Theory of surface spin waves in ferromagnetic semiconductors

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A Green's-function formalism combined with the transfer-matrix method is used to calculate the surface spin wave modes in semi-infinite ferromagnetic semiconductors (FMS's) with a (001) surface and the surface magnetization in the ferromagnetic phase, $T \leq T_c$. The theoretical results were applied to narrow-band as well as to wide-band FMS's. [S0163-1829(98)02811-2]

I. INTRODUCTION

There has been considerable interest in the study of surface excitations in various magnetically ordered systems. It is now established from theory as well as from experiment that the magnetic properties at surfaces may differ from those of the corresponding bulk. In a semi-infinite ferromagnet or antiferromagnet the spectral intensity of the bulk spin waves becomes modified and in addition to the bulk spin wave excitations there may also be localized (or surface) spin waves (SSW's), the amplitudes of which decay exponentially away from the surface of the material toward the interior (see for review Refs. 1–3). Several theoretical studies[4–7] have shown that the presence of a surface, at which the coordination number is reduced, leads to a strong enhanced magnetism. In some cases, this enhancement is strong enough that the surface is magnetically ordered at temperatures above the critical temperature of the bulk.

Most of the SSW works are concerned with magnetic systems. The semi-infinite magnetic semiconductors have been not so intensively investigated. The magnetic excitations in bulk ferromagnetic semiconductors (FMS's) are obtained already, where two different frequency spin wave branches exist corresponding to ''acoustic'' and ''optical'' branches.[8,9] Shen and Li[10] have studied the SSW in a semi-infinite antiferromagnetic and ferrimagnetic semiconductor at low temperatures in the narrow-band limit, where the hopping exchange interaction of conduction electrons can be omitted. The dispersion relations of surface excitations are obtained by use of Green's-function theory. The influence of the s-d (or s-f) interaction on the SSW spectra is discussed. Semi-infinite magnetic semiconductors with a site-diluted free surface in the narrow-band limit and at low temperatures have been investigated by Shen, Shen, and Li.[11] The magnetic properties of thin films containing itinerant electrons interacting with localized spins and the problem of interlayer exchange coupling have been considered by Urbaniak-Kucharczyk.[12,13] Calculations are presented within the frame of a Green's-function formalism of the magnetization distribution across the layer and the thickness dependence of the Curie temperature. Gopalan and Cottam[14] have used the s-d interaction model to study the bulk and surface magnetic excitations of a semi-infinite FMS. Results are deduced for both narrow-band and wide-band FMS, but only for low temperatures, $T \ll T_c$, where the magnetization $\langle S^z \rangle \equiv S$.

In this paper we will study the surface excitations in FMS's using a Green's-function technique combined with the transfer-matrix method,[15,16] in both cases, narrow-band as well as wide-band FMS's for all temperatures below T_c. To our knowledge, there is no investigation on such a problem in the current literature.

II. THE MODEL AND THE MAGNETIC MATRIX GREEN'S FUNCTION

In this section we present calculations for obtaining the magnetic Green's function for a semi-infinite FMS occupying the half-space $z \geq 0$ and described by the s-d (or s-f) interaction model:

$$H = H_M + H_E + H_{ME}. \tag{1}$$

H_M is the Heisenberg Hamiltonian for the ferromagnetically ordered d electrons,

$$H_M = -\frac{1}{2} \sum_{l,\delta} J_{l,l+\delta} \mathbf{S}_l \mathbf{S}_{l+\delta} - g\mu_B H_0 \sum_l S_l^z, \tag{2}$$

where $\mathbf{S}_l$ and $\mathbf{S}_{l+\delta}$ are the spin operators for the localized spins at sites l and $l+\delta$ in the semi-infinite system, the sum on δ is over nearest neighbors only, $J_{l,l+\delta}$ is the exchange interaction, and H_0 is a static magnetic field applied in the z direction (the direction of the static magnetization).

H_E represents the usual Hamiltonian of the conduction-band electrons,

$$H_E = \sum_{l,\delta,\sigma} t_{l,l+\delta} a_{l\sigma}^{+} a_{l+\delta,\sigma} - g_e \mu_B H_0 \sum_l s_l^z, \tag{3}$$

where $t_{l,l+\delta}$ is the hopping integral.

The most important term in Eq. (1) is the operator H_{ME}, which couples the two subsystems (2) and (3) by an intra-atomic exchange interaction I_l,

$$H_{ME}=-\sum_l I_l \mathbf{S}_l \mathbf{s}_l . \tag{4}$$

The spin operators $\mathbf{s}_l$ of the conduction electrons at site l can be expressed as $s_l^+=a_{l+}^+ a_{l-}$, $s_l^z=(a_{l+}^+ a_{l+}-a_{l-}^+ a_{l-})/2$, where $a_{l\sigma}^+$ and $a_{l\sigma}$ are Fermi-creation and -annihilation operators at site l, respectively; $\sigma=\pm 1$ corresponds to the spin-up and -down state.

