*Physics of the Solid State, Vol. 44, No. 10, 2002, pp. 1840–1844. Translated from Fizika Tverdogo Tela, Vol. 44, No. 10, 2002, pp. 1758–1761.*
*Original Russian Text Copyright © 2002 by Shabanova, Krasnosvobodtsev, Varlashkin, Golovashkin.*

**METALS AND SUPERCONDUCTORS**

# Effect of Ion Irradiation on the Upper Critical Magnetic Field in Electronic and Hole *d*-Wave Semiconductors

**N. P. Shabanova, S. I. Krasnosvobodtsev, A. V. Varlashkin, and A. I. Golovashkin**
*Lebedev Physical Institute, Russian Academy of Sciences, Leninskiĭ pr. 53, Moscow, 119991 Russia*
*e-mail: varlash@sci.lebedev.ru*

Received November 13, 2001

**Abstract**—The effect of ion irradiation on the upper critical magnetic field $H_{c2}$ in electronic and hole high-temperature superconductors is studied. It is shown that the variation of $H_{c2}$ may be connected with the *d*-wave symmetry of the order parameter.© *2002 MAIK “Nauka/Interperiodica”.*

## 1. INTRODUCTION

Studies of various groups of high-temperature superconductors (HTSC) subjected to ion irradiation have revealed an anomalous character of variation of the upper critical magnetic field with increasing radiation defect concentration [1, 2]. The classical growth of $H_{c2}$, which is usually caused by electron scattering from radiation-induced defects, was not observed. Attempts to noticeably increase $H_{c2}$ even by irradiating high-quality epitaxial films to doses that did not give rise to a change in the critical temperature with increasing electrical resistivity were unsuccessfull.

Studies of conventional superconductors featuring the phonon mechanism have shown that scattering from defects plays a dominant role in the variation of the upper critical field in the cases where irradiation does not produce noticeable changes in the electronic structure. This situation can be exemplified using the NbC superconducting compound [3, 4]. In other cases, for instance, in $Nb_3Sn$, where the electronic characteristics undergo a strong variation, it is this variation that determines the behavior of $H_{c2}$ under irradiation [5].

This publication reports on a study of the effect of radiation defects on the variation of electronic characteristics and conduction-electron scattering in electronic and hole cuprate HTSCs, as well as of the part that these variations play in the anomalous behavior of $H_{c2}$.

## 2. EXPERIMENT

We studied *c*-oriented epitaxial films of $YBa_2Cu_3O_{7-\delta}$ (YBCO), $HoBa_2Cu_3O_{7-\delta}$ (HBCO), and $Nd_{2-x}Ce_xCuO_{4-\delta}$ (NCCO) prepared *in situ* by two-beam laser ablation [6, 7]. The films were irradiated by energetic helium ions at room temperature and at $T$ = 77 K [8]. We measured temperature dependences of the electrical resistivity in a normal state and investigated the resistive superconducting transitions in a dc magnetic field oriented perpendicular to the film surface. The temperature dependence of the upper critical field $H_{c2}(T)$ was determined from the shift of the resistive transition.

## 3. RESULTS AND DISCUSSION

Figure 1 shows the superconducting resistive transitions in an NCCO epitaxial film observed in a magnetic field before and after irradiation of the film to a low helium ion dose. We see that although the electrical resistivity ρ of the material increased almost twofold as a result of the irradiation, the temperature dependence of $H_{c2}$ virtually did not change. Irradiation to higher doses changed the slope $-dH_{c2}/dT$ of the temperature dependence of the upper critical magnetic field only

