

On the Ionization of Barium on Hot  
Rhenium Surfaces

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**I N S T I T U T F Ü R P L A S M A P H Y S I K**

**G A R C H I N G B E I M Ü N C H E N**



# INSTITUT FÜR PLASMAPHYSIK

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Introduction

The use of alkali atoms for a plasma generated by thermionic

**ABSTRACT:** Due to both the high ionization and the high evaporation energy of Barium, together with the high work function of Rhenium it is expected that also for rather high temperatures of the emitter, the coating of the emitter surface by Ba atoms cannot be neglected. This coating has considerable influence on the work function of the emitter and on the individual desorption energies. On the other hand, a clean Re surface provides only a relatively small flux of thermally emitted electrons, so that it may be difficult to establish an electron sheath in front of the emitter.

Based on a theory given by Rasor and Warner<sup>(6)</sup> and on experimental results obtained for the system Ba - W by Utsugi and Gomer<sup>(7)</sup>, the properties of the system Ba - Re are evaluated. Thereby it is found that the relative potential distribution within the undisturbed part of the plasma column is unaffected by a change of the emitter properties.

turn is determined by ion-electron collisions rather than by like particle collisions. The results obtained in the report mentioned - although they show the desired tendency - are not able to explain also quantitatively the experimental results of ref. 3 and 4 (mean ion energy was larger than the emitter temperature, and mean particle density evaluated from probe data much higher than the one determined by the method of resonant light scattering).

It seems to be worthwhile, therefore, to ask whether the observed



## Introduction

The use of alkali earth for a plasma generated by thermionic emission from hot metal surfaces has the advantage that plasma parameters such as mean particle density and ion temperature can be obtained by spectroscopic means and no probes are necessary to be exposed to the plasma<sup>(1)</sup>. Several such experiments have been performed by using a Ba plasma<sup>(2,3)</sup> but agreement between data obtained spectroscopically and those obtained from Langmuir probes is not yet achieved. In a previous report<sup>(4)</sup> it has been shown that the radial electric field in the Q-machine for usual mean particle densities causes a certain deviation from the equilibrium state, as a consequence of which the mean ion energy is slightly increased above the temperature of the end plates and the loss rate of the ions is somewhat increased as well. These effects vanish for a "collision dominated" plasma, where "collision dominated" in this connection has to be understood such that the mean life time of the ions within the plasma is long in comparison to the equipartition time which in turn is determined by ion-electron collisions rather than by like particle collisions. The results obtained in the report mentioned - although they show the desired tendency - are not able to explain also quantitatively the experimental results of ref. 3 and 4 (mean ion energy much larger than the emitter temperature, and mean particle density evaluated from probe data much higher than the one determined by the method of resonant light scattering).

It seems to be worthwhile, therefore, to ask whether the observed



are used it is very difficult to adjust for completely symmetrical conditions. Therefore one is forced to assume that, in property of the Ba plasma used in these particular experiments rather than a general behaviour. This assumption is supported by the fact that quantitative agreement is usually obtained between microwave and probe measurements in an alkali plasma, at least if some care is taken with respect to the probe measurements.

It is the purpose of this report, therefore, to investigate in somewhat more detail the ionization process of Ba atoms on a hot Re surface. This will be done by evaluating the different energies and frequencies involved, and by taking the influence of the sheath voltage (but not the spatial distribution of the potential) on the production rate of ions into account.

### Surface processes

It is not evident that the generation of a plasma by contact ionization on a hot metal surface can be treated by assuming equilibrium conditions, as has been stressed by W. Weiershausen<sup>(5)</sup>. If a plasma is contained within a box of uniform temperature and work function it will be in equilibrium with the walls and detailed balance of all individual processes will be established. This means that the loss rate of any species is equal to its production rate and no process has to be assumed to convert one species into another one (p.e. an atom into an ion). This behaviour is generally different in a Q-machine which usually consists of an emitter and a reflector facing each other; such a device is asymmetric about its midplane. But even if two emitters



modation coefficient is equal to one, (i.e. that all particles hitting the plates come into thermal equilibrium with the plates). Therefore, one is forced to assume that, in general, at least a fraction of the ions (for single ended operation and an electron sheath at the emitter the total amount of the ions) produced at the emitter is lost elsewhere and has to be replaced by ionizing neutrals if stationary state is required. It will be checked later if the characteristic time for fluctuations between the atomic and ionic state of the adsorbed particle is short compared to the life time of the adsorbed particle. Only in this case one would expect that the ratio of desorbing ions to desorbing atoms is not shifted to much towards the desorbing atoms as compared to the ratio under equilibrium conditions. For a strong ion sheath on the emitter, however, the number of desorbing ions reflected by the sheath voltage can become so large that the deviation from equilibrium conditions on the emitter surface becomes negligibly small anyway.

Due to the above statements the statistical treatment seems to be more appropriate to this problem than the thermodynamical one. Therefore, the lines of Rasor and Warner<sup>(6)</sup> will be followed and the experimental results by Utsugi and Gomer<sup>(7)</sup> will be used. The desorption energy of Ba atoms from a W surface as given in ref.7 agrees approximately with the one obtained by Moore and Allison<sup>(8)</sup>. When judging the applicability of the results of ref.7 to this problem, advantage will be taken of the fact that most of the particles evaporated are evaporated as atoms as will be seen later.

For the following treatment it shall be assumed that the accom-

modation coefficient is equal to one, (i.e. that all particles hitting the plates come into thermal equilibrium with the plates). This includes the assumption that all frequencies involved are sufficiently large to guarantee that the ratio of the number of adsorbed atoms to the one of adsorbed ions is given by the Boltzmann factor

$$\frac{\theta_a}{\theta_i} = q \exp \left( - \frac{U_E}{U_{th}} \right) \quad (1)$$

where  $\theta_{a,i}$  is the fraction of the emitter surface coated by atoms respectively, and  $\nu_{a,i}$  the corresponding frequency factors. The numerical value of  $q$  is essentially determined by the properties of the emitter, the adsorption energy  $U_E$  being equal to  $6.6 \cdot 10^{-14}$  eV/cm<sup>2</sup> and according to ref. 7 equal to  $6.9 \cdot 10^{-14}$  eV/cm<sup>2</sup>. Therefore,

$$\theta_i + \theta_a = \theta \quad (2)$$

$eU_E$  is the difference in energy between the atomic and ionic state of the adsorbed particle and  $eU_{th}$  is the thermal energy as defined by the relation

$$eU_{th} = kT \quad (3)$$

$q$  is the ratio of the quantum mechanical weight factors

$$q = \frac{g_a}{g_i} = \frac{1}{2} \quad \text{for Ba} \quad (4)$$

which is equal to 2 for the alkali metals but equal to  $\frac{1}{2}$  for the alkali earths.

The flux density,  $\phi_{i,a}$ , of desorbing ions and atoms, respec-



tively, is given by

$$\phi_i = \theta_i \sigma \nu_i \exp\left(-\frac{U_{di}}{U_{th}}\right) \quad (5)$$

$$\phi_a = \theta_a \sigma \nu_a \exp\left(-\frac{U_{da}}{U_{th}}\right) \quad (6)$$

where  $\sigma$  is the density of adsorbed particles forming a monolayer.  $eU_{di,a}$  are the desorption energies for ions and atoms, respectively, and  $\nu_{i,a}$  the corresponding frequency factors. The numerical value of  $\sigma$  is essentially determined by the properties of the substrate and according to ref.7 equal to  $6.6 \cdot 10^{14} \text{ cm}^{-2}$  and according to ref.9 equal to  $6.9 \cdot 10^{14} \text{ cm}^{-2}$ . Therefore, the following mean value will be used for the numerical computations

$$\sigma = 6.7 \cdot 10^{14} \text{ cm}^{-2} \quad (7)$$

which is valid for the hexagonal crystal structure of Re.

It is convenient to introduce into eqs.(5) and (6) the total degree of coating,  $\theta$ , as defined by eq.(2) instead of  $\theta_i$  and  $\theta_a$ . This will be done with the help of eq.(1)

$$\theta_i = \theta \frac{1}{1 + q \exp\left(-\frac{U_E}{U_{th}}\right)} \quad (8)$$

the sum of all these energies has to vanish. It is interesting to note that  $U_j$  is the only quantity (12) which is independent of the properties of the adsorbed ion.

$$\theta_a = \theta \frac{q \exp\left(-\frac{U_E}{U_{th}}\right)}{1 + q \exp\left(-\frac{U_E}{U_{th}}\right)} \quad (9)$$

If stationary state is required the sum of  $\phi_a$  and  $\phi_i$  must be yielding the flux of incoming particles,

$$\phi_i = \theta \sigma v_i \frac{\exp\left(-\frac{U_{di}}{U_{th}}\right)}{1 + q \exp\left(-\frac{U_E}{U_{th}}\right)} \quad (10)$$

Therefore, an ionization probability,  $\gamma$ , can be defined by

$$\phi_a = \theta \sigma v_a \frac{q \exp\left(-\frac{U_{da} + U_E}{U_{th}}\right)}{1 + q \exp\left(-\frac{U_E}{U_{th}}\right)} \quad (11)$$

which by using eqs. (10) - (13) becomes

A relation between the different energies involved is given by the equation

$$U_E + U_{da} + U_j - \varphi - U_{di} = 0 \quad (12)$$

The so obtained  $\gamma$  is identical with the one following from the

which describes the following cycle process: Consider an adsorbed ion. Then the energy  $eU_E$  is required to get an electron from the conduction band of the substrate and to convert the adsorbed ion into an adsorbed atom.  $eU_{da}$  is then needed to desorb the atom and  $eU_j$  to ionize the free atom. By falling back into the conduction band of the substrate the electron gains the energy  $e\varphi$  ( $\varphi$  being the work function) and the ion gains the energy  $eU_{di}$  if it becomes reabsorbed. Now the initial state is reestablished which means that

$$v_1 = v_a \quad (16)$$



the sum of all these energies has to vanish. It is interesting to note that  $U_j$  is the only quantity in eq.(12) which is independent of the properties of the substrate.

