Polarized-optics contrast in $Y_1Ba_2Cu_3O_{7-x}$ high-temperature superconductors

V. K. Vlasko-Vlasov, M. V. Indenbom, and Yu. A. Osip'yan
Institute of Solid State Physics, Academy of Sciences of the USSR

(Submitted 10 February 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 6, 312–315 (25 March 1988)

The contrast between twins in reflected polarized light has been studied on various faces of orthorhombic $Y_1Ba_2Cu_3O_{7-x}$ single crystals. The results show that only the component of the light which has a polarization along the Cu-O chains in the (001) basal plane undergoes a phase delay during reflection. This result may be evidence in favor of a 1D conductivity in rare-earth cuprates.

When high-temperature superconductors of the 1-2-3 type are cooled below a temperature on the order of a few hundred degrees, they switch from a tetragonal phase to an orthorhombic phase. This transition should be accompanied by the appearance of an additional anisotropy in their properties, because of the appearance of a difference between the crystallographic axes *a* and *b* (of the [100] type) in the basal plane. However, it has not previously been possible to detect this anisotropy because of the fine twin structure, which raises the symmetry of the crystal, since the *a* and *b* axes trade places in twin domains of different phases.[1]

In a study of the basal surface of single crystals of superconducting rare-earth barium cuprates in linearly polarized light, it is possible to distinguish twin domains of fairly large size. Light reflected from these domains acquires an elliptical polarization.[1,2] By analyzing this polarization one can determine the anisotropy of the refractive indices and the absorption coefficients, which are related to the electrical properties of the medium, including those in the *a*, *b* plane.[2] In this letter we report a polarized-optics study of the yttrium-barium cuprate $Y_1Ba_2Cu_3O_{7-x}$. The results show that the anomalous properties of this compound stem exclusively from one of the orthorhombic axes lying in the basal plane: the *b* axis, which is the axis along which Cu-O chains lie.

In the experiments we used single-crystal wafers of $Y_1Ba_2Cu_3O_{7-x}$ with a developed *a*, *b* basal plane, with typical dimensions of 1 × 1 mm and a thickness (along the *c* axis) ~ 20 μm (the temperature of the superconducting transition is about 90 K). Without a preliminary processing, the crystals were studied under a polarizing microscope with normal reflection.

Figure 1 shows the typical pattern observed in the *a*, *b* plane. In this case, the photograph was taken in crossed polarizers, with a small additional path difference introduced by a compensator. The contrast of the dark and bright fringes in Fig. 1, which lie along [110] crystallographic directions, is inverted when the sample is rotated 90° around the optic axis of the microscope. An analysis carried out with the help of Berek and Sénarmont compensators showed that these regions differ in that the *a'* axis is in mutually perpendicular directions: parallel to respectively the [100] and [010]

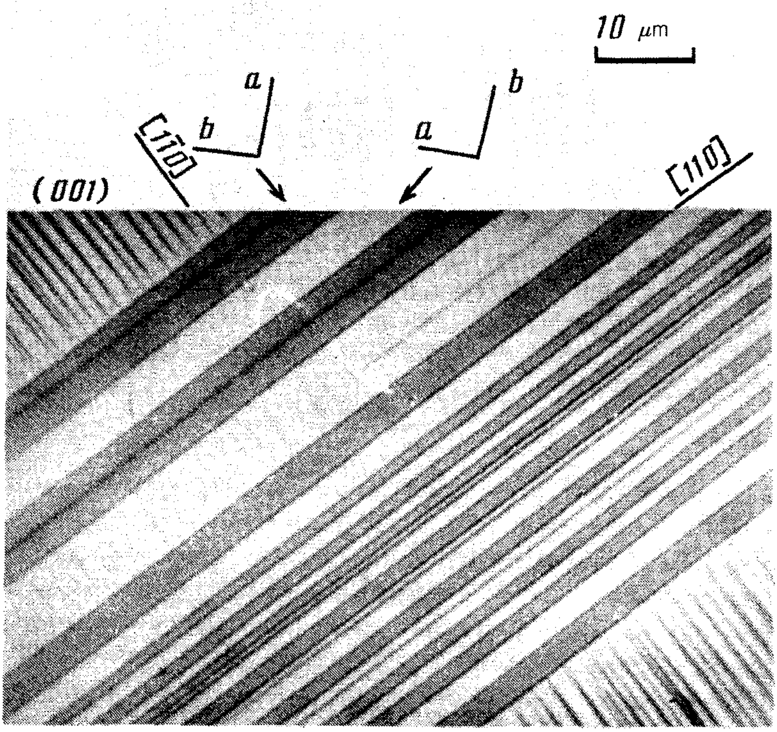

FIG. 1. Twins manifested in reflected polarized light in the basal plane.

directions. The situation is such that when light polarized along this direction is reflected from the surface of the sample, it undergoes a phase delay φ_a which is larger than that $b' - \varphi_{b'}$ for light which is polarized along the b' axis, which is normal to it. At a wavelength $\lambda = 546$ μm, set by a monochromator, we have $\varphi_{a'} - \varphi_{b'} = 14.1 \pm 1.5°$. This figure is about half the value which was found in Ref. 2 for $Eu_1Ba_2Cu_3O_{7-x}$ single crystals. It is natural to compare the a' and b' axes and the crystallographic a and b axes of an orthorhombic crystal, which trade places in twin domains of different phases, to which (in turn) the dark and bright bands in Fig. 1 correspond. To establish a mutually one-to-one correspondence between the a', b' and a, b axes in the crystals, we imposed nonuniform thermoelastic stresses. We observed the formation of zones with the b' axis directed predominantly along the compression direction. Consequently, b' runs parallel to the short axis of the crystal, a (correspondingly, $a' \parallel b$).

