

change interaction of the carriers with the impurity magnetic ions and make it possible to compare in greater detail the theory of these effects with experiment.

In CdTe crystals, doping with Fe^{2+} or Mn^{2+} ions leads, besides the effects investigated in^[1], to shifts of the exciton energy in the absence of a magnetic field.^[5] These shifts do not follow from the model of^[1]. The absence of such shifts in ZnTe : Mn in the presence of a rather large exchange interaction between the carriers and the magnetic impurity confirms that the shifts observed in^[5] are not of exchange origin.

¹A. Komarov, S.M. Ryabchenko, O.V. Terlets'kii, I.I. Zheru, and R.D. Ivanchuk, Zh. Eksp. Teor. Fiz. 73, 608 (1977) [Sov. Phys. JETP 46, 318 (1977)].

²K. Cho, W. Dreybrodt, D. Heisenger, and S. Suga, Proc. Twelfth Intern. Conf. on Physics of Semiconductors, Stuttgart, 1974, publ. by Teubner, Stuttgart (1974), p. 945; K. Cho, S. Suga, W. Dreybrodt, and F. Willman, Phys. Rev. B, 11, 1512 (1975).

³M. Altarelli and N.O. Lipari, Phys. Rev. B 7, 3798 (1973).

⁴M. Suffczynski and W. Wardzynski, Phys. Lett. A 36, 29 (1971).

⁵I.F. Skitsko, Author's Abstract of Candidate's Dissertation, Singularities of Influence of Iron-Group Impurities and of Deformations on Excitons in CdTe, Chernovtsy Univ., 1975; N.P. Gavaleshko, R.D. Ivanchuk, M.V. Kurik, and I.F. Skitsko, Fiz. Tverd. Tela (Leningrad) 18, 2371 (1976) [Sov. Phys. Solid State 18, 1383 (1976)].

Concerning the stability of the critical state in type-II superconductors

R. G. Mintz

Institute of High Temperatures, USSR Academy of Sciences

(Submitted 1 March 1978)

Pis'ma Zh. Eksp. Teor. Fiz. 27, No. 8, 445-448 (20 April 1978)

Electromagnetic-field and temperature oscillations preceding the jump of the magnetic flux in type-II superconductors are considered.

PACS numbers: 74.40.+k, 74.60.-w

The question of the stability of the critical state in hard and combined superconductors has been repeatedly discussed in the literature. The corresponding criteria for the onset of jumps of the magnetic flux, obtained in an approximation linear in the small perturbations, are well known.^[1,2] Much has been left undone in the investigation of the evolution of the resultant instability, and accordingly, the finite flux jumps.^[1] This paper is devoted to a determination, in the linear approximation, of the region of existence of bounded oscillating perturbations of the temperature Θ , of the electric field \mathbf{E} , and of the magnetic field \mathbf{H} .

The evolution of the perturbations of Θ , \mathbf{E} , and \mathbf{H} is described by the heat-conduction equation and by the system of Maxwell's equations

$$\begin{cases} \nu \Theta = \kappa \Delta \Theta + j_c \mathbf{E} \\ \Delta \mathbf{E} = \frac{4\pi}{c^2} \frac{\partial \mathbf{j}}{\partial t} \end{cases} \quad (1)$$

where $\mathbf{j} = \mathbf{j}_c + \sigma \mathbf{E} + (\partial \mathbf{j}_c / \partial T) \Theta$, ν , κ , σ are respectively the specific heat, the thermal conductivity, and the electric conductivity (in the resistive state) of the superconductor, and j_c is the density of the critical current (for simplicity we consider Bean's model of the critical state $j_c = j_c(T)$).

We seek the solution of the system (1) in the form $\Theta = \Theta(r) \exp(\Gamma t)$, $\mathbf{E} = \mathbf{E}(r) \exp(\Gamma t)$. To determine the spectrum of the eigenvalues Γ it is necessary to impose thermal and electrodynamic boundary conditions on Eqs. (1).

