case of an antiferromagnetic interlayer, when the widths of domain walls are tens of ångströms.

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Quantum interference of a moving charge density wave on columnar defects containing magnetic flux [1]

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1. Introduction

As is known, below the temperature of Peierls transition a condensed state is formed in quasi-one-dimensional conductors — the charge density wave (CDW), characterized by a gap in the excitation spectrum and the space modulation of the density $\rho(x)$ of charge condensed in the CDW [3]:

$$\rho(x) = \rho_0 \left[1 + \alpha \cos(Qx + \varphi)\right] ,$$

where α and φ are the amplitude and phase of CDW, with a period of $1/Q$ equal to the inverse Fermi wave vector $2\pi/Q = 2\pi/2k_F$. In the external electric field exceeding a certain threshold, the CDW can move and give a collective contribution to conductivity, which depends on the total density of the charge condensed under the gap [3]. The movement of the CDW is accompanied by the generation of narrow-band oscillations, whose frequency is proportional to the velocity of propagation of the CDW [4]. Several theories [5–8] have been put forward for describing the motion of CDWs, which can be divided into two classes. One treats the motion of a CDW as the motion of a classical object, either rigid [5] or in the form of a deformable medium [6], in a periodic potential. The other considers a CDW as a quantum object, and its motion as coherent tunneling [8]. Until recently, however, there had been no convincing demonstrations of the quantum nature of CDWs. Most of the observed properties of CDWs, including the narrow-band generation, were well enough described by the appropriate classical models [5–7]. Quantum tunneling of CDWs was only surmised at very low temperatures [9, 10].

At the same time, there were theoretical predictions of the possible observation of quantum interference effects of CDWs in a ring of quasi-one-dimensional conductor of small diameter (comparable with the coherence length of the CDW), containing magnetic flux [11]. As the CDW moves along the ring consisting of one conducting chain, oscillations of magnetoresistance with the period corresponding to a change of flux in the ring equal to one 'superconducting' magnetic flux quantum $\Phi_0 = hc/2e$ were predicted. This theory stimulated the experimental quest for quantum interference effects in materials with CDWs [1, 2], the results of which are discussed below.

2. Results and discussion

The idea of the experiment was to select a thin (less than 1 micrometer) crystal with the CDW ($NbSe_3$), containing columnar defects (CD) created by the bombardment of the material with heavy ions with an energy of the order of 1 GeV. As is known [12], a CD is a homogeneous amorphous cylinder in the material crystal matrix, about 10 nanometers in diameter and 10 micrometers long. It is formed along the track of the travelling particle because of melting and subsequent fast quenching of matter. Since each CD is created by one identical particle, they all have the same size. It was assumed that since the defect is smaller than the amplitude coherence length of the CDW across the chains, the CDW passing the defect will 'flow around' it, retaining the coherence of motion. In a magnetic field directed along the axis of the defect, the CD will behave as a solenoid giving an Aharonov – Bohm contribution [13] to the phase of the wave function of the CDW having passed the defect. In the limit of coherent motion of the CDW throughout the entire crystal, the contributions from individual defects may be synchronized, much increasing the probability of detection of the effect.

Selected perfect single crystals of $NbSe_3$ were irradiated at two large accelerators: VIKSI (Berlin), and GANIL (Caen, France). Part of the specimen was usually shielded from irradiation for comparison studies. There were several series of irradiation with ions of Xe, Pb, and U with energies from 0.3 to 6 GeV. The density of defects varied from 2×10^9 to 2×10^{10} def. per square centimeter. The direction of motion of heavy ions in the beam corresponded to the a^* axis of the irradiated crystal. The divergence of the beam was less than 0.5°. The diameter of defects was measured by TEM and HREM techniques, and was about 16 nm (see inset to Fig. 1).

