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MAGNETIC PROPERTIES OF SEMICONDUCTOR-ANTIFERROMAGNET SUPERLATTICES*

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Magnetic resonance investigations of ultra-thin antiferromagnetic EuTe layers show a specific behaviour in the quasi-2D antiferromagnetic ordering: (i) an anisotropy of the critical broadening, (ii) a substantial increase in the Néel temperature and (iii) an anisotropic shift of the resonance frequency which diverges at the Néel point. The results show that exchange coupling is stronger in quasi-2D than in 3D antiferromagnetic samples and that correlation of spin chains aligned in the perpendicular direction occurs already well above the Néel point.

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There is a substantial difference between the macroscopic and the microscopic nature of antiferromagnets (AFs). Macroscopic AFs are described by stable Néel sublattices with opposite spin orientation and the magnetizations of the sublattices compensate each other completely. For microscopic objects, in contrast, quantum mechanical calculations show that there is no stable magnetization of any sublattice. Neighbouring spins are anti-correlated but the mean value of each individual spin vanishes. There is no obvious answer which type of AF is more appropriate for ultra-thin AF layers where one dimension is a microscopic one. In this paper we show that magnetic phase transitions of such layers can be regarded as an ordering of short quantum AF strings which are oriented from one interface to another.

The Eu chalcogenides are known as magnetic model systems where coupling among the spins is described by pure Heisenberg coupling. We investigate the magnetic resonance ("EPR") of a series of MBE grown EuTe/PbTe superlattices (SLs) and we compare the experimental results obtained with those from a few

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micrometer thick EuTe layers grown also on (111) BaF_2 substrates, the same PbTe buffer using the same technology. In our superlattices, the antiferromagnetic layers of $N = 1\ldots 7$ monolayer (ML) thickness are separated by semiconducting PbTe layers of $M = 5\ldots 24$ ML thickness.

Both superlattices and thick layers exhibit a single EPR line above the Néel point and a Zeeman-like mode of antiferromagnetic resonance (AFMR) below the critical temperature. The details of the AFMR will be published elsewhere. Here we mention only that the Néel temperatures, determined from the two types of resonances, coincide with an accuracy of 2 K.

For both types of samples the EPR frequency reflects axial symmetry and the g-factor follows the classical expression

$$g^2 = g_{\rm p}^2 \cos^2 \alpha + g_{\rm in}^2 \sin^2 \alpha, \qquad (1)$$

where α describes the angle between the magnetic field and the direction perpendicular to the sample surface. The mean g-factor, defined by $g_0 = (g_{\rm in} + 2g_{\rm p})/3$, is close to 2 and almost temperature independent. The anisotropy of the g-factor increases with decreasing temperature. In Fig. 1a the inverse of both $g_{\rm in} - g_0$ and $g_{\rm p} - g_0$ are plotted as a function of temperature. At high temperatures, the data show linear variation according to

$$\frac{g_{\rm in} - g_{\rm p}}{g_0} = \frac{W}{T + \Theta} \qquad (2)$$

indicating that the resonance shift is proportional to the magnetic susceptibility, and thus that the effect is caused by classical magnetic anisotropy. The sign of the anisotropy shows that the "in-plane" orientation of the magnetic moments is more favourable. The magnitude of the anisotropy, which is described by the parameter W, is rather small. It is only slightly bigger than the anisotropy originating from magnetic dipole coupling, the shape anisotropy.

In both types of samples we observe the so-called critical broadening of the line width in the critical temperature range, i.e., at temperatures slightly above the critical temperature. In Fig. 1b the cube of the line width is plotted as a function of temperature. It is seen that the line width follows a power law: $\Delta\omega = \Delta\omega_0 (T - T_{\rm N})^{-\gamma}$. The critical exponent γ is about 1/3, both for thick and for quasi-2D samples. The estimated Néel temperature for thick EuTe layers is equal to the value known from literature ($T_{\rm N} = 9.6$ K). Surprisingly, for the SL samples we observe a substantial increase in the critical temperature which for a SL with thicker layers (7 ML) reaches values of up to 18 K.

Another experimental finding, which is characteristic of the quasi-2D AF layers only, is the anisotropy of the line width in the critical region. For SLs, which are characterised by a big Néel temperature (and thus probably by weak interdiffusion at the interface), the line width for perpendicular orientation of the magnetic field is twice as big as for in-plane orientation. We conclude from this observation that the local field distribution, which causes the broadening effect, is anisotropic — fluctuations in the direction perpendicular to the layers are much stronger than those in plane.

