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Spin waves and temperature dependence of magnetization in strained EuS films

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Abstract. Magnetic properties of ultrathin EuS films with strain effects taken into account are studied within the framework of the Green function formalism. Standard RPA and more general procedures employed by Callen are used for decoupling of higher order functions generated by exchange and anisotropy terms, respectively. Parameters of the model such as exchange integrals in strained structures and anisotropy constants are estimated on the basis of experimental data obtained with use of SQUID and FMR techniques. Strong influence of stress on spin–wave dispersion relations, especially on high-energy modes, is found. A shift of curves representing magnon DOS towards higher energies is obtained in the presence of stress. All these modifications lead to a slower decrease of the magnetization with increasing temperature and to an enhancement of the critical temperature. The results are consistent with experimental data. Investigations of the course of the magnetization curves for various film thickness also confirm experimental results.

1. Introduction

EuS–PbS multilayers form new non-metallic ferromagnetic–diamagnetic structures. Both EuS and PbS are semiconductors crystallizing in a rock salt structure and their lattice parameter mismatch is only 0.5%. It allows the growth of epitaxial pseudomorphic EuS–PbS multilayers with the total thickness of the structure exceeding 1000 Å. The EuS–PbS multilayers grown on KCl and BaF_2 substrates have been recently investigated with use of SQUID and ferromagnetic resonance (FMR) techniques [1–4]. Measurements have been performed mainly for structures with thick non-magnetic PbS spacers (∼50 monolayers (ML)) giving information concerning magnetic properties of ultrathin ferromagnetic EuS films. Since the non-magnetic PbS spacers are quite thick the individual EuS layers in EuS–PbS multilayers can be considered as magnetically decoupled. It has been revealed that even films consisting of only 2 ML show magnetic phase transitions. The critical temperature corresponding to ferromagnetic-paramagnetic transition T_C depends on the film thickness as well as on the type of substrate. For systems on KCl(100) substrates higher values of T_c have been obtained than for similar structures deposited on BaF_2(111). The Curie temperature T_C for thick EuS layers (200 ML) on KCl(100) substrate has been found to be equal to 17.3 K. This value is higher than the critical temperature of bulk EuS (16.6 K), though such systems can in fact mimic the bulk ones. The enhancement of T_c has been interpreted as an effect of stress resulting from the difference of the thermal expansion coefficients between the substrate and the structure. On the other hand, for thick EuS films deposited on BaF_2(111) a reduction of T_c has been observed.

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The critical temperature depends strongly on the number of monolayers (N) in the film. Namely, for very thin films (N<10) T_C is found to decrease significantly with N decreasing, whereas for thicker systems changes of T_C are rather small [1].

Measurements performed with use of FMR give information concerning the volume and interface anisotropy. The anisotropy constants were determined [1, 4]. It was found that EuS layers with $N > 2$ ML magnetize in a plane of the structure due to the dominant effect of the volume (shape) anisotropy.

The aim of the present paper is a theoretical analysis of the influence of stress as well as of film thickness on temperature dependence of magnetization in EuS systems. Calculations are performed within the framework of the Heisenberg Hamiltonian with use of Green function formalism. Spin–wave dispersion relation and the magnon density of states (DOS) in strained ultrathin films are also investigated. Calculations are based on the approach presented in detail elsewhere [5].

2. EuS thin films

In Eu-compounds exchange interactions with the nearest (NN) and the next nearest (NNN) neighbours should be taken into account [6, 7]. The appropriate integrals are denoted by J_1 and J_2. For EuS system the following values are assumed: $J_1 = 0.228$ K, $J_2 = -0.118$ K [7]. Integral J_1 appears to be strongly dependent on the band structure and on the lattice constant a [8, 9]. Therefore, in layer EuS systems stress which results in a compression of in-plane lattice parameter, influences J_1 leading to changes of T_C.

Calculations are based on the Hamiltonian

$$H = -\sum_{nn'ij} J_{nn'ij} S_{ni} S_{n'j} - \sum_{ni} K_n (S_{ni}^z)^2 - g\mu_B H_0 \sum_{ni} S_{ni}^z \tag{1}$$

with exchange, anisotropy and Zeeman terms taken into account. In layer systems two indices are used to describe a position of spin, namely n corresponding to a plane index and i being a vector in a given plane. Interactions with NN and NNN are taken into account. Integral J_1 is assumed to change with position vector in a following way