The studies on differential current-voltage characteristics of the exposed specimens and the spectra of Shapiro steps [14] at the frequency of about 10 MHz revealed that the introduction of columnar defects to concentrations of up to 10^{10} def. per square centimeter had little effect on the transport characteristics of CDWs, and the coherence of motion of CDWs is preserved over the entire length of the specimen (about 0.5 mm) [2]. Such samples were selected for measurements of magnetoresistance, which were performed with the Bitter magnet in fields up to 23 T at the laboratory of high magnetic fields (Grenoble). The specimen was usually equipped with six probes, which permitted simultaneous measurement of magnetoresistance on both the part containing the columnar defects and the defect-free part. With fixed temperature and current through the specimen, the magnetic field slowly swept up to its maximum and back. The results of measurements were stored and averaged over both scans.

[1] Based on Refs [1, 2].

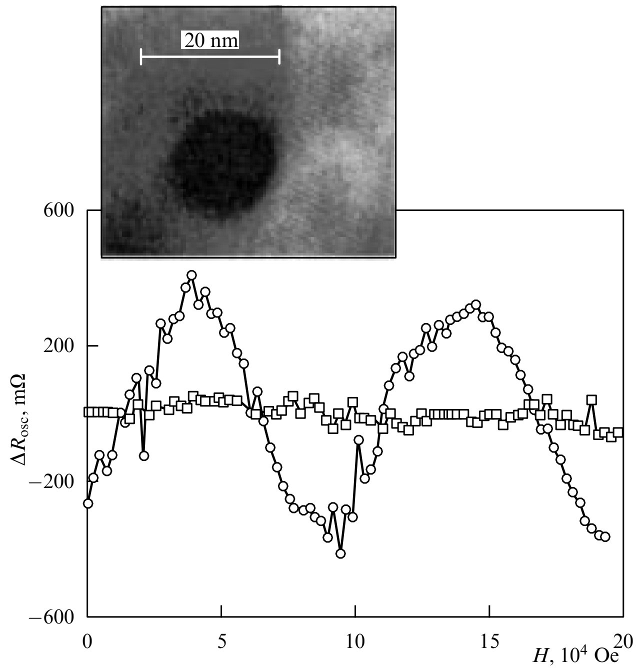

Figure 1. Oscillating part of the magnetoresistance (minus quadratic background) in the regime of a sliding CDW as function of magnetic field ($H||a^*||$ to the CD axis) in an $NbSe_3$ (B1-1) specimen with a concentration of 4×10^9 columnar defects per square centimeter; $I = 180$ μA, $I_t = 100$ μA, $T = 52$ K [1]. The inset shows a CD image obtained with high-resolution transmission electron microscopy HREM: ○ irradiated part of the specimen; □ unirradiated part of the specimen.

In the regime of sliding CDW, an oscillating component of magnetoresistance was discovered in the part containing the CD with a period of approximately 10 T, while the defect-free part under the same conditions exhibited no oscillations [1] (Fig. 1). In the pinned CDW state, magneto-oscillations were not observed for both parts. Further detailed studies of conditions of oscillation occurrence and comparison of their periods with the magnitude of flux trapped by the defect [2] revealed the following.

(1) Oscillations were observed on four specimens. Within an experimental accuracy of 15%, their period corresponds to a change of flux in the defect by one magnetic flux quantum $hc/(2e)$ and does not depend on the temperature (36–52 K) or the concentration of defects ($3 \times 10^9 - 10^{10}$ def. cm^{-2}) (see Table 1).

(2) The amplitude of oscillations achieves its maximum with the currents of $(2-3)\,I_t$, where I_t is the threshold current corresponding to depinning of the CDW, and quickly falls off when the current either increases or approaches the threshold.

(3) Oscillations are observed in the field parallel to the axis of defects and disappear when the field is perpendicular to the axis of defects (Fig. 2).

(4) Oscillations are observed on perfect thin specimens containing CDs and are not found in samples thicker than 1 micrometer. Oscillations also disappear when the columnar defects degrade after the specimen is stored at room temperature for several months.