To study the magnetic excitations of the system we introduce two Green's functions,

$$G_{ij}(t)=\langle\langle S_i^+(t);S_j^-(0)\rangle\rangle \tag{5}$$

and

$$G'_{ij}(t)=\langle\langle s_i^+(t);S_j^-(0)\rangle\rangle . \tag{6}$$

It is easy to show that the equations of motion for the Fourier transform of the Green's functions (5) and (6) in the RPA have the following form:

$$\begin{aligned}&\left(\omega-g\mu_B H_0-I_i\langle s_i^z\rangle-\sum_\delta J_{i,i+\delta}\langle S_{i+\delta}^z\rangle\right)G_{ij}(\omega)\\&\quad+\langle S_i^z\rangle\sum_\delta J_{i,i+\delta}G_{i+\delta,j}(\omega)=2\langle S_i^z\rangle\delta_{ij}-I_i\langle S_i^z\rangle G'_{ij}(\omega)\end{aligned} \tag{7}$$

and

$$(\omega-g_e\mu_B H_0-I_i\langle S_i^z\rangle)G'_{ij}(\omega)=I_i\langle s_i^z\rangle G_{ij}(\omega). \tag{8}$$

Combining Eqs. (7) and (8) we obtain

$$\begin{aligned}&\left(\omega-g\mu_B H_0-I_i\langle s_i^z\rangle-\frac{I_i^2\langle S_i^z\rangle\langle s_i^z\rangle}{\omega-g_e\mu_B H_0-I_i\langle S_i^z\rangle}\right.\\&\quad\left.-\sum_\delta J_{i,i+\delta}\langle S_{i+\delta}^z\rangle\right)G_{ij}(\omega)\\&=2\langle S_i^z\rangle\delta_{ij}-\langle S_i^z\rangle\sum_\delta J_{i,i+\delta}G_{i+\delta,j}(\omega).\end{aligned} \tag{9}$$

It must be noted that the random phase approximation (RPA) is not so good very close to T_c, but in our case where we want to obtain the temperature dependence of the magnetisations for all temperatures below T_c it is a good approximation. If we have to discuss, for example, the dependence of the critical temperature on the layer, $T_c(n)$, for thin films then we must go beyond the RPA and must take into account the correlation effects. On introducing the two-dimensional Fourier transform $G_{n_i n_j}(\mathbf{k}_\parallel,\omega)$, one has the following form:

$$\langle\langle S_i^+;S_j^-\rangle\rangle_\omega=\frac{2\langle S_i^z\rangle}{N}\sum_{\mathbf{k}_\parallel}\exp[i\mathbf{k}_\parallel(\mathbf{r}_i-\mathbf{r}_j)]G_{n_i n_j}(\mathbf{k}_\parallel,\omega), \tag{10}$$

where N is the number of sites in any of the lattice planes, $\mathbf{r}_i$ and n_i represent the position vectors of site i and the layer index, respectively, and $\mathbf{k}_\parallel=(k_x,k_y)$ is a two-dimensional wave vector parallel to the surface. The summation is taken over the Brillouin zone.

We assume for simplicity only nearest-neighbour exchange interactions and take $J_{ij}=J_s$; $I_i=I_s$; $t_{ij}=t_s$; $\langle S_i^z\rangle=\langle S_s^z\rangle$; $\langle s_i^z\rangle=\langle s_s^z\rangle$ on the surface layer ($i=1$) and $J_{ij}=J$; $I_i=I$; $t_{ij}=t$; $\langle S_i^z\rangle=\langle S^z\rangle$; $\langle s_i^z\rangle=\langle s^z\rangle$ in the bulk. As a result the equation of motion for the Green's function (9) of the semi-infinite FMS for $T\leqslant T_c$ has the following matrix form:

$$(\omega-\mathbf{H})\mathbf{G}(\mathbf{k}_\parallel,\omega)=\mathbf{R}, \tag{11}$$

where $\mathbf{H}$, $\mathbf{G}$, and $\mathbf{R}$ are $\infty\times\infty$ matrices. $\mathbf{H}$ can be expressed as

$$H=\begin{pmatrix} V & -k_1 & 0 & 0 & 0 & 0 & \dots\\ -k & U & -k & 0 & 0 & 0 & \dots\\ 0 & -k & Q & -k & 0 & 0 & \dots\\ 0 & 0 & -k & Q & -k & 0 & \dots\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots\end{pmatrix}_{\infty\times\infty}$$