$$J_1(R) = J_1(R_0) + \frac{\mathrm{d}J_1}{\mathrm{d}R}\Delta R \tag{2}$$

where R_0 represents an undistorted distance between NN in bulk materials. The derivative $\mathrm{d}J_1/\mathrm{d}R$ estimated from high-pressure neutron diffraction measurements of bulk EuS is equal to -1.492 K Å^{-1} [9]. Changes of in-plane $J_{1\parallel}$ and inter-plane $J_{1\perp}$ integrals are taken into account. Calculations are performed for $J_{1\parallel}^e = 0.237$ K, $J_{1\perp}^e = 0.232$ K. These values correspond to J_1 determined according to equation (2) with $\Delta R_\parallel$ and $\Delta R_\perp$ related to changes of in-plane $\Delta a_\parallel$ and inter-plane $\Delta a_\perp$ lattice constants estimated for an experimentally observed, partialy relaxed EuS system [1]. Values $J_{1\parallel}^{nr} = 0.308$ K, $J_{1\perp}^{nr} = 0.261$ K obtained with $\Delta R_\parallel$ and $\Delta R_\perp$ corresponding to a completely non-relaxed system considered in [3] are also taken into account. To show the main trend of stress effects some calculations are performed for systems with extremely strong deformation. Changes of J_2 appear to be very small [9] and can be neglected.

The second term in the Hamiltonian (1) represents an anisotropy energy. It should be pointed out that the origin of the anisotropy is not discussed in the paper. It seems to us that the assumed term with the effective, position dependent constant, allows one to describe adequately an influence of anisotropy on magnetic properties of the thin film. FMR investigations performed for EuS–PbS structures show that the volume anisotropy overtakes the surface one already for systems with EuS films thicker than 1–2 ML [1, 4]. So, the magnetic moment is lying in the film plane. Such a configuration is assumed in the paper

with the z-axis of the coordinate system chosen in the film plane. Experimental data obtained for structures deposited on KCl(100) and $BaF_2(111)$ substrates [1] allow us to determine the effective anisotropy acting on atom in surface and inner planes (see also [10]). The appropriate effective anisotropy constants are denoted by K_S and K_V. Taking into account the fact that the bulk lattice constant reduced to 10 K is equal to 5.955 Å [3] the volume and surface anisotropy constants per atom are estimated to be equal to: $K_V = 0.22$ K, $K_S = 0.15$ K for structures with (111) symmetry (BaF_2 substrate) and $K_V = 0.207$ K, $K_S = 0.155$ K for systems on KCl(100) substrate. Changes of the lattice constant in the film plane resulting from the stress have been taken into account according to [3]. It seems reasonable to assume that effective anisotropy constants with values K_V and K_S determined on the basis of FMR measurements include any significant magneto-elastic effects.

The last term in the Hamiltonian (1) corresponds to Zeeman energy in an external magnetic field. To obtain results which can be related to SQUID measurements [1] the external field equal to 1 mT is taken into account.

The magnetostatic effects are not taken into account in the Hamiltonian (1). The influence of these effects is especially important in systems with magnetization perpendicular to the film plane or systems in external magnetic field close to the critical one because of the possibility of a formation of canted structure [11]. However, it seems to us that in the case of EuS layers with the magnetic moment lying in the film plane and in the presence of a magnetic field far below the critical one, the description based on the Hamiltonian (1) with effective anisotropy terms taken into account can be reasonable [12]. Problems could appear when the field close to the critical one is applied perpendicularly to the z-axis [11,12]. Such a case is not the subject of our investigations. It should also be pointed out that the main aim of our work is to develop the relatively simple theoretical approach to describe the dominant mechanism of the influence of stress on low-temperature properties of ultrathin EuS layers. According to experimantal data [1, 9] one can assume that the dominant effect comes from the stress-induced changes in the exchange term of the Hamiltonian.

Green function formalism is used for investigation of the temperature dependence of magnetization (see [5]). The function $G_{nn'ij} = \langle\langle S^+_{ni}, S^-_{n'j}\rangle\rangle$ is introduced with S^+, S^- being components of spin operator. The standard RPA scheme is used for decoupling of higher order functions entered the equation of motion through the exchange term. However, a more general procedure employed in case of bulk materials by Anderson and Callen [13] is used to decouple functions generated by anisotropy term, namely

$$\langle\langle S^+_{ni}S^z_{ni} + S^z_{ni}S^+_{ni}, S^-_{n'j}\rangle\rangle \to 2\langle S^z_n\rangle p_n(T)\langle\langle S^+_{ni}, S^-_{n'j}\rangle\rangle \tag{3}$$