If stationary state is required the sum of  $\phi_a$  and  $\phi_i$  must be equal to the flux of incoming particles,

$$\phi_o = \phi_i + \phi_a \quad (13)$$

Therefore, an ionization probability,  $\gamma$ , can be defined by

$$\gamma = \frac{\phi_i}{\phi_o} \quad (14)$$

which by using eqs.(10) - (13) becomes

$$\gamma = \frac{1}{1 + q \frac{\nu_a}{\nu_i} \exp\left(\frac{U_j - \psi}{U_{th}}\right)} \quad (15)$$

The so obtained  $\gamma$  is identical with the one following from the Langmuir-Saha equation, except for the factor of  $\nu_a / \nu_i$  appearing in the denominator which arose from the formal introduction of  $\nu_{i,a}$  into the eqs.(8) and (9). Under equilibrium conditions  $\nu_a$  must be equal to  $\nu_i$  as follows by a comparison of eq.(15) with the Langmuir-Saha equation. For the problem considered here it has to be checked whether the assumption of thermal equilibrium between the adsorbed particles and the emitter is appropriate, i.e. to which extent the assumption

$$\nu_i = \nu_a \quad (16)$$

is satisfied. This will be estimated in the following way: The state of the adsorbed particle undergoes thermal fluctuations between the atomic and the ionic one, and in thermal equilibrium the rate of surface ionization processes must be equal to the rate of recombination processes. The latter quantity is determined by the number of electrons available per unit time for the adsorbed ion under consideration. This quantity might be estimated by using the Richardson formula but replacing the work function by  $U_E$  and deviding the current density by  $e\sigma$

$$v_e = \frac{c U_{th}^2}{\sigma} \exp\left(-\frac{U_E}{U_{th}}\right) \quad (17)$$

Now, the different energies have to be evaluated. In eq. (12)  $U_E$  where  $eC$  is the Richardson constant ( $e$  being the elementary charge)

$$C = 2.3 \cdot 10^{28} \text{ cm}^{-2} \text{ sec}^{-1} \text{ V}^{-2} \quad (18)$$

The characteristic time,  $\tau$ , for establishing the equilibrium distribution is then obtained by

$$\tau \approx \frac{1}{v_e} \cdot \frac{\theta_a}{\theta_i}$$

$$= \frac{g \sigma}{c U_{th}^2} = 4.90 \text{ V} \quad (19)$$

which is of the order of  $10^{-12}$  sec. This characteristic time is much shorter than the life time of the adsorbed particles - at least for the system under consideration - and consequently,



eq.(16) should be satisfied with a high degree of accuracy. Thus, eqs.(10) and (11) can be written as follows

$$\phi_i = \theta \sigma \nu \frac{\exp\left(-\frac{U_{di}}{U_{th}}\right)}{1 + q \exp\left(-\frac{U_E}{U_{th}}\right)} \quad (20)$$

$$a = \theta \sigma \nu \frac{q \exp\left(-\frac{U_{da} + U_E}{U_{th}}\right)}{1 + q \exp\left(-\frac{U_E}{U_{th}}\right)} \quad (21)$$

Now, the different energies have to be evaluated. In eq.(12)  $U_j$  is a known quantity and has the value for Ba

$$U_j = 5.21 \text{ V} \quad (22)$$

The values of  $U_{da}$  and  $\varphi$  may be obtained by extrapolating the experimental data for the system Ba - W to the system Ba - Re. The work function,  $\varphi_0$ , for a clean surface of polycrystallin Re was measured by several authors dealing with the problems of contact ionization

- ref. 6:  $\varphi_0 = 4.90 \text{ V}$
- ref.10:  $= 4.97 \text{ V}$
- ref. 9:  $= 4.86 \text{ V}$

yielding a mean value

$$\varphi_0 = 4.91 \text{ V} \quad (23)$$

The dependence of  $\varphi$  on  $\theta$  for Ba - Re will be assumed to be the same as the one given in ref.7 for Ba - W. This may be justified since the reduction in work function of the substrate with increasing degree of coating is due to the polarization of the adsorbed atoms and is thus essentially a property of the ad-atoms. This procedure is furthermore supported by the experimental results of ref.6 when comparing the systems Cs - W and Cs - Re. Therefore,  $\varphi(\theta)$  as given in fig.1 will be considered as a known quantity.

It is a somewhat larger problem to estimate the desorption energy,  $U_{da}$ , of Ba atoms from a Re surface. This quantity is given in ref.7 for the system Ba - W. But W possesses a body centered crystal structure whereas Re is of the hexagonal type and it might be dangerous, therefore, to take for the system Ba - Re the same values as found for the system Ba - W. In ref.6, however, an empirical formula is given which usually describes the atom desorption energies with satisfactory accuracy

$$U_{da} = b \sqrt{h_o \cdot h_a} \quad (24)$$

where  $b$  is a constant  $.5 < b < 1$ , and  $h_{o,a}$  are the evaporation energies of the substrate and the bulk adsorbate, respectively. This formula shall be used here only in order to transform the values of  $U_{da}$  obtained for Ba - W into the ones for Ba - Re, by which method the somewhat uncertain quantity  $b$  is eliminated

$$U_{da}(\theta)(Ba - Re) = \sqrt{\frac{h_o(Re)}{h_o(W)}} U_{da}(\theta)(Ba - W) \quad (25)$$



In ref.6  $h_0 = 8.8$  eV is quoted for W whereas  $h_0 = 7.8$  eV for Re can be found in ref.11, yielding

$$U_{da}(\theta)(\text{Ba} - \text{Re}) = 0.94 U_{da}(\theta)(\text{Ba} - \text{W}) \quad (26)$$

$U_{da}(\theta)$  as plotted in fig.2 is based upon the results of ref.7. If one relies on these data one has to be sure that it was really the quantity  $U_{da}$  which was measured in the experiment of ref.7. In order to judge this one has to remember that the experiments have been undertaken by using a field emission microscope in the following way: (1) The Re tip is "illuminated" by a beam of Ba atoms in order to obtain a certain deposit. (2)  $\theta$  is measured by measuring the effective work function of the tip. (3) The tip is heated for a certain time interval to a certain temperature. (4)  $\theta$  is measured again and the number of particles which are desorbed in the mean time is taken as a measure for the atom desorption energy. In this case it is advantageous that most of the particles desorb as atoms, otherwise it would not be clear if not the flux of desorbing ions could be inhibited by space charge effects leading to a too large desorption energy. Therefore,  $U_{da}$  as given in fig.2 should be reliable, at least from this point of view.

In order to be able to describe the behaviour of the system Ba - Re one more quantity of eq.(12) must be known. The most reliable theoretical background is found for the desorption energy,  $U_{di}$ , of the ions, which for  $\theta \rightarrow 0$  is given essentially

by the image force  $f$  is positive but smaller than unity and

$$F = \frac{1}{4\pi\epsilon_0} \cdot \frac{e^2}{4r^2} \quad (27)$$

where  $r$  is the distance between the ion under consideration and the metal surface. Therefore, the energy,  $U_{dio}$ , to remove the ion from its nearest distance from the emitter to infinity is given by

$$U_{dio} = \frac{e^2}{16\pi\epsilon_0 r_i} \quad (28)$$

where  $r_i$  is the ionic radius

$$r_i(\text{Ba}) = 2.25 \cdot 10^{-8} \text{ cm} \quad (29)$$

yielding an ion desorption energy for  $\theta \rightarrow 0$

$$U_{dio} = 1.59 \text{ V} \quad (30)$$

This energy becomes a function of  $\theta$  since the double layer - formed by the adsorbed particles - which reduces the work function of the substrate provides simultaneously a potential barrier for desorbing ions. Therefore, one has to write

$$U_{di}(\theta) = U_{dio} + f \Delta\varphi \quad (31)$$

where  $\Delta\varphi$  is defined by

$$\varphi(\theta) = \varphi_0 - \Delta\varphi \quad (32)$$

The factor  $f$  in eq.(31) is positive but smaller than unity and accounts for the effect that the adsorbed ions stay in a distance  $r_i$  from the emitter surface and have thus to penetrate only the fraction  $f$  of the dipole sheath when leaving the emitter, whereas the electrons starting from the Fermi level "feel" the total potential drop within the double sheath. For the magnitude of the factor  $f$  theoretical arguments are given for typical cases in ref.6. For the problem under consideration the value

$$f = 2 - \sqrt{2} = 0.59 \quad (33)$$

seems to be appropriate. This expression was obtained by assuming the temperature of the substrate high enough to lead to a random distribution of the ions over the emitter surface. It is believed that for the temperatures considered here the mobility of the adsorbed particles is large enough to satisfy the assumption of random distribution. For this model  $f$  was found to be independent of  $\theta$ . The values of  $U_{di}$  so obtained are given in fig.3 as a function of  $\theta$ .

Now, eq.(12) can be written in the following form

$$U_E = U_{dio} + \varphi_0 - (1 - f)\Delta\varphi - U_j - U_{da} \quad (34)$$

where  $U_{dio}$ ,  $\varphi_0$ ,  $f$ ,  $\Delta\varphi$ ,  $U_j$ ,  $U_{da}$  are given by eqs.(30), (23), (33), (22), and by figs.1 and 2.  $U_E$  vs.  $\theta$  as given by eq.(34) is plotted in fig.4.

$$(\phi_1)_{\theta=0} = \frac{\exp\left\{-\frac{1}{U_{th}}(U_{dio} + r\Delta\varphi)\right\}}{1 + \exp\left\{-\frac{1}{U_{th}}[U_{dio} + \varphi_0 - (1-f)\Delta\varphi - U_j - U_{da}]\right\}} \quad (37)$$



Sheath Effects

When evaluating the production rates of ions the sheath in front of the emitter has to be taken into account which is necessary in order to provide electron and ion balance. By an electron sheath all ions are accelerated towards the plasma, meaning that in this case the ion production rate is unaffected by the sheath voltage except for the Schottky effect which leads to a small reduction of the ion desorption energy<sup>(12)</sup> by an amount

$$\Delta U_{di} = - \sqrt{\frac{e E}{4 \epsilon_0}} \tag{35}$$

where the effective electric field is of the order of

$$E \approx - \frac{U_s}{\lambda_D} \tag{36}$$

$U_s$  being the sheath voltage and  $\lambda_D$  the Debye length. A typical value of  $E$  would thus be 1 kV/cm yielding for  $\Delta U_{di} \approx - 0.014$  V which is small compared to all the uncertainties involved and can be neglected therefore.

Consequently, in case of an electron sheath existing on the emitter the flux of desorbing ions is equal to the flux of ions entering the plasma and is obtained by combining the eqs.(20), (31) and (34)

$$(\phi_i)_{es} = \theta \sigma \nu \frac{\exp \left\{ - \frac{1}{U_{th}} (U_{dio} + f \Delta \varphi) \right\}}{1+q \exp \left\{ - \frac{1}{U_{th}} [U_{dio} + \varphi_0 - (1-f) \Delta \varphi - U_j - U_{da}] \right\}} \tag{37}$$

In case of an ion sheath at the emitter the ions produced by surface ionization have to overcome the sheath voltage in order to reach the plasma. Therefore, the flux of ions entering the plasma column is reduced by the factor  $\exp(-U_s/U_{th})$

$$(\phi_i)_{is} = (\phi_i)_{es} \exp\left(-\frac{U_s}{U_{th}}\right) \quad (38)$$

where the sheath voltage,  $U_s$ , is determined by the electron balance condition

$$j_R \exp\left(\frac{U_s}{U_{th}}\right) = -\frac{1}{2\sqrt{\pi}} n e v_{eth} + j_e \quad (39)$$

Here  $j_R$  is the electron emission saturation current (C being given by eq.(18))

$$j_R = -e C U_{th}^2 \exp\left(-\frac{\phi}{U_{th}}\right) \quad (40)$$

$v_{eth}$  the most probable velocity of the electrons

$$v_{eth} = \sqrt{\frac{2 e U_{th}}{m_e}} \quad (41)$$

$n$  the mean particle density within the undisturbed plasma region and  $j_e$  accounts for a possible electron current from the emitter to the collecting plate; for the following treatment  $j_e$  will be

assumed to be negligibly small. Thus, eq.(38) becomes

$$(\phi_i)_{is} = 2\sqrt{\pi} \frac{c U_{th}^2}{n v_{eth}} \theta \sigma \nu \frac{\exp \left\{ -\frac{1}{U_{th}} [U_{dio} + \varphi_o - (1-f)\Delta\varphi] \right\}}{1+q \exp \left\{ -\frac{1}{U_{th}} [U_{dio} + \varphi_o - (1-f)\Delta\varphi - U_j - U_{da}] \right\}} \quad (42)$$

The mean particle density entering in this equation is determined by

$$(\phi_i)_{is} = \frac{1}{2\sqrt{\pi} a} n v_{ith} \quad (43)$$

where the quantity "a" accounts for the different plasma conditions.