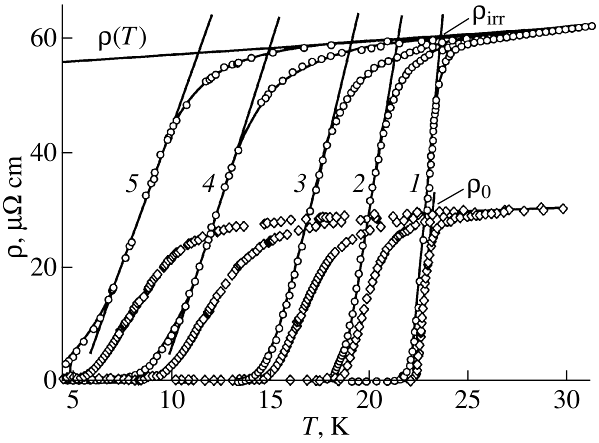

**Fig. 1.** Superconducting transitions in an epitaxial NCCO film in a magnetic field before and after irradiation by energetic $He^+$ ions to a dose of $1 \times 10^{13}$ cm$^{-2}$. Curves (*1*–*5*) were obtained in magnetic fields 0, 5, 10, 20, and 30 kOe, respectively. Determination of the electrical resistivity in a normal state near $T_c$ of the original ($\rho_0$) and irradiated ($\rho_{irr}$) samples is shown.

weakly even when the critical temperature $T_c$ decreased strongly.

The broadening of the superconducting transition in the YBCO and HCCO films in a magnetic field was stronger [5]. Under irradiation, the slope $-dH_{c2}/dT$ decreased approximately proportional to the critical temperature.

The variation in $H_{c2}$ of the cuprate HTSCs observed to occur under irradiation was found to be very similar to that of the part of $H_{c2}$ of conventional superconductors that is commonly called the clean-base term (Fig. 2).

In the absence of scattering, the slope $(-dH_{c2}/dT)$ corresponds to the clean-base term determined by the quantity $T_c/\langle v^2\rangle$, where $\langle v^2\rangle$ is the Fermi surface-averaged square of the Fermi velocity [9, 10]. Scattering from defects increases the upper critical magnetic field [11, 12]. The slope of the temperature dependence $-dH_{c2}/dT$ near $T_c$ can be written, with inclusion of scattering, as

$$-dH_{c2}/dT \sim \frac{T_c}{\langle v^{*2}\rangle}(1+\lambda_{\mathrm{tr}}). \tag{1}$$

The quantity $\lambda_{\mathrm{tr}}$ grows with decreasing electron mean free path $l$ or relaxation time $\tau = l/v^*$:

$$\lambda_{\mathrm{tr}} = \frac{\hbar}{2\pi k T_c \tau^*} = 0.882\frac{\xi_0}{l}. \tag{2}$$

Here, $\hbar$ is the Planck constant, $k$ is the Boltzmann constant, and $\xi_0 = 0.18\hbar v^*/kT_c$. The above expressions are written for a tight-binding superconductor, where $\tau^* = \tau(1+\lambda)$ and $v^* = v/(1+\lambda)$, with $\lambda$ being the electron–phonon coupling constant.

The effect of electron scattering from radiation defects on $H_{c2}$ was demonstrated in the case of the conventional superconductors NbC and $Nb_3Sn$ in [3, 5]. In the case where defects do not affect the electronic structure and $T_c$ noticeably, the variation of the $T_c/\langle v^{*2}\rangle$ factor (or the clean-base term) in Eq. (1) is relatively small. The increase in $H_{c2}$ is caused by the growth of $\lambda_{\mathrm{tr}}$, which is a result of the decrease in the mean free path.

We note that scattering from normal impurities and defects in conventional superconductors does not affect the critical temperature (Anderson's theorem) [13]. The variation in $T_c$ is connected in this case with a variation in the electronic characteristics.

Unlike $T_c$ of conventional superconductors, the critical temperature of high-temperature cuprates is sensitive to scattering. This is connected with the odd $d$-wave symmetry of the order parameter [14], which has been revealed in both hole and electronic HTSCs [15, 16]. Estimates made for a fairly pure superconductor with an odd order parameter suggest that the critical temperature in the case of scattering from defects can be written as $T_c = T_{c0}(1 - \pi\hbar/(2kT_{c0}\tau))$ [17]. Here, $T_{c0}$ is the critical temperature in the absence of scattering and $\hbar/(\pi k T_{c0}\tau) \ll 1$. In view of Eq. (2), we can recast this as $T_c = T_{c0}/(1 + \pi^2\lambda_{\mathrm{tr}})$.