with

$$k_1=J\langle S_s^z\rangle,\quad k=J\langle S^z\rangle,$$

$$V=g\mu_B H_0+I_s\langle s_s^z\rangle+\frac{I_s^2\langle S_s^z\rangle\langle s_s^z\rangle}{\omega-g_e\mu_B H_0-I_s\langle S_s^z\rangle}+4J_s\langle S_s^z\rangle(1-\gamma(\mathbf{k}_\parallel))+J\langle S^z\rangle,$$

$$U=g\mu_B H_0+I\langle s^z\rangle+\frac{I^2\langle S^z\rangle\langle s^z\rangle}{\omega-g_e\mu_B H_0-I\langle S^z\rangle}+4J\langle S^z\rangle(1-\gamma(\mathbf{k}_\parallel))+J\langle S_s^z\rangle+J\langle S^z\rangle,$$

$$Q=g\mu_B H_0+I\langle s^z\rangle+\frac{I^2\langle S^z\rangle\langle s^z\rangle}{\omega-g_e\mu_B H_0-I\langle S^z\rangle}+4J\langle S^z\rangle(1-\gamma(\mathbf{k}_\parallel))+2J\langle S^z\rangle,$$

$$\gamma(\mathbf{k}_\parallel)=\tfrac{1}{2}[\cos(k_x a)+\cos(k_y a)].$$

In order to obtain the solutions of the matrix equation (11), we define two infinite-dimensional column matrices $\mathbf{G}_n$ and $\mathbf{R}_n$ with the elements given by $(\mathbf{G}_n)_m=G_{mn}$ and $(\mathbf{R}_n)_m=2\langle S_n^z\rangle\delta_{mn}$, so that Eq. (11) yields

$$(\omega-\mathbf{H})\mathbf{G}_n=\mathbf{R}_n , \tag{12}$$

which could be resolved easily by reference to the transfer-matrix method.[15,16] We introduce the two transfer functions:

$$T_1=\frac{G_{2i+1,m}}{G_{2i,m}},\quad T_2=\frac{G_{2i,m}}{G_{2i-1,m}}\quad (i\geqslant 1). \tag{13}$$

Substituting T_1 and T_2 into one column of Eq. (11), the following Green's functions can be obtained:

$$G_{11}=\frac{1}{\omega-V+k_1T_2}, \tag{14}$$

$$G_{22}=\frac{1}{\omega-U+\left(kT_1-\dfrac{k_1k}{\omega-V}\right)},\tag{15}$$

$$G_{33}=\frac{1}{\omega-Q+\left(kT_2-\dfrac{k^2}{\omega-U-\dfrac{k_1k}{\omega-V}}\right)},\tag{16}$$

and so on, where

$$T_1=\frac{1}{2k}\left[-\omega+U\pm\sqrt{\omega-U-4k^2\,\frac{\omega-U}{\omega-Q}}\right],\tag{17}$$

$$T_2=\frac{1}{2k}\left[-\omega+Q\pm\sqrt{\omega-Q-4k^2\,\frac{\omega-Q}{\omega-U}}\right].\tag{18}$$

As is well known, the poles of the Green's functions give the dispersion relation of the spin waves; therefore, the SSW spectrum can be given from Eq. (14) by the following expression:

$$\omega_s-V(\omega_s)+k_1T_2(\omega_s)=0,\tag{19}$$

which has to be numerically calculated. We get an equation of the seventh degree. It must be pointed out, however, that the seven roots obtained from Eq. (19) must be checked because extra expressions have been multiplied. We must make sure that the root does not make the expressions (ω_s-U), (ω_s-Q), etc. vanish. As a matter of fact, only two of the seven roots satisfy these requirements and therefore represent the true SSW spectra, corresponding to the ''acoustic'' and ''optical'' branches of FMS's.

The thus-obtained two solutions for the SSW can be used for the evaluation of the relative localized-spin magnetization of the surface $\langle S_s^z\rangle$:[2]

$$\langle S_s^z\rangle=\frac{1}{N}\sum_{\mathbf{k}_\parallel}\,[(S+0.5)\coth[(S+0.5)\beta\omega_s]-0.5\coth(0.5\beta\omega_s)].\tag{20}$$

However, the surface magnetization involves the SSW's ω_s, which are depending (through V and T_2, Q and U) on the surface and the bulk magnetization and spin waves, the surface and bulk conduction-electron magnetization and energy, so that all expressions must be solved self-consistently.

