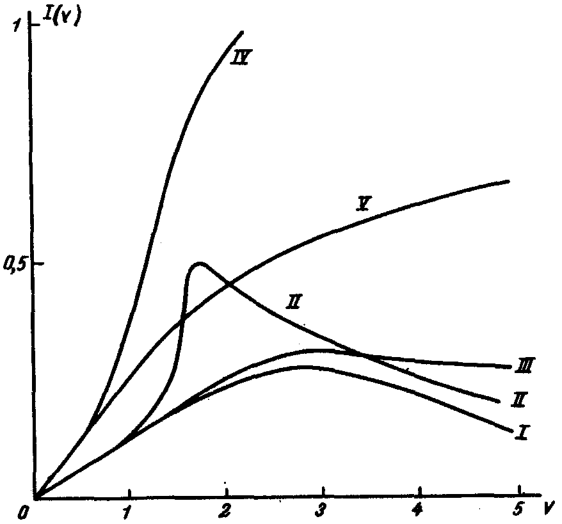

Current-voltage characteristic I(v) = vN(v) in bimolecular recombination: I, III, V - Φ = 0; II - Φ = 5: IV - Φ = 7.

between the drift velocity v and the field E may be nonlinear if the carrier mobility depends on E. We shall henceforth define the current-voltage characteristic as the function $I(v) = vN(v)$; when $v \sim E$, this characteristic is the usual current-voltage characteristic. It is seen from the presented expressions that for a crystal in the form of a plate the function I(v) is sublinear for large v, and for a crystal in the form of a cylinder the characteristic has a negative slope. Thus, in the case of bimolecular recombination, the occurrence of the pinch can be detected by the start of the drooping of the current-voltage characteristic. This feature was observed experimentally by A. P. Shotov.

The figure shows typical current-voltage characteristics. Curves I, II, and III pertain to a cylindrical crystal geometry, and curves IV and V to a planar geometry. Curves I, II, and IV represent a nondegenerate plasma, and curves III and V a degenerate one. Here $\Phi = sr/d$, where r is the recombination time in a weakly-nonequilibrium plasma and d is the half-thickness of the plate (radius of the cylinder). The figure was drawn for the case $L \gg d$ with arbitrary scales for v and I; the ordinate scales are different for the plate and for the cylinder.

The main features of the current-voltage characteristics should be realized at an average current density in the crystal of about 10^5 A/cm^2.

[1] I. I. Boiko, ZhETF Pis. Red. 5, 421 (1967) [JETP Lett. 5, 343 (1967)]; Fiz. Tverd. Tela 9, 2929 (1967) [Sov. Phys.-Solid State 9, 2303 (1968)].

SCREENING OF SHOCK-WAVE RADIATION BY A GAS NOT IN THERMODYNAMIC EQUILIBRIUM AHEAD OF THE FRONT

E. G. Popov
Earth Physics Institute, USSR Academy of Sciences

Submitted 28 November 1968
ZhETF Pis. Red. 9, No. 3, 176 - 179 (5 February 1969)

Experiment [1-3] and theory [4,5] show that the brightness temperature of the front of a strong shock wave is lower than the gas temperature behind the front. The gas ahead of the front is heated by the short-wave radiation and loses its transparency to the long-wave radiation of the front, as a result of which the brightness temperature corresponding to this radiation drops. Quantitative estimates of the phenomenon, obtained by Raizer [5] for a shock wave in air assuming thermodynamic equilibrium of the gas in the screening layer, are in satisfactory agreement with the experimental results [2, 3]. However, similar estimates for shock waves in argon and xenon do not agree with experiment [3]. The possible cause of the disparity is the absence of thermal equilibrium in the gas of the screening layer; this cause was noted in [3] and is corroborated below.

The width of the screening layer is determined by the free path ℓ of the quanta absorbed by the cold gas ahead of the front, and the time of stay of the gas in the layer is determined by the quantity $\tau = \ell D$, where D is the velocity of the front. In argon, krypton, and xenon of normal density, $\ell \approx 10^{-3}$ cm [6], yielding at D = 10 km/sec a time $\tau \approx 10^{-9}$ sec, which is comparable with the time of the relaxation processes in the heated gas.

The heating of the gas by the photoionizing radiation of the front is determined [4] by

$$S = DE \tag{1}$$

where E - energy of 1 cm^3 of gas, $S = f(z)\, 2\pi c^{-2} h^{-3} \int_I^\infty [\exp(\epsilon/kT) - 1]^{-1} \epsilon^3 d\epsilon$, $f(z) = 2\int_1^\infty \xi^{-3} \exp(-\xi z) d\xi$ is a function that takes into account the absorption of the radiation flux along the optical coordinate z, I is the ionization potential, and T is the temperature behind the front. We determine analogously the number of photoelectrons n_e per cm^3:

$$s = Dn_e,$$

where

$$s = f(z)\, 2\pi c^{-2} h^{-3} \int_I^\infty [\exp(\epsilon/kT) - 1]^{-1} \epsilon^2 d\epsilon.$$

