Oscillations in the work function of a single-crystal $YBa_2Cu_3O_{7-\delta}$ film in a strong magnetic field

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Oscillations have been detected in the work function of a single-crystal $YBa_2Cu_3O_{7-\delta}$ thin film ($d \approx 600$ Å; $T_c = 85$ K) in fields of 120–150 kOe at a temperature of 1.4 K.

Learning about the electronic structure of the high-T_c superconductors is of considerable interest for identifying the mechanism for high-T_c superconductivity and also for reaching an understanding of many other unusual properties.

Research on the photoelectron emission spectra[1,2] has revealed the basic characteristics of the band structure of several of these compounds, but the electronic states cannot be studied directly at the Fermi level because of the inadequate energy resolution and the inadequate momentum resolution of these methods.

Reconstructing the shape of the Fermi surface from the positron annihilation spectra is seriously complicated by the fact that only ~7% of the signal stems from states at the Fermi surface; the other 93% comes from inner atomic shells and filled valence bands.[3] As a result, experiments taking many months[4] have yielded no information at all on the Fermi surface of $YBa_2Cu_3O_{7-\delta}$.

The first data on the Fermi surface of $YBa_2Cu_3O_{6.97}$ in the normal state were obtained from measurements of the de Haas–van Alphen effect in fields in the megagauss range.[5] In those experiments, a field pulse ~ 10 μs long was produced by an explosive method. The samples consisted of a compound compact of crystallites ≈ 10 μm oriented by a magnetic field. In a method of this sort, it is obviously a very difficult matter to carry out a systematic study of the topology of the Fermi surface or of the dependence of the extremal cross sections on the oxygen content, the orientation, etc.

In this letter we are reporting the first experimental results of a study of the effect of a magnetic field on the work function of single-crystal $YBa_2Cu_3O_{7-\delta}$ thin films.

In planning the experiments we were guided by the following considerations.

1. The quantization of the orbital motion of the electrons of a metal in a strong magnetic field is known to lead to oscillations in the density of states. The frequency of these oscillations is determined by extremal cross sections of the Fermi surface. One consequence of these oscillations, for example, is the de Haas–van Alphen effect. If we assume that the electronic configuration remains constant, we conclude that the oscillations in the density of states should give rise to oscillations in the chemical potential and thus the work function.[6,7] A search for oscillations of this sort in single crystals of beryllium[8] and bismuth[9] led to a negative result. This negative result was attributed to a canceling effect of magnetostriction: The oscillations in μ associated with oscillations in the density of states were canceled by oscillations in μ associated with magnetostrictive oscillations of the volume.[1)] The magnetostrictive component can be eliminated by carrying out the experiment on a thin single-crystal film which is attached securely to an insulating substrate.

2. Uniformity of the magnetic field is important for detecting oscillations in μ. A thin superconducting film in a transverse magnetic field $H < H_{c2}$ is always in a mixed state.[11] In the case of $YBa_2Cu_3O_{7-\delta}$, the average distance (r) between vortices in a field $H \sim 150$ kOe can be estimated to be $r = \xi \sqrt{H_{c2}/H} \approx 30$ Å. This figure is much smaller than the penetration depth λ. Induced superconducting currents can also be ignored, since even at $j_{cr} \approx 10^7$ A/cm^2 and at a film thickness $d = 1000$ Å the field produced by these currents would not exceed 50 Oe.

The films for the present study were prepared[12] by a combination of crystallization by laser evaporation and the hot-wall method, on freshly cleaved faces of an MgO single crystal in the $\{100\}$ orientation. The (001) planes of the films were parallel to the (001) planes of the substrates, and the $\langle 110 \rangle$ direction of the films coincided with the $\langle 110 \rangle$ direction of the substrates. Gold contacts were deposited by laser vacuum deposition. The transition temperature was found from resistance measurements to be $T_c = 85$ K for a film 600 Å thick.

