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ELECTRIC DOMAINS IN METALS AT LOW TEMPERATURES

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Résumé.- On montre que les caractéristiques courant-tension des métaux, soumis à un champ magnétique assez intense pour provoquer une rupture cohérente, présentent des instabilités. On étudie les domaines qui se développent en conséquence de cette situation et on détermine les paramètres des structures stables de domaines. On prévoit un nouveau type de domaines "cycliques" particuliers aux métaux.

Abstract.- It is shown that current-voltage characteristics of metals under "coherent" magnetic break-down at low temperatures can be N-shaped. Electric domain instabilities developing in this situation are studied and stable domain structure parameters found. A new type of "cyclic" domains peculiar to metals is predicted.

The Gunn effect is now well known. It occurs in semi-conductors with N-shaped current-voltage characteristic /1/ and is due instability of inhomogeneous distributions of the electric field  $\vec{E}$  over the I-V characteristic segment with  $\partial j / \partial \vec{E} < 0$  ( $j$  is the current density) and consists in spontaneous formation of electric domains moving along  $\vec{j}$ . This paper is to show that in metals some similar phenomena can take place at low temperatures and to discuss their general features.

Our principal attention will be paid to the mechanisms responsible for the N-type I-V characteristic associated with the coherent magnetic break-down (CMB) /2/. This is the term for the situation where the  $\omega_H \tau^* > 1$  inequality is valid, where  $\omega_H$  is the characteristic Larmor frequency and  $\tau^*$  the electron lifetime in the stationary state of the magnetic break-down spectrum. (Owing to an electron interaction with dislocation deformation fields and phonons, in general may be less than  $\tau_{imp}$ , the electron-impurity relaxation time.)

We shall consider a common case where all the classical electron orbits in magnetic field  $\vec{H} = \{0, 0, H\}$  are closed and the magnetic break-down combines them in the  $\vec{P}$ -space into a current "magnetic break-down layer" (MB layer, whose thickness is  $\delta P$ ) of periodic magnetic break-down configurations open along one of the basic vectors of the reciprocal lattice,  $\vec{b} = \{0, b, 0\}$  (current  $\vec{j} = j, 0, 0$ ). The energy spectrum inside the MB layer consists of magnetic bands  $E_n(P_z, P_x) = E_n(P_z, P_x + \Delta P_x)$ , which are broadened Landau levels where  $n$  is the number

of the magnetic band,  $P_z$  the momentum projection on the direction of  $\vec{H}$ , period  $\Delta P_x = 2\pi e \hbar H / cb \sim (10^{-4} - 10^{-5})b$ . For the magnetic break-down probability  $W(H) \sim 1$ , the characteristic magnetic band width and separation  $\sim \hbar \omega_H$ , and the average electron velocity along the x-axis,  $\langle v_x \rangle = \partial E_n / \partial P_x$ , inside the MB layer is of order of the Fermi velocity  $v_F$  ( $\langle v_y \rangle = 0$ ). Outside the MB layer,  $\langle v_{x,y} \rangle = 0$ , and hence the MB layer contribution to  $j$  dominates at  $\beta \equiv (b/\delta P)(1/\omega_H^2 \tau^* \tau_{imp}) \ll 1$ .

a) One of the CMB mechanisms of the non-linear nature of  $j(\vec{E})$  is based on electron localization in field  $\vec{E} = \{E, 0, 0\}$  inside quantum "traps" of a width  $\Delta x \sim \hbar \omega_H / eE$  due to the energy conservation law  $e\vec{E} \cdot \vec{x} + E_n(P_z, P_x) = \text{const}$ . If the parameter  $\gamma_{dyn} = \Delta x / \lambda^* (\lambda^* = v_F \tau^*)$ , then, for  $\beta \ll 1$ , we have  $j \sim \omega_{dyn}^2 \tau^* / E$ . Thus, the N-type I-V is the case, if  $\gamma_{dyn} \lesssim 1$ . The "dynamic" mechanism described can be realized experimentally, if the angle between  $\vec{H}$  and the plane perpendicular to  $b$  is about  $10^{-3} - 10^{-2}$  radn.

b) If  $\gamma_{dyn} > 1$ , then the non-linearity of  $j(\vec{E})$  may be caused by electron diffusion on energies  $E_n(P_z, P_x)$  due to field  $\vec{E}$ . We formulate the principal idea of the "diffusion" mechanism, assuming that the energies ranges,  $\Delta_n = [E_n^{(min)}, E_n^{(max)}]$  and  $\Delta_{n+1}$  do not overlap (where  $E_n^{(max)}$  and  $E_n^{(min)}$  are the absolute maximum and minimum of  $E_n(P_z, P_x)$  inside the MB layer). This may be the case in low  $\delta P$  metals ( $\delta P \lesssim \sqrt{e\hbar H/c}$ ) if  $\vec{H}$  is parallel to the symmetry axis (e.g., Be, Ru, Al). In this case, the main contribution to  $j$  (with  $\beta \ll 1$ ) is due to