For a monotonic distribution of the potential within the sheath (which is unlikely, however)

$$a = 1 \quad (44)$$

Any non monotonic distribution of the potential within the sheath leads usually to a mean velocity of the ions parallel to the magnetic field larger than  $\frac{1}{2\sqrt{\pi}} v_{ith}$  and thus "a" has to be smaller than unity in order to satisfy eq.(43).

By using eqs.(43) and (45)

$$v_{ith} = \sqrt{\frac{2 e U_{th}}{m_i}} \quad (45)$$

one obtains for  $(\phi_i)_{is}$

$$a(\phi_i)_{is}^2 = \sqrt{\frac{m_e}{m_i}} c U_{th}^2 \theta \sigma \nu \frac{\exp \left\{ -\frac{1}{U_{th}} [U_{dio} + \varphi_o - (1-f)\Delta\varphi] \right\}}{1+q \exp \left\{ -\frac{1}{U_{th}} [U_{dio} + \varphi_o - (1-f)\Delta\varphi - U_j - U_{da}] \right\}} \quad (46)$$



For the system Ba - Re the energy level of the atomic state of the adsorbed particles is much lower than the level of the ionic one

$$\frac{\theta_a}{\theta_i} \gg 1 \quad (47)$$

Therefore, the 1 in the denominator of eqs.(21), (37) and (46) can safely be neglected which leads to much simpler expressions for the individual fluxes

$$\phi_a = \theta \sigma \nu \exp \left( - \frac{U_{da}}{U_{th}} \right) \quad (48)$$

$$(\phi_i)_{es} = \theta \sigma \nu \cdot \frac{1}{q} \exp \left\{ - \frac{1}{U_{th}} [U_j + U_{da} - \varphi_0 + \Delta\varphi] \right\} \quad (49)$$

$$a(\phi_i)_{is}^2 = \theta \sigma \nu \cdot \sqrt{\frac{m_e}{m_i}} c U_{th}^2 \cdot \frac{1}{q} \exp \left\{ - \frac{1}{U_{th}} (U_j + U_{da}) \right\} \quad (50)$$

The values for  $\nu$  will be taken from ref.7, although they are given for the system Ba - W. But the results are not so sensitive to small errors in  $\nu$ ; the essential change when changing  $\nu$  is the degree of surface coated by adsorbed particles.

The transition from an ion to an electron sheath when changing the input flux of particles is found by combining eqs.(39) and (43) for  $U_s = 0$ . Such a transition appears (1) for a low input flux, i.e. if the flux of emitted ions becomes so small that the

space charge can be compensated by the electrons available,  
(2) for an increasing input flux, if with increasing coating the work function is so much reduced that the increased electron emission current is again able to compensate the space charge.  
(3) A third transition might appear for  $\theta$  in the neighbourhood of unity but is not of interest here. (This general behaviour has been pointed out already by Langmuir.) Therefore, an ion sheath will be present at the emitter if

$$a \phi_i > \sqrt{\frac{m_e}{m_i}} c U_{th}^2 \exp\left(-\frac{\phi}{U_{th}}\right) \quad (51)$$

is satisfied.  $\frac{1}{e} j_R$  and the right hand side of (51) vs.  $\theta$  are plotted in figs.7 and 8.

$\phi_i$  vs.  $\theta$ ,  $\phi_i$  vs.  $\phi_o$  and  $\phi_i/\phi_o$  vs.  $\phi_o$  are shown in figs.11-13.

### Conclusions

It is interesting to note that for the low input fluxes quoted in fig.12  $\phi_i$  is increasing proportional to the square root of the input flux until a maximum of  $\phi_i$  is reached. Then, due to the sharp decrease in work function,  $\phi_i$  is decreasing sharply with increasing input flux. The maximum of  $\phi_i$  coincides roughly with the transition from an ion to an electron sheath. That means that for all fluxes and for all  $\theta < .1$  quoted within the figures an ion sheath is present on the emitter. Furthermore, as seen from fig.12, for a constant input flux of particles the flux of ions entering the plasma is a strong function of the temperature of

the emitter. The same behaviour has been found during the experiments of ref.2. The two results are compared in fig.14 and show a rather good agreement.

The radial electric field strength within the plasma is given by the variation of the plasma potential across the plasma column. This potential variation is easily calculated by assuming that the Fermi level of the emitter forms an area of equipotential which shall be called zero. Then it follows for the plasma potential,  $U_{pl}$ ,

$$U_{pl} = -\varphi_0 + \Delta\varphi + U_s \quad (52)$$

where  $U_s$  is given by eqs.(39) (for  $j_e = 0$ ), (40) and (43)

$$U_s = \varphi_0 - \Delta\varphi - U_{th} \left[ \ln \left( \sqrt{\frac{m_e}{m_i}} c U_{th}^2 \right) - \ln (a \phi_i) \right] \quad (53)$$

Thus,  $U_{pl}$  becomes

$$U_{pl} = -U_{th} \left[ \ln \left( \sqrt{\frac{m_e}{m_i}} c U_{th}^2 \right) - \ln (a \phi_i) \right] \quad (54)$$

That means that any change in work function due to adsorbed particles is compensated by a corresponding change in sheath voltage<sup>+</sup>). Therefore, also under the conditions assumed in this report

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<sup>+</sup>) This includes the case that for emitter temperatures smaller than  $\approx 2000$  °K adsorbed oxygen could lead to a considerable increase of the work function of the emitter<sup>(13)</sup>.



the radial electric field is given (for  $U_{th} = \text{const}$ ) by

$$E_r = - \frac{d U_{pl}}{d r} \quad (55)$$

$$= \frac{U_{th}}{n} \nabla_r n \quad (56)$$

as obtained already in ref.4 under more restricting conditions.

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Figure Captions

All curves are given for the system Ba - Re and for three different values of  $U_{th}$  (if there is any dependence on  $U_{th}$ ) 0.18, 0.20 and 0.22 V. The corresponding temperatures are T equal to 2090, 2320 and 2550 °K.

fig. 1 The change in work function of the substrate,  $\Delta\varphi$ , vs. the fraction of surface coated,  $\theta$ .

fig. 2 Desorption energy of atoms,  $U_{da}$ , vs.  $\theta$ .

fig. 3 Desorption energy of ions,  $U_{di}$ , vs.  $\theta$ .

fig. 4 Energy to convert an adsorbed ion into an adsorbed atom,  $U_E$ , vs.  $\theta$ .

fig. 5 Preexponential factor,  $\theta \sigma \nu$ , for the individual desorption rates vs.  $\theta$ .

fig. 6 Ratio of the number of adsorbed atoms to the one of adsorbed ions,  $\theta_a/\theta_i$ , vs.  $\theta$ .

fig. 7 Saturation flux,  $-j_R/e$ , of thermally emitted electrons vs.  $\theta$ .

fig. 8 Flux of ions for which the sheath voltage is vanishing vs.  $\theta$ .

fig. 9  $\exp(-U_{di}/U_{th})$  vs.  $\theta$ .

fig.10 Flux of desorbing atoms,  $\phi_a$ , vs.  $\theta$ .

fig.11 Flux of desorbing ions,  $\phi_i$ , vs.  $\theta$ .

fig.12 Flux of desorbing ions vs. total input flux,  $\phi_o$ .

fig.13 Ionization probability,  $\phi_i/\phi_o$ , vs.  $\phi_o$ .

fig.14  $\phi_i$  vs.  $U_{th}$  for a constant input flux ( $10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$ ).



Appendix

After having finished this report a paper by E. Ya. Zandberg and A. Ya. Tontegode<sup>(14)</sup> came to the authors knowledge. In this paper the surface ionization properties of Cs, K, Na, and Li on polycrystalline Re surfaces have been investigated experimentally. The results are listed within the following table

	$U_j$ V	$\varphi_i$ [V]	$\varphi_i^*$ [V]
Cs	3.89	-	-
K	4.34	4.9	-
Na	5.14	5.25	5.14
Li	5.39	5.45	5.34

$$\varphi_e^* = 4.93 \pm 0.04 \text{ V}$$

where  $\varphi_i$  is the effective work function for surface ionization of the individual system. The values have been obtained by measuring the temperature dependence of the emitted ion current upon keeping the input flux of neutrals constant.  $\varphi_i^*$  has been obtained by taking into account that the electric field present in these particular experiments reduces the ion desorption energy by an amount of 0.11 eV.  $\varphi_i^*$  is then the quantity which has to be compared with the assumptions of this report since it has been shown that the Schottky effect can safely be neglected under the conditions assumed in this report.

The result of ref. 14 is that the effective work function for surface ionization,  $\varphi_i^*$ , is increasing with increasing ionization potential of the beam atoms whereas the effective work function for electron emission,  $\varphi_e^*$ , is independent of the nature of the

length for the time during which the particle is adsorbed on the emitter surface, is exponentially decreasing with increasing temperature. This means that for a high temperature most of the particles do not stay long enough at the emitter surface in order to find a region of high work function. Consequently, the effective work function for surface ionization is expected to decrease with increasing temperature and finally to reach the value found for K. Such a process can probably not be excluded when evaluating the effective work function from the observed temperature dependence of the ionization probability. For the temperature range considered in this report - where surface diffusion can be neglected<sup>(7)</sup> - this explanation would yield that  $\varphi_0 = 4.9$  V is indeed the appropriate number for the problem under consideration.

- (4) Assuming the other extreme to be correct,  $\varphi_i^*$  would have to be of the order of 5.2 V for Ba, just equal to the ionization potential of Ba. This would lead to an ionization probability,  $\gamma'$  (according to eq.(15) for  $U_{th} = 0.2$  V)

$$\gamma' \approx \frac{2}{3} \quad (55)$$

instead of

$$\gamma \approx \frac{1}{3} \quad (56)$$

for the assumptions of this report. Therefore, the ionization probability would be increased only by a factor of 2. But, since surface diffusion can be neglected, this increase of the ionization probability is restricted only to that small fraction of the total emitter surface possessing the high work function. Thus, the effective ionization probability

beam atoms. For elements with low ionization potential  $\varphi_i^*$  and  $\varphi_e^*$  are found to be equal to each other. The reason for this behaviour is that the surface of a polycrystalline emitter consists of patches with different work functions dependent on the crystallographic planes forming the individual surface elements. In such a case electron emission is heavily weighted by regions of low work function, whereas, according to eq. (15), the ionization probability increases with increasing work function.