III. CALCULATION OF THE ONE-ELECTRON GREEN'S FUNCTION

In order to obtain the conduction-electron magnetization $\langle s_i^z\rangle$ we must define the one-electron Green's function $g_{ij\sigma}(E)=\langle\langle a_{i\sigma};a_{j\sigma}^+\rangle\rangle$. The equation of motion is given by

$$[E+0.5\sigma(g_e\mu_BH_0+I_i\langle S_i^z\rangle)]g_{ij\sigma}(E)=\delta_{ij}+\sum_\delta\,t_{i,i+\delta}g_{i+\delta,j\sigma}(E).\tag{21}$$

Analogously to the previous section, after a two-dimensional Fourier transformation we get for the matrix Green's function the following expression:

$$(E-\mathbf{N})\mathbf{g}(\mathbf{k}_\parallel,E)=\mathbf{I}\tag{22}$$

with

$$N=\begin{pmatrix} N_s & k & 0 & 0 & 0 & \dots\\ k & N & k & 0 & 0 & \dots\\ 0 & k & N & k & 0 & \dots\\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots\end{pmatrix}_{\infty\times\infty},$$

where

$$k=t\gamma(\mathbf{k}_\parallel),$$

$$N_s=-\frac{\sigma}{2}\,(g_e\mu_BH_0+I_s\langle S_s^z\rangle)+4t_s\gamma(\mathbf{k}_\parallel),$$

$$N=-\frac{\sigma}{2}\,(g_e\mu_BH_0+I\langle S^z\rangle)+4t\gamma(\mathbf{k}_\parallel).$$

$t_s=-W_s$ and $t=-W$, where W_s and W are the conduction-band width on the surface layer and in the bulk, respectively. For the different Green's functions we obtain

$$g_{11}=\frac{1}{E-N_s-kT_2},\tag{23}$$

$$g_{22}=\frac{1}{E-N-k\left(T_1+\dfrac{k}{E-N_s}\right)},\tag{24}$$

$$g_{33}=\frac{1}{E-N-k\left(T_2+\dfrac{k}{E-N-\dfrac{k^2}{E-N_s}}\right)}\tag{25}$$

and so on with

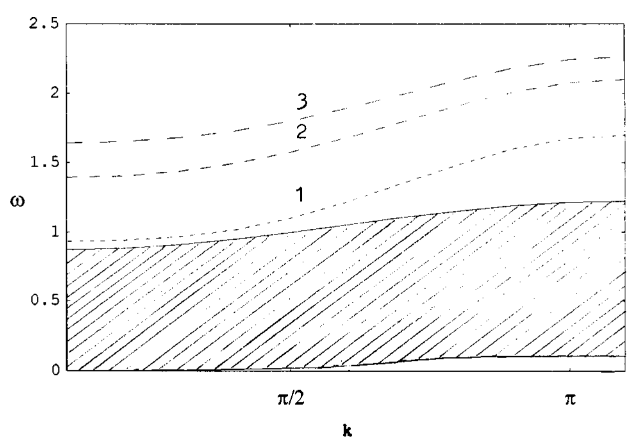

FIG. 1. The spin-wave frequencies ω plotted against k_xa, ($a=1$) for $T=0$, $H=0$, $S=\frac{3}{2}$, $I_b=0.5$ eV, $J_b=J_s=0.1$ eV, $W=0.375$ eV, $t_s=0.2t_b$, and different I_s values 1, $I_s=1.1I_b$; 2, $1.5I_b$; 3, $1.75I_b$.

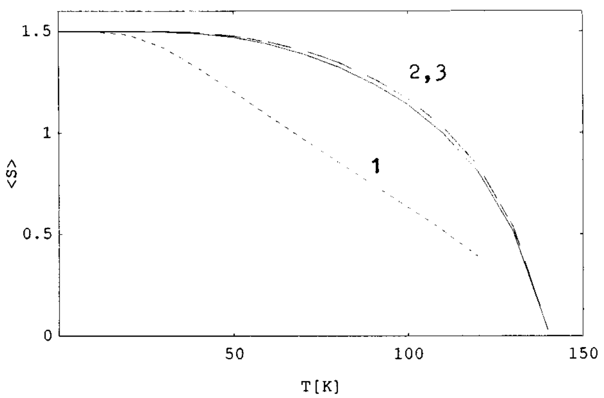

FIG. 2. Temperature dependence of the localized-spin magnetizations $\langle S_b^z \rangle$ (solid line) and $\langle S_s^z \rangle$ (dashed lines) for narrow-band FMS's with $H=0$, $S=3/2$, $I_b=0.5$ eV, $J_b=J_s=0.1$ eV, $W=0.1$ eV, $I_s=0.2I_b$ for different t_s values 1, $t_s=0.5t_b$; 2, $2t_b$; 3, $5t_b$.

