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 [a], D. Lipp[b], A. Gladun[b], A. Kreyssig [b], K. Koepernik[c], P. Gegenwart[c], T. Cichorek [c]

[a]Institut f. Festkörper- und Werkstofforschung Dresden, P.O. Box 270016, D-01171 Dresden, Germany

[b]Technische Universität Dresden, D-01062 Dresden, Germany

[c]Max-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. $B_{c2}(T)$, $c_p(B)$ 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-$C(2p_{x,y})$ 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 isoelectronic 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 suppression 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

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

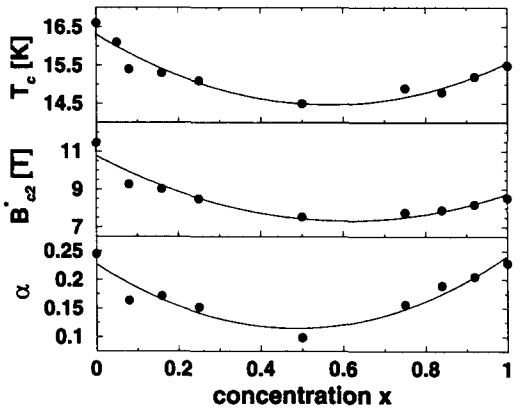

Figure 1. Composition dependence of the critical temperature (a) the extrapolated upper critical field B^*_{c2} at zero temperature (b) and its exponent α measuring the positive curvature near T_c (c).

*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

$$c_p \propto TB^{1-\beta}, \quad (2)$$

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 α=β=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 α can be reproduced (Fig. 2). Comparing the calculated $N(0)$ values with the measured Sommerfeld constants $\gamma_s \propto N(0)(1+\lambda)$, we arrive at total electron-phonon coupling constants λ=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 1.5%. 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 anomalous disorder effects near the clean limit can be described within the effective two-band model.

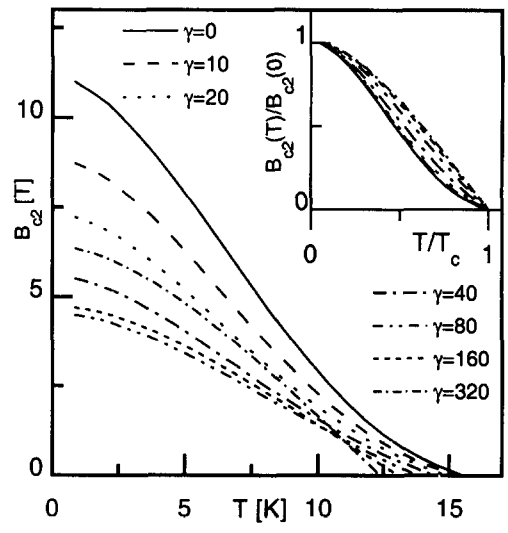

Figure 2. Upper critical field B_{c2} vs. temperature T within the two-band model for various degrees of disorder given by the impurity scattering rate γ (in cm^{-1}). Inset: the same in relative units.

The SFB 463 and the DFG are gratefully acknowledged for financial support.

REFERENCES

1. C. Lai, M. Lin, Y. You, and H. Ku , Phys. Rev. B 51 (1995) 420.
2. J. Freudenberger, S.-L. Drechsler, G. Fuchs, A. Kreyssig, K. Nenkov, S. Shulga, K. Müller, and L. Schultz, Physica C 306 (1998) 1.
3. M. Nohara, M. Isshiki, F. Sakai, H. Takagi, J. Phys. Soc. Jpn. 68 (1999) 1078.
4. S. Shulga, S.-L. Drechsler, G. Fuchs, K. Müller, K. Winzer,M. Heinecke, and K. Krug, Phys. Rev. Lett. 80 (1998) 1730.
5. H. Michor, private communication
6. S.-L. Drechsler, S. Shulga, K. Müller, G. Fuchs, J. Freudenberger, G. Behr, H. Eschrig, L. Schultz, M. Golden, H. von Lips, J. Fink, V. Narozhnyi, H. Rosner, P. Zahn, A. Gladun, D. Lipp, A. Kreyssig, M. Loewenhaupt, K. Koepernik, K. Winzer, K. Krug, Physica C 317-318 (1999) 117.