Contact Phenomena in a Plasma

L. A. SENA AND N. S. TAUBE
Scientific Research Institute for Direct Current, Ministry of Electric Power Plants, USSR
(Submitted to JETP editor November 9, 1954)
J. Exptl. Theoret. Phys.(U.S.S.R.) 30, 287-290 (1956)

Jumps in the potential at a boundary between regions of a plasma with different concentrations and temperatures of electrons are considered from the point of view of the classical theory of contact phenomena in metals. Measurements carried out in a discharge tube with two parts of a positive column differing in their concentrations of electrons confirmed the admissibility of such a procedure.

THE basic properties of the plasma of an ionized gas render it in many respects like a metal as represented in the classical theory of Drude. To such properties belong, in the first place, the quasi-neutrality of the plasma in the presence of a simultaneous high concentration of charged particles, and the maxwellian distribution of electron velocities on which is superposed a directed movement in the electric field, determining almost completely the electrical conductivity of the plasma. The analogy between a metal and a plasma has, of course, definite limitations. Thus, for example, while the increase in current strength in a metal is determined, for a given concentration of electrons, by the increase in the longitudinal gradient, in a plasma, on the other hand, for an almost constant gradient (sometimes even falling with increasing current density), the growth of the current is connected with an increase in the concentration of electrons.

At the same time the analogy between a plasma and the classical model of a metal is not limited to the properties just mentioned, but extends also to several more specialized phenomena, such as, for example, the Hall effect.[1] And here we will take up the phenomena at the boundary between two regions of a plasma with different electron concentrations or temperatures.

If the first region is characterized by an electron concentration n_1 and an electron temperature T_1, and the second by n_2 and T_2, then between these two regions there arises a potential difference ΔU, which in the absence of a directed current between the regions is determined, as in the classical theory of metals, by the expression[2]

$$\Delta U = \frac{k}{e}\int_{n_1}^{n_2} \frac{1}{n}\frac{d(Tn)}{dn}\,dn. \qquad (1)$$

Here the integration is carried out over the entire region of change of concentration and temperature.

As is well known, the difference in potential calculated for a metal under actual conditions according to formula (1) amounts to only some thousandths or hundredths of a volt. Actually the observed potential jumps at the boundary between two metals do not depend on the cause we have just mentioned, but on the difference in the work functions, which amounts to something between tenths of a volt and 1-2 volt.

In the electron plasma the picture is the reverse. If we try to evaluate the "work function" for taking an electron from the plasma as the work done by a mirror image force extending from infinity to an intermediate position between the electrons, then even for very high concentrations of electrons -- of the order of $10^{12} - 10^{14}$ cm^{-3} -- this work turns out to be equal to a few thousandths of an electron volt. At the same time the difference in potential between regions of a plasma with an electron temperature of the order of 10^{4}°K and a ratio of concentrations of the order of a few times unity may reach several volts.

When the electron temperatures of the contiguous regions of the plasma are different, the exact calculation by means of formula (1) is made more difficult, since ordinarily the temperature and concentration distributions of the electrons, which one needs in order to substitute for the $T(n)$ occurring under the integral sign, are not previously known. For a monotonic change in temperature formula (1) may be written in the form

$$\Delta U = \frac{k}{e}\left(T_2 - T_1 + \overline{T}\ln\frac{n_2}{n_1}\right), \qquad (2)$$

where $\overline{T}$ is a value of the electron temperature

[1] M. I. Rodin and G. V. Spivak, Compt. rend. Acad. Sci. USSR, Nouv. Ser. **24**, 247 (1939). (In English.).

[2] P. I. Lukirskii, *Foundations of Electronic Theory*, Moscow-Leningrad, 1929, Ch. 5.

intermediate between T_1 and T_2. As a rough approximation we may take $\bar{T} = 1/2(T_1 + T_2)$. The problem is notably simplified if the contiguous regions differ only in concentration, so that $T_1 = T_2$. In this case

$$\Delta U = (k/e)\, T \ln (n_2/n_1). \tag{3}$$

For an experimental demonstration of the proposed representation of the "contact" potential difference in a plasma, we took just this latter case, as being the more simply analyzable. The representation was realized in practical form in the discharge tube drawn schematically in Fig. 1.

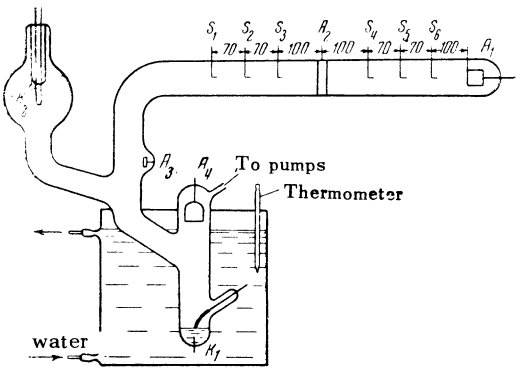

FIG. 1. Tube used in the experiments.