$$T_1=T_2=\frac{E-N\pm\sqrt{(E-N)^2-4k^2}}{2k}. \tag{26}$$

The surface conduction-electron energy is given by the poles of the Green's function g_{11}:

$$E_s=N_s+kT_2(E_s) \tag{27}$$

and can be used for the calculation of the surface conduction-electron magnetization:

$$\langle s_i^z \rangle = \frac{n_+-n_-}{2}, \tag{28}$$

where n_+ and n_- are the numbers of conduction electrons in the spin-up and spin-down bands, respectively.[9] The expressions (19), (20), (27), and (28) form a closed system of self-consistent equations, the solution of which leads to these four quantities on the surface. So, through the renormalized conduction-electron energy and the conduction-electron magnetization $\langle s_s^z \rangle$ we take into account the t dependence of the SSW spectrum (19) and our theoretical results can be applied to narrow-band FMS's ($W \ll IS$) such as $CdCr_2Se_4$ as well as to wide-band FMS ($W \gg IS$) such as EuO.

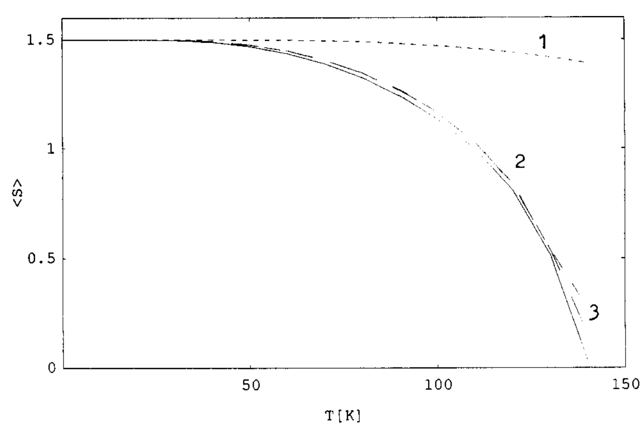

FIG. 3. Temperature dependence of the localized-spin magnetizations $\langle S_b^z \rangle$ and $\langle S_s^z \rangle$ for the same parameters as in Fig. 2 but with $I_s=2I_b$ and different t_s values 1, $t_s=0.5t_b$; 2, $2t_b$; 3, $5t_b$.

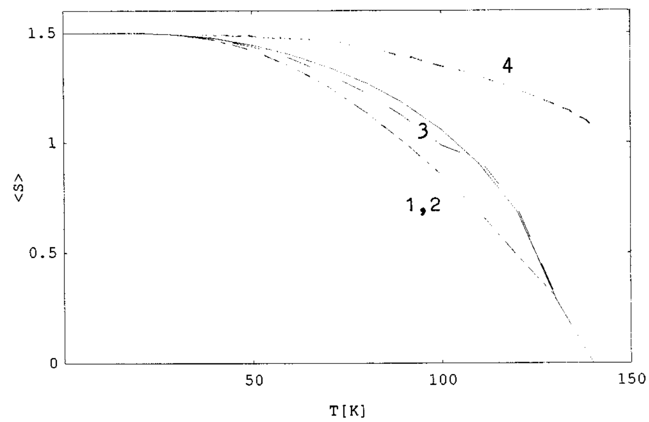

FIG. 4. Temperature dependence of $\langle S_b^z \rangle$ and $\langle S_s^z \rangle$ for wide-band FMS's with $W=1$ eV, $I_s=2I_b$, and different t_s values 1, $t_s=4t_b$; 2, $2t_b$; 3, $0.5t_b$; 4, $0.1t_b$.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section we shall present the numerical calculations of our theoretical results, which are obtained with the product of MATHEMATICA. The spin-wave frequencies are plotted for $T=0$ in Fig. 1 against $k_x a$ for a semi-infinite ferromagnetic semiconductor (the bulk spin-wave continuum is shaded). For $I_s<I_b$ we obtain only an acoustic branch, which is localized under the bulk continuum. With increasing of I_s it appears an additional optical spin-wave branch at large $k_x a$ values. For $I_s>I_b$ we get only an optical branch (Fig. 1). The bulk spin waves each appear as a continuum with upper and lower edges corresponding to $k_z=\pi/a$ and $k_z=0$, respectively, while the surface spin waves appear as discrete branches that may be above or below the continuum depending on the ratios I_s/I_b. We find that the surface s-d interaction I_s affects greatly the SSW frequencies. This is consistent with the work of Shen, Shen, and Li.[11] A similar behavior in the dependence of $\omega(k)$ on the spin-spin interaction constants J_s/J_b was obtained by Gopalan and Cottam.[14] The SSW energy decreases with rising of the hopping term t_s, in agreement with the results of Gopalan and Cottam.[14]

We have investigated the temperature dependence of the localized-spin magnetization $\langle S^z \rangle$ and the conduction-electron magnetization ρ of the bulk and the surface for both