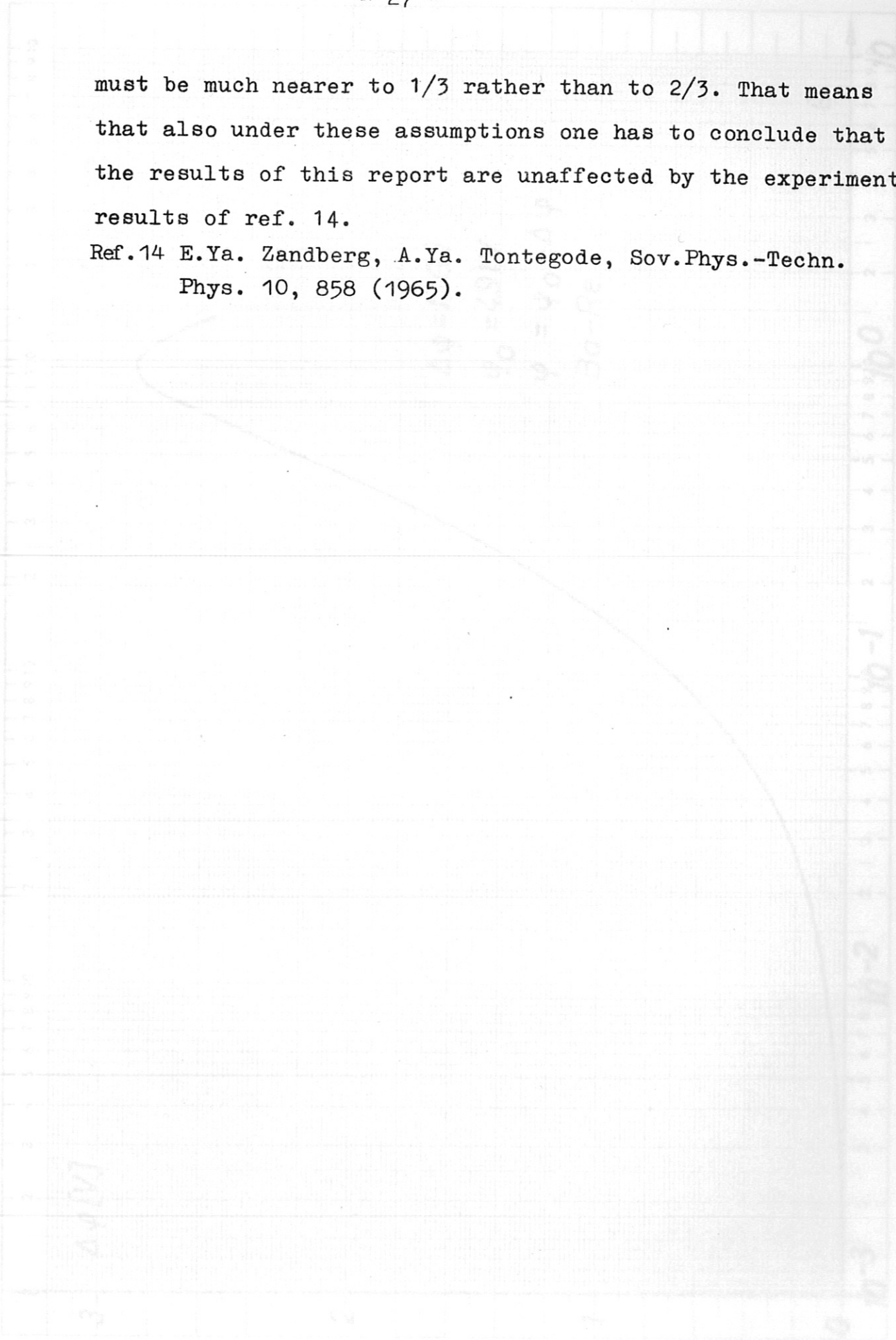
With respect to this report the following conclusions can be drawn:

- (1) The effective work function,  $\varphi_e^*$ , for electron emission agrees well with the mean value given in eq.(23), which number has been used throughout this report. (It should be remembered that the most interesting cases of this report are governed by the rate of electron emission).
- (2) The effective work function for surface ionization of K agrees with the one found for electron emission. That must mean that a large fraction of the emitter surface has this particular work function, and the contribution of surface elements with higher work function (although they yield a larger ionization probability) must be negligibly small; otherwise the contribution of these surface elements should have been found in the temperature dependence of the ionization probability for K.
- (3) For elements with a larger ionization potential, Na and Li, higher effective work functions are reported. However, in this case surface diffusion becomes important, since the atoms are assumed to be ionized preferably on such surface elements having a high work function. But the mean diffusion



must be much nearer to  $1/3$  rather than to  $2/3$ . That means that also under these assumptions one has to conclude that the results of this report are unaffected by the experimental results of ref. 14.

Ref.14 E.Ya. Zandberg, A.Ya. Tontegode, Sov.Phys.-Techn. Phys. 10, 858 (1965).