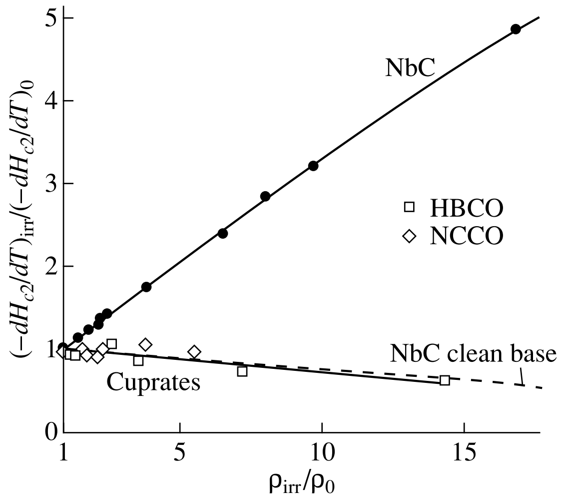

**Fig. 2.** Reduced slope $(-dH_{c2}/dT)_{\mathrm{irr}}/(-dH_{c2}/dT)_0$ plotted vs. reduced electrical resistivity $\rho_{\mathrm{irr}}/\rho_0$ for NbC, HBCO, and NCCO films irradiated by $He^+$ ions. $(-dH_{c2}/dT)_0$ and $\rho_0$ are the characteristics of the original sample. The dashed line shows the variation of the clean-base term for NbC.

Thus, the scattering-induced decrease in the critical temperature of a $d$-wave superconductor lowers the upper critical magnetic field rapidly, so that the factor $(1 + \lambda_{\mathrm{tr}})$ in Eq. (1) can be neglected. As a result, the scattering-induced variation of the slope $-dH_{c2}/dT$ for a $d$-wave superconductor can be qualitatively described by the expression

$$-dH_{c2}/dT \sim \frac{T_c}{\langle v^{*2}\rangle} \sim \frac{T_{c0}}{\langle v^{*2}\rangle(1+\pi^2\lambda_{\mathrm{tr}})}. \tag{3}$$

Equation (3) shows that the variation of the slope $-dH_{c2}/dT$ for a $d$-wave superconductor is determined by the ratio $T_c/\langle v^{*2}\rangle$ in both cases of variation of the electronic characteristics and changes in scattering.

This accounts qualitatively for the observed character of variation of the upper critical magnetic field of cuprate HTSCs with decreasing electron mean free path.

HTSC irradiation changes not only the mean free path but also the conduction electron concentration $N$. The relation

$$\rho = \frac{mv}{Ne^2 l} \tag{4}$$

($m$ and $e$ are the effective mass and charge of an electron, respectively) shows that the electrical resistivity $\rho$ can grow both as a result of a decrease in the mean free path caused by radiation defects and through a change in the electronic characteristics.

