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Journal of Magnetism and Magnetic Materials 272–276 (2004) 1991–1992

journal of magnetism and magnetic materials

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Thermoelectric power and Shubnikov-de Haas effect in magnetic impurity-doped Bi_2Te_3 and Bi_2Se_3

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Abstract

Shubnikov-de Haas and Hall effect measurements were carried out on the diluted magnetic semiconductors p-$Bi_{2-x}Fe_xTe_3$ and n-$Bi_{2-x}Fe_xSe_3$. By increasing the Fe content, the hole concentration decreases in p-$Bi_{2-x}Fe_xTe_3$, while the electron concentration increases in n-$Bi_{2-x}Fe_xSe_3$. This demonstrates that iron atoms act as donors in both type of materials. The Seebeck coefficient α increases in p-$Bi_{2-x}Fe_xTe_3$ with increasing Fe content, while it decreases in n-$Bi_{2-x}Fe_xSe_3$.

PACS: 72.15.Jf; 75.50.−y

Keywords: $Bi_{2-x}Fe_xSe_3$; $Bi_{2-x}Fe_xTe_3$; Shubnikov-de Haas effect; Thermopower

Recent experiments have demonstrated that it is possible to grow single crystals of the novel Fe-doped diluted magnetic semiconductors p-Bi_2Te_3 and n-Bi_2Se_3. Concentrations of Fe with $x \leqslant 0.08$ in the formula $Bi_{2-x}Fe_xTe_3$ and $x \leqslant 0.06$ in the formula $Bi_{2-x}Fe_xSe_3$ have been achieved. In $Bi_{2-x}Fe_xTe_3$ ferromagnetism was found with the Curie temperature, T_C, increasing as a function of x up to $T_C = 12\,K$ for $x = 0.08$ [1,2]. The easy-axis for magnetization is the C_3 crystallographic axis. In n-type $Bi_{2-x}Fe_xSe_3$ samples ferromagnetism was not detected.

Here, we report Shubnikov-de Haas (SdH) and Hall effects measurements carried out in a long-pulse ($\sim 1\,s$) high-magnetic field installation ($B_{max} = 40\,T$) at $T = 4.2\,K$. In Fig. 1, we show the oscillating part of the transverse magnetoresistivity $\Delta\rho = \rho(B) - \rho(0)$ for p-$Bi_{2-x}Fe_xTe_3$ and n-$Bi_{2-x}Fe_xSe_3$ samples. There is a single frequency in n-$Bi_{2-x}Fe_xSe_3$ and first and second harmonics in p-$Bi_{2-x}Fe_xTe_3$. The second harmonic in SdH in p-$Bi_{2-x}Fe_xTe_3$ is due to spin-splitting (see Fig. 1).

The data show a decreasing hole concentration with increasing x for p-$Bi_{2-x}Fe_xTe_3$, and an increasing electron concentration with increasing x in n-$Bi_{2-x}Fe_xSe_3$. Thus the Fe atoms act as donors in both materials. From the Shubnikov-de Haas frequencies the hole concentration, p, the electron concentration, n, and the Fermi-energy E_F were evaluated (see Table 1). Our results indicate that, while in n-$Bi_{2-x}Fe_xSe_3$ the electron system is degenerate ($kT \ll E_F$), in p-$Bi_{2-x}Fe_xTe_3$ the hole system cannot be treated as completely degenerate, nor as completely non-degenerate at 300 K ($kT \approx E_F$).

Alloys $A_2^{V}B_3^{VI}$ have excellent room temperature thermoelectric properties and have served as the backbone of the thermoelectric cooling technology. As such, the influence of magnetic iron doping on their thermoelectric properties should be studied. We have measured the thermoelectric power α, in the temperature range $77\,K \leqslant T \leqslant 300\,K$ (see Fig. 2). At 300 K, α increases in $Bi_{2-x}Fe_xTe_3$ due to Fe doping while in $Bi_{2-x}Fe_xSe_3$ α decreases. The thermoelectric power shows an almost linear decrease with decreasing temperature in all samples. The thermopower α is given by

$$\alpha(T) = \frac{k_B}{e}\left(\frac{(2r+5)F_{r=3/2}(\eta)}{(2r+3)F_{r+1/2}(\eta)} - \eta\right), \quad (1)$$

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0304-8853/$ - see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/j.jmmm.2003.12.787