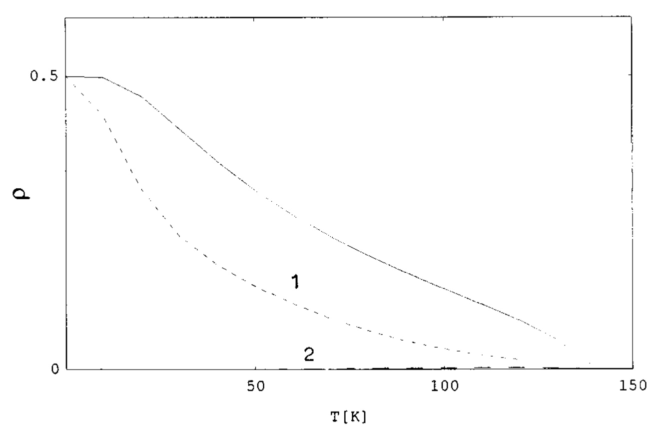

FIG. 5. The conduction-electron magnetizations ρ_b and ρ_s as a function of temperature T for narrow-band FMS's with $W=0.1$ eV, $I_s=0.2I_b$, and different t_s values 1, $t_s=0.5t_b$; 2, $2t_b$.

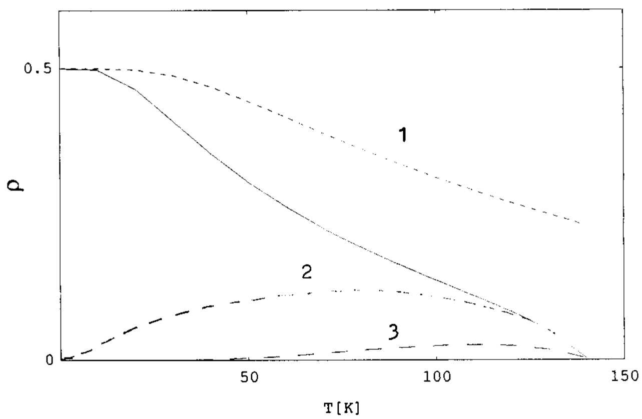

FIG. 6. The conduction-electron magnetizations ρ_b and ρ_s as a function of temperature T for $W=0.1$ eV, $I_s=2I_b$, and different t_s values 1, $t_s=0.2t_b$; 2, $2t_b$; 3, $5t_b$.

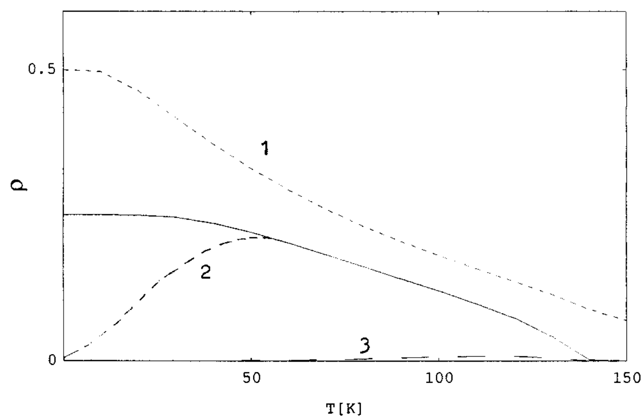

FIG. 8. Temperature dependence of ρ_b and ρ_s for $W=0.375$ eV, $I_s=1.2I_b$, and different t_s values 1, $t_s=0.2t_b$; 2, $0.5t_b$; 3, $1.2t_b$.

narrow-band ($W\ll 0.5IS$) and wide-band ($W\gg 0.5IS$) FMS's. The Bloch bandwidth W can be estimated from the measured red shift of the optical absorption edge.[17] For typical magnetic semiconductors it is $W\simeq 2.00$ eV (for EuO); 0.90 eV (for EuS); 0.55 eV (for EuSe); 0.45 eV (for EuTe); 0.2 eV (for $CdCr_2Se_4$). For $CdCr_2Se_4$ $I_b=0.5$ eV, $S=3/2$; for EuX $I_b=0.2$ eV, $S=7/2$. We shall discuss first $\langle S^z\rangle$ (T) for the simple cubic lattice. Figure 2 shows the temperature dependence of $\langle S^z\rangle$ for $W=0.1$ eV (i.e., $W\ll 0.5IS$), $I_b=0.5$ eV, $S=1.5$, and $I_s=0.2I_b$ (i.e., $I_s<I_b$). The solid line represents in all figures the bulk spin-wave magnetization $\langle S_b^z\rangle$, whereas the dashed lines—the surface magnetization $\langle S_s^z\rangle$. With increasing of t_s the surface magnetization rises and moves to the bulk magnetization. For $t_s=0.5t_b$ we obtain that $\langle S_s^z\rangle<\langle S_b^z\rangle$. The thermal variation of $\langle S_s^z\rangle$ expresses the linear temperature dependence in the temperature region near T_c^b, as observed in many semi-infinite ferromagnetic systems both theoretically[18] and experimentally.[19] For $W=0.1$ eV but $I_s=2I_b$, i.e., $I_s>I_b$, we obtain that the surface magnetization $\langle S_s^z\rangle$ is always greater compared with the bulk magnetization $\langle S_b^z\rangle$ (Fig. 3). With increasing of t_s $\langle S_s^z\rangle$ decreases, what is the opposite behavior of the case $I_s<I_b$ (Fig. 2). For $I_s>I_b$ we get $T_c^s>T_c^b$.