electrons from  $\Delta_n$ . Since the diffusion flow across the boundaries of  $\Delta_n$  is small in  $\beta$ , then if  $\gamma_{diff} = \tau_{diff}/\tau_E \ll 1$  ( $\tau_{diff} = (b/\delta P)\delta E_n^2 \tau^*/(e\mathcal{E}\lambda^*)^2$  is the characteristic time of the diffusion change of  $E_n$  by an amount of  $\delta E_n = E_n^{(max)} - E_n^{(min)}$ ,  $\tau_E$  is the characteristic time of the electron-phonon energy relaxation), the diffusion distributes electrons inside  $\Delta_n$  almost uniformly, and current  $j$  becomes  $\propto \mathcal{E}_{diff}^{+1} \propto \mathcal{E}^{-1}$ . The "diffusion" mechanism causes the N-type I-V characteristics throughout the range  $\gamma_{diff} \leq \gamma_{cr} \sim 1$ ,  $\beta \leq \beta_{cr} \sim 1$ .

In contrast to semiconductors, in metals the spatially inhomogeneous distributions of  $\mathcal{E}$  occurring at  $j_0(\mathcal{E}_2) < j < j_0(\mathcal{E}_1)$  ( $\mathcal{E}_{1,2}$  are the extreme points of the N-type I-V characteristic  $j_0(\mathcal{E})$ ;  $\mathcal{E}_1 < \mathcal{E}_2$ ) develop under the local electrical neutrality condition so that the current density  $j=j(t)$  ( $t$  being the time) is constant along the whole sample. If  $\lambda = (\mathcal{E}_2 - \mathcal{E}_1)/\mathcal{E}_1 \ll 1$  the equation for  $\mathcal{E}$  has the form :

$$-\sigma_1 t_0 \frac{\partial \mathcal{E}}{\partial t} + \sigma_1 \lambda_0^2 \frac{\partial^2 \mathcal{E}}{\partial \xi^2} - j_0(\mathcal{E}) = j(t), \quad \xi = x - St, \quad \sigma_1 = j_0(\mathcal{E}_1)/\mathcal{E}_1 \quad (1)$$

Here  $x$  is a coordinate along  $\vec{j}$ , constants  $t_0 > 0$  and  $\lambda_0$  are the characteristic time and spacial scales, respectively, of the non-local functional relating  $j$  to  $\mathcal{E}$ ; constant  $S$  has the sense of the electric domain velocity. Estimates for  $t_0, \lambda_0, S$  are : (a) the "dynamic" mechanism :  $t_0 \sim \tau^*$ ,  $\lambda_0 \sim \lambda^*$ ,  $S \sim v_F \sim 10^8$  cm/s; (b) the "diffusion" mechanism :  $t_0 \sim \tau_E$ ,  $\lambda_0 \sim v_F \sqrt{\tau^* \tau_E} (\delta P/b)$ ,  $S \sim \lambda_0/\tau_E \sim 10^6$  cm/s. For the heat flux from the metal  $q \lesssim 1$  W/cm and the sample thickness  $d \lesssim 10^{-1}$  cm, magnitudes of  $\mathcal{E}_{1,2}$  are  $10^{-4} - 10^{-5}$  CGSE.

Equation (1) admits of a stable automodel solution of the soliton type  $\mathcal{E}(x,t) \equiv \mathcal{E}_{sol}(\xi), \lim_{\xi \rightarrow \pm\infty} \mathcal{E}_{sol}(\xi) = 0$  similar to the Gunn domain in semiconductors in its structure and excitation manner. In metals where  $\mathcal{E}_{1,2}$  are less than in semiconductors by a factor of  $10^6 - 10^8$  times, experiments may be arranged in a new contact-free manner : in an N-type I-V sample shaped as cylindric tube of an arbitrary cross-section shape (with the length  $L_0$ ) the field  $\mathcal{E}$  is induced with a variable magnetic field flux  $\phi(t)$ . The flux may be produced by any means provided that the adiabatic condition

$\frac{d\phi}{dt} \ll S/L_0, t_0^{-1}$  is fulfilled. If  $L_0 \gg d$  there is a finite region in the plane  $\{\mathcal{E}, (\frac{2\pi\lambda_0}{L_0})^2\}$  where any initial distribution of  $\mathcal{E}$  develops into a periodic automodel solution  $\mathcal{E}(x,t) = \mathcal{E}(\xi) = \mathcal{E}(\xi + L_0)$  ( $x$  is an

arc length along the contour) unambiguously determined by the equation (1) and the condition

$$\int_0^{L_0} dx (x,t) \equiv L_0 \bar{\mathcal{E}}(t) = - \frac{d\phi}{dt} / c; \quad |\bar{\mathcal{E}} - \mathcal{E}| \lesssim |\mathcal{E}_2 - \mathcal{E}_1|, \mathcal{E}_1 < \bar{\mathcal{E}} < \mathcal{E}_2.$$

In metals "temperature" electric domains (with  $S \lesssim 10^2$  cm/s) can also exist due to the dependence of the conductivity on the temperature and the sample Joule heating.

References

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