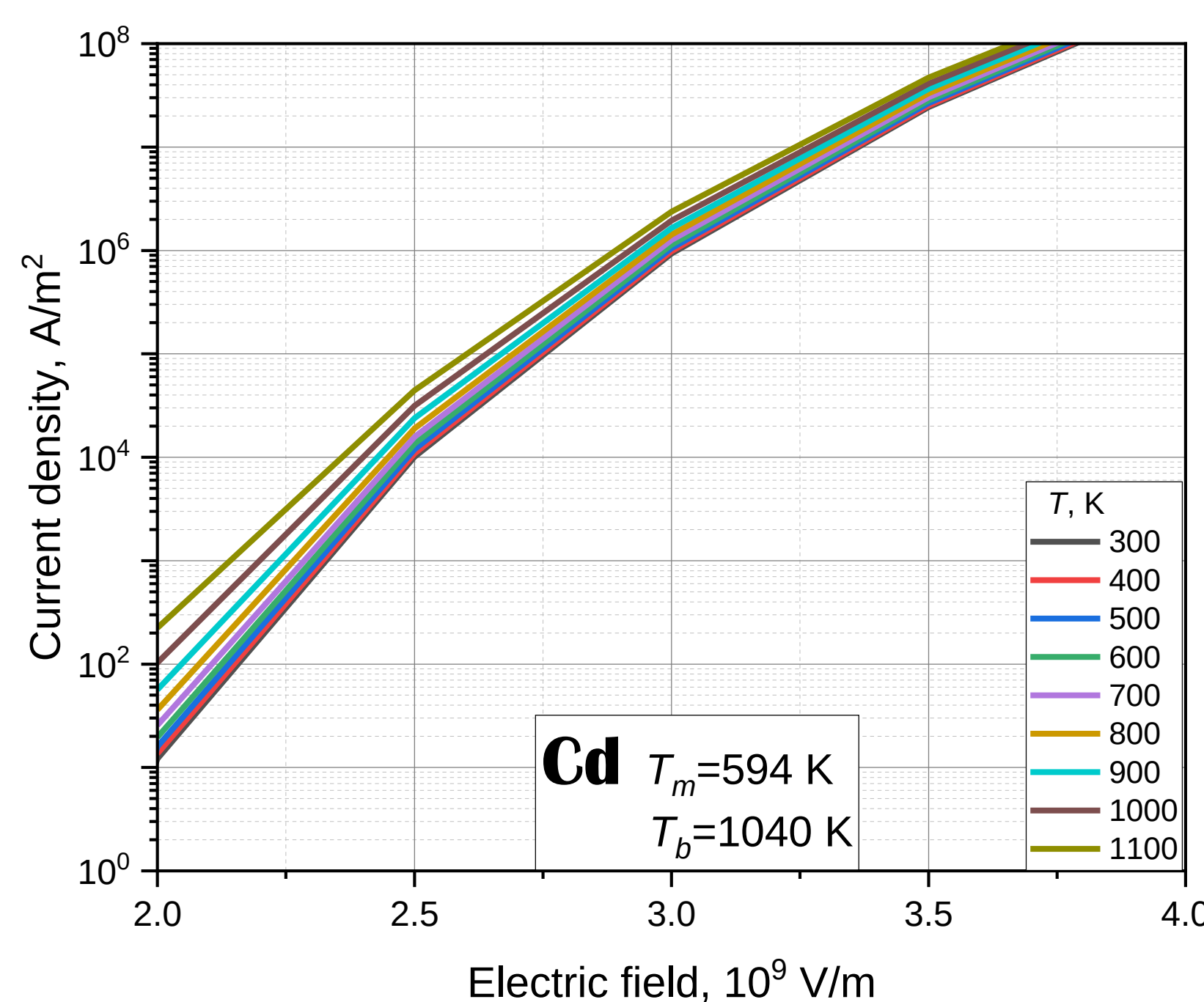
$$\begin{pmatrix} \psi(z) \\ \psi'(z) \end{pmatrix} = \begin{pmatrix} \psi_1(z) & \psi_2(z) \\ \psi_1'(z) & \psi_2'(z) \end{pmatrix} \begin{pmatrix} A_j \\ B_j \end{pmatrix} \quad \begin{pmatrix} A_1 \\ B_1 \end{pmatrix} = T_{12} T_{23} \dots T_{N-1,N} \begin{pmatrix} A_N \\ B_N \end{pmatrix} = T \begin{pmatrix} A_N \\ B_N \end{pmatrix}$$

$$hk_1 (|A_1|^2 - |B_1|^2) = hk_N (|A_N|^2 - |B_N|^2) \quad A_1 \neq 0, B_N = 0$$