Abnahme in %

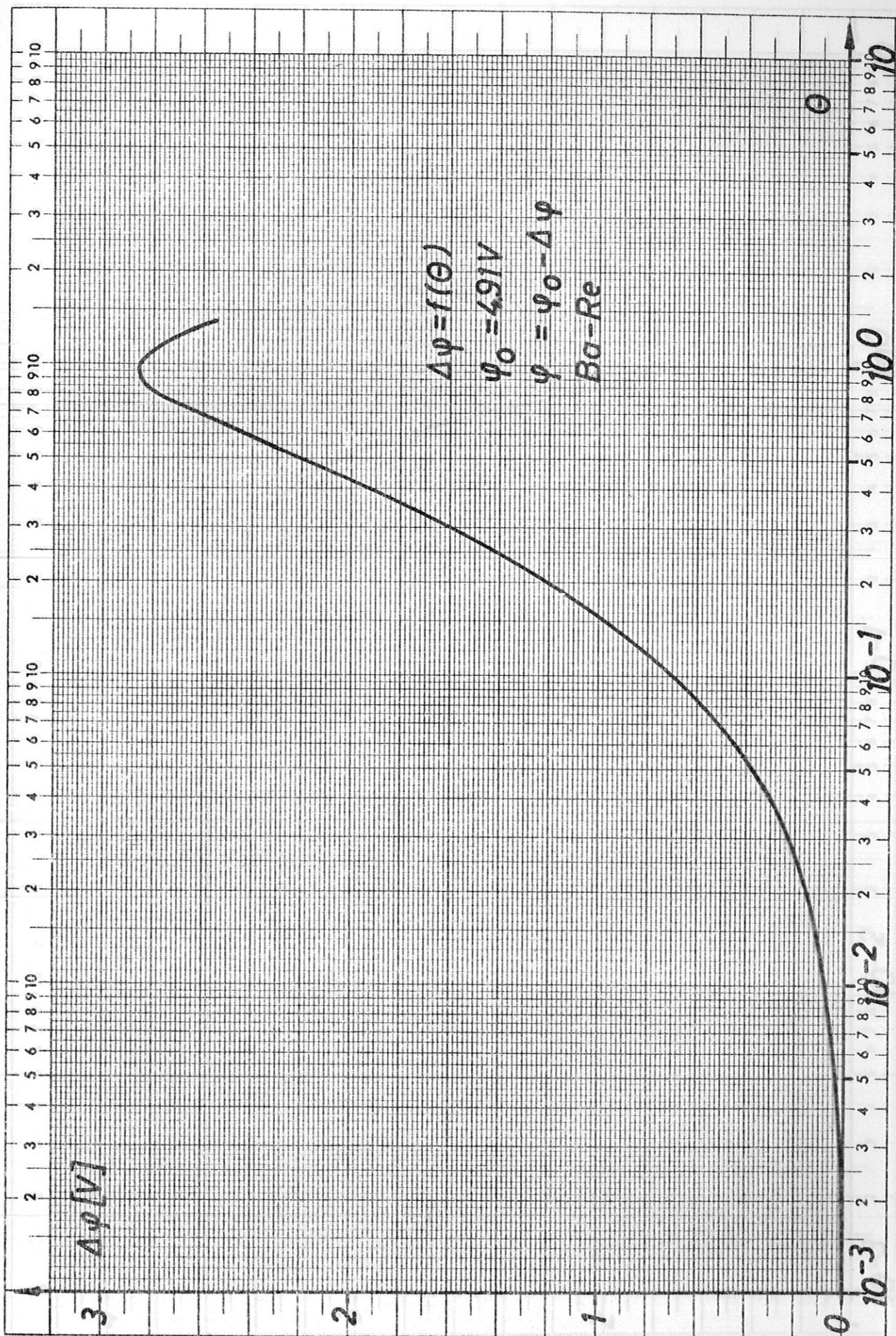


fig.1



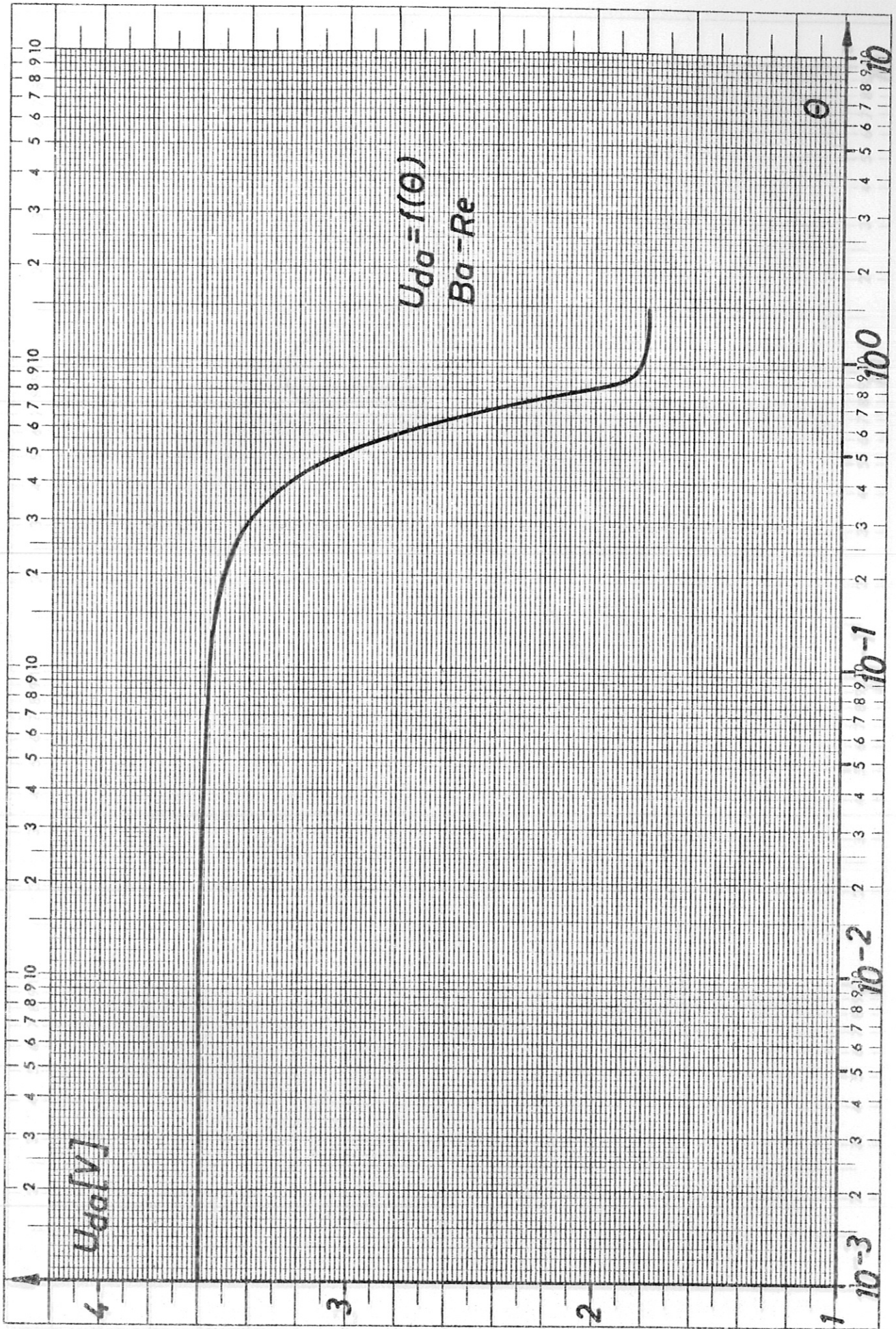


fig. 2



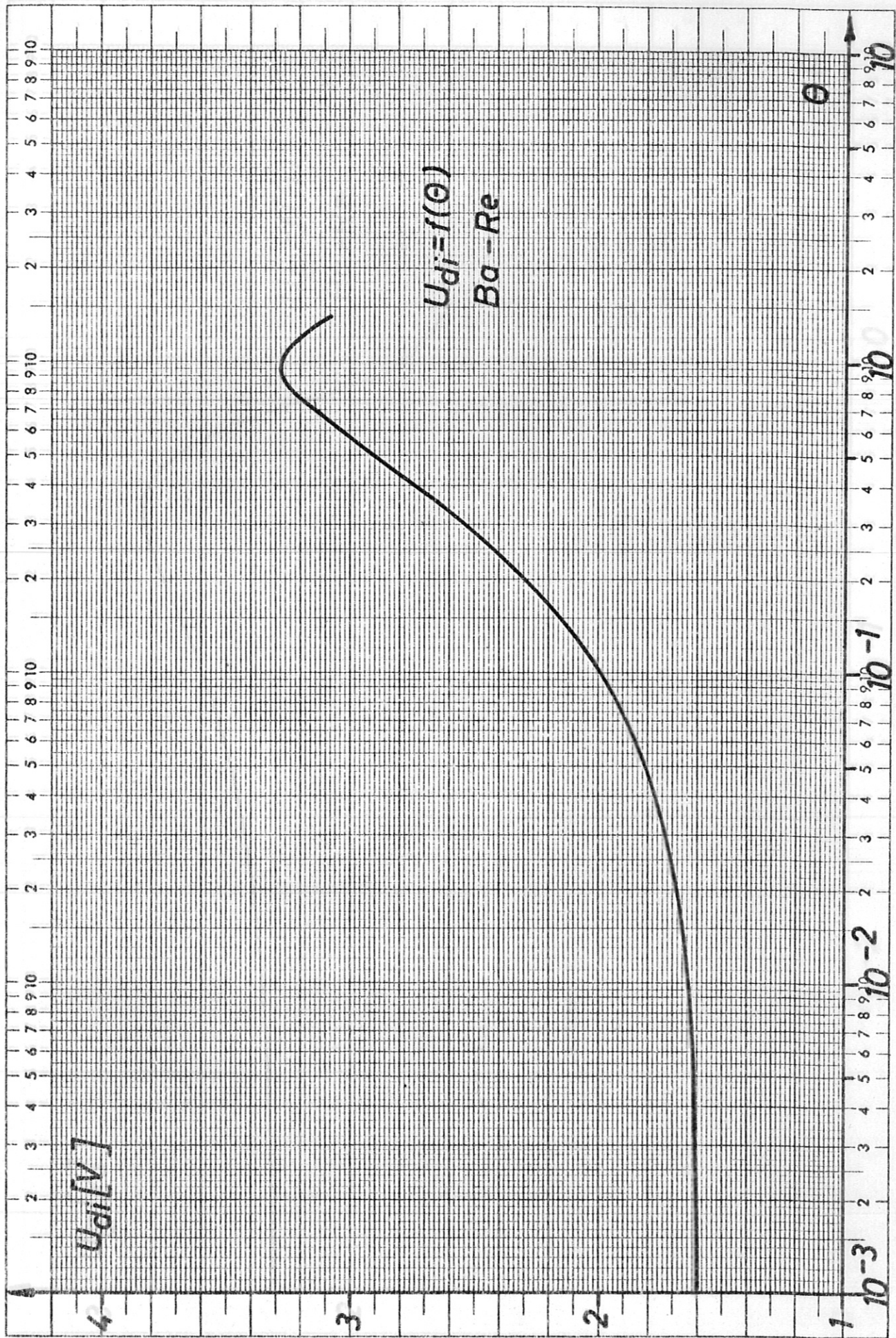


fig.3