with

$$p_n = 1 - \frac{1}{2S^2}[S(S+1) - \langle(S^z_n)^2\rangle]. \tag{4}$$

The Green functions satisfy $N \times N$ matrix equation of the form

$$P(E)G = M \tag{5}$$

here M corresponds to an N-dimensional vector with components $2\langle S_n\rangle\delta_{nn'}$, with $\langle S_n\rangle$ being the magnetic moment in the nth layer. G is a vector corresponding to $G_{nn'}(k, E)$, where $G_{nn'}$ denotes a two-dimensional Fourier transform of the function $G_{nn'ij}$. $P(E)$ is $N \times N$ matrix of the form given in [5]. Numerical diagonalization of *P(E)* allows us to determine spin–wave energy $E_\tau(k)$ as well as the square amplitude of the τth mode in the layer with index $n - A_{\tau n}(k)$ [5]. Then, following the procedure outlined by Callen [14] it is possible to derive the quantity $\langle e^{rS_n}\rangle$ which allows one to obtain an expression for the layer magnetization

$$\langle S_n\rangle = S\left[\frac{\mathrm{d}}{\mathrm{d}r}\langle e^{rS_n}\rangle\right]_{r=0}$$

valid over the entire temperature region. We find (see also [15])

$$\langle S_n \rangle = \frac{(S+1+\Phi_n)\Phi_n^{2S+1} + (S-\Phi_n)(1+\Phi_n)^{2S+1}}{(1+\Phi_n)^{2S+1} - \Phi_n^{2S+1}} \tag{6}$$

here S denotes spin equal to 7/2 in Eu-compounds. The quantity Φ_n depends on square amplitudes of spin–wave modes in nth layer as well as on energies of the modes in a way

$$\Phi_n = \frac{1}{N_\parallel} \sum_k \sum_\tau \frac{A_{\tau n}(k)}{e^{\beta E_\tau(k)} - 1} \tag{7}$$

where $\beta = 1/k_B T$ with k_B being a Boltzmann constant.

$\langle (S_n^z)^2 \rangle$ which enters the equation of motion through the decoupling procedure (equations (3) and (4)) can be also expressed by means of function Φ_n in a way similar to the one employed by Callen [14]. Therefore, both $\langle S_n \rangle$ and $\langle (S_n^z)^2 \rangle$ directly depend on Φ_n and can be calculated self-consistently at a given temperature. Such an approach is used in the paper and is called the Callen approach.

Using the theorem of Callen and Shtrikman [16] one can directly relate the correlation function $\langle (S_n^z)^2 \rangle$ and magnetization $\langle S_n \rangle$, namely

$$\langle (S_n^z)^2 \rangle = S(S+1) - S\sigma_n cth\left(\frac{3}{2(s+1)}\frac{\sigma_n}{\tau}\right) \tag{8}$$

with $\sigma_n = \langle S_n \rangle / S$ and $\tau = T/T_C^N$. The transition temperature T_C^N corresponding to a system which consists of N layers is determined according to the formula [1]

$$T_C^N = T_C^\infty \left(1 - \frac{c}{N}\right) \tag{9}$$

with $T_C^\infty = 17.3$ K for thick EuS films on KCl(100) substrate and c being a numerical parameter given in [1]. Brillouin function corresponding to T_C^N is taken for σ (in this case the magnetization does not depend on the layer index n). The correlation function $\langle (S_n^z)^2 \rangle$ calculated in such a way is used to determine $p(T)$ (equation (4)) which enters the equation of motion. Then, the local magnetization $\langle S_n \rangle$ is calculated according to formula (6). Such an approach is called here Callen–Shtrikman–Brillouin approach. In fact results obtained for $\langle S_n \rangle$ are not self-consistent ones. Therefore, σ given by the Brillouin function can be treated as a zero approximation. In the next step the correlation function $\langle (S_n^z)^2 \rangle$ can be found according to formula (8) with σ calculated previously from equation (6). The procedure is repeated until self-consistency is achieved. Such an approach is called the Callen–Shtrikman approach. Calculations of the magnetization with different approaches will be presented and comparisons will be given and discussed.

3. Spin waves in strained films

Experimental data [1] show that in EuS layer structures on KCl(100) substrate stress plays an important role, whereas its influence can be neglected for systems with (111) symmetry deposited on BaF_2. Therefore, only the (100) case is considered in this work. In Eu-compounds a presence of stress strongly influences the exchange integral J_1 [1,9] leading in case of thin films to an anisotropy of exchange interactions.