The temperature dependence of the localized-spin magnetization in the case of wide-band FMS's is demonstrated in Fig. 4 for $W=1$ eV and $I_s=2I_b$. With decreasing of t_s the surface magnetization rises, for $t_s=2t_b$ and $4t_b$ we get that $\langle S_s^z\rangle<\langle S_b^z\rangle$, whereas for $t_s=0.1t_b$ we have $\langle S_s^z\rangle>\langle S_b^z\rangle$ for all temperatures. For $t_s>t_b$ the surface magnetization has a linear temperature dependence.

Let us now discuss the temperature dependence of the conduction-electron magnetization ρ for band occupation $n=1$ $(0\leq n\leq 2)$. We begin with the case of narrow-band FMS's. The bulk behavior is consistent with our results for infinite systems.[9] We have to consider three different cases: $W\lesseqgtr 0.5IS$.[9] Figure 5 shows $\rho(T)$ for $W<0.5IS$, for example, $W=0.1$ eV and $I_s=0.2I_b$. From the curves can be seen that $\rho_s<\rho_b$. With increasing of the surface hopping term t_s $(t_s>t_b)$ ρ_s decreases. For small t_s values $(t_s<t_b)$ we obtain a linear temperature dependence of ρ_s in agreement with the experimental data of Paul *et al.*[19] For $I_s=2I_b$ the behavior of ρ_s is complicated. For $t_s>t_b$ (Fig. 6, curves 2 and 3) ρ_s is zero at $T=0$, then increases with rising temperature T, and at $T=T_c$ is zero again. With decreasing of t_s ρ_s grows. For $t_s=0.2t_b$ is $\rho_s>\rho_b$ and decreases with $T\rightarrow T_c$ (curve 1). For $W=0.5IS=0.375$ eV we start with $I_s=0.2I_b$ (Fig. 7). For all t_s we obtain $\rho_s<\rho_b$. At low temperatures ρ_s increases with rising temperature, goes through a maximum, and at $T=T_c$ is zero. With increasing of t_s ρ_s decreases and,

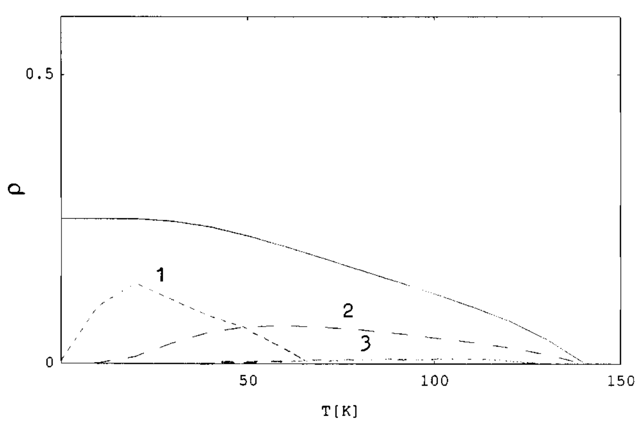

FIG. 7. Temperature dependence of ρ_b and ρ_s for $W=0.375$ eV, $I_s=0.2I_b$, and different t_s values 1, $t_s=0.1t_b$; 2, $0.5t_b$; 3, $2t_b$.