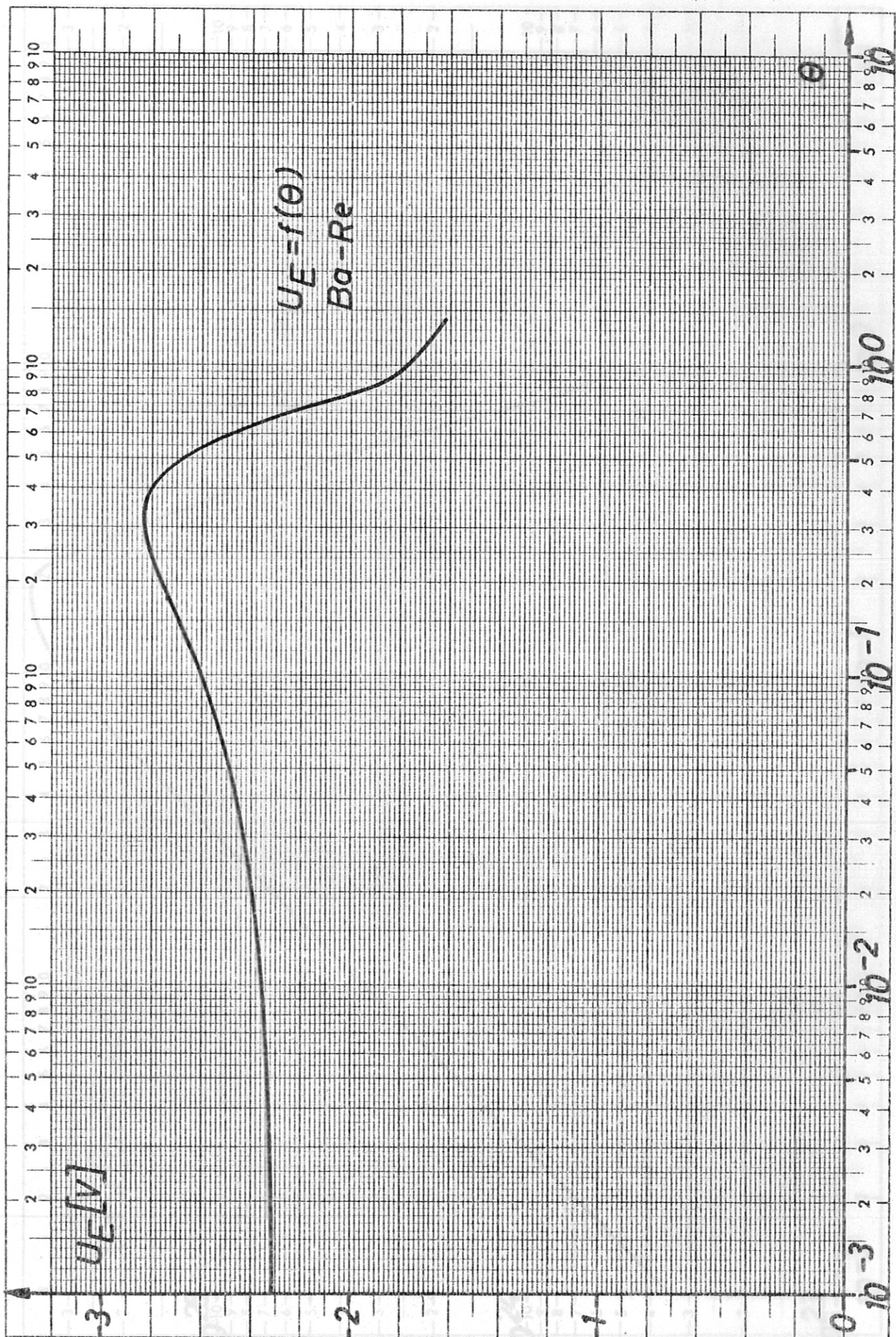


fig.4



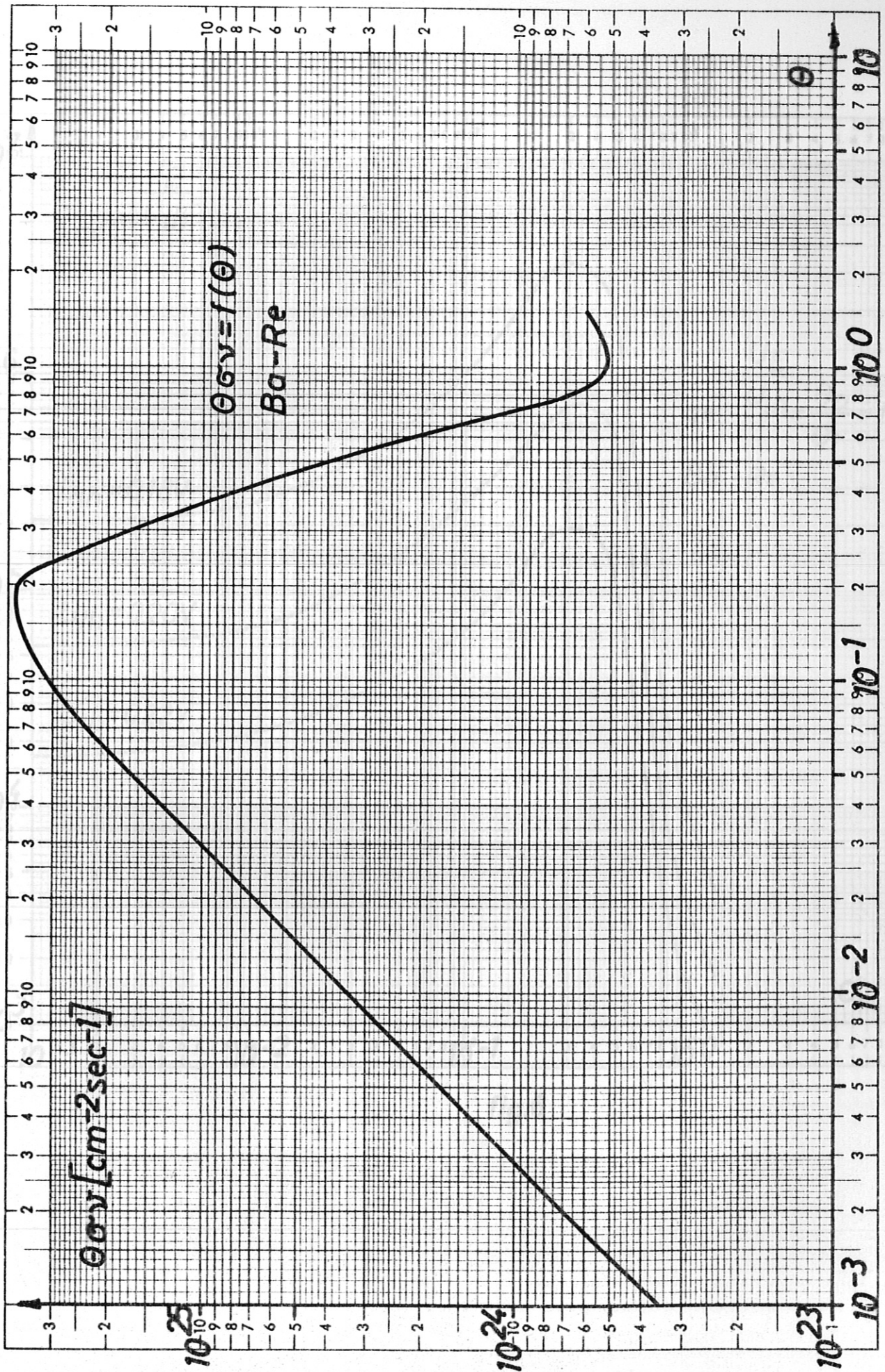


fig. 5

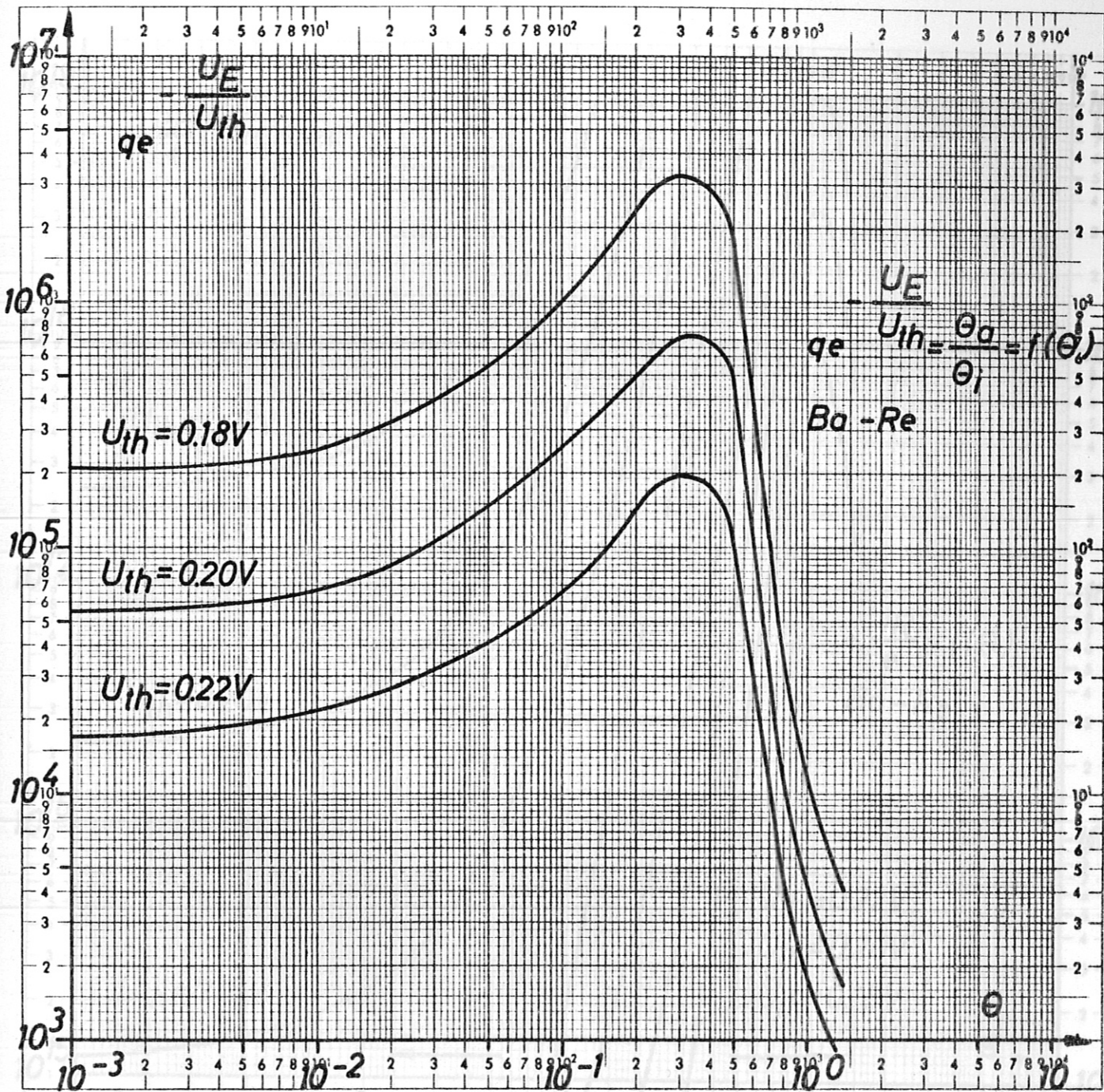


fig.6



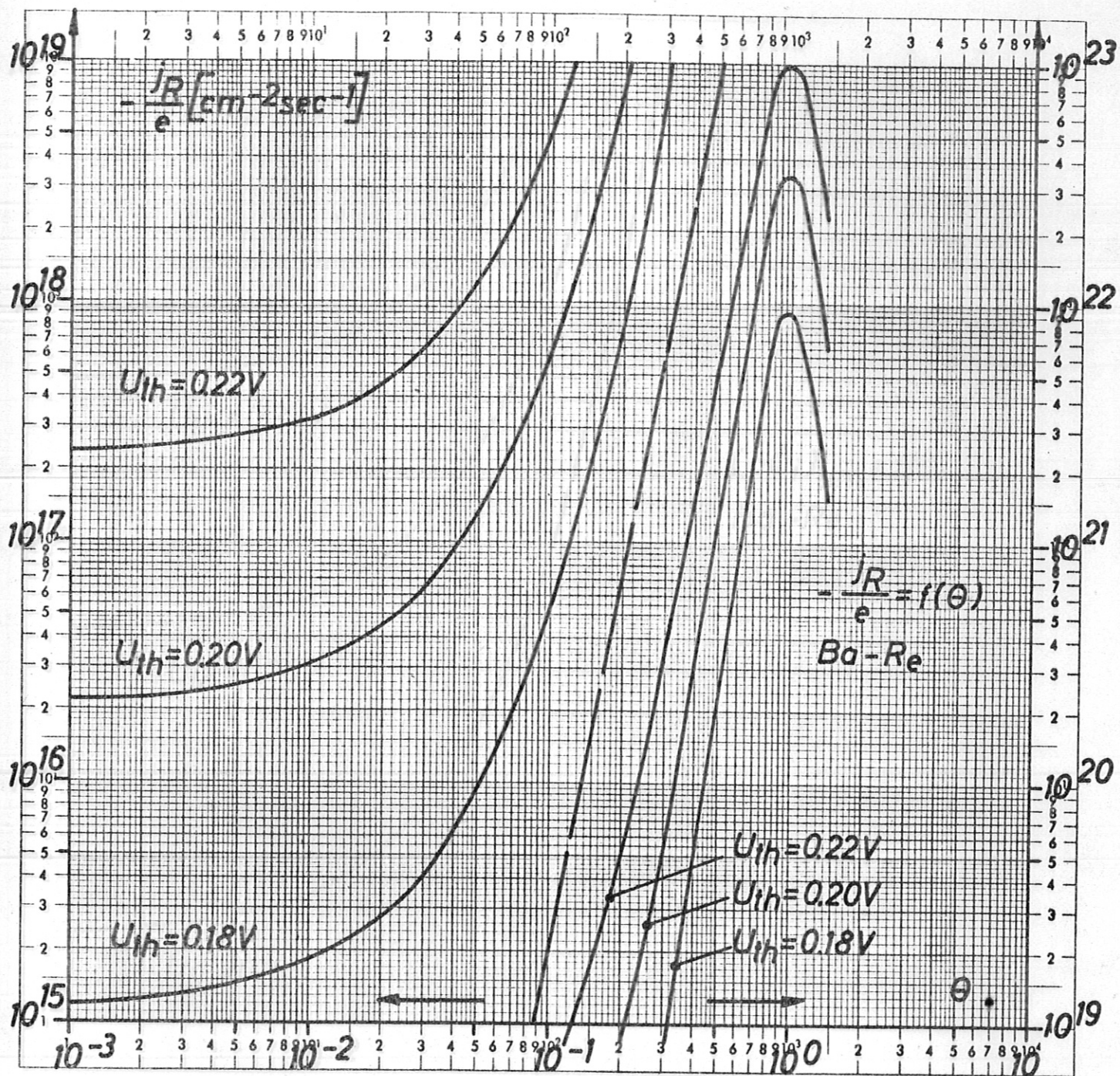