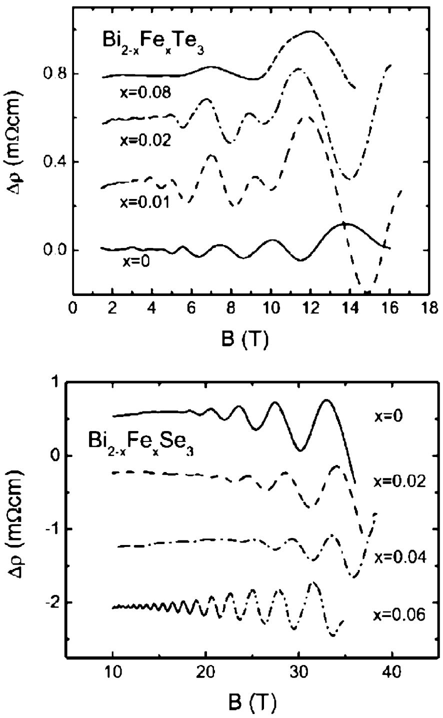

Fig. 1. Oscillations of the transverse magneto-resistivity for p-$Bi_{2-x}Fe_xTe_3$ and n-$Bi_{2-x}Fe_xSe_3$ at $T = 4.2\,K$.

Table 1
Frequency f of the SdH oscillations, the Fermi-energy E_F and the SdH hole p and electron n concentrations for p-$Bi_{2-x}Fe_xTe_3$ and n-$Bi_{2-x}Fe_xSe_3$

p-$Bi_{2-x}Fe_xTe_3$				n-$Bi_{2-x}Fe_xSe_3$			
x	f (T)	E_F (meV)	P_{SdH} ($10^{18}\,cm^{-3}$)	x	f (T)	E_F (meV)	n_{SdH} ($10^{18}\,cm^{-3}$)
0	26	37.8	7.5	0	150	145	1.9
0.01	23	33.5	6.3	0.02	162	156	2.1
0.04	18	26.4	4.4	0.04	218	208	3.7
0.08	11	16.7	2.2	0.06	242	233	5.1

where $\eta = E_F/k_BT$ is the reduced Fermi energy, $F_r(\eta) = \int[x^r/(e^{x-\eta}+1)]\,dx$ is the Fermi integral and r a parameter characterizing the scattering mechanism; $r = -\frac{1}{2}$ for acoustic phonon scattering, $\frac{1}{2}$ for polar optical scattering and $r = -\frac{3}{2}$ for ionized impurity scattering.

By fitting the data in Fig. 2 to Eq. (1), using E_F calculated from the SdH data, we have extracted the temperature dependence of r (see Fig. 3). The effective scattering parameter is not equal to $-\frac{1}{2}$ and depends on doping. We conclude that the change of α is mainly due to the change in carrier concentration in both type of samples.

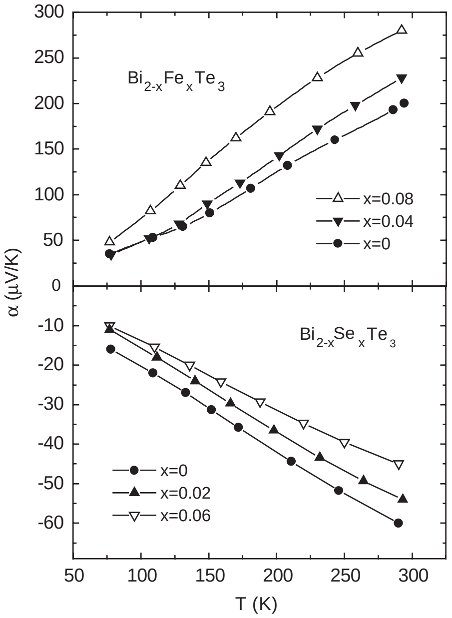

Fig. 2. Temperature variation of the thermopower of p-$Bi_{2-x}Fe_xTe_3$ and n-$Bi_{2-x}Fe_xSe_3$.

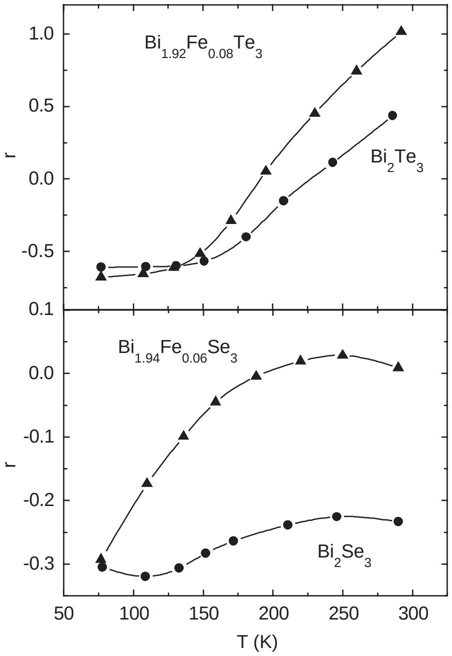

Fig. 3. Temperature dependence of the scattering parameter r for $Bi_{2-x}Fe_xTe_3$ and $Bi_{2-x}Fe_xSe$.

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