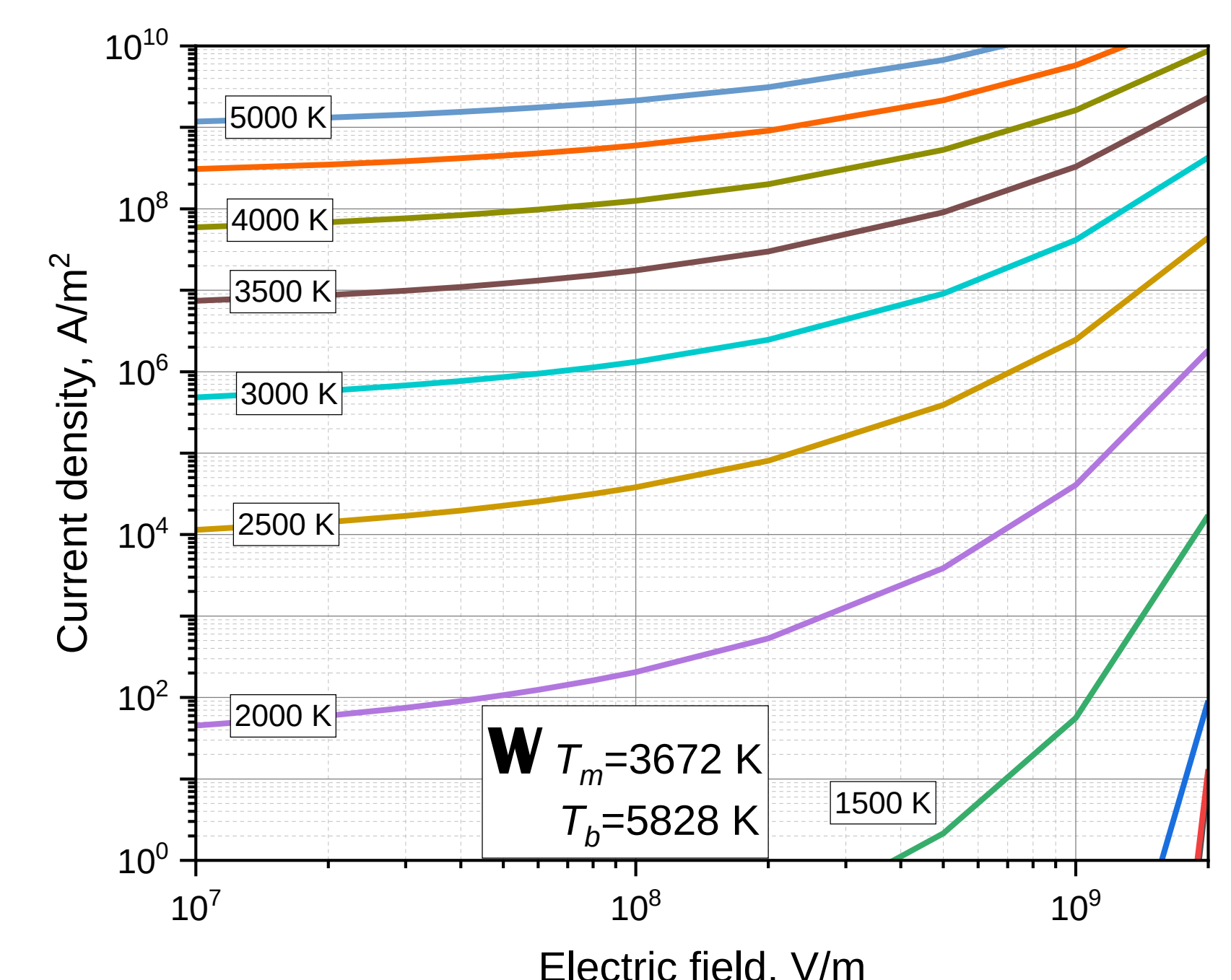
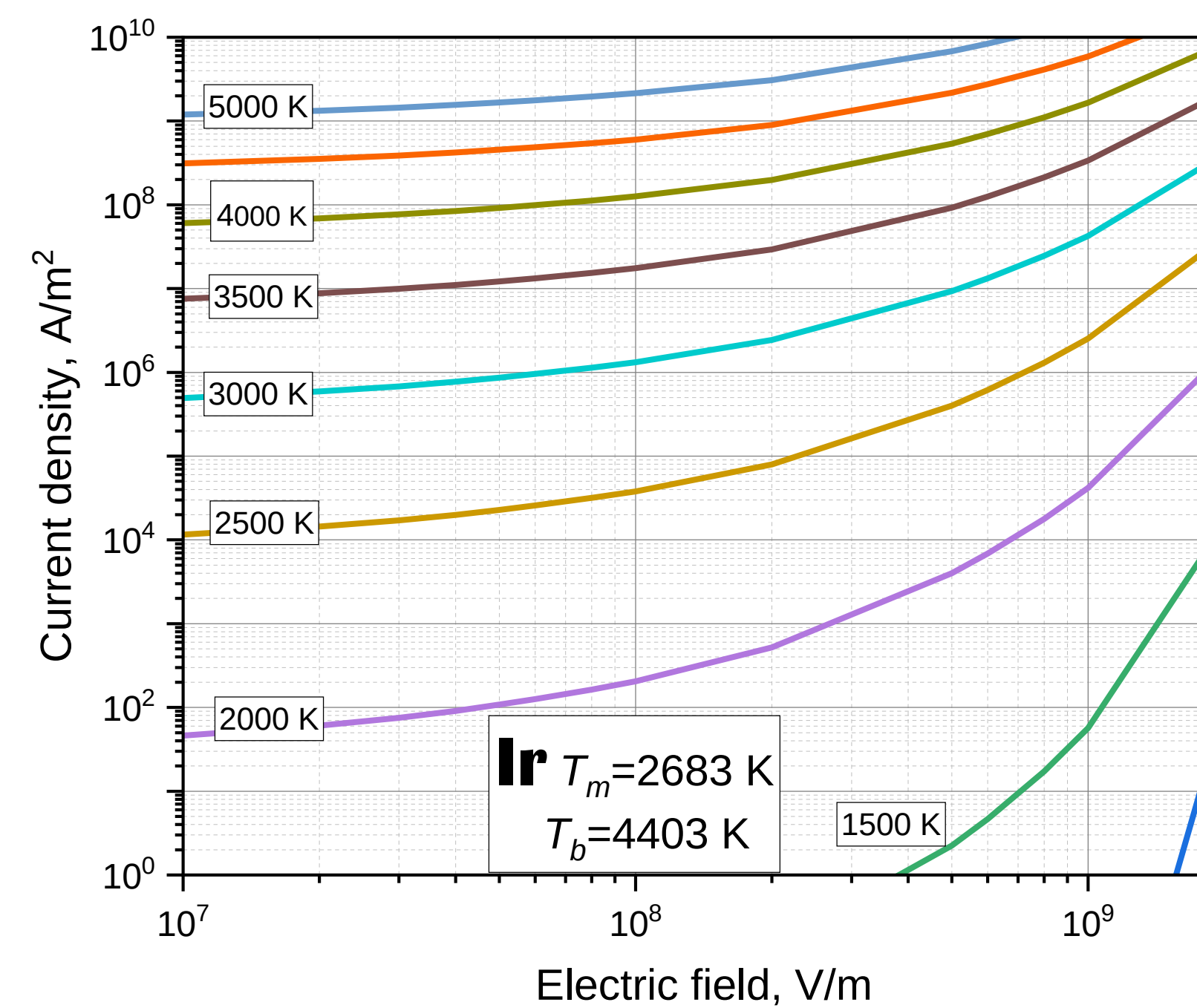
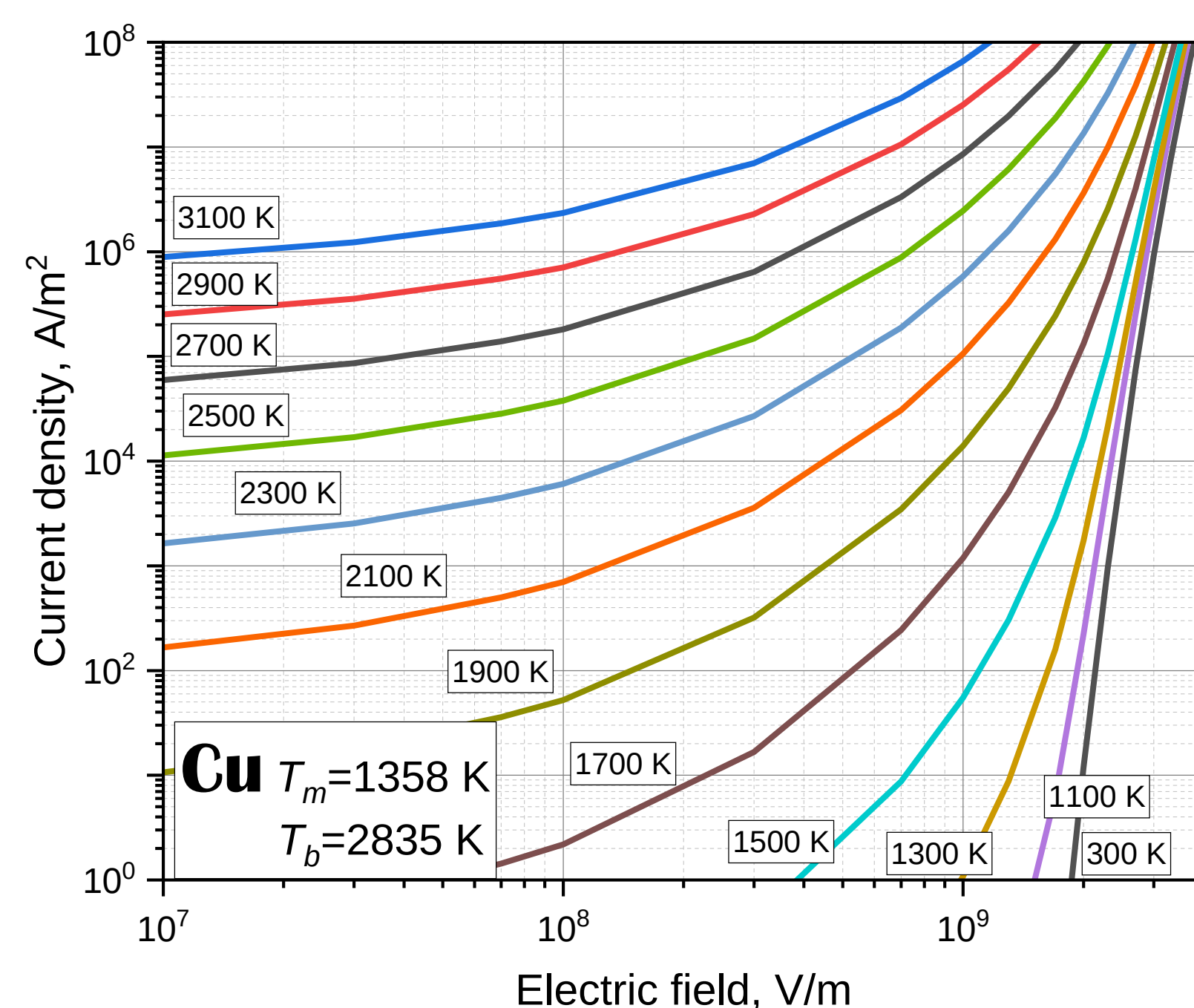
