# FERROMAGNETIC AND SPIN GLASS ORDERINGS IN AMORPHOUS Fe–Sb ALLOYS

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We have studied the magnetic properties of amorphous Fe–Sb alloys over a wide composition range with 1.4 K $\leq T \leq$ 400 K and 0 kG $\leq H \leq$ 50 kG. The magnetic phase diagram reveals ferromagnetic and spin glass phases as well as re-entrant transitions.

Various magnetic orderings have been observed in amorphous alloys [1]. The advantages of a wide composition range and similar short-range order make amorphous alloys good candidates in studying the evolution of magnetism in alloys. Structural disorder and dilution of the ferromagnetic species by a non-magnetic element induce local fluctuations in the magnetic ordering and the appearance of anti-ferromagnetic interactions. Competing ferro- and anti-ferromagnetic interactions as well as local random anisotropy can result in spin glass behavior. In this report we present magnetic properties of a newly fabricated system of amorphous $Fe_xSb_{100-x}$.

All the samples were deposited onto liquid-nitrogen cooled Kapton or Cu substrates by a high-rate sputtering system. X-ray diffraction confirmed the amorphicity of the samples with $3 \leq x \leq 80$. Magnetic measurements were performed by using a SQUID magnetometer within the temperature range of 1.4–400 K and field variation of 0–50 kG.

The field dependence of magnetization at 5 K of several Fe–Sb samples is shown in fig. 1. The magnetization can be easily saturated for samples with $x \geq 65$, indicating dominant ferromagnetic interactions in these samples. As the Fe concentration is reduced ($x \leq 60$), the approach to saturation becomes slower. This means that a non-collinear magnetic structure has developed, due to the gradual emergence of anti-ferromagnetic interactions and local random anistropy.

Spin glass and, more interestingly, re-entrant behavior have been observed in the composition range of $40 \leq x \leq 61$ as revealed by the temperature dependence of the magnetization under a small dc field of 30 G. Below $x = 54$ (fig. 2), a cusp at $T_f$ and the irreversible behavior below $T_f$ between the zero-field-cooled (ZFC) and field-cooled (FC) measurements are characteristics of spin glass ordering. In the range of $55 \leq x \leq 61$ there appears a double transition in the ZFC curve at temperatures $T_f$ and $T_c$ (fig. 2). Although the transition from para- to ferromagnetic phase is rather broad, we chose $T_c$ as the Curie temperature based on the kink-point

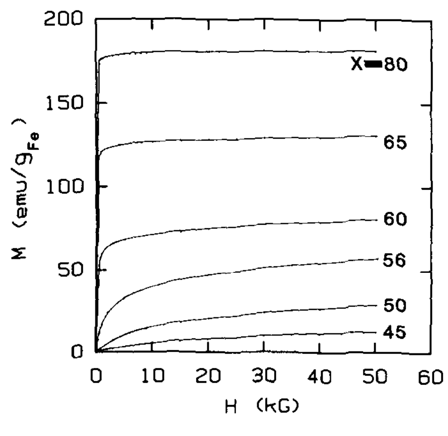


Fig. 1. Field dependence of the magnetization of Fe–Sb alloys at 5 K.

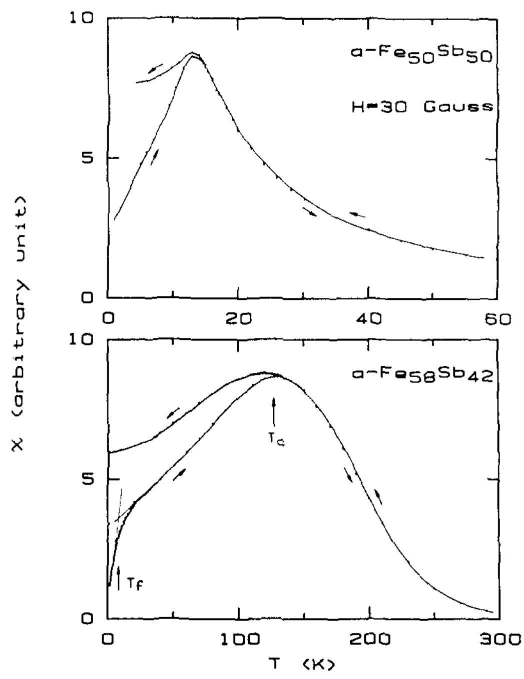


Fig. 2. Typical susceptibility versus temperature curves with a field of $H$ = 30 G. top: $Fe_{50}Sb_{50}$; bottom: $Fe_{58}Sb_{42}$.

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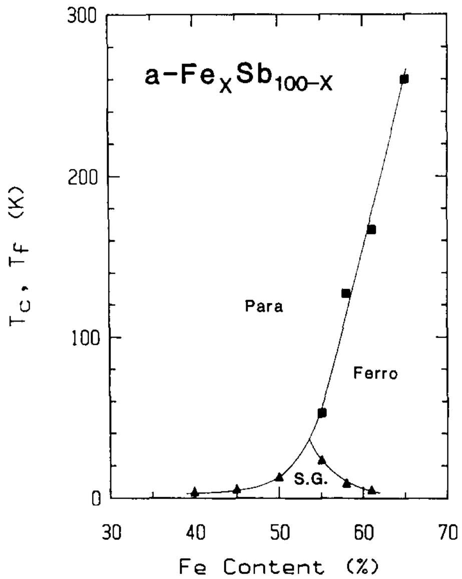


Fig. 3. Magnetic phase diagram of Fe–Sb alloys. $T_c$ (square): Curie temperature; $T_f$ (triangle): spin-freezing temperature.

method. $T_f$ is the transition temperature from ferromagnetic to spin glass ordering. One notes that the irreversibility in the FC curve sets in at temperatures higher than $T_f$. This is probably caused by the broadening of the spin glass transition, just like the broadening of the onset of the ferromagnetic ordering. Another and more fundamental reason is that between the ferromagnetic and spin glass phases there is a mixed phase with both ferromagnetic ordering and spin glass ordering as pointed out by Gabay and Toulouse [2].

Based on the low field magnetization measurements a magnetic phase diagram of the Fe–Sb system can be constructed as depicted in fig. 3. Similar phase diagrams have also been obtained in several other amorphous alloy systems such as Fe–Sn [3] and $(Fe–Ni)_{75}P_{16}B_6Al_3$ [4]. The phase diagram with re-entrant behavior is often claimed to be consistent with the prediction of the Sherrington–Kirkpatrick model [5]. That model, as indicated by Gabay and Toulouse, is deficient, because the re-entrant phase is a more complicated mixed phase as mentioned above.

In summary, a magnetic phase diagram is obtained for amorphous Fe–Sb alloys fabricated over a wide composition range. Samples with $x \geq 65$ exhibit primarily ferromagnetic ordering. In the intermediary range of $54 \leq x \leq 61$, magnetic re-entrant behavior is observed. As the Fe concentration is reduced further ($x = 54$), samples are spin-glass-like.

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