A mercury vapor discharge was maintained between one of the cathodes -- K_1, of mercury, or K_2, of wolfram -- and the auxiliary anodes A_3 and A_4. Two anodes were located in the main tube, the hollow cylinder A_1 at the end of the tube and A_2 in the form of a ring of width 12 mm in flat contact with the wall. Six cylindrical wolfram probes S, of length 7 mm and diameter 0.215 mm, were spaced along the axis of the tube. The distances between the probes are indicated in the drawing. In order to establish a definite vapor density the entire lower part of the tube was immersed in a vessel of water.

By using suitable resistances in order to set up various values of the currents I_1 and I_2 in the circuits of the anodes A_1 and A_2, we could create different concentrations of electrons in the parts of the discharge tube: n_2 to the left of anode A_2 and n_1 between anodes A_2 and A_1. For practical purposes the ratio of the concentrations n_2 and n_1 with this arrangement could be estimated as

$$n_2/n_1 = (I_1 + I_2)/I_1. \tag{4}$$

Due to the fact that the cross section of the tube was uniform along its entire length and the applied current density and vapor pressure of mercury were sufficiently small, cascade processes should not have played any important role, and we may suppose that the electron temperatures in the two parts of the tube were the same. This should be correct, at any event, at a sufficiently great distance from the transition region. A few remarks concerning the phenomena in this region will be made below. We merely note here that the electron temperature measurements which were carried out in each experiment at all probes gave results coinciding within the limits of the accuracy of the measurements.

The analysis of the results of the probe measurements was carried out in the following manner. On the one hand the jump in potential ΔU was calculated from formula (3), using the values of the electron temperatures and the ratios of the electron concentrations [determined both from the probe characteristics and from formula (4)]. On the other hand, the potential distribution along the tube was plotted from the measured values (Fig. 2). From the graph given in Fig. 2, the jump in poten-

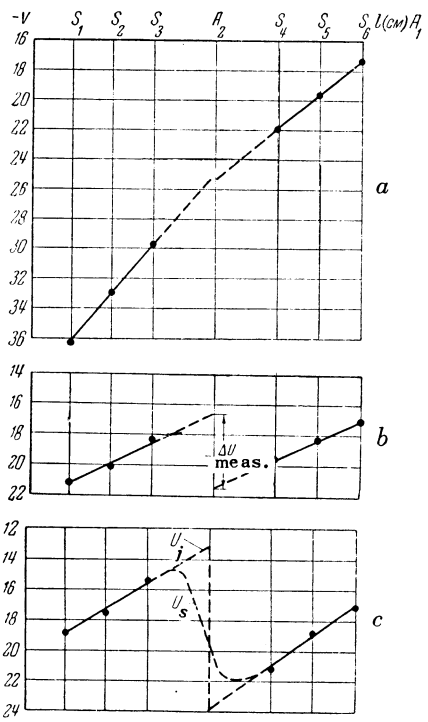

FIG. 2. Potential distribution in the tube, as measured by the probes; *a*: $I_1 = 1{,}2$ amp. $I_2 = 0$ amp. $T = 22000°$ K; *b*: $I_1 = 0{,}2$ amp. $I_2 = 1$ *a*:, $T = 28000°$K *c*: $I_1 = 0{,}4$ amp. $I_2 = 0{,}8$ amp. $T = 26000°$ K

tial is determined by extrapolating the potential curves from the left and right parts of the tube back to the "surface of contact", which is taken as the surface at which the anode was located.

With respect to the two means of determining ΔU, we may make the following remarks. The application of formula (3), which is correct in the absence of a directed current, does not seem completely legitimate under the present experimental conditions. We must also take account of the fact that for a distribution of concentrations such as occurs in the experiment, the directed current of electrons moving toward anode A_1, when in the region between the two sections of the plasma, is moving in a retarding field. In this region the energy balance is upset, the average energy of the electrons decreases, and the very form of the electron velocity distribution function may change. All this, in its turn, has an effect on the potential distribution. Taking into account, however, that the directed electron current is small in comparison with the disordered, we may expect that these circumstances will not have a great effect on the magnitude of the jump in potential.

With respect to the determination of ΔU from the graph of the potential distribution, it should be pointed out here that the true plot of the potential in the transition region is given, of course, not by the broken line U_j, with an infinitely sharp jump, but by some smoothed curve U_s drawn schematically in Fig. 2b. Consequently the jump ΔU determined by extrapolation of the linear parts of the potential distributions will be somewhat larger than that which actually occurs.

The remarks just made should be kept in mind when estimating the extent of coincidence of the calculated and measured results for the potential jump. The results of all the measurements are given in the table. The currents I_1 and I_2 are given in the first two columns, the ratio of the concentrations n_1/n_2 in the next, the electron temperature in the fourth, and finally, in the last two, the calculated and measured potential jumps.

