Itinerant metamagnetic properties of MnSi under high pressures

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Abstract

The magnetization of MnSi was measured under high pressures up to 1.7 GPa and high magnetic fields up to 9 T. The magnetic transition at T_C is second-order for $P < 1.2$ GPa and first order for 1.2 GPa $< P <$ 1.54 GPa. The magnetic ordering vanishes for $P >$ 1.54 GPa. An itinerant metamagnetic transition is observed in the two higher pressure regions. The B-T phase diagrams determined in the three regions are different from each other.

Key words: MnSi, pressure effect, itinerant electron metamagnetism, magnetic phase diagram

A B20-type compound MnSi is an itinerant electron ferromagnet with a Curie temperature of T_C =29 K and has an ordered magnetic moment of 0.4 μ_B on each Mn atom. The spin structure becomes a helical one with long period along the ⟨111⟩ direction due to the Dzyaloshinsky-Moriya interaction [1]. When the magnetic field applied, the spin structure changes to a conical and then to an induced ferromagnetic one at $B \sim$ 0.6 T at ambient pressure [2]. The magnetic properties under high pressure have extensively been investigated in recent years [3,4]. By applying pressure, T_C shifts to the low temperature side. The transition at T_C is second order for $P < P_t = 1.2$ GPa and first order in the range $P_t < P < P_c$, where P_c (∼1.5 GPa) is the critical pressure for the disappearance of magnetism. Around P_c, the magnetic properties are very different from those at ambient pressure. Koyama et al. [5] found the itinerant metamagnetic transition (IMT) at $P =$ 1.5 GPa. According to a theory of IMT [6], three types of magnetic phase diagrams in the B-T plane are expected for MnSi under high pressure. In the present study, we precisely measured the magnetization at low temperatures down to 1.4 K under high pressures up to 1.7 GPa and magnetic fields up to 9 T to determine the magnetic phase diagram of MnSi.

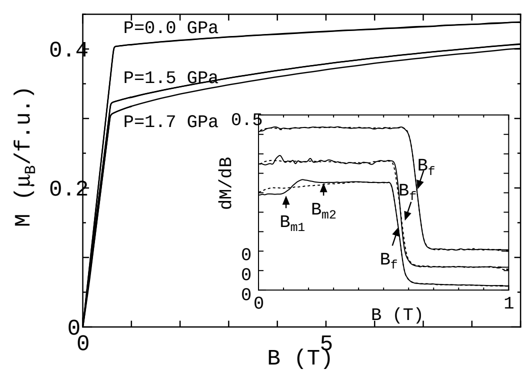

Fig. 1. Magnetization curves for 1.4 K at 0, 1.5 and 1.7 GPa. Inset shows the differential susceptibility curves. Solid and dotted curves indicate increasing and decreasing field processes.

A single crystal of MnSi was grown by a Czochralski method. The crystal was cut into a pillar shape for magnetization measurements. Magnetic fields were applied along the ⟨111⟩ direction. The magnetization was measured using an extraction-type magnetometer with a nonmagetic piston-cylinder cramp cell made of a CuTi alloy.

First we show in Fig. 1 the magnetization processes of MnSi for $T = 1.4$ K at 0, 1.5 and 1.7 GPa. The critical field B_f, at which the magnetic state changes from the conical to the induced ferromagnetic one, decreases

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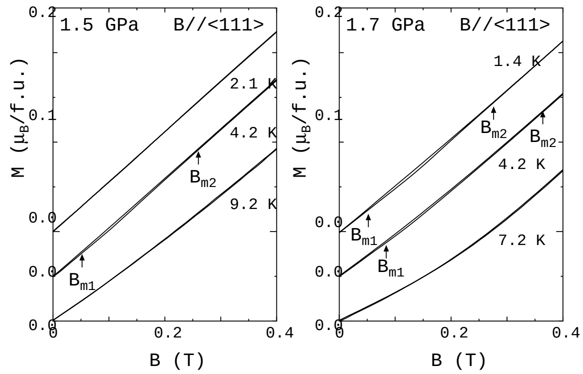

Fig. 2. Magnetization curves of MnSi for several temperatures at 1.5 and 1.7 GPa.