A picture similar to that described above is observed at the (100) end face of the single crystals (Fig. 2). This picture corresponds to twin domains for which the normal to the surface is the a or b axis, respectively. The boundaries of the twins are all oriented along the crystallographic c axis. An unexpected result was the behavior of the contrast at the end face when the sample was rotated around the optic axis of the

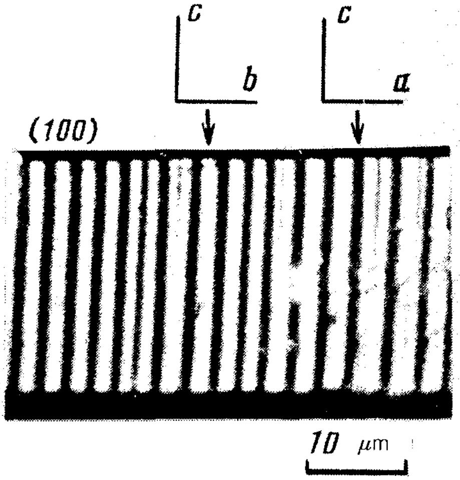

FIG. 2. Twins at the end face of a crystal.

microscope. While the contrast became inverted in domains in which the a axis was perpendicular to the surface (bc domains), the intensity of the reflected light remained essentially unchanged in domains with a b normal (ac domains).

The difference between the phase shifts in the reflection of light polarized along b and along c was measured in the bc domains; the result, $\varphi_b - \varphi_c$, turned out to be equal to the difference $\varphi_b - \varphi_a$, within the measurement error. On the other hand, the value of $\varphi_a - \varphi_c$ turned out to be close to zero, in accordance with the observed absence of a change in the contrast in the ac domains.

In a phenomenological study, the phase shift which occurs upon the reflection of a light wave of polarization i ($i = a,b,c$) from a crystal with a refractive index n_i and an absorption coefficient k_i is[3] $\varphi_i = \arctan\{2k_i/(n_i^2 + k_i^2 - 1)\}$. Analysis of the behavior $\varphi(n,k)$ shows that the measured phase shifts should correspond to $\varphi_b \approx 14°$, and we should have $\varphi_a \approx \varphi_c \approx 0$. (In general, there is the further possibility that φ_a and φ_c would be equal with nonzero values, but such a degeneracy seems less likely.)

Since the experimental values of n (for unpolarized light in the visible range) are greater than 1, while the values of k are less than 1 (Ref. 4), the values of k_i must satisfy the inequality $k_a \sim k_c \ll k_b < 1$. We have been able to observe that thinned crystals transmit light polarized along a quite well, while they are nearly opaque for light polarized along b. We thus have confirmation of this relation among absorption coefficients. In metals, the most significant changes in k_i stem from variations in the optical-frequency conductivity σ (Ref. 3). In this case, the conditions adopted on the k_i should correspond to a value of σ along b which is significantly larger than the values along a and c. These conclusions correlate completely with dc measurements of the anisotropy of the conductivity at room temperature.[5] Those measurements showed that the conductivity in the basal plane is roughly 40 times that along the normal to this plane. It should be kept in mind, of course, that the optical-frequency conductivity differs from the dc conductivity.

In summary, the results of this polarized-optics study, which provide evidence in favor of a 1*D* conductivity along the *b* axis, can apparently be regarded as confirmation of the chain model.[6]

In conclusion we would like to point out that an optical analysis of the anisotropy of the electrical properties in any plane will require measuring the phase shift for all three polarizations of the light (*a*, *b*, and *c*), not for just two, as in the experiments of Ref. 2, for axes in the basal plane.

We wish to thank G. A. Emel'chenko for furnishing the $Y_1Ba_2Cu_3O_{7-x}$ single crystals.

[1] D. C. Larbalestier *et al.*, J. Appl. Phys. **62**, 3308 (1987).
[2] K. Semba *et al.*, Jpn. J. Appl. Phys. **26**, L1645 (1987).
[3] A. V. Sokolov, Optical Properties of Metals, Gos. izd. Fiz.-mat. lit., Moscow, 1961.
[4] A. V. Bazhenov *et al.*, Spectroscopy of High-Temperature Superconductors, Nauka, Moscow, 1988.
[5] L. I. Buravov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 50 (1988) [JETP Lett. **47**, 60 (1988)].
[6] S. Massida, J. Ju, A. J. Freeman, and D. D. Koelling, Phys. Lett. **A122,** 198 (1987).

Translated by Dave Parsons