Superconductivity in clean and disordered nonmagnetic borocarbides

S.-L. Drechsler a, H. Rosner a, S.V. Shulga a *, H. Eschrig a, J. Freudenberger a, G. Fuchs a, K. Nenkov a †, K.-H. Müller b, D. Lipp b, A. Gladun b, A. Kreyssig b, K. Koeppen c, P. Gegenwart c, T. Cichorek c

aInstitut f. Festkörper- und Werkstofforschung Dresden, P.O. Box 270016, D-01171 Dresden, Germany
bTechnische Universität Dresden, D-01062 Dresden, Germany
cMax-Planck-Institut f. Chemische Physik fester Stoffe, D-01187 Dresden, Germany

The effect of weak substitutional disorder in the rare-earth intermediate layer in between the NiB-networks upon various thermodynamic properties in the superconducting state of $Y_xLu_{1-x}C(NiB)_2$ is investigated theoretically as well as experimentally. The suppression of the upper critical field and its positive curvature near $T_c$ are shown to be a highly sensitive measure of small amounts of disorder even at the rare-earth site.

Keywords: Transition metal borocarbides, Electronic structure, Disorder, Superconductivity

1. INTRODUCTION

The anomalous disorder dependence of several thermodynamic properties in the superconducting state, e.g. $B_{c2}(T)$, $\alpha$ and to less extent also $T_c$ in contrast to $B_{c1}$ and normal state resistivity seems to be a generic feature of rare-earth transition metal borocarbides (nitrides) (RTBC(N)). In the electronic sense RTBC(N) can be divided into two subsystems: the (TB)$_2$-C(2p$_z$) network and the remaining R-C(2p$_z$) layer. Since the position of the Fermi Energy $E_F$ within the sharply peaked density of states (DOS) is strongly affected by nonisoelectronic substitutions, the isoionic substitutions at the R-site can be considered as a convenient tool to study the effect of disorder with tiny shift of $E_F$.

2. EXPERIMENT

With the above aim the thermodynamic properties of polycrystalline mixed $Y_xLu_{1-x}C(NiB)_2$ systems have been investigated as a function of $x$ (Fig. 1). The critical temperature $T_c$ and the upper critical field $B_{c2}$ are somewhat suppressed from both end values of $x$. The largest suppres-

Figure 1. Composition dependence of the critical temperature (a) the extrapolated upper critical field $B_{c2}^*$ at zero temperature (b) and its exponent $\alpha$ measuring the positive curvature near $T_c$ (c). The range is near $x \approx 0.5$ to 0.6. This is in sharp contrast to the predictions of a phenomenological analysis [1] where for an optimal Ni-Ni distance realized in our samples near $x = 0.6$ [2], a maximum of $T_c \approx 17$ K has been predicted. In addition, several peculiarities such as the positive curvature of $B_{c2}(T)$ near $T_c$

$$B_{c2}(T) = B_{c2}^* \left(1 - \frac{T}{T_c}\right)^{1+\alpha}, 0.3 < \frac{T}{T_c} \leq 0.98$$ (1)

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*On leave from: Institute of Spectroscopy, RAS, Russia
†On leave from: Int. Lab. High Magnetic Fields, Wroclaw, Poland and ISSP-BAS, Sofia, Bulgaria
as well as the nonlinear field dependence of the electronic specific heat $c_p$ in the mixed state

$$c_p \propto TB^{1-\beta},$$

are weakened by the disorder but are yet clearly visible for all $x$ in contrast to the case of a 20% substitution for Ni by Pt [3] where $\alpha=\beta=0$. For our samples, including also single crystals, $\alpha \leq 0.45$ holds and it provides a more sensitive measure of the disorder than $\beta \leq 0.67$ does.

3. THEORY AND DISCUSSION

The unusual positive curvature and the absolute value of the upper critical field of high quality pure single crystals can be well explained within the effective two-band model[4]. Using the parameter set given in Ref. 4 supplemented with an increasing impurity scattering rates $\gamma = \gamma_{ab} = \gamma_b = 2\gamma_a = 2\gamma_{ba}$, the suppression of $B_{c2}(T)$ and of $\alpha$ can be reproduced (Fig. 2). Comparing the calculated $N(0)$ values with the measured Sommerfeld constants $\gamma_a \propto N(0)(1 + \lambda)$, we arrive at total electron-phonon coupling constants $\lambda = 1.05$ and 1.1 for $x = 1$ and $x = 0$, respectively.

Our band structure calculations performed in the coherent potential approximation for the mixed $Y_xLu_{1-x}C(NiB)_2$ systems at the experimental values of the lattice constants [2] predict only a weak dependence of the total DOS upon $x$. The calculated maximal relative suppression of $N(0)$ near $x = 0.6$ is about 15%. Admitting an additional suppression of $N(0)$ of the same order due to local lattice distortions caused by the different ionic radii, the experimentally found [5] suppression of the Sommerfeld constant $\gamma_s(x) \propto T_c(x)$ can be reproduced only, if a sizeable ($\sim 10\%$) suppression of the coupling constant $\lambda(x)$ is assumed. We attribute this effect to indirect disorder effects such as hardening of the soft phonon frequencies near 4 and 7 meV which are closely related to the nested parts of the Fermi surface [6]. The anomalous suppression of $H_{c2}$ in the quasi-clean limit with increasing disorder can be explained by a combination of direct and indirect effects.

To summarize, isoelectronic substitutions at the R-site cause relatively weak disorder effects compared with those at the T-site. The anoma-

Figure 2. Upper critical field $B_{c2}$ vs. temperature $T$ within the two-band model for various degrees of disorder given by the impurity scattering rate $\gamma$ (in cm$^{-1}$). Inset: the same in relative units.

lous disorder effects near the clean limit can be described within the effective two-band model.

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REFERENCES

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