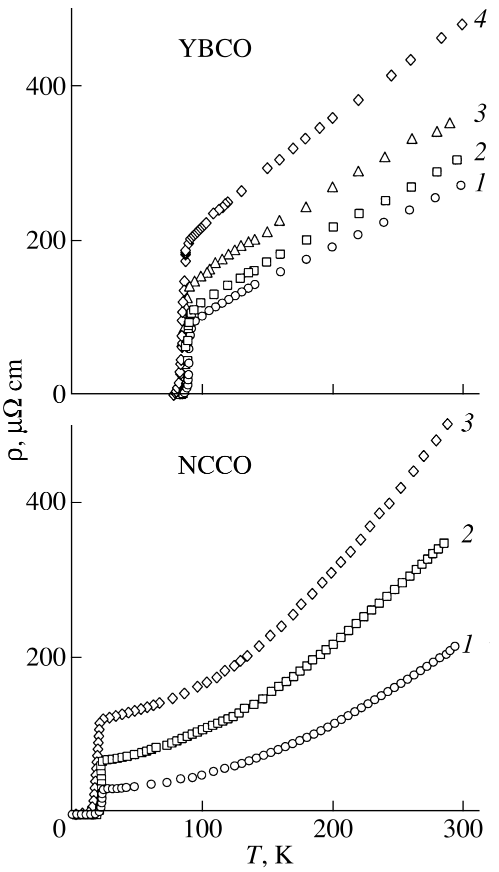

**Fig. 3.** Temperature dependences of the electrical resistivity of epitaxial films of high-temperature superconductors irradiated by He$^+$ ions to various doses $F$ equal to (a) (*1*) 0, (*2*) $6 \times 10^{14}$, (*3*) $1.6 \times 10^{15}$, and (*4*) $2.6 \times 10^{15}$ cm$^{-2}$; and (b) (*1*) 0, (*2*) $1 \times 10^{13}$, and (*3*) $1 \times 10^{14}$ cm$^{-2}$.

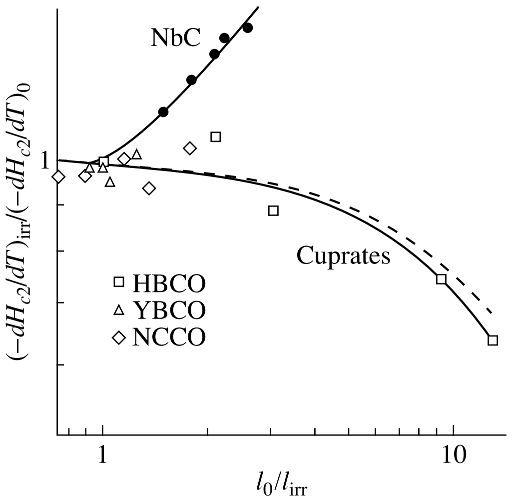

**Fig. 4.** Variation of reduced slope $-dH_{c2}/dT$ with increasing reduced reciprocal mean free path of electrons $l_0/l_{\rm irr}$ measured for epitaxial films of the high-temperature cuprate superconductors HBCO, YBCO, and NCCO irradiated by He$^+$ ions. $(-dH_{c2}/dT)_0$ and $l_0$ are the characteristics of the original sample. Shown for comparison are data for the conventional superconductor NbC; dashed line is the clean-base term.

Irradiation of cuprates brings about not only a growth of the residual resistivity associated with defects but also an increase in the slope $d\rho/dT$ of the temperature dependence of the electrical resistivity $\rho(T)$ (Fig. 3). The temperature dependence of $\rho$ is determined by that of the mean free path. If $\rho(T)$ follows a linear dependence, the slope $d\rho/dT$ can be considered as a measure of the variation of the quantity $mv/N$ under irradiation. The ratio of $d\rho/dT$ to the resistivity $\rho_n$ close to $T_c$ varies in proportion to the electron mean free path under irradiation:

$$\frac{1}{\rho_n}\frac{d\rho}{dT} \sim l. \tag{5}$$

This permits one to estimate the irradiation-induced variation in $l$ and $mv/N$ from data on the temperature dependence of $\rho(T)$.

The irradiation-induced variation of $mv/N$ and of the electron mean free path $l$ near $T_c$ was directly estimated for YBCO (Fig. 3) and HBCO [5], as well as for NbC, which feature a close-to-linear dependence of the electrical resistivity on temperature. In the case of NCCO, for which the $\rho(T)$ dependence is nonlinear, qualitative estimates were obtained.

It was shown that irradiation of YBCO, HBCO, and NCCO brings about a noticeable decrease in the electron mean free path in these HTSCs. Unlike conventional superconductors, however, the slope $-dH_{c2}/dT$ was not found to increase.

The decrease in the upper critical magnetic field observed in HBCO may be due to a strong effect of scattering on the critical temperature of the $d$-wave superconductor. The small coherence length of hole HTSCs, $\xi(0) \sim 20$ Å, makes realization of the pure-superconductor approximation $\lambda_{\rm tr} \ll 1$ possible, where Eq. (3) becomes valid.