TABLE

I_1, amps	I_2, amps	$\frac{n_2}{n_1}$	$T \cdot 10^{-3}$°K	$\Delta U_{calc.}$	$\Delta U_{meas.}$
1,2	0	1	22	0	0
1,0	0,5	1,5	25	0,87	1
0,3	1,5	6	28	3,53	4
0,2	1,0	6	28	4,3	5,5
0,1	1,0	11	29	6	5
0,1	1,0	11	26	5,4	6
0,1	1,4	15	27	6,3	7
0,04	0,8	21	18	4,7	5
0,04	0,8	21	26	6,85	11
0,04	1,3	32,5	27	8,2	10,5
0,04	0,4	11	27	5,6	5
0,04	0,6	16	27	6,45	7
0,2	2	11	28	5,8	8
0,2	2	11	30	6,3	8

In order to represent graphically the degree of separation between the calculated and measured values of ΔU, $\Delta U_{calc.}$ was plotted as abscissa and $\Delta U_{meas.}$ as ordinate in Fig. 3. We see that as a rule $\Delta U_{meas.}$ is somewhat larger than $\Delta U_{calc.}$. This agrees with the remarks made above concerning the exaggerated evaluation of the jump which results from our method of measuring it.

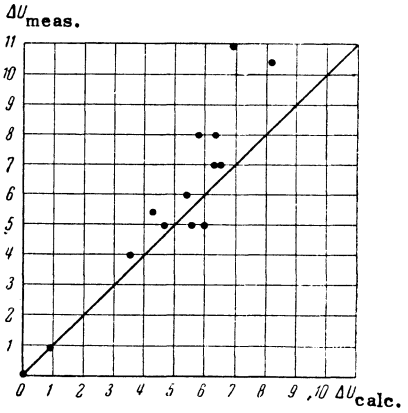

FIG. 3. Comparison of the calculated and measured values of the potential jump.

The case which we have considered of "contact" potential difference between contiguous regions of

a plasma is, as we have said, an extremely simple one. However, in principle it is possible to extend our proposed approach to the consideration of phenomena in an inhomogeneous plasma and to more complicated cases, in which there occur differences in the electron temperatures as well as in their concentrations.

Translated by M. G. Gibbons
53

SOVIET PHYSICS JETP VOLUME 3, NUMBER 2 SEPTEMBER, 1956

Paramagnetic Resonance in Synthetic Ruby

M. M. ZARIPOV AND IU. IA. SHAMONIN*
Kazan State University

(Submitted to JETP editor November 19, 1954)
J. Exptl. Theoret. Phys. (U.S.S.R.) **30**, 291-295 (February, 1956)

The paramagnetic resonance absorption spectrum in monocrystals of synthetic ruby containing from 0.1 to 0.01% Cr is investigated at a frequency of 9.58×10^9 cycles. A theoretical explanation of the observed spectrum is given. By comparison of the results of theory and experiment there are found: the splitting of the basic level of energy in the electrical field of the crystal ($\delta = 0.38$ cm^{-1}) and the factors of spectroscopic splitting $g_{\parallel} \approx g_{\perp} = 1.98$.

IN the majority of investigations on the paramagnetic resonance of elements of the iron group, the hydrated salts of these elemests were studied. In compounds of this type the internal electrical field causing splitting of the basic condition of the magnetic ion is created mainly by the molecules of water surrounding the ion in the form of an octahedron. For this reason the electrical field acting on the ion is divided into a strong cubic field created by the molecules of water and a weak field of much lesser symmetry caused by the remaining atoms of the lattice.

The paramagnetic properties of the investigated specimens of synthetic ruby are due to Cr^{+++}, which at low concentrations isomorphically displaces Al^{+++} in the lattice of corundum.[1] Closely surrounding the Cr^{+++} ion in the ruby is the octahedron of oxygen; here the chromium ion is not located at the center of the octahedron, but is displaced from the center along its trigonal axis, which is the optical axis of the crystal. On the whole, the individual cell of the ruby possesses a trigonal symmetry with respect to this self-same axis of the oxygen octahedron. Consequently, the internal electrical field within the ruby, created basically by the ions of oxygen, must be a powerful trigonal field.

* Experimental portion of the work carried out by Iu. Ia. Shamonin.

[1] E. S. Rudnitskaia, Works (Trudy) of the Institute of Crystallography, Academy of Sciences, USSR 8, 1953, p. 13.

1. RESULTS OF MEASUREMENT

The fine structure of paramagnetic resonance absorption in monocrystals of synthetic ruby containing from 0.1 to 0.01% Cr was investigated at room temperature at a frequency of 9.58×10^9 cycles.

The investigated specimens were placed in a cavity resonator which was excited by a magnetic H_{112} wave. The power through the resonator served as the magnitude being measured. The external constant magnetic field which varied from 0 to 5500 oersteds was modulated by a frequency of 50 cycles with an amplitude of modulation of $A_{max} \approx \pm 350$ oersteds. Due to such broad modulation, the resonance curves were traced out completely on the screen of the oscilloscope.

The optical axis of the monocrystals had been determined previously at the Institute of Crystallography of the Academy of Sciences, U.S.S.R. However, for our purposes, the accuracy of this determination was inadequate. For more precise establishment of the optical axis, the great position sensitivity of several lines of the magnetic spectrum of ruby with respect to the magnitude of the angle between the directions of the optical axis and the constant field was employed. Coincidence of the optical axis with the axis of rotation of the crystal, perpendicular to the constant field, was established by the constancy of position of all lines of the spectrum on the oscilloscope screen.