fig. 7

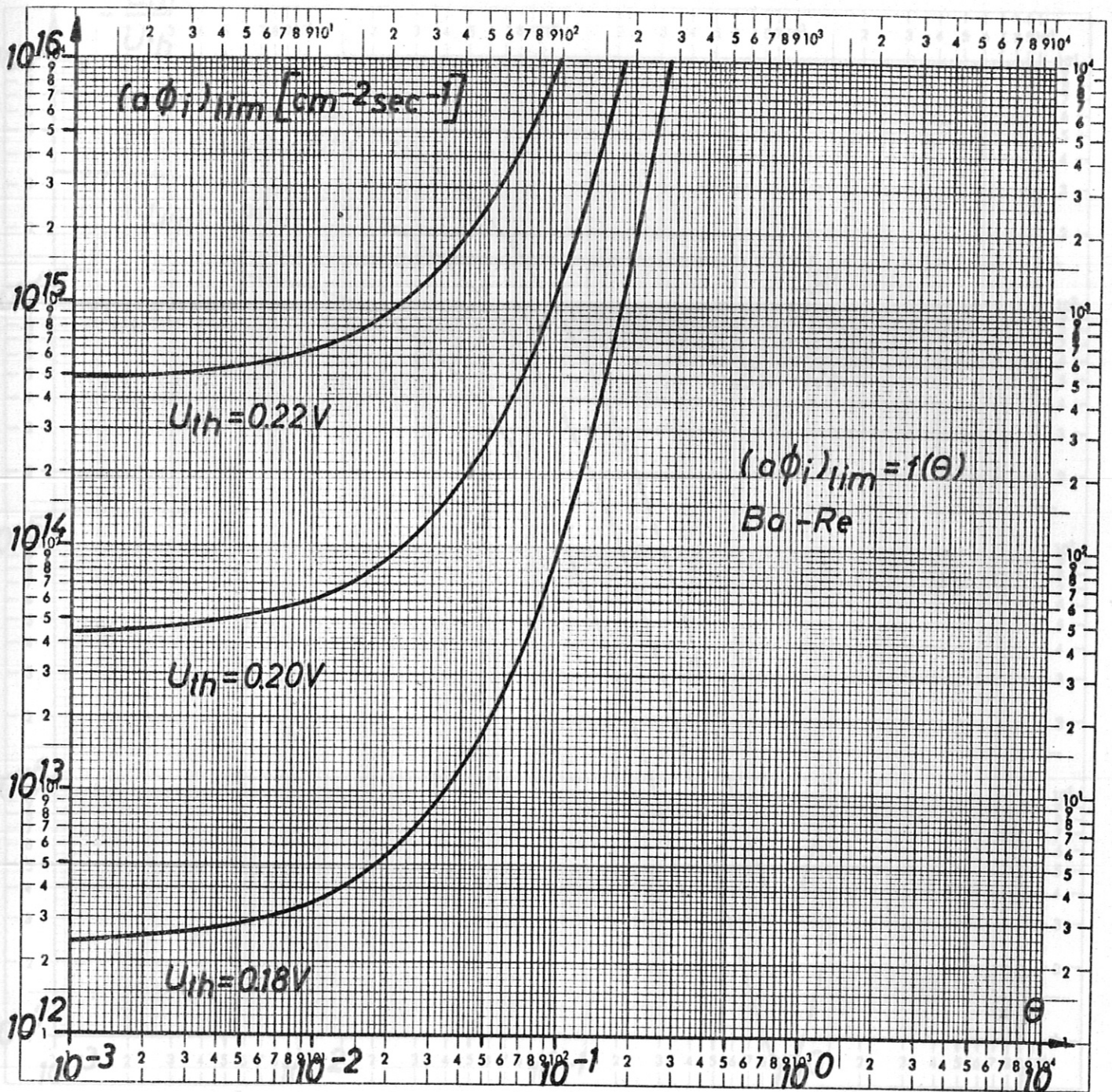


fig. 8



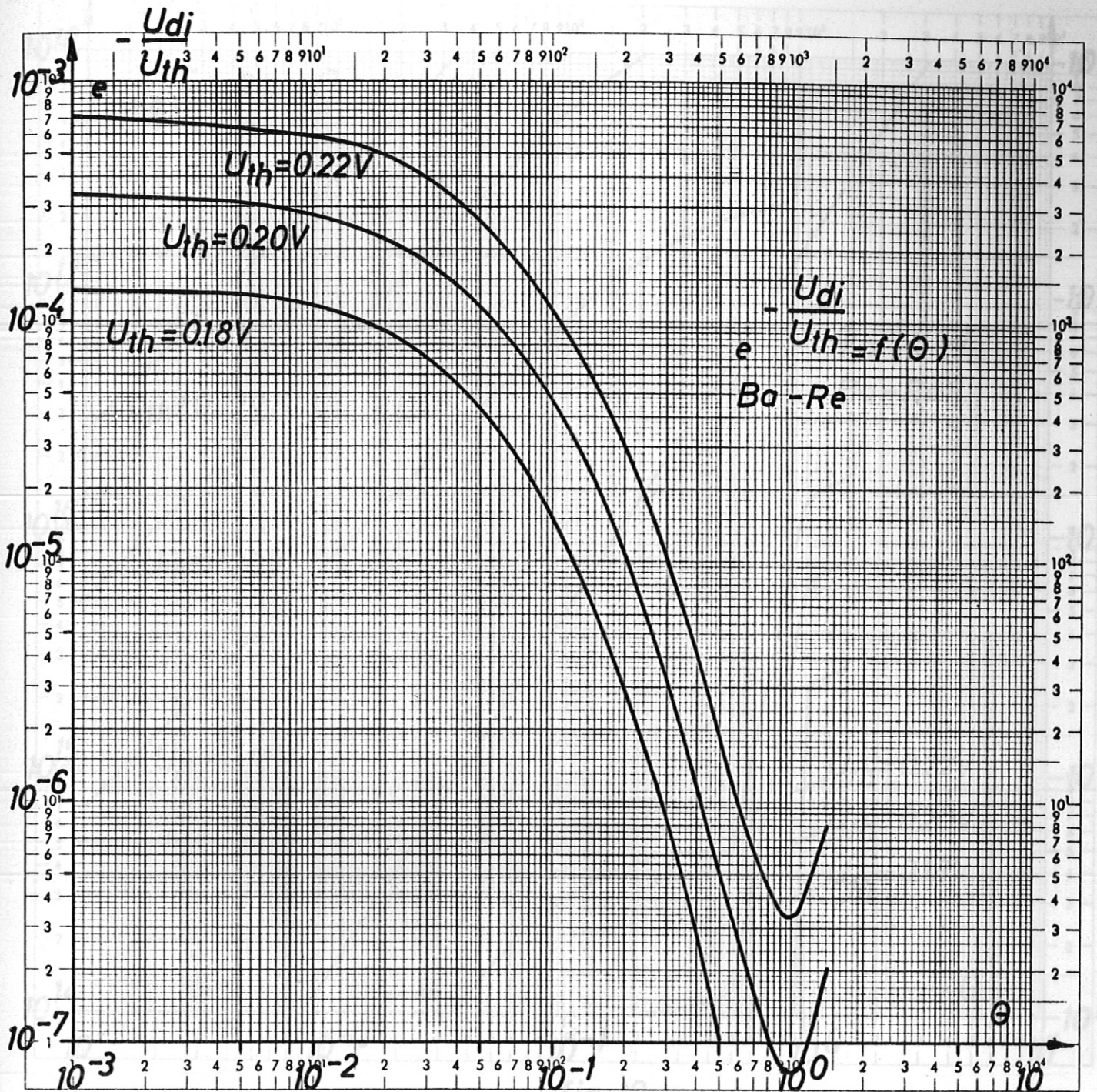


fig.9



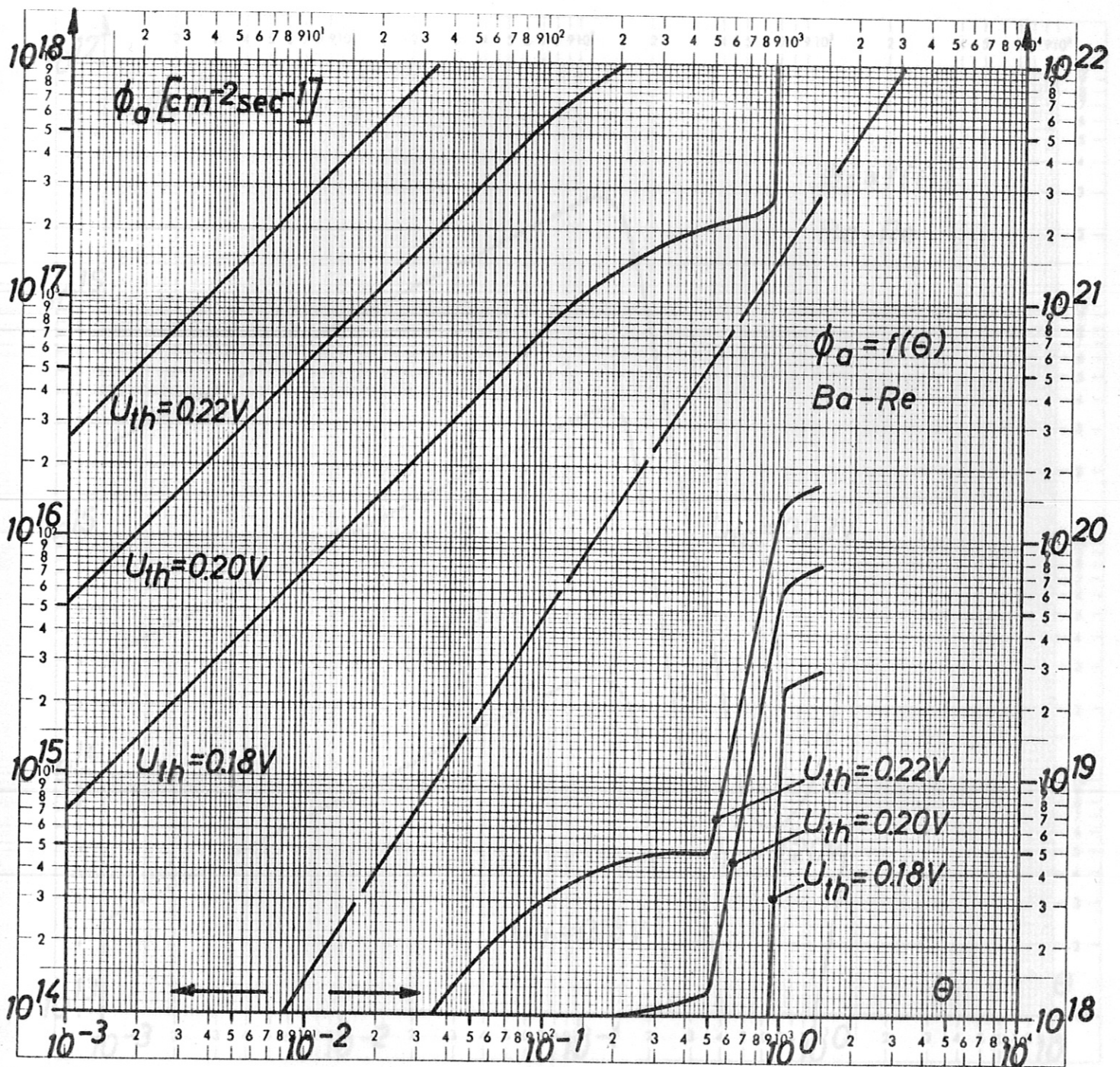


fig. 10

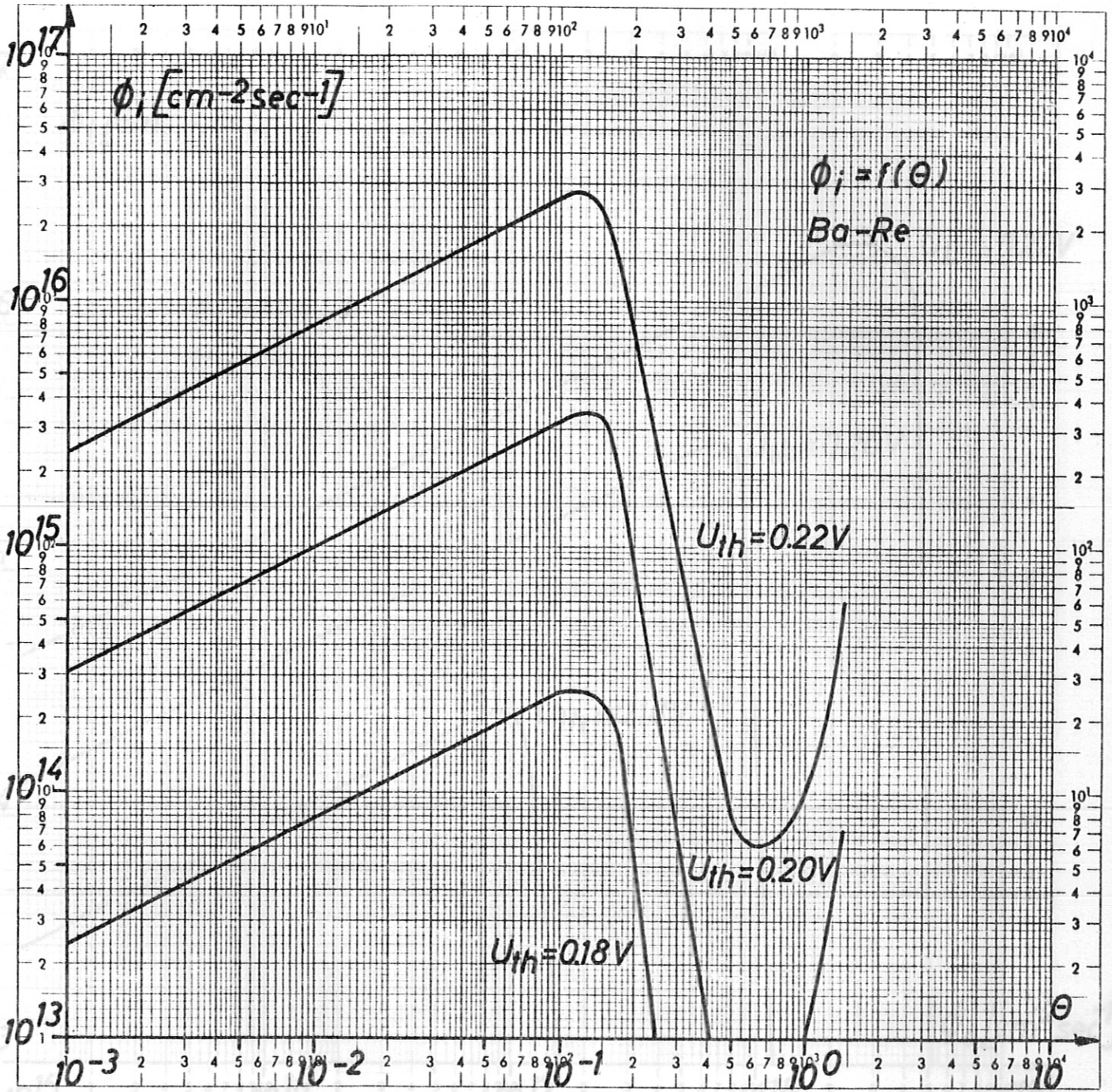