The method used to measure the oscillations in the work function was based on a determination of the change in the charge on a measurement capacitor consisting of the test sample and a bronze electrode.[9] This instrument was similar in design to that of Ref. 8, with certain refinements.[13] The analog signals from the electrometer output and from the magnetic field pickup were measured by digital voltmeters and stored in a personal computer. An average was taken over several recordings in the field range 120–150 kOe to reduce the noise. These measurements were carried out at the Interna-

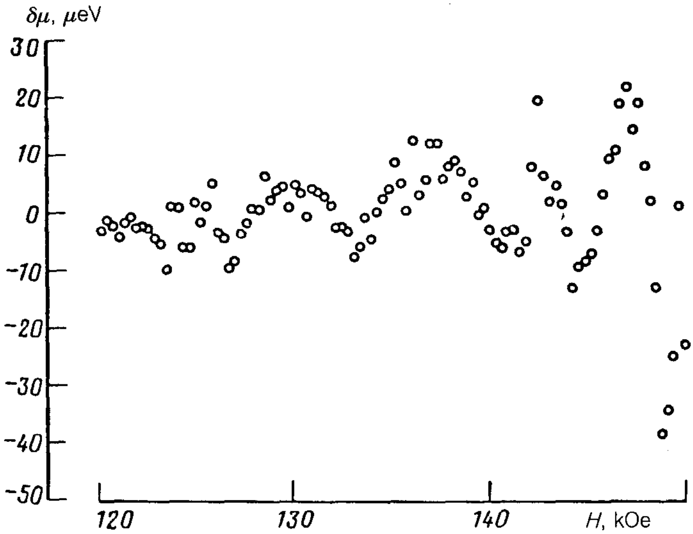

FIG. 1. Result found by averaging five recordings of the oscillations in the work function of a thin single-crystal film of $YBa_2Cu_2O_{7-\delta}$. These measurements were taken at $T = 1.4$ K. Each point shown corresponds to ≈ 12 original points.

tional Laboratory of Strong Magnetic Fields and Low Temperatures in Wrocław, Poland.

Figure 1 shows the oscillations in μ observed in a film 600 Å thick at $T = 1.4$ K. Figure 2 shows the Fourier spectrum of these oscillations. Oscillations were not observed in a film 800 Å thick at $T = 4.2$ K.

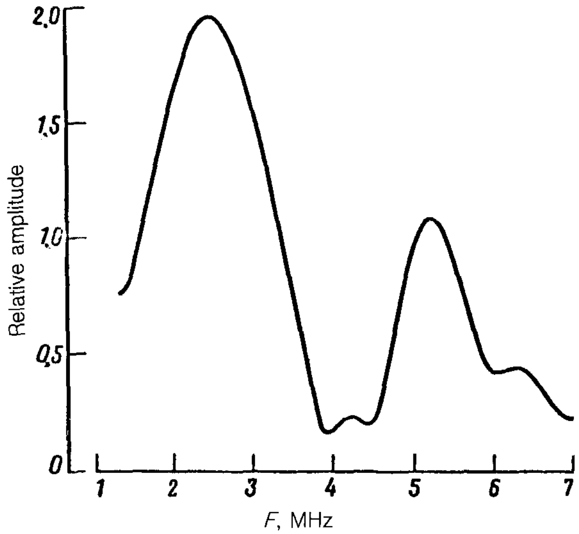

FIG. 2. Spectrum of the Fourier oscillations.

The frequencies of the observed oscillations are lower by a factor of 2–2.5 than those observed in Ref. 5, possibly because of a lower oxygen content in the film which we studied. The transition temperature $T_c = 85$ K is noticeably lower than the $T_c = 93$ K of the samples of Ref. 5.

Comparing the results found in Ref. 5 and our own data with the calculations of Refs. 14 and 15, we conclude that both the de Haas–van Alphen effect and the oscillations in μ stem from hole tubes surrounding S–R edges of the Brillouin zone. According to the calculations, these tubes should disappear at $\delta > 0.1$. This circumstance could explain the pronounced sensitivity of the oscillation frequencies to the oxygen content.

In summary, we have proposed and implemented a method for carrying out a systematic study of the Fermi surface of high-T_c superconducting compounds.

(1) A different explanation was offered in Ref. 10.

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