Superconductivity in intermetallic compound Mo$_7$Re$_{13}$X(X = B, C)

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Abstract

We report here the physical properties of a new intermetallic superconductor Mo$_7$Re$_{13}$X(X = B, C) ($T_c = 8.3$ K (X = B) and 8.1 K (X = C)). The crystal structure of Mo$_7$Re$_{13}$X is the β-Mn-type (cubic, space group: P4$_1$32) and the Re atoms form a tilted octahedron. The magnetization ($M$–$H$) curves show a typical type-II superconductivity; the lower critical field $H_{c1}(0)$, upper critical field $H_{c2}(0)$ and Ginzburg–Landau (GL) parameter value $k_B$ are, respectively, 3.0 Oe, 15.4 T and 101 for X = B and 3.1 Oe, 14.8 T and 98 for X = C. The superconducting gap versus $k_B T_c$ values are 4.4 for X = B and 4.2 for X = C, which implies that superconductivity in Mo$_7$Re$_{13}$X(X = B,C) can be described by an s-wave strong coupling regime.

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1. Introduction

Discovery of high-$T_c$ superconductivity in MgB$_2$ at 39 K [1] has sparked renewed interest in searching for a new superconductor in intermetallic compounds. We have developed new superconductors in transition metals-boron and/or carbon systems. Intermetallic superconductors including light elements have a comparatively high $T_c$ because of the presence of high-frequency phonons due to light elements [2,3]. We have succeeded in discovering superconductivity in W$_7$Re$_{13}$X(X = B, C) at 7.2 K for X = B and 7.3 K for X = C [4]. W$_7$Re$_{13}$X(X = B, C) has a β-Mn-type structure (cubic, space group: P4$_1$32) and the sites are occupied by W and Re atoms which form tilted octahedra [5,6] (Fig. 1).

In the framework of BCS theory, a higher density of states near $E_F$ and lighter elements resulting in higher frequency phonon modes enhanced transition temperature [7,8]. In this sense, we searched for a higher $T_c$ superconductor by substituting the other transition metals at W and Re sites and III b and IV b elements at light element sites and successfully synthesized Mo$_7$Re$_{13}$X(X = B, C). In this paper, we report the superconducting properties of Mo$_7$Re$_{13}$X(X = B, C).

2. Experimental details

Samples were prepared from appropriate mixtures of powdered Mo (99.9%), Re (99.99%) and amorphous B (99.5%) or C (99.95%) and synthesized by arc melting in Ar atmosphere. Powder X-ray diffraction data were obtained using a conventional X-ray spectrometer (RAD-C; RIGAKU) with Cu Kα1. Magnetic susceptibilities were collected using a Superconducting QUantum Interference Device (SQUID) magnetometer (MPMSR2: Quantum Design Co., Ltd.). Electrical resistivities were measured by a conventional four-probe d.c. method (PPMS: Quantum Design Co., Ltd.). Magnetization versus magnetic field ($M$–$H$) curves were obtained and heat capacity measurements were performed by PPMS (Quantum Design Co., Ltd.).

3. Experimental results and discussion

Fig. 2 shows the powder X-ray diffraction patterns of Mo$_7$Re$_{13}$X(X = B, C). The diffraction peaks were successfully indexed for a β-Mn-type structure (space group: P4$_1$32). We could not synthesize β-Mn-type samples without light elements. B or C presumably plays an important role in stabilizing the β-Mn-type crystal structure of Mo$_7$Re$_{13}$X(X = B, C), which is the same as in W$_7$Re$_{13}$X(X = B, C).

The temperature dependence of magnetic susceptibilities upon field cooling process is shown in Fig. 3 under a magnetic field of 10 Oe. Marked decreases in magnetic susceptibility were clearly observed at 8.3 K in Mo$_7$Re$_{13}$B and at 8.1 K...
in Mo$_7$Re$_{13}$C. Fig. 4 shows the temperature dependence of electrical resistivity. Electrical resistivities clearly decreased at 8.5 K (X = Z$_B$) and 8.3 K (X = Z$_C$) and reached to zero at 8.2 K (X = Z$_B$) and 8.0 K (X = Z$_C$). We determined that the $T_c$ values of Mo$_7$Re$_{13}$B and Mo$_7$Re$_{13}$C are 8.3 and 8.1 K, respectively.

As displayed in Fig. 5, $M$–$H$ curves show typical type-II superconducting behavior. From the data in Fig. 5, the $H_{c1}$ values were determined at the cross point between magnetic field virgin curve and the $(M_{up}+M_{down})/2$ curve, which were 30 Oe for X = B and 31 Oe for X = C. We also calculated that the penetration depths: $\lambda$ are 4700 Å (X = B) and 4600 Å (X = C) using $\mu_0H_{c1}\sim\phi_0/\lambda^2$, where $\mu_0$ denotes the magnetic permeability in vacuum and $\phi_0$ denotes the quantum flux. $H_{c2}(T)$ values were determined from the onset temperature at various applied magnetic fields (Fig. 6). The data are linear between 0 and 8 T with slopes ($-dH_{c2}(T)/dT = -2.68 T/K$ (X = B) and $-2.65 T/K$ (X = C). These slopes can be used to estimate $H_{c2}(0)$ value ($H_{c2}(0) \approx 0.69 \times (-dH_{c2}(T)/dT \times T_c)$) in dirty limit type-II superconductors [9,10], which is 15.4 T.
The coherence length $\xi$ is determined to be 46 Å (X = B) and 47 Å (X = C) using $\mu_0H_{c2} \sim \phi_0/2\pi\xi^2$. The Ginzburg–Landau parameter value $\kappa$ is consequently 101 for X = B and 98 for X = C.

The temperature dependence of electronic heat capacity revealed a jump near $T_c$ in the $C_{el}$ versus $T$ plot (Fig. 7). $C_{el}$ below $T_c$ can be fitted to $\exp(-\Delta_0/k_BT_c)$-dependence, from which the $2\Delta_0/k_BT_c$ values are estimated to be 4.4 (X = B) and 4.2 (X = C). These values are larger than the 3.5 obtained from BCS theory. We conclude that Mo$_7$Re$_{13}$X(X = B,C) can be described by an s-wave strong coupling regime.

In the W$_7$Re$_{13}$X(X = B,C) superconductor, light elements play an important role in stabilizing the $\beta$-Mn-type structure and have a small contribution to the superconducting state. The light element in Mo$_7$Re$_{13}$X(X = B,C) functions the same as that of W$_7$Re$_{13}$X(X = B,C).

4. Summary
In this study, we succeeded in synthesizing the superconductor Mo$_7$Re$_{13}$X(X = B,C) and presented its superconducting properties. The physical properties of Mo$_7$Re$_{13}$X(X = B,C) are summarized in Table 1.

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