At first, the influence of stress on spin–wave energies and DOS is investigated. Calculations are performed for structures with various values of $J_{1\parallel}$ and $J_{1\perp}$. In order to emphasize the influence of stress essentially different values of parameters are chosen. Energies of spin–wave modes are determined for the unstrained film and for systems with strong deformation taken into account. At first, in-plane and perpendicular strain effects are

investigated separately, and calculations are performed with $J_{1\parallel}$ or $J_{1\perp}$ modified. The results are depicted in figures 1(a) and 1(b). Solid lines correspond to the unstrained structure, while dotted lines represent dispersion relations characteristic of system with a strong deformation. According to figure 1(a) one can see that a strong in-plane contraction corresponding to $J_{1\parallel} = 1.5J_1 = 0.324$ K and $J_{1\perp} = J_1$ leads to essential modifications of dispersion curves, especially for wave-vectors close to the boundary of two-dimensional Brillouin zone. It should be pointed out that states with low k are not influenced. Results show that higher energy is required to excite short spin waves in a structure with in-plane compression. On the other hand, a deformation in the growth direction strongly influences long-wavelength modes leading to the essential enhancement of energies for $k \approx 0$ (figure 1(b)). Results depicted in figure 1(b) (dotted lines) are obtained for $J_{1\parallel} = J_1$ and $J_{1\perp} = 0.275$ K. Such a value of $J_{1\perp}$ was estimated as corresponding to extremely strong in-plane deformation ($J_{1\parallel} = 1.5J_1$) via Poisson effect with the ratio $\Delta a_\perp/\Delta a_\parallel = -0.17$ found experimentally. Dispersion curves calculated with both in-plane and perpendicular deformations taken into account are presented in figure 1(c) (dotted lines). In comparison to unstrained films very strong modifications take place, especially for high-energy modes. According to figures 1(a)–1(c) it can be seen that effects of parallel and perpendicular deformations are additive. Results obtained for more realistic systems are depicted in figure 1(d). The presented dispersion relations (dotted lines) are calculated with exchange integrals estimated for a completely non-relaxed EuS–PbS layer structure ($J_{1\parallel} = J_{1\parallel}^{nr} = 0.308$K, $J_{1\perp} = J_{1\perp}^{nr} = 0.261$K). Also in this case quite strong modifications can be observed.

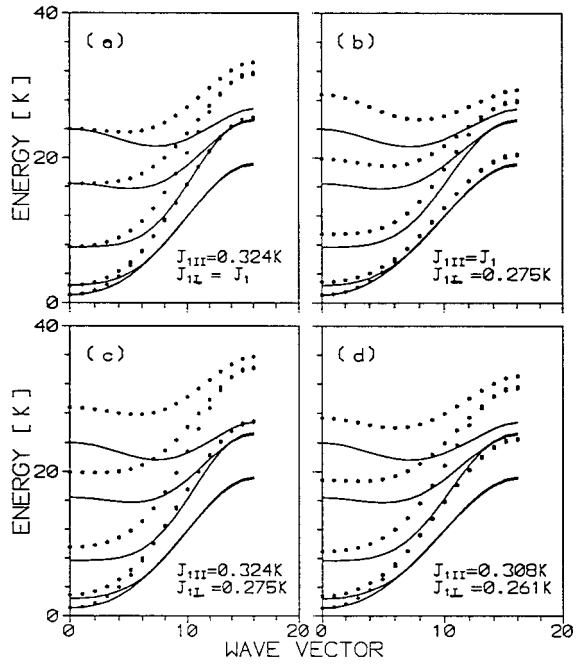

Figure 1. Dispersion relations of spin–wave modes in unstrained (solid lines) and strained (dotted lines) films with N=5 ML. Modifications of exchange integrals (given in the figure) are taken into account. In high wave vector regions spin–wave branches are quite close, but no degeneracy takes place.

Stress can influence anisotropy constants via magneto-elastic effects. It is relatively difficult to describe the effect in a quantitative way for the system under consideration. Therefore, just to investigate the main trend, we assume somewhat arbitrarily a strong lowering of K and calculate spin–wave energies with both exchange and anisotropy constants modified. Dispersion curves obtained for $J_{1\|} = 1.5J_1 = 0.324$ K, $J_{1\perp} = 0.275$ K and $K'_V = 0.5K_V = 0.1035$ K, $K'_S = 0.051$ K are presented in figure 2. Curves calculated for unstrained film are also given (solid lines). According to the figure one can see that energies of spin waves with vector k close to zero are only slightly modified. However, in general, spin–wave energies are also enhanced in this case. The enhancement is quite strong for short wavelength modes.