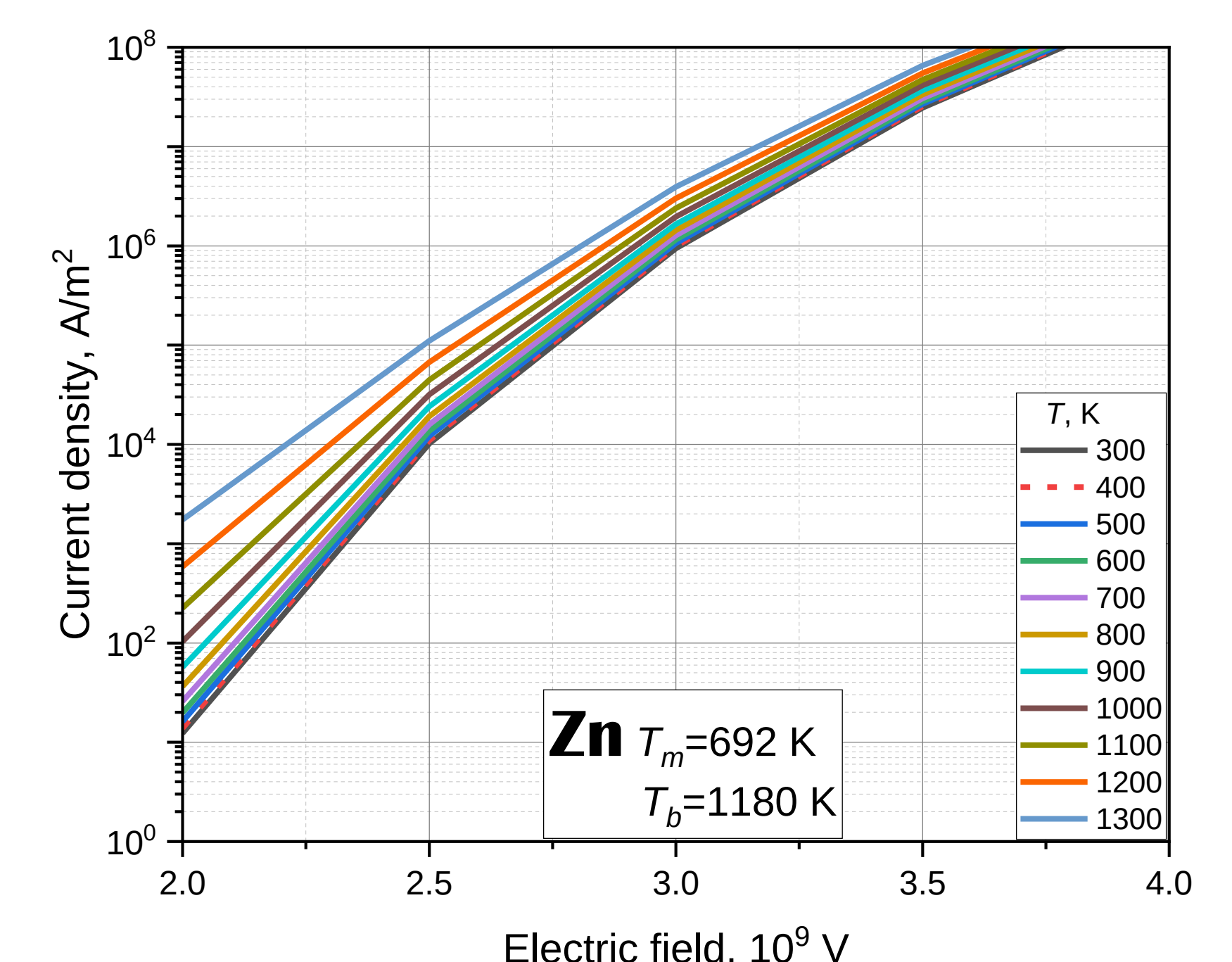
$$\left| \frac{B_1}{A_1} \right|^2 + \frac{k_N}{k_1} \left| \frac{A_N}{A_1} \right|^2 = 1 \quad T = \frac{k_N}{k_1} \left| \frac{1}{t_{11}} \right|^2$$