These results indicate that the oscillations of magnetoresistance are quantum in nature. They are only observed in the case of coherent motion of the CDW, and when all defects are identical (freshly irradiated specimens). As shown in Ref. [2],

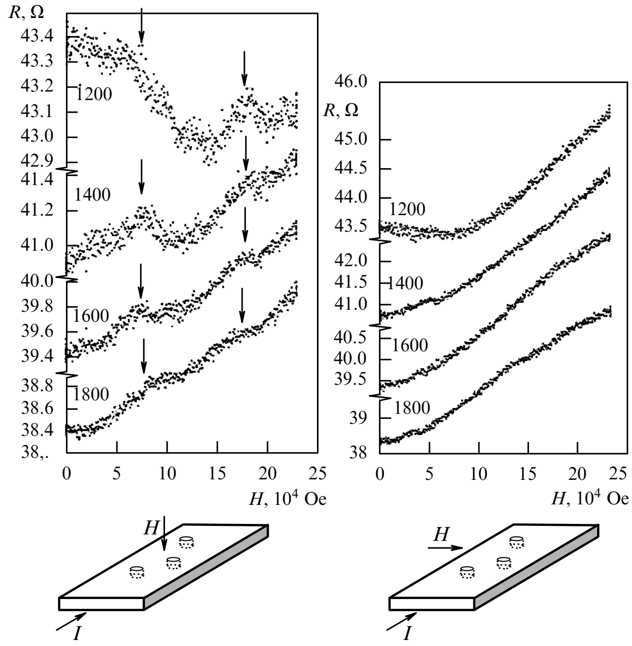

Figure 2. Magnetoresistance of part of the $NbSe_3$ (G2-2) specimen containing CDs with the concentration 3×10^9 def. per square centimeter in the regime of sliding CDW at different fixed currents above the threshold $I_t = 600$ μA for two orientations of a magnetic field: (a) $H||a^*$, and (b) $H \perp a^*$ ($T = 40$ K).

Table 1. Analysis of the period of magneto-oscillations of conductivity of CDW

Specimen number	C, 10^9 def. cm^{-2}	T, K	D, nm	$\Delta H(\pi D^2/4)/\Phi_0$
B1-1	4	52	15	0.86
G1-1	5	50	16	0.85
		36	16	0.84
G1-3	10	36	16	0.89
G2-2	3	40	16	0.97

Note: C — concentration of defects; T — temperature of measurements; D — diameter of columnar defect; ΔH — period of oscillations. The error in determination of $\Delta H(\pi D^2/4)/\Phi_0$ was 15%.

the coherence of a moving CDW disappears when the current is increased above $(2-3)\,I_t$, and in specimens whose thickness is greater than the phase coherence length along the a^* axis, which is about 1 micrometer. Oscillations are observed at high temperatures of the order of 50 K, when the single-particle interference effects [15] are negligibly small. Accordingly, one may conclude that oscillations result from quantum interference of a coherently moving CDW on columnar defects containing magnetic flux.

The microscopic picture of the phenomenon is not yet quite clear, but from experimental evidence one may surmise that the definitive elementary charge is equal here to $2e$ — that is, the same as associated with quantum interference phenomena in superconductors. How far this analogy goes is yet to be found. Also remaining open is the question concerning the existence and observability of persistent currents in such nanostructures with CDWs and effects similar to the Josephson effect in heterostructures with CDWs [16]. Notice that effects similar to Andreev reflection from the interface between normal metal and superconductor were recently demonstrated with local injection of carriers into the boundary between normal metal and the CDW (Au – $K_{0.3}MoO_3$) [17].

The discovered phenomenon of quantum interference of a moving CDW poses new questions, the answers to which will ensure better understanding of the mesoscopic properties of condensed state with CDWs. Also clear is the need for further experimental studies, and for a new microscopic theory to explain the quantum properties of CDWs. Recent theoretical models [18, 19] explain some aspects of the phenomenon from various standpoints. In our opinion, however, these models are far from giving a complete description of the phenomenon.

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