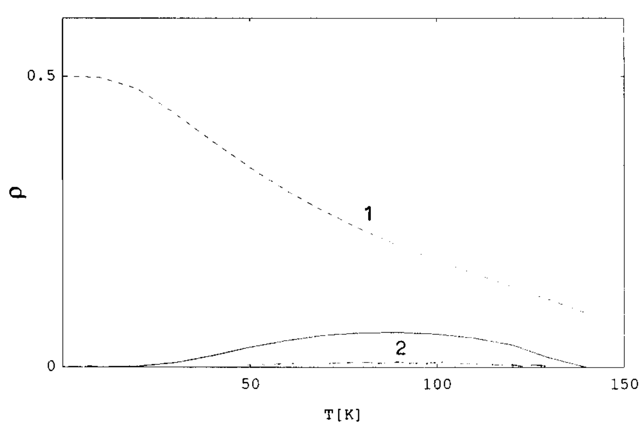

FIG. 9. Temperature dependence of ρ_b and ρ_s for $W=1$ eV, $I_s=1.2I_b$, and different t_s values 1, $t_s=0.1t_b$; 2, $2t_b$.

for example, for $t_s=2t_b$ nearly vanishes. For $I_s=1.2I_b$ (Fig. 8) we obtain a similar behavior as for $I_s=0.2I_b$, but for small t_s values, $t_s=0.2t_b$, ρ_s is larger compared with ρ_b, $\rho_s>\rho_b$, at all temperatures and we obtain again a linear temperature dependence of ρ_s. Finally we will discuss the wide-band limit (Fig. 9) for $W>0.5IS$, for example $W=1$ eV, and $I_s=1.2I_b$. For $t_s=0.1t_b$ we get that $\rho_s\gg\rho_b$ for all temperatures. At $T=0$ ρ_s is maximum, $\rho_s=0.5$, then it decreases nearly linear with T. For $t_s>t_b$ ρ_s vanishes.

V. CONCLUSIONS

A Green's-function technique combined with the transfer-matrix method is used to study the SSW modes in semi-infinite FMS's with a (001) surface. We have obtained the temperature dependence of the localized-spin and conduction-electron magnetization in the ferromagnetic phase. The theoretical results are applied to narrow-band FMS's, such as $CdCr_2Se_4$, and to wide-band FMS's, such as EuO. To our knowledge, the results on $\langle S_s^z\rangle(T)$ and $\rho(T)$ for narrow- and wide-band FMS's are given for the first time.

Most of the experimental studies of SSW to date have been for magnetic systems. It would be of considerable interest to have experimental studies carried out for magnetic semiconductor materials that would be well described by the s-d model and the method employed in this paper. Suitable techniques for studying the excitations could include inelastic light scattering (Brillouin and Raman spectroscopy) and magnetic resonance (ferromagnetic resonance, spin-wave resonance, etc.). These methods have already been applied to investigate surface and bulk spin waves in various magnetic materials.[1,2]

Several extensions of the present work are possible. These include further investigations on semi-infinite antiferromagnetic and ferrimagnetic semiconductors and in certain diluted systems by consideration of higher temperatures and both limit cases, narrow-band and wide-band magnetic semiconducting systems.

[1] D. L. Mills, in *Surface Excitations*, edited by V. M. Agranovich and R. Loudon (North-Holland, Amsterdam, 1984), p. 379.
[2] M. G. Cottam and D. R. Tilley, *Introduction to Surface and Superlattice Excitations* (Cambridge University Press, Cambridge, 1989).
[3] T. Kaneyoshi, *Introduction to Surface Magnetism* (CPC Press, Florida, 1991).
[4] R. Richter, J. G. Gay, and J. R. Smith, Phys. Rev. Lett. **54**, 54 (1985).
[5] R. H. Victora and L. M. Falicov, Phys. Rev. B **31**, 7335 (1985).
[6] G. Allan, Phys. Rev. B **19**, 4774 (1979).
[7] G. Allan, Surf. Sci. Rep. **1**, 121 (1981).
[8] A. Babcenco and M. G. Cottam, J. Phys. C **14**, 5347 (1981).
[9] J. M. Wesselinowa, Phys. Status Solidi B **120**, 585 (1983).
[10] W. Z. Shen and Z. Y. Li, Phys. Status Solidi B **171**, 493 (1992).
[11] M. R. Shen, W. Z. Shen, and Z. Y. Li, Phys. Status Solidi B **175**, 477 (1993).
[12] A. Urbaniak-Kucharczyk, Phys. Status Solidi B **186**, 263 (1994).
[13] A. Urbaniak-Kucharczyk, Phys. Status Solidi B **188**, 795 (1995).
[14] S. Gopalan and M. G. Cottam, Phys. Rev. B **42**, 10 311 (1990).
[15] Y. Zhou and T. Lin, Phys. Lett. A **134**, 257 (1989).
[16] S. T. Dai and Z. Y. Li, Phys. Lett. A **146**, 450 (1990).
[17] W. Nolting, U. Dubil, and M. Matlak, J. Phys. C **18**, 3687 (1985).
[18] T. Kaneyoshi, J. Magn. Magn. Mater. **89**, L1 (1990).
[19] O. Paul, S. Toscano, W. Hursch, and M. Landolt, J. Magn. Magn. Mater. **84**, L7 (1990).