At the same time, estimates made for YBCO and HBCO for low irradiation doses and for zinc substituting for copper [18] showed that the relative variation of $mv/N$ is comparable to that of $1/l$ or exceeds it. The dependence of $H_{c2}$ on electronic characteristics may turn out to be substantial in this case. In particular, a decrease in the conduction electron concentration may result in a fast decrease in $T_{c0}$ in Eq. (3) as the Fermi level passes through the singularity in the density of states [17]. In all cases, hole HTSCs exhibit a common pattern of $H_{c2}$ variation; namely, the slope $-dH_{c2}/dT$ decreases approximately in proportion to the critical temperature (Fig. 5). One may think that the variation of the quantity $T_c/\langle v^{*2}\rangle$ for these superconductors is determined by that of $T_c$.

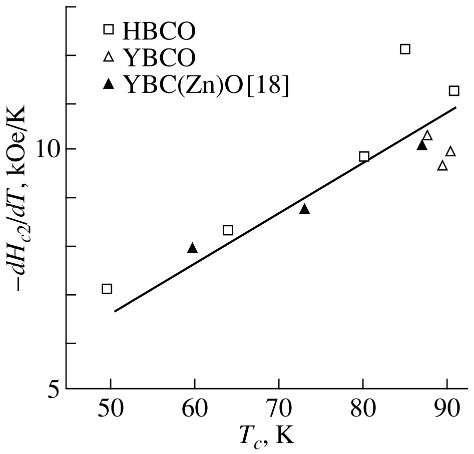

**Fig. 5.** Slope $-dH_{c2}/dT$ plotted vs. critical temperature $T_c$ for epitaxial films of the hole high-temperature superconductors HBCO and YBCO irradiated by helium ions and of zinc-doped YBCO [18].

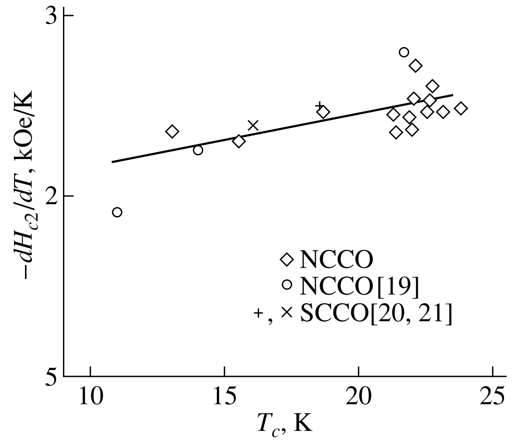

**Fig. 6.** Slope $-dH_{c2}/dT$ plotted vs. critical temperature $T_c$ for electronic high-temperature superconductors, namely, for NCCO epitaxial films irradiated by helium ions, with different Nd/Ce contents and with different oxygen composition [19], as well as for SmCeCuO [20, 21].

Electronic high-$T_c$ superconductors NCCO and SmCeCuO (SCCO) exhibit a weak tendency to a decrease in the slope $-dH_{c2}/dT$ with decreasing critical temperature as a result of irradiation or a change in the oxygen content [19] and in the rare-earth content ratio (Fig. 6). The values of the critical field near $T_c$ (and of the slope $-dH_{c2}/dT$) obtained for these compounds practically coincide [20, 21]. It is not possible to enhance scattering considerably in these cuprates using irradiation (Fig. 4). Even very low irradiation doses bring about a decrease in the critical temperature, because these compounds are superconducting within a very narrow oxygen content interval. The quantity $m\nu/N$ also exhibits a noticeable variation. A decrease in the conduction electron concentration (a change in the Fermi level) can cause a decrease not only in $T_c$ but also in $\nu^*$. Therefore, the observation of a small irradiation-induced decrease in the slope $-dH_{c2}/dT$ for electronic superconductors may be assigned to features in the electronic structure which govern the variation of the quantity $T_c/\langle \nu^{*2} \rangle$.

## 4. CONCLUSION

Thus, it has been shown that the absence of growth of the upper critical magnetic field in hole and electronic HTSCs observed to occur with decreasing electron mean free path under irradiation by energetic ions may be accounted for by the *d*-wave symmetry of the order parameter. The change in the conduction electron concentration caused by radiation-induced defects should play a substantial role in the variation of the upper critical magnetic field. Under variation of the electronic characteristics, the quantity $H_{c2}$ behaves qualitatively similar to the clean-base term in the expression for the upper critical magnetic field of a conventional superconductor.