Consider, for example, a thermally insulated semi-infinite sample in an external magnetic field $H \parallel z$ parallel to the surface (the yz plane). In this case $E(L) = 0$ ($L = cH/4\pi j_c$ is the depth of penetration of the magnetic field), the temperature and the heat flux $\kappa \partial \Theta / \partial x$ are continuous at $x = L$, $\partial H(0) / \partial t = \partial E(0) / \partial x = 0$, and $\partial \Theta(0) / \partial x = 0$. Since $\partial j_c / \partial H = 0$, the system (1) consists of linear equations with constant coefficients. From the condition that it have a solution (the vanishing of the corresponding determinant), we easily obtain an equation for the determination of Γ :

$$(\lambda - K_1^2) K_2 \operatorname{tg} K_2 - (\lambda + K_2^2) K_1 \operatorname{th} K_1 = \sqrt{\lambda} (K_1^2 + K_2^2), \quad (2)$$

where

$$\lambda = \Gamma \frac{L^2 \nu}{\kappa}, \quad K_{1,2}^2 = \pm \frac{\lambda(1+r)}{2} + \sqrt{\frac{\lambda^2(1-r)^2}{4} + \lambda\beta},$$

$$\beta = \frac{1}{\nu j_c} \left| \frac{dj_c}{dT} \right| \frac{H^2}{4\pi}, \quad r = \frac{4\pi}{c^2} \frac{\kappa \sigma}{\nu}.$$

The stability limit of the region $\operatorname{Im} \lambda = 0$, $\operatorname{Re} \lambda(\beta, \tau) > 0$, as usual, corresponds to $\beta = \beta_c(\tau)$.^[2,3] In most superconductors $\tau \ll 1$, i.e., the heat propagation is much slower than the diffusion of the magnetic field. This condition makes it possible to obtain analytically the relation $\beta_c = \beta_c(\tau)$: $\beta_c = \beta_0(1 + 2\sqrt{\tau})$, $\beta_0 = \pi^2/4$, $\lambda_c = \lambda(\beta_c) = \beta_0 \sqrt{\tau} \gg 1$.^[2] Solving (2) at $\beta \sim \beta_c$ and under the condition $\operatorname{Re} \sqrt{\lambda} \gg 1$, we get

$$\lambda_{1,2} = \frac{\beta - \beta_0 \pm \sqrt{(\beta - \beta_0)^2 - 4\beta_0 \tau}}{2\tau}. \quad (3)$$

As seen from (3), in the region $\beta_0 < \beta < \beta_c$ or $H_0 < H < H_j$ (here H_0 and H_j are determined from the conditions $\beta(H_0) = \beta$, $\beta(H_j) = \beta_c$) the eigenvalue spectrum turns out to be complex: $\lambda = \lambda_0 + i\lambda_1$, with $\lambda_0 > 0$. We note that at $\beta = \beta_0$ we have $\lambda = i\beta_0\sqrt{\tau} \doteq \tau\lambda_c$.

Thus, in a narrow interval directly ahead of the jump of the magnetic flux $H_0 < H < H_j$ ($(H_j - H_0)/H_j = \sqrt{\tau} \ll 1$), oscillations of the electric field and of the temperature can be observed. We consider the situation in the magnetic-field range $H_0 < H < H_j$ in greater detail. The equation (1) and the ensuing relation (2) are valid if a linear connection exists between the current j and the electric field E . The last condition is satisfied only if $E \geq E_0(T)$, where $E_0(T)$ is the boundary of the linear section on the $j = j(E, T)$ curve, so that the values of the electric field in the sample greatly influences the character of the observed effects.

Assume that initially there is no electric field. Then even a large fluctuation will decrease after a time $t_1 \sim L^2\nu/\lambda_1\kappa$ to such an extent that the condition $E < E_0(T)$ is satisfied everywhere in the sample, after which the perturbation will certainly attenuate.^[2] Consequently, the growth of fluctuations with an increment $\Gamma = \lambda_0\kappa/\nu L^2$ at the initial instant leads to a change of the magnetic flux only by a finite amount. Thus, one will observe in experiment only bounded magnetic-flux jumps proportional to the amplitude of the initial perturbation.