fig. 11



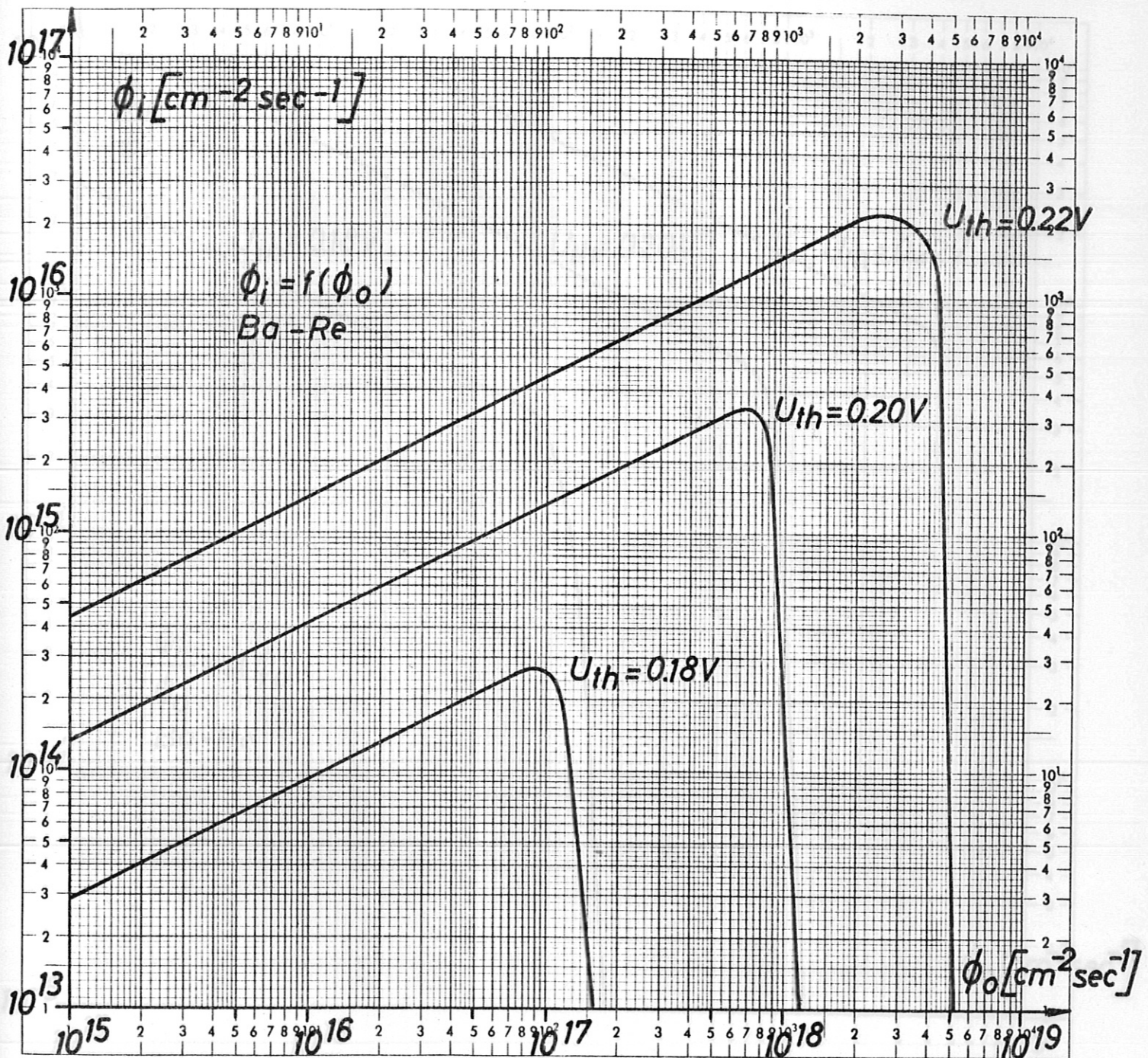


fig.12



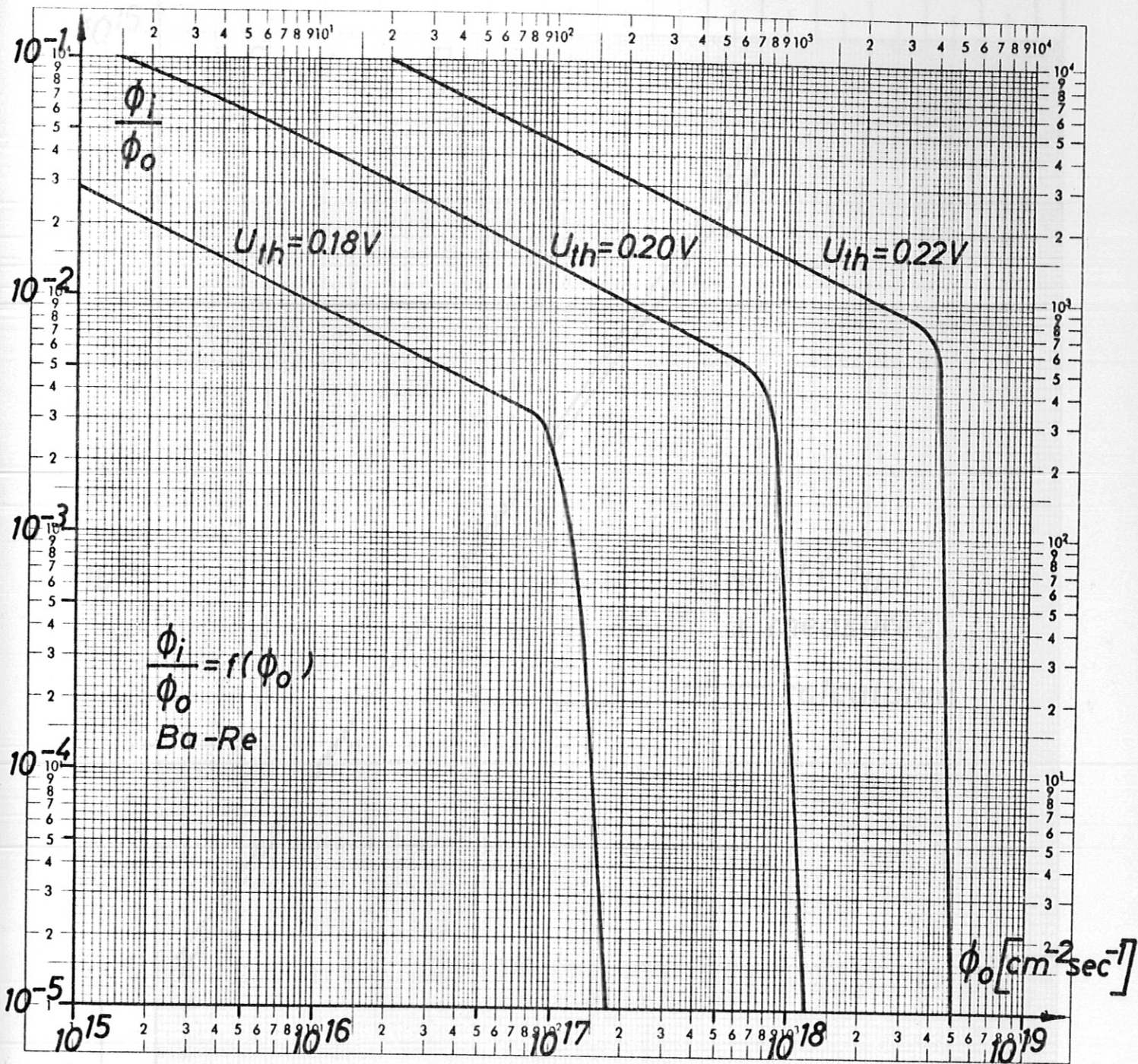


fig.13

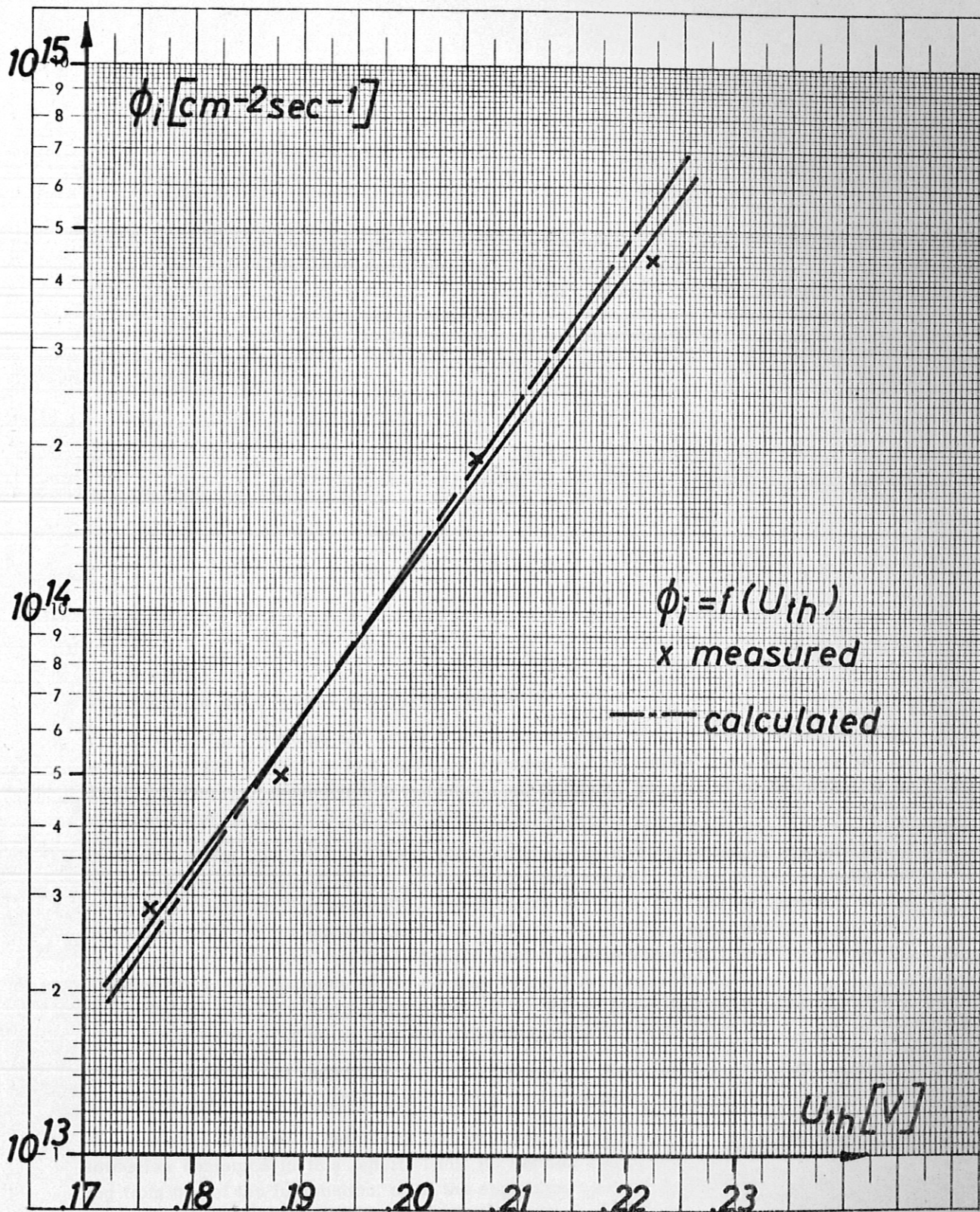


fig. 14