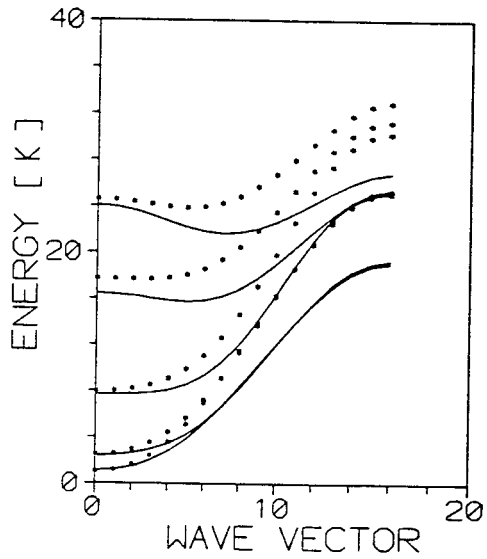

Figure 2. Dispersion relations of spin–wave modes for strained films with $J_{1\|} = 0.324$ K, $J_{1\perp} = 0.275$ K, $K_{V'} = 0.1035$ K, $K_{S'} = 0.0521$ K (dotted lines) and for the unstrained case (solid lines).

Local DOS calculated for strained and unstrained structures are presented in figure 3 for two different temperatures. Only modifications of exchange integrals are taken into account. It can be seen that in unstrained films, low energy peaks dominate in surface and central layers. The presence of stress influences DOS strongly leading to a shifting of the curves towards higher energies. Moreover, the DOS of the central plane is relatively low and practicaly constant in a wide energy region, but it is enhanced at high energies. Therefore, stress effects will influence the magnetization curves leading to an increase of T_C.

4. Influence of stress on magnetization curves

The mean layer magnetization defined as

$$m(T) = \frac{1}{N}\sum_n \langle S_n \rangle \tag{10}$$

with N denoting the number of planes in the film is evaluated numerically dependent on temperature. $\langle S_n \rangle$ and $\langle (S_n^z)^2 \rangle$ are calculated in a self-consistent way. It should be pointed out

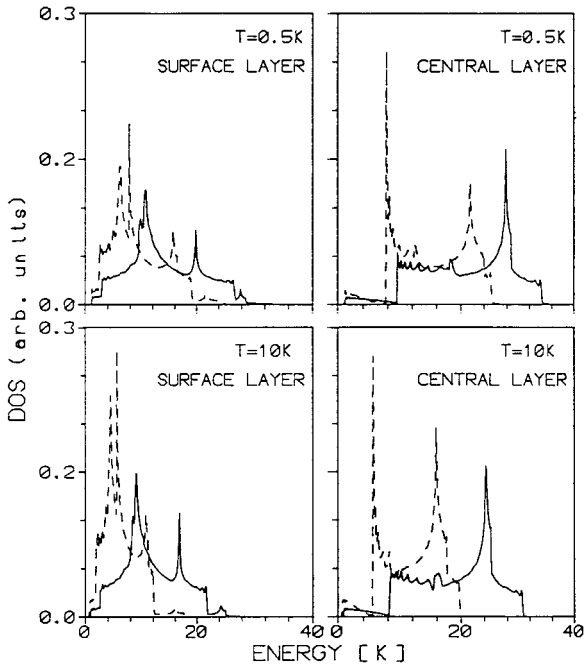

Figure 3. Densities of states at $T = 0.5$ and 10 K for surface and central layers in unstrained (dashed lines) and strained (solid lines) structures with N=5 ML. $J_{1\|} = 0.324$ K, $J_{1\perp} = 0.275$ K are assumed.

that it is difficult to obtain self-consistent solutions up to the Curie temperature. This problem has also been noticed and discussed by other authors (see e.g. [17]).