In the investigation of the stability of the critical state in an external magnetic field that varies at a given rate \dot{H} , there is initially present an electric field $E \sim (L/c)\dot{H}$. If $(L/c)\dot{H} > E_0(T)$ or $\dot{H} > cE_0(T)/L$, then oscillations of the electric field with amplitude up to $(L/c)\dot{H}$ can in fact develop in the sample. Let us estimate the number N of oscillations observed at a given value of \dot{H} . Since the magnetic field lies in the interval $\Delta H = H_j - H_0 = \sqrt{\tau} H_j$ during the time interval $\Delta t = H_j\sqrt{\tau}/\dot{H}$, it follows that N can be estimated as the ratio of Δt to the characteristic period of the oscillations, whence $N \sim \Delta t / \text{Im}\Gamma = H_j\kappa/\dot{H}L^2\nu$; it is seen that $N \gtrsim 1$ at $\dot{H} \lesssim H_j(\kappa/\nu L^2)$. Thus, the oscillations can be observed if the rate of change of the external magnetic field is in the range $cE_0(T)/L < \dot{H} < H_j\kappa/\nu L^2$, or

$$\frac{E_0}{H_j} 4\pi j_c < \dot{H} < \tau 4\pi j_c \frac{j_c}{\sigma H_j}.$$

It can be shown that in a semi-infinite sample the oscillations are produced at an arbitrary heat outflow from the boundary. It is likewise easy to investigate the evolution of the perturbations in samples of finite dimensions. In particular if the heat outflow is small in this case, then the period of the oscillations turns out to be relatively large (even at $\tau \ll 1$). A similar problem can be solved also for superconductors with $\tau \gg 1$.

We note in conclusion that potential-difference oscillations observed^[4,5] in the investigation of flux jumps against the background of an external magnetic field that grows with constant velocity correspond apparently to the case $\tau \lesssim 1$ and to poor cooling.

I am grateful to I.M. Rutkevich for a useful discussion of the work.

- ¹A. Campbell and J.E. Evetts, *Critical Currents in Superconductors* (Russ. transl.), Mir, 1970.
²R.G. Mints and A.L. Rakhmanov, *Usp. Fiz. Nauk* **121**, 499 (1977) [*Sov. Phys. Usp.* **20**, 249 (1977)].
³M.G. Kremlev, *Pis'ma Zh. Eksp. Teor. Fiz.* **17**, 312 (1973) [*JETP Lett.* **17**, 233 (1973)].
⁴S. Shimamoto, *Cryogenics* **14**, 508 (1974).
⁵J. Chikaba, *Cryogenics* **10**, 306 (1970).

Runaway of the front of a shock wave near a metallic surface, and mechanism of the destruction on the current sheath in a noncylindrical Z-pinch

A. L. Velikovich and M. A. Liberman

Institute of Physics Problems, USSR Academy of Sciences

(Submitted 2 March 1978)

Pis'ma Zh. Eksp. Teor. Fiz. **27**, No. 8, 449-451 (20 April 1978)

It is shown that heating the surface of an anode and of a gas layer adjacent to it by radiation of a current sheath is the cause of the runaway of part of the current-sheath front adjacent to the anode. The evolution of this process is also the cause of the destruction of the current sheath of the plasma focus.

PACS numbers: 52.40.Kh, 52.55.Ez

In a number of experiments (see^[1,2]) on a noncylindrical Z pinch ("plasma focus") it was observed that when a small amount of a heavy impurity is added to the deuterium (D + 1% Xe), runaway and destruction of the current sheath is observed near the surface of the anode. The runaway becomes noticeable after 2-2.5 μsec at distances of about 20 cm from the center of the anode. The destruction of the current sheath occurs after 4-4.5 μsec at a distance of about 10 cm from the center of the anode.

In the present article we propose the following mechanism for the runaway and the destruction of the current sheath of the Z pinch. In the course of the discharge, the shock-wave front, which is perpendicular to the surface of the anode, moves together with the sheath towards the axis of the Z pinch with increasing velocity.^[1,2] The radiation coming from the hot gas behind the front is partially absorbed by the surface of the anode and heats the latter. The gas layer adjacent to the anode is isobarically heated in turn by the thermal conductivity of the gas, and its density decreases in inverse proportion to the temperature. The sections of the shock-wave front near the anode, propagating through the gas with lower density, begin to accelerate. In fact, if T , ρ , and u are respectively the temperature, the density of the heated gas, and the velocity of the shock-wave front in the heated gas, while T_0 , ρ_0 , and u_0 are these quantities far from the anode, then from the condition that the pressure is constant behind the shock-wave front (subsonic flow) we have