This "cigar"-shaped distribution of the local field fluctuations is independently confirmed also by a characteristic g-shift observed in the critical temperature range for quasi-2D layers. As it is shown in Fig. 1a, the $g_{\rm p}$ value behaves like

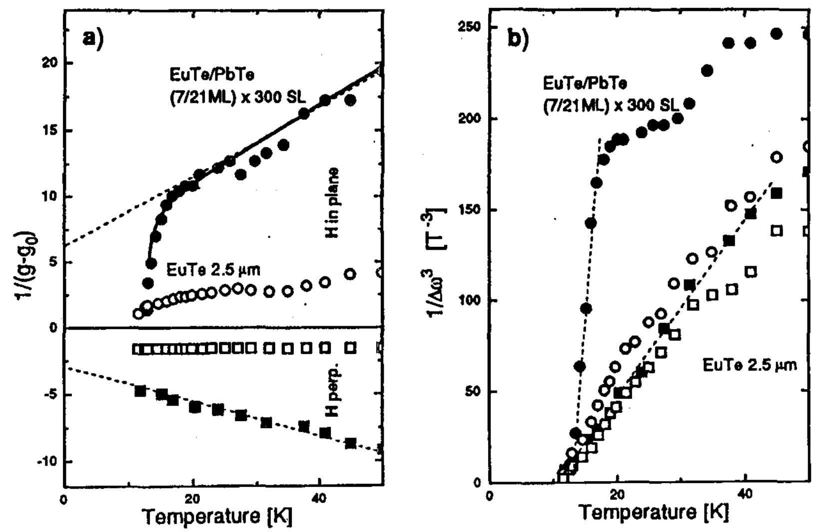

Fig. 1. (a) Inverse g-shift vs. temperature, (b) inverse cube of the line width. Circles — magnetic field in-plane, squares — perpendicular field. Open symbols — 3D EuTe, full symbols — superlattice.

the magnetic anisotropy but for $g_{\rm in}$ an extra increase is observed with decreasing temperature and it diverges at the Néel point. The analysis of the mean value of the magnetic fields, i.e., the sum of the external field and the local fluctuations, $\boldsymbol{H}_0+\boldsymbol{h}$, leads to the conclusion that for a cigar-shaped distribution of fluctuations, h, the correction of the resonant field caused by the anisotropic fluctuations can be described by

$$\langle H_{\rm in}^{*}\rangle = \sqrt{\langle H_{\rm in}\rangle + h_{\rm p}^2 + h_{\rm in}^2}. \tag{3}$$

Here $h_{\rm p}^2$ and $h_{\rm in}^2$ describe the second moments of the fluctuations in the two directions perpendicular to the applied field. For the evaluation of the solid line in Fig. 1 the fluctuation amplitudes were taken from the measured widths of the resonance line.

In the critical temperature range the EPR line width is determined by the sum of second moments due to dipolar coupling to all surrounding spins. This total second moment, M_2, is motionally narrowed by time dependent critical fluctuations. The resulting line width is, in general, determined by the product $\Delta\omega = M_2\omega_{\rm f}$, where $\omega_{\rm f}$ is the temperature dependent fluctuation frequency. In cubic crystals the second moment is isotropic. Thus it cannot cause anisotropy of the local fluctuations. In addition, the weak observed magnetic anisotropy is, by orders of magnitude, too small to explain the observed anisotropy of local fluctuations. Thus the effect has to originate from a nonsymmetric effect of line narrowing.

The anisotropy of the narrowing becomes evident if we consider the line width as a sum of independent contributions from surrounding spins (such a procedure is allowed for a weak spin correlations among neighbours). The line width then is given by

$$\Delta\omega = \sum_i M_2^i \omega_f^i. \tag{4}$$

In the case of the planar symmetry of quasi-2D layers, the experimental results (observed for various experimental configurations) show that the contribution to the local field fluctuations caused by spins situated along the strings perpendicular to the sample plane is much bigger than the contributions from neighbouring spins within the layer plane. This interpretation is based on the fact that the contribution to the second moment which originates from neighbouring spins situated along the magnetic field direction is four times bigger than the contribution of a similar neighbour situated in the plane perpendicular to the applied field.

Summarising, the anisotropy of fluctuations is caused by the anisotropic effect of exchange narrowing. Fluctuations originating from neighbours within the same layer are motionally averaged due to spin diffusion, whereas fluctuations caused by neighbouring spins which are distributed along the direction perpendicular to the layer are not narrowed. Therefore, we conclude that in the critical temperature range, a quasi-2D EuTe layer can be considered as a fluctuating set of solid AF "wall to wall" strings. This indicates that the exchange energy of such strings is substantially bigger than the energy of similar strings oriented in-plane or a similar string in a 3D AF. Such a conclusion is strongly supported by the fact that quasi-2D layers are characterised by a much higher Néel temperature. It is also confirmed by the fact that the mean binding energy of a quantum string, in contrast to the classical model, increases for short strings [2].

When interdiffusion is stronger, the discussed effects, which are attributed to the quasi-2D character, vanish. In such diluted layers, local spin correlations become determined by the geometric configuration of the local spins. The line width becomes isotropic, the g-shift caused by the anisotropy of the relaxation rates vanishes, and the Néel temperature decreases.

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