From (1) and (2) we get for the average photoelectron energy ε_e

$$\varepsilon_e = S/s - I. \tag{3}$$

The table lists the values of n_e and ε_e for a shock wave in argon of normal density ($f(z) = 1 - n_e$ at the front, and the connection between T and D, Fig. 2, is taken from [1]). The electron-ion relaxation time is estimated by the Landau formula:

$$\tau_{ei} = 3{,}15 \cdot 10^8 A T^{3/2}\,(\mathrm{eV})/n_i Z^2 \ln\Lambda. \tag{4}$$

The values of τ_{ei}, referred to the time τ that the gas remains in the layer, are listed in the table (it was assumed that T(eV) = ε_e and $n_i = n_e$). The electron relaxation is faster: $\tau_{ee}/\tau_{ei} \approx m_e/m_i \approx 10^{-5}$; therefore $\tau_{ee}/\tau \ll 1$ and an electron temperature T(eV) = ε_e is established in the layer.

An estimate of the electron-atom relaxation time by means of the formula [4]

$$\tau_{ea} = m_a / 2 m_e \bar{v}_e \bar{\sigma}_{ea} n_a, \tag{5}$$

where σ_{ea} is the cross section of elastic scattering of the electrons by the atoms [7], yields $\tau_{ea}/\tau \approx 30$ to 10. Thus, $\tau_{ei}/\tau \gg 1$ and $\tau_{ea}/\tau \gg 1$ - no energy is transferred from the photo-

D, km/sec	8	10	12	14	16	18	20	22
$n_e \cdot 10^{-17}$	0,39	1,72	5,90	18.1	40.0	66,0	112	175
ϵ_e, eV	2.8	3,5	4,2	5,8	7.4	8.4	10	12
τ_{ei}/τ	182	77	38	24	18	15	13	11
$T' \cdot 10^{-3}$, °K	9,6	10,9	12,5	15,4	16,7	18.7	22.0	33.0
$T \cdot 10^{-3}$, °K	0,6	1,7	5,0	13,5	15,3	17,6	20.7	27.0

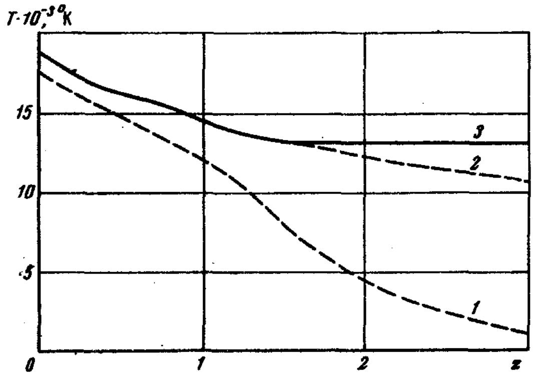

Fig. 1. Heating of argon ahead of the front, D = 18 km/sec; 1 - thermodynamic-equilibrium temperature T, 2 - temperature T' corresponding to partial thermodynamic equilibrium, 3 - electron temperature T_e of non-equilibrium gas.

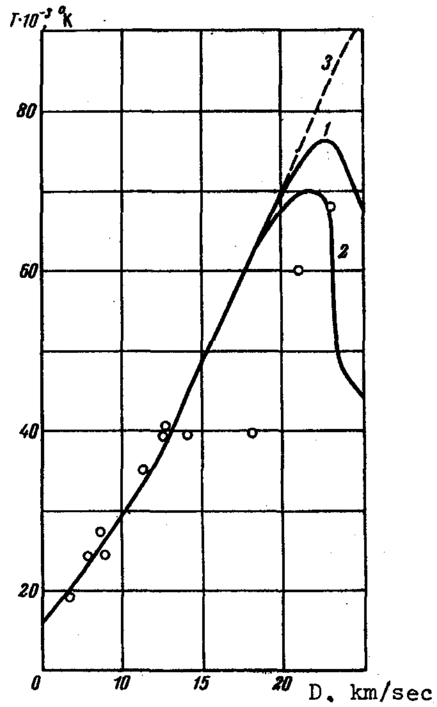

Fig. 2. Brightness temperature in yellow light (λ = 560 nm) of a shock wave in argon of normal density: 1 - thermodynamic equilibrium in screening layer, 2 - no equilibrium in the layer, 3 - temperature behind the front, o - values of the brightness temperature measured in [3].

