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Journal of Magnetism and Magnetic Materials 272–276 (2004) 1242–1243
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

# The effect of proximity-induced spin density wave order and interface roughness on magnetic coupling in Fe/Cr multilayers

Vladimir N. Men'shov, Victor V. Tugushev*

*Russian Research Centre, "Kurchatov Institute", Moscow 123182, Russia*

**Abstract**

A microscopic model of proximity-induced spin density wave is suggested for the description of exchange coupling and non-collinear ordering of Fe layers in Fe/Cr layered structures with rough interfaces. The systems with relatively thick Fe and thin Cr layers are particularly considered. The Ginzburg–Landau expansion for the free energy is used to reveal the optimal magnetic configuration depending on spacer and roughness parameters, as well as on interface morphology.


*PACS:* 75.70.Cn; 75.30.Fv

*Keywords:* Fe/Cr multilayers; Spin-density wave; Roughness; Interlayer exchange coupling

A mechanism of magnetic coupling of ferromagnetic Fe layers in Fe/Cr multilayers has been the subject of special attention and intensive controversy for a long time. The role of spin-density wave (SDW) in this coupling was recently supposed to be very important [1]. Also it is well known that Fe/Cr interface morphology determined by the sample preparation procedure has a crucial influence on the coupling behavior [2]. The problem of SDW formation near the rough interface in Fe/Cr multilayers is exceedingly complex because of the necessity to take into account many factors, both geometrical and physical. In particular, there exist spatial fluctuations (both long- and short-range) of Coulomb and exchange interaction potentials between Fe and Cr layers near the interface. On the one hand, these fluctuations are connected to relatively smooth effects of Fe–Cr interdiffusion, but on the other hand, more severe consequences are provided by interfacial steps. Generally speaking, the SDW can respond to the presence of a roughness in several ways experiencing the magnitude and angular deformations both in the direction of the structure growth and in the interface plane. Averaging over the short-range (of the order of an interatomic distance) interfacial disorder can in principle be performed within framework of the standard model of SDW scattering on the point impurities [3]. However, the influence of the long-range fluctuations of the interfacial relief related to changes of the spacer thickness poses a much serious problem, which we will discuss in this work.

Recently, we have suggested a self-consistent model describing the SDW formation inside the spacer in Fe/Cr multilayer, based on the idea of charge and spin density redistribution near metal/metal interface [4,5]. This model has been successfully used to analyze the formation of collinear magnetic configurations in terms of short-range order and local phase transition into the state with inhomogeneous SDW amplitude. The key features of the phase diagram $(T, L)$ of the system, where $T$ is the temperature, $L$ is the spacer thickness, have been also explained in such a way. The effect of steps on magnetic configuration has been also qualitatively discussed [6]. In the case of large terraces, every step was established to induce the formation of an AFM domain wall with 90° rotation of the SDW polarization vector in chromium spacer. We have shown that noncollinear rather than collinear magnetic configuration of Fe layers becomes energetically favorable in the

*Corresponding author. Tel.: +95-196-9335; fax: +95-196-9194.

*E-mail address:* vvtugushev@mail.ru (V.V. Tugushev).

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doi:10.1016/j.jmmm.2003.12.077

presence of an isolated step between large terraces at the interface. In this work we study the formation of noncollinear magnetic configurations and interlayer coupling at finite concentration of steps and different interface geometry.

We consider the model of a three-layer fragment of Fe/Cr(0 0 1) superlattice comprising two ferromagnetic layers (Fe) separated by antiferomagnetic spacer (Cr). The iron layers are assumed to be sufficiently thick for magnetization within them to be considered as uniform and independent of $T$. The magnetizations of ferromagnetic and antiferomagnetic layers are implied to lie in the interface plane. We write the free energy $F = F_v + F_s$ of the system in form of the Ginzburg–Landau expansion over the SDW order parameter $\vec{A}$ and its gradients. The volume ($F_v$) and the surface ($F_s$) parts of the energy are defined as

$$F_v = \tfrac{1}{2}\int [c_1 \Delta^2 + c_2 v_F^2 (\partial \Delta(r)/\partial r)^2 + c_2 \Delta^4]\, dx\, dy\, dz,$$

$$\begin{aligned} F_s = \tfrac{1}{4}\int & dy\, dz[v(l,y,z)\Delta^2(l,y,z) \\ & + v(-l,y,z)\Delta^2(-l,y,z) \\ & + \tfrac{1}{2}\int dy\, dz[A(l,y,z)\Delta(l,y,z) \\ & + A(-l,y,z)\Delta(-l,y,z)]. \end{aligned} \quad (1)$$

Expressions for coefficients ($c_1$, $c_2$, $v$, $A$) have been done in Refs. [4–6], $v_F$ is the Fermi velocity.

Varying functional $F$ with respect to order parameter $\Delta$ yields the self-consistency equation with the boundary conditions. We maintain that in case of the thin spacer ($L \ll D$, where $D$ is interpolation length [5]) the value of $\Delta$ is nearly uniform within whole antiferromagnetic layer. However, the orientation of the SDW vector is varied on "angular" correlation length, $\sim\sqrt{L\Delta/A}$, (where positive quantity $A$ is proportional to value of the exchange interaction between Fe and Cr spins at interface) due to the presence of steps. Indeed, the thermodynamic potential $F[\Delta]$ is reduced to the effective Hamiltonian of sin-Gordon type. It contains both the "kinetic" term describing the rigidity of SDW in Cr spacer and the "potential" term describing the frustrations of exchange potential at Fe/Cr interface. Modeling the interfacial roughness as the periodical one-dimension row of steps, we have rigorously obtained the equilibrium distribution of SDW vector within the spacer. We also found the general expression for an effective coupling energy $E(\Psi)$ of magnetic moments of adjacent Fe layers through Cr spacer as a function of angle $\Psi$ between these moments. Detailed exposition of the calculating procedure would lead us far beyond the scope of this article. Therefore, we reproduce here only the research summary.

Let $\Lambda$ be the fraction of the spacer fragments containing an odd number of Cr monolayers, $\rho$ is the density of steps. In the limit of low density of steps ($\zeta\rho \ll 1$) our theory predicts the following angular dependence of the interlayer interaction:

$$E(\Psi) = -A\Delta[\Lambda \cos(\Psi/2) + (1-\Lambda)\sin(\Psi/2)], \quad (2)$$

which differs principally from that proposed in the biquadratic exchange model [1]. The minimum of function $E(\Psi)$ from Eq. (2) is attained at the nontrivial angle $\Psi_0(0,\pi)$ for all $\Lambda$ different from 0 and 1. The value of $\Psi_0$ depends only on parameter $\Lambda$, the last characterizes the geometric perfection of Fe/Cr interface.

In the limit of high density of steps ($\zeta\rho \gg 1$) and at $\Lambda = 1/2$ the interlayer interaction has the form

$$E(\Psi) = J_1 \cos\Psi + J_2 \cos^2\Psi, \quad (3)$$

corresponding to that in the well known biquadratic model, where $J_1 = -A\Delta(\Lambda - 1/2)$ and $J_2 = A\Delta/96(\zeta\rho)^2$, i.e. the biquadratic coupling parameter is inverse proportional to the spacer thickness. The comparison of expressions (1) and (3) shows that the magnitude of the interlayer coupling decays significantly with degradation of the interface quality.

The mechanism of interlayer interaction advanced by us cannot be reproduced within the framework of the standard indirect exchange scheme of RKKY type. It is in principle absent when the spacer is paramagnetic and exists only in systems exhibiting long-range or short-range AFM order.

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