with increasing pressure together with the magnetization at B_f. On the other, the high field susceptibility increases with pressure. At $P = 1.7$ GPa, a hysteresis is observed in low fields below 0.3 T. In the inset, the differential susceptibility (dM/dB) curve is shown. The hysteresis can be seen clearly only for the curve at 1.7 GPa. For $B < B_{m1}$, MnSi shows paramagentic behavior. The magnetization rapidly increases in increasing fields between B_{m1} and B_{m2}. The magnetic structure may be conical for $B_{m2} < B < B_f$ and the induced ferromagnetic state is stabilized for $B > B_f$.

Fig. 2 shows the magnetization processes for several temperatures at 1.5 and 1.7 GPa. The hysteresis at 1.7 GPa becomes narrow as the temperature increases and completely vanishes at 7.2 K. In the case of 1.5 GPa, the magnetic ordering exists and there is no hysteresis below $T_C = 3.2$ K. However, the hysteresis appears at 4.2 K and disappears again at 9.2 K. This indicates that IMT occurs in MnSi just above T_C and the hysteresis becomes narrow as the temperature increases.

We found three types of magnetic phase diagrams as shown in Fig. 3. The critical fields, B_{m1}, B_{m2} and B_f, are determined from the differential susceptibility curves measured in increasing field processes. The open squares denote the phase boundary between the magnetically ordered and the paramagnetic region, which were determined by the temperature dependence of the magnetization at various fields. In the pressure region $P < P_t$, the ground state is magnetic with a helical structure and the transition at T_C is second order. By applying magnetic fields, this state changes to a conical one and subsequently an induced ferromagnetic state is stabilized at $B \sim 0.6$ T. There is no IMT. In the region $P_t < P < P_c$, the ground state is also a helical one, but the transition at T_C is first order. When the magnetic field is applied just above T_C, the paramagnetic state changes abruptly to a conical one via the transition region $B_{m1} < B < B_{m2}$. This phenomenon is considered as IMT [6]. In the region $P > P_c$, the magnetic ordering disappears and the ground state is paramagnetic. The IMT is observed in this region.

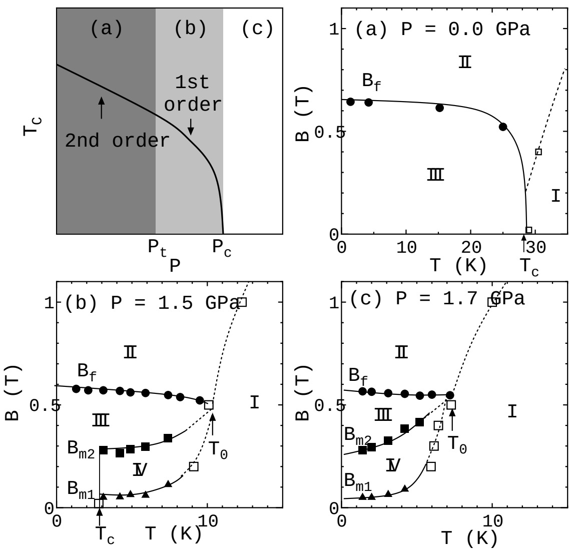

Fig. 3. Schematic pressure dependence of T_C and magnetic phase diagrams for $P < P_t$ (a), $P_t < P < P_c$ (b) and $P > P_c$ (c). Regions I, II, III and IV are paramagnetic, induced ferromagnetic, conical and metamagnetic transition ones, respectively.

It should be noted that the type of the transition at T_C is different in the pressure regions $P < P_t$ and $P_t < P < P_c$ and IMT appears in $P_t < P$. With increasing temperature, the critical fields B_{m1} and B_{m2} increase and the hysteresis becomes narrow. The IMT vanishes at a temperature T_0 and T_0 decreases with increasing pressure. These characteristics are observed also in other itinerant electron metamagnets [6]. In the case of MnSi, three magnetically ordered states appear due to the Dzyaloshinsky-Moriya interaction. If this interaction does not exists, MnSi is considered as a typical ferromagnetic itinerant electron metamagnet.

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