electrons to the atoms and the ions. The times of relaxation of the electron excitation τ^* and of ionization τ_i are estimated [4] from:

$$\tau^* = 1/\beta^* n_e, \qquad (6)$$

where

$$\beta^* = \bar{v}_e \sigma^* g_1 / g^* (E^*/\epsilon_e + 2), \ \sigma^* = C\epsilon_e,$$

and C = 0.7 x 10^{-17} cm^2/eV for the first excited levels of argon with E* = 11.5 eV and g* = 8;

$$\tau_i = 1/a_i n_a, \qquad (7)$$

where

$$a_i = \bar{v}_e \sigma_i (I/\epsilon_e + 2)\exp(- \cdot /\epsilon_e), \ \sigma_i = C\epsilon_e,$$

and C = 2 x 10^{17} cm^2/eV. Estimates yield $\tau^*/\tau \ll 1$ and $\tau_i/\tau \ll 1$, meaning that the photoelectrons lose energy in the inelastic collisions with the atoms (estimates using the cross sections from [7] indicate that the ionization of Ar^+ can be neglected). Consequently, radiant heating from the front leads to larger (compared with thermodynamic equilibrium) ionization and excitation of the atoms in the layer, at the expense of the kinetic energy possessed by the atoms and ions in the case of equilibrium, and also as a result of the loss to the second ionization. Inasmuch as the absorption of the long-wave radiation is determined by the concentration of the excited and ionized atoms in the layer, it is natural to expect a larger screening of the front than in the case of equilibrium. The table lists the temperatures T' of the gas ahead of the front, determined from (1) and corresponding to partial dynamic equilibrium (with account taken of only the contribution made to the energy E by the first ionization, excitation, and energy of the electrons); for comparison, we give the equilibrium values T. Since $T' < \epsilon_0$ and formulas (4) - (7) presuppose that T_e is constant, only repeated estimates at $T_e = T'$ will make it possible to determine whether the relaxation processes terminate in an establishment of partial equilibrium. These estimates, obtained with allowance for the role of the excited atoms in the ionization relaxation, show that partial equilibrium takes place at $T' > 13000^{\circ}K$, when $\tau^*/\tau < 1$. Figure 1 shows the equilibrium and non-equilibrium profiles of the layer, and Fig. 2 the brightness temperature of a shock wave in argon. Details of the calculation of the brightness temperature and the results of such a calculation for shock waves in xenon and krypton will be published later.

The author is grateful to M. A. Tskikulin and Yu. P. Raizer for useful discussions.

[1] I. Sh. Model', Zh. Eksp. Teor. Fiz. 32, 714 (1957) [Sov. Phys.-JETP 5, 589 (1957)].
[2] A. E. Voitenko, I. Sh. Model', and I. S. Samodelov, Dokl. Akad. Nauk SSSR 169, 547 (1966) [Sov. Phys.-Dokl. 11, 596 (1967)].
[3] Yu. A. Zatsepin, E. G. Popov, and M. A. Tsikulin, Zh. Eksp. Teor. Fiz. 54, 112 (1968) [Sov. Phys.-JETP 27, 63 (1968)].
[4] Ya. B. Zel'dovich and Yu. P.Raizer, Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavelenii (Physics of Shock Waves and of High-temperature Hydrodynamic Phenomena), Nauka, 1966 [Academic Press, 1966].
[5] Yu. P. Raizer, Zh. Eksp.Teor. Fiz. 33, 101 (1957) [Sov. Phys.-JETP 6, 77 (1958)]
[6] A. N. Zaidel' and E. Ya. Shreider, Spektroskopiya vakuumnogo ul'trafioleta (Spectroscopy of Vacuum Ultraviolet), Nauka, 1967.
[7] E. W. McDaniel, Collision Phenomena in Ionized Gases, Wiley, 1964.

DIFFERENTIAL RESISTANCE OF SUPERCONDUCTORS OF THE SECOND KIND

I. Ya. Fogel', V. G. Volotskaya, L. N. Korovin, and I. M. Dmitrenko
Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences
Submitted 16 December 1968
ZhETF Pis. Red. 9, No. 3, 180 - 184 (5 February 1969)

It follows from Abrikosov's theory [1] that a magnetic field penetrates in superconductors of the second kind in the form of vortices. In the form of a transport current, the Lorentz forces cause the vortices to move, and this leads to energy dissipation. If the Lorentz force acting on the vortices greatly exceeds the pinning force, then the vortex motion has the character of a viscous flow. In the region of the viscous flow, the voltage produced in the superconductor depends linearly on the transport current. The differential resistance $\rho_f = dV/dI$ is then connected with the magnetic field by Kim's [2] empirical relation $\rho_f = \rho_n H/H_{c2}(0)$. The value of ρ_f is determined experimentally from the slope of the linear section of the current-voltage characteristic. According to [2], the differential resistance characterizes the volume properties of a superconductor of the second kind.

We have measured the current-voltage characteristics in a wide range of fields, in single-crystal and polycrystalline samples of PbIn alloys with concentrations from 22 to 24 at.% In. The initial components were chosen to be Pb and In of high purity. At these concentrations, the alloys constitute a solid solution with face-centered cubic lattice. The composition of the samples was verified by chemical analysis, and the single-crystal orientation was determined by x-ray diffraction. In all experiments, the long axis of the sample was perpendicular to the direction of the external magnetic field, and the transport current was directed along the sample axis. The measurements were made on samples in the form of round cylinders and plates. The V(I) curves were measured both point-by-point and recorded with a two-coordinate plotting potentiometer.

For all samples, we plotted the critical current I_c and the resistance R against the