To realize the main trend of stress effects on magnetization curve several values of $J_{1\|}$ with corresponding $J_{1\perp}$ are taken into account. First of all, calculations are performed for $J^e_{1\|} = 0.237$ K, $J^e_{1\perp} = 0.232$ K and $J^{nr}_{1\|} = 0.308$ K, $J^{nr}_{1\perp} = 0.261$ K. These values correspond to J_1 determined for a partly relaxed EuS system and for a non-relaxed one [3]. The results are presented in figure 4 where temperature dependences of the magnetization are depicted for a EuS film consisting of 5 ML. For comparison, results obtained for unstrained structure and for extremely strong deformation ($J_{1\|} = 0.324$ K, $J_{1\perp} = 0.275$ K) are also given. According to figure 4 it can be observed that an increase of exchange integrals resulting from stress leads to a slower decrease of the magnetization, and therefore, to an enhancement of the critical temperature. The effect is quite strong and an essential increase of T_C can be obtained for the case of large deformation. Results obtained with use of SQUID for thin EuS films deposited on KCl(100) also indicate a significant enhancement of T_C caused by stress. It should be pointed out that the increase of the Curie temperature for the non-relaxed EuS–PbS structure estimated on the basis of experimental data is as high as 6.2 K [1, 3]. Therefore, one can state that the determined trend is the same as that found in SQUID measurements. However, a direct, quantitative comparison is rather difficult because of problems with a strict determination of T_C for thin films. On the other hand, more adequate evaluation of T_C is possible for bulk materials. Calculations based on Hamiltonian (1) with Anderson–Callen decoupling procedure give an experimentally observed value of T_C equal to 16.6 K for the anisotropy constant $K = 0.85J_1$ with $J_1 = 0.228$ K. An increase of J_1 caused by stress leads to an enhancement of the critical

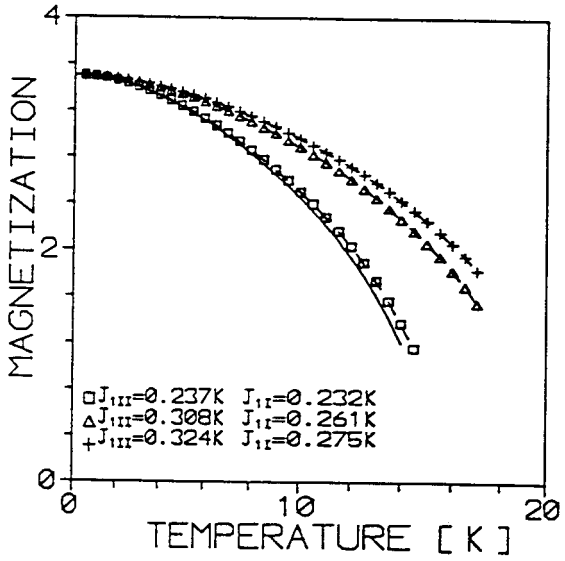

Figure 4. Temperature dependences of magnetization calculated for $N = 5$ ML and various values of J_1. Solid and dashed lines correspond to unstrained and strained films, respectively.

temperature giving $T_C = 17.6$ K for $J_1 = 0.237$ K. The obtained value is only slightly higher than measured for thin EuS films ($T_c = 17.3$ K).

The above results have been obtained with $p_n(T)$ determined according to equation (4) with $\langle (S_n^z)^2 \rangle$ calculated self-consistently using the formalism worked out by Callen [14] (the Callen approach). However, it is reasonable to check if the magnetization curve depends on a method of calculation of the function $\langle S_n \rangle$. So, the approach based on the Callen–Shtrikman theorem is also used [16] (the Callen–Shtrikman approach). It allows one to express $\langle (S_n^z)^2 \rangle$ directly by $\langle S_n \rangle$. Brillouin function corresponding to T_c^N estimated experimentally is taken as a zeroth approximation for $\langle S_n \rangle$. Next, $p_n(T)$ is calculated with $\langle S_n \rangle$ determined during the first step. Results obtained with the use of various approaches for $\langle (S_n^z)^2 \rangle$ are presented in figure 5 for a film with $N = 5$ ML and $J_{1\parallel} = 0.237$ K, $J_{1\perp} = 0.232$ K. Points obtained for $m(T)$ with $p(T)$ determined using only the Brillouin function are also given (Callen–Shtrikman–Brillouin approach). One can see that differences in the course of curves calculated with various approaches taken into account are not very essential. Slightly higher values of magnetization are found only for temperatures quite close to T_C in the case with $\langle (S_n^z)^2 \rangle$ determined according to the Callen approach.

To compare the results obtained in the paper with experimental curves normalized magnetization dependent on temperature is depicted in figure 6. Data of SQUID measurements for 10 Å thick film are given (stars). The theoretical curve corresponds to $N = 3$ ML. The solid line represents Callen–Shtrikman approach with use of the Brillouin function taken as a zeroth approximation. The figure shows that in the temperature region in which self-consistent solutions can be obtained, calculated results are quite close to experimental points. Therefore, it seems to us that Green function formalism based on the Hamiltonian (1) with Anderson–Callen decoupling scheme quite well describes EuS systems under consideration.

