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MAGNETIC ANISOTROPY IN $Pb_{1-x-y}Sn_yMn_xTe$ STUDIED BY FERROMAGNETIC RESONANCE

P.J.T. EGGENKAMP, T. STORY*, C.H.W. SWÜSTE, H.J.M. SWAGTEN AND W.J.M. DE JONGE

Department of Physics, Eindhoven University of Technology (EUT)
PO Box 513, 5600 MB Eindhoven, The Netherlands

We will report on the anisotropy in (Pb)SnMnTe, studied by ferromagnetic resonance. We have found a cubic anisotropy with $a = 73 \times 10^{-4}$ cm^{-1} for $Sn_{1-x}Mn_xTe$ and $a = 200 \times 10^{-4}$ cm^{-1} for $Pb_{0.28-x}Sn_{0.72}Mn_xTe$. We will indicate some possible explanations for this anomalously large anisotropy.

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In the diluted magnetic semiconductor $Pb_{1-x-y}Sn_yMn_xTe$ a variety of magnetic phases has been observed at low temperatures [1, 2]. In order to investigate the nature of these phases, we started electron spin resonance experiments. From high temperature experiments we were able to determine the s–d exchange parameter in $Pb_{0.28-x}Sn_{0.72}Mn_xTe$ [3]. At low temperatures an anisotropic magnetic behaviour in the ferromagnetic phase was found [3, 4]. In this paper we report on the study of this anisotropy.

We have performed X-band spectroscopy on oriented single crystals of $Pb_{0.28-x}Sn_{0.72}Mn_xTe$ and $Sn_{1-x}Mn_xTe$ with x ranging from 0.01 to 0.04. The samples were grown using the Bridgman technique, and oriented using the Laue technique. Typical sample sizes are $5 \times 5 \times 0.3$ mm^3. After polishing the sample carefully, it was glued to the cavity wall using GE varnish. In this way the orientation of the sample was accurate within 5°. The external magnetic field was rotated with respect to the cavity. The sample was oriented in such a way that the magnetic field was always near a high symmetry plane of the crystal. The measurements were performed at temperatures between 1.3 and 4.2 K all below T_C (ferromagnetic resonance, FMR).

At all temperatures and field directions a single Dysonian line was observed, similar to the line shapes observed at higher temperatures [3]. The resonance field was obtained from a computer fit of the line. The rms deviation of this fit was typically of the order of 3%. Figure 1 shows the resonance field as a function of the direction of the magnetic field at various temperatures for $Pb_{0.26}Sn_{0.72}Mn_{0.02}Te$. The figure clearly demonstrates the effect of the anisotropy. The maximum shift

*Permanent address: Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warszawa, Poland.

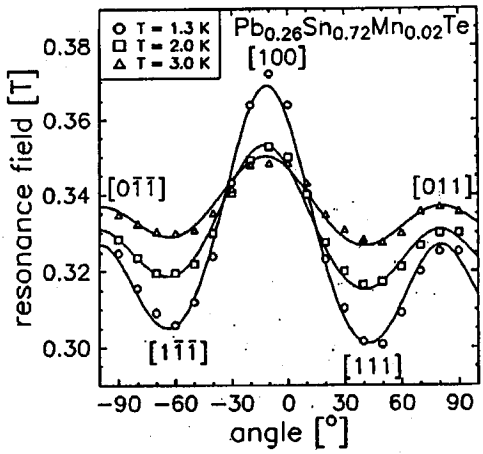

Fig. 1. Resonance field as a function of the direction of the external magnetic field at various temperatures for $Pb_{0.26}Sn_{0.72}Mn_{0.02}Te$. Symbols represent the measurements, full lines are the curves fitted with our model (see text).

of the resonance field is 72 mT. The shift decreases at higher temperatures. The resonance field is the highest in the [100] direction and the smallest in the [111] direction. This indicates a cubic symmetry of the anisotropy, with the $\langle 111 \rangle$ axes as the easy axes, and the $\langle 100 \rangle$ axes as the hard axes. Similar results were obtained in the other samples of $Pb_{0.28-x}Sn_{0.72}Mn_xTe$ and $Sn_{1-x}Mn_xTe$. The shift of the resonance field of $Sn_{1-x}Mn_xTe$ was less than that in $Pb_{0.28-x}Sn_{0.72}Mn_xTe$. In both cases the shift is independent of the manganese concentration.

In order to describe our results we will use the free energy density $F = F_m + F_a + F_d$, in which

$$F_m = -\mathbf{B} \cdot \mathbf{M}, \tag{1}$$

$$F_a = \frac{a}{6}\left(S_x^4 + S_y^4 + S_z^4\right) = K_1\left(\alpha_x^4 + \alpha_y^4 + \alpha_z^4\right), \tag{2}$$

$$F_d = \frac{1}{4}\left(3D_\perp - 1\right)M_\perp^2 = B_d M \alpha_\perp^2, \tag{3}$$

where α_i's are the direction cosines of the magnetisation, and K_1 is an effective anisotropy parameter. Both $\left(S_x^4 + S_y^4 + S_z^4\right)$ and M depend on temperature [5], which is reflected in a temperature dependence of K_1 and B_d. Demagnetisation had to be included in the model, because the magnetic field was turned from the sample plane to the sample's normal.