RESULTS

The emission of electrons from cathodes made of selected materials (Cd, Zn, Cu, Ir, W) is obtained. It occurs by collective effects (high temperature in the cathode, high electric field on the cathode surface). These effects characterize the arc regime of operation of electric discharges.



The electron emission current density from cathodes made of Cd and Zn reaches values of (10^6-10^7) A/m² for surface electric field of about 3×10^9 V/m. A temperature increase up to the melting point T_m or even up to the boiling point T_b does not give a rise of the current density for weak electric fields. The main mechanism of electron emission is the field emission. For a surface electric field of $(1-3) \times 10^7$ V/m, a field enhancement factor between 100 and 300 is needed.



With cathodes made of Cu, a current density of (10^6-10^7) A/m² can be reached at temperatures below and slightly above the melting point and an electric field of $(2-3) \times 10^9$ V/m.

For temperatures approaching the boiling point, the required electric field lowers down to $\sim (10^8-10^9)$ V/m.

Cathodes made of Ir and W can withstand high temperatures before melting. They can provide a field-enhanced thermionic electron emission with a current density of (10^6-10^7) A/m² and for electric field in the order of 10^7 V/m (in case of W) or 10^8 V/m.

References:

[1] M. Baeva, Application of the transferred matrix method to a unified evaluation of the cathodic electron emission AIP Advances **8**, 085322 (2018); <https://doi.org/10.1063/1.5041314>