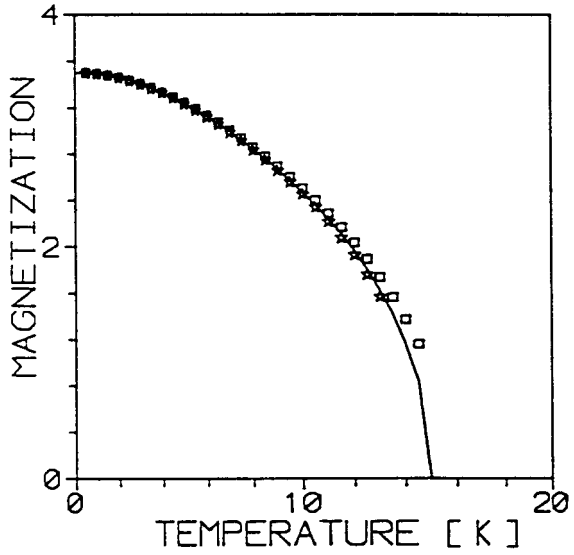

Figure 5. Temperature dependence of the magnetization calculated with various approaches for $\langle (S_n^z)^2 \rangle$: Callen–Shtrikman (solid line), Callen–Shtrikman–Brillouin (stars), Callen (squares).

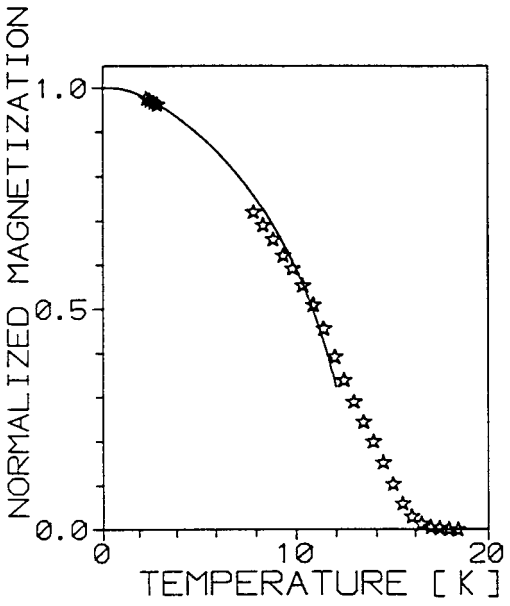

Figure 6. Normalized magnetization versus temperature. Stars; SQUID data for 10 Å thick EuS, solid line; theoretical results for $N = 3$ ML with Callen–Shtrikman approach.

5. Thickness dependence of magnetization curves

To study the influence of film thickness on the course of the magnetization curve calculations are performed for EuS systems with $N = 3, 5, 7, 11$ and 18 ML. Structures of (100) symmetry are considered with anisotropy of exchange integral J_1, caused by stress, taken into account. $J_{1\parallel}$ equal to 0.237 K and $J_{1\perp} = 0.232$ K are assumed in the calculations. In all cases $\langle (S_n^z)^2 \rangle$ is

determined using Callen–Shtrikman theorem with Brillouin function, which corresponds to T_C^N (equation (9)), treated as a zeroth approximation. Self-consistent calculations are performed.

The calculated results are depicted in figure 7. A fast decrease of the magnetization is obtained for very thin films, especially for 3 ML. Moreover, for low N (3, 5, 7 ML) changes in the course of magnetization curve are essential. Such results seem to be consistent with SQUID data [1]. On the other hand, temperature decrease of magnetization is much slower for structures consisting of 11 and 18 ML. It should be also pointed out that curves corresponding to $N = 11$ and 18 ML are quite close to one another. A weak dependence of the Curie temperature on film thickness was found experimentally for structures with $N > 10$ ML. Therefore, the obtained results seem to be consistent with experimental ones.

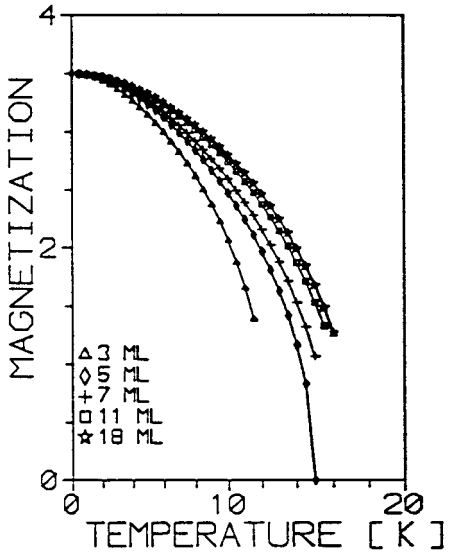

Figure 7. Temperature dependences of magnetization for $N = 3, 5, 7, 11$ and 18 ML, respectively.