The values of K_1, B_d and the Landé factor g have been obtained by calculating the field for which the FMR resonance condition is fulfilled, and comparing this to our measurements (full curves in Fig. 1). In each case good agreement with the experimental data could be obtained. From these fits we obtained the values of the Landé factor g, the effective anisotropy parameter K_1, and the demagnetising field B_d at various temperatures. From the temperature dependence of these

parameters (as obtained from fits for a sample of $Sn_{0.96}Mn_{0.04}Te$) we can conclude that g increases slightly with decreasing temperature, in accordance with our previous data on powdered samples [3]. The demagnetising field was found to be proportional to the magnetisation, which was measured independently [6] confirming the applicability of the model. The demagnetising field was roughly consistent with an approximately ellipsoidal shape of the actual sample. Finally, we found that the temperature dependence of K_1 can be understood from the temperature dependence of $(S_x^4 + S_y^4 + S_z^4)$ [5], as shown in Fig. 2 in the case of $Sn_{1-x}Mn_xTe$. In this calculation we have described the magnetisation data at $B = 0.33$ T by a Brillouin function with $T_C = 6.5$ K. The best fit was obtained

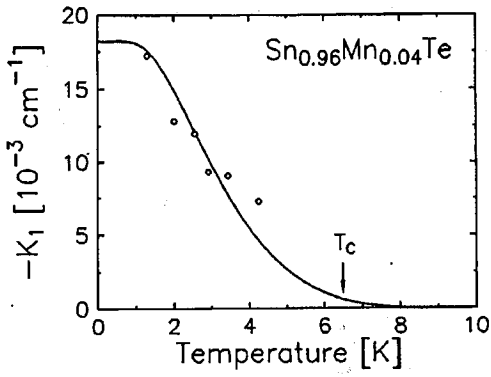

Fig. 2. Temperature dependence of the anisotropy parameter for $Sn_{0.96}Mn_{0.04}Te$. Circles represent results of the fits to the measurement, the full line is the description according to the model with $B = 0.33$ T and $a = 73 \times 10^{-4}$ cm^{-1}.

with $a = (73 \pm 6) \times 10^{-4}$ cm^{-1}. In $Pb_{0.28-x}Sn_{0.72}Mn_xTe$ we were not able to perform accurately a complete temperature analysis, but the value at 1.3 K yields a lower bound to the anisotropy constant of $a = 200 \times 10^{-4}$ cm^{-1}. Usually, fine structure is evidenced by a splitting of the resonance line, but, despite the large value of a, this splitting is much smaller than the observed linewidth.

Both values of a reported above are much larger (up to an order of magnitude) than the values usually reported for Mn^{2+}-ions in various hosts [7], particularly in $Pb_{1-x}Mn_xTe$, for which $a = 36 \times 10^{-4}$ cm^{-1} was reported [8]. An important difference between $Pb_{1-x}Mn_xTe$ and $Pb_{0.28-x}Sn_{0.72}Mn_xTe$ or $Sn_{1-x}Mn_xTe$ is the carrier concentration. These carriers are generated by vacancies in the crystal lattice, which may locally distort the crystal lattice. This distortion may induce a non-cubic crystal field on a nearby Mn-ion, which increases the anisotropy. Because of the random distribution of both Mn-ions and vacancies, the net effect to the anisotropy may be cubic again, which is observed in the measurements. The difference between $Pb_{0.28-x}Sn_{0.72}Mn_xTe$ and $Sn_{1-x}Mn_xTe$ having the same carrier density, may be attributed to an extra distortion, due to the difference in ionic radii of Pb^{2+} and Sn^{2+}.

Another explanation involves the interaction between the Mn-ions and the conduction electrons. This may have an anisotropic magnetisation in the conduction electron system as an effect. This will result in an overestimation of the single spin anisotropy, only if the *s–d* exchange parameter is negative [9]. Up to now the sign of the *s–d* exchange parameter is not determined experimentally.

Concluding, we have observed anomalously large cubic anisotropy in (Pb)SnMnTe using FMR experiments. The anisotropy parameter is $a = (73 \pm 6) \times 10^{-4}$ cm^{-1} in $Sn_{1-x}Mn_xTe$ and at least $a = 200 \times 10^{-4}$ cm^{-1} in $Pb_{0.28-x}Sn_{0.72}Mn_xTe$. Possible explanations include a local contraction of the semiconductor lattice to accommodate the Mn-ions, and an anisotropy in the conduction-electron system.

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