## ACKNOWLEDGMENTS

The support of the Russian Scientific Council on Research and Development, "Topical Problems in the Physics of Condensed Media" ("Superconductivity" project no. 98027), is gratefully acknowledged.

## REFERENCES

1. S. I. Krasnosvobodtsev, N. P. Shabanova, V. S. Nozdrin, and A. I. Golovashkin, Fiz. Tverd. Tela (St. Petersburg) **41**, 1372 (1999) [Phys. Solid State **41**, 1256 (1999)].
2. J. Y. Lin, S. J. Chen, S. Y. Chen, *et al.*, Phys. Rev. B **59**, 6047 (1999).
3. S. I. Krasnosvobodtsev, N. P. Shabanova, E. V. Ekimov, *et al.*, Zh. Éksp. Teor. Fiz. **108**, 970 (1995) [JETP **81**, 534 (1995)].
4. N. P. Shabanova, S. I. Krasnosvobodtsev, V. S. Nozdrin, *et al.*, Czech. J. Phys. **46**, 853 (1996).
5. N. P. Shabanova, S. I. Krasnosvobodtsev, V. S. Nozdrin, and A. I. Golovashkin, Fiz. Tverd. Tela (St. Petersburg) **38**, 1969 (1996) [Phys. Solid State **38**, 1085 (1996)].
6. A. I. Golovashkin, E. V. Ekimov, S. I. Krasnosvobodtsev, *et al.*, Physica C (Amsterdam) **162–164**, 715 (1989).
7. V. S. Nozdrin, S. I. Krasnosvobodtsev, O. M. Ivanenko, *et al.*, Pis'ma Zh. Tekh. Fiz. **22** (24), 1 (1996) [Tech. Phys. Lett. **22**, 996 (1996)].
8. N. P. Shabanova, V. S. Nozdrin, S. I. Krasnosvobodtsev, *et al.*, Kratk. Soobshch. Fiz., No. 12, 35 (1999).
9. L. P. Gor'kov and T. K. Melik-Barkhudarov, Zh. Éksp. Teor. Fiz. **45**, 1493 (1963) [Sov. Phys. Tech. Phys. **18**, 1031 (1964)].

10. B. J. Dalrymple and D. E. Prober, J. Low Temp. Phys. **56**, 545 (1984).
11. L. P. Gor'kov, Zh. Éksp. Teor. Fiz. **37**, 1407 (1959) [Sov. Phys. JETP **10**, 998 (1960)].
12. N. R. Werthamer, in *Superconductivity,* Ed. by R. D. Parks (Marcel Dekker, New York, 1969), Vol. 1, p. 321.
13. P. W. Anderson, J. Phys. Chem. Solids **11**, 26 (1959).
14. H. Won and K. Maki, Physica C (Amsterdam) **282–287**, 1837 (1997).
15. C. C. Tsuei, J. R. Kirtley, C. C. Chi, *et al.*, Phys. Rev. Lett. **73**, 593 (1994).
16. C. C. Tsuei and J. R. Kirtley, Phys. Rev. Lett. **85**, 182 (2000).
17. A. A. Abrikosov, Int. J. Mod. Phys. B **13**, 3405 (1999).
18. J. Schroeder, M. Ye, J. F. Marneffe, *et al.*, Physica C (Amsterdam) **278**, 113 (1997).
19. J. Herrmann, M. C. Andrade, C. C. Almasan, *et al.*, Phys. Rev. B **54**, 3610 (1996).
20. M. C. Andrade, C. C. Almasan, Y. Dalichaouch, and M. B. Maple, Physica C (Amsterdam) **184**, 378 (1991).
21. M. A. Crusellas, J. Fontcuberta, and S. Pinol, Phys. Rev. B **48**, 4223 (1993).

*Translated by G. Skrebtsov*

SPELL: unsuccessfull