Next, the temperature dependence of the local magnetization is analysed. According to figure 8 one can see that in 11 ML thick film, curves corresponding to the local moment are very close to one another except the surface (squares). This means that apart from surfaces magnetization profiles are relatively flat across the film. The presence of low-lying surface modes leads to a fast decrease of the surface magnetization. Moments of inner layers are influenced by the surface in a rather moderate way, particularly for the central plane. It should be pointed out that the central layer magnetization decreases in practically the same way as the bulk one. In the figure the magnetization of bulk EuS with stress effects taken into account is represented by long-dashed line. The course of the mean layer magnetization (short-dashed line) for the 11 ML case is quite close to the magnetic moment of inner planes. So, it rather weakly depends on the film thickness. On the other hand, for very thin films (3 ML) the influence of the film thickness is much more pronounced. First of all, the central layer magnetization is strongly influenced by the presence of the surface. Moreover, the course of the mean magnetic moment is similiar to the behaviour of surface magnetization rather than the central layer one (figure 9). In the case of MnTe(100) films with antiferromagnetic ordering of the type III the magnetization curve of relatively thin film mimics the temperature dependence of the magnetic moment in the bulk system [18]. It may well be that this is a characteristic feature of magnetic semiconductors. It would, however, require further more

detailed experimental investigations.

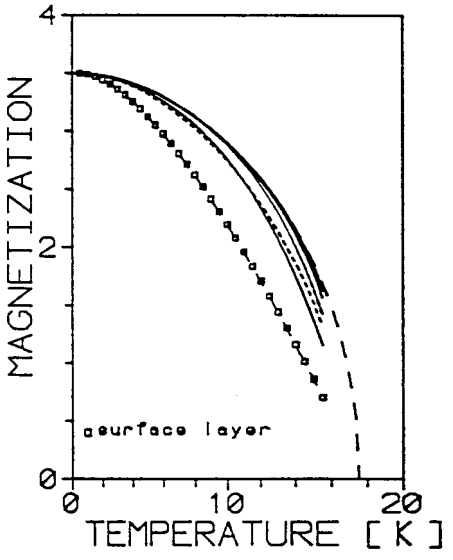

Figure 8. Local magnetizations in subsequent layers of 11-ML thick film. Solid lines correspond to magnetization of inner layers. Short-dashed and long-dashed lines correspond to the mean layer magnetization and to bulk one (with stress taken into account), respectively.

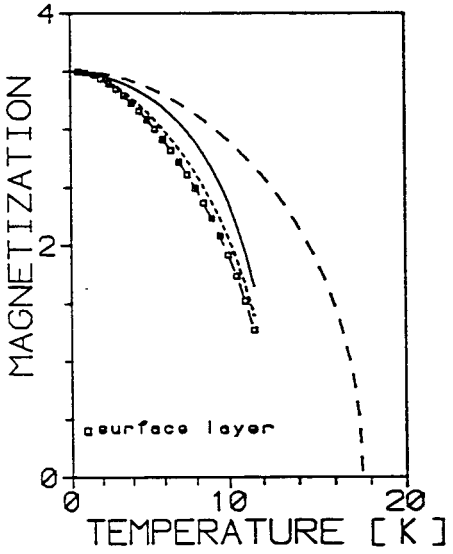

Figure 9. The same as in figure 7 but for $N = 3$ ML.

6. Summary and discussion

The temperature dependence of magnetization in ultrathin EuS films has been studied within the framework of Green function formalism. This approach allows one to describe systems under consideration with stress effects taken into account. According to the obtained results the presence of stress in ultrathin films strongly influences spin–wave modes leading to a slower decrease of magnetization at higher temperatures and therefore, to an increase of the critical temperature. Such a conclusion is fully consistent with experimental data obtained by means of SQUID.

A fast decrease of the magnetization has been also found for very thin films consistent with the experiment. Theoretical and experimental curves for EuS films of thickness corresponding to 3 ML and 10 Å, respectively, are quite close to one another confirming the consistency of the results. For thicker films ($N = 11, 18$ ML) flatter magnetization curves have been obtained with the behaviour rather close to the bulk case. This also seems to confirm experimental results.

It should be pointed out that the theoretical results presented in this paper have been obtained with no intermixing effects at EuS–PbS interfaces taken into account. Therefore, the calculated curves may appear too flat leading to a slightly higher T_c. Preliminary calculations with such effects included giving faster decrease of the magnetization with temperature. It is, however, rather difficult to achieve good self-consistency in all cases under consideration.

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