INFLUENCE OF THE INTERFACE ROUGHNESS ON THE INTERLAYER COUPLING IN MAGNETIC SUPERLATTICES

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ABSTRACT

The interface roughness disturbs the planar geometry and the restraint conditions imposed (by interface potentials) on the motion of the mobile charge carriers create deviation from integral (spectral) dimensionality. In our contribution we calculate the interlayer coupling that accounts for the fractional dimensionality and show that effect interface roughness on the interlayer coupling can be accounted for by an exchange-like term which exhibits $\pi/2$ phase shift with respect to the conventional interlayer coupling derived for ideally flat interfaces.

INTRODUCTION

Recent advances in nanotechnology allow fabrication of artificially structured superlattices /SL/ with highly controlled variable chemical composition and thickness of layers. Because of their potential application in construction of electronic devices the magnetic SL become an object if intense interest. Generally the magnetic SL is a 1D structure of alternating ferromagnetic and nonmagnetic metal homogenous layers. The most unusual feature of magnetic SL is the surprisingly long period of the interlayer oscillatory, RKKY-reminiscent, magnetic coupling. There are two equivalent approaches to the description of the interlayer magnetic coupling in the SL system. Both assume that the interlayer coupling is mediated by the free electrons within the nonmagnetic metal spacer. In the approach by Bruno [1] bases on the quantum-well confinement of the free electrons that mediate the coupling. The other approach by Yafet [2] assumes that the interlayer magnetic coupling can be obtained via direct summation of magnetic interactions (across the metallic spaces) between ionic magnetic moments that populate the interfaces. In the latter case the characteristic features of the interlayer coupling such as occurrence of long periods as well as multiperiodic oscillations can be explained when discrete structure of the SL is considered. In any case the ideally flat planar interface and integral dimensionality of the free electron system is assumed. However, the interface scan exhibit roughness, which can modify the interlayer coupling. In the following we will consider a more general model which accounts for the nonitegral spectral dimensionality and surface roughness.

RKKY INTERACTION

The anisotropy of the free electron mobility in the laminar systems must be reflected in the anisotropy of the free electron spectrum. Calculations with an anisotropic spectrum are tedious and rarely give exact results. Therefore, to calculate the RKKY exchange intergrals in an anisotropic system, we will apply the method of effective spectral dimensionality by He [3]. This method is based on the observation that the anisotropic interactions in 3D space become isotropic ones in lower (fractional) dimension space, where the dimension is the Hausdorff dimension and is determined by the degree of anisotropy [3-4]. In this case a single parameter - dimensionality – contains all of the information about the perturbation, that arises due to the superlattice potentials. In this approach the fractional dimenssion is not the dimension of fractal [4]. It is not related to the geometric property directly, but to the electronic one. This means although the ionic (mass) distribution shows no self-similarity, the density of the free electron eigenstates shows fractional power law scaling $n(E)dE = (E-E_o)^{\alpha/2-1}dE$ (fractional spectral dimension). In principle the effective spectral dimension of the free electrons that are confined within quantum-well determined by rectangular potential barriers varies iwitin thw $2 < \alpha < 3$ range. However, in the case of parabolic quantum-wells the effective spectral dimensionality equals four (α=4) [5]. Extensive analytical discussion of how the FD is associated with the number of the free electron modes can be found in [6]. However, in the following, we will assume the FD α to be a phenomenological parameter extracted from experimental: optical spectroscopy, NMR, ESR or EPR data (for details see [7] and references therein). Since the perturbational approach to the RKKY interaction involves integration over dynamical states of the free electrons, the fact that the space is isotropic (though αD) offers evident calculational advantages. In the case of magnetic systems, that exhibit parabolic dispersion, approach along this line appeared very sucessfull and both RKKY-exchange [8] and interlayer coupling parameters in the systems with parabolic dispersion and of fractional spectral dimensionality within perturbative approach can be obtained .

The starting point for any description of metallic-like magnetic systems is the case of dilute alloys, when a few TM or RE ions are immersed in the sea of host conduction electrons. The effective interaction between RE or TM localized moments is mediated via the free electrons. Within perturbative approach, the RKKY interaction between magnetic moments of the magnetic ions (μ_i and μ_j) can be written as [8]

$$H(R_{ij}) = \frac{1}{2}\cdot A^2\chi(R_{ij})\cdot\mu_i\cdot\mu_j, \tag{1}$$

where $\chi(R_{ij})$ is the nonuniform static susceptibility. The explicit form of the $\chi(R_{ij})$ is given by [8]

$$\chi(R_{ij}) = -T\sum_l G(i\omega_l, R)^2, \tag{2}$$

where $\omega_l=\pi T(2l+1)$ are the Matsubara frequencies and the electronic Green's function is

$$G(i\omega,\bar{R}) = \int\frac{d^\alpha k}{(2\pi)^2}\cdot\frac{e^{i\bar{k}\cdot\bar{r}}}{i\varpi-\varepsilon_k}, \tag{3}$$

with ε_k being the free electron spectrum. The RKKY exchange integral J(r) between ionic magnetic moments in the case of effective (in general fractional) dimensionality α of the electron gas that mediates the RKKY interaction is given by [6] , [9-10]

$$J(r) = J_o\cdot r^{\alpha-2}\cdot\left(J_v(k_F r)\cdot Y_v(k_F r) + J_{v+1}(k_F r)\cdot Y_{v+1}(k_F r)\right), \tag{4}$$

with $J_v(x)$ and $Y_v(x)$ being the Bessel and Neumann functions [7], while $v=(\alpha/2-1)$ is determined by the fractional spectral dimensionality α [6].

ROUGHNESS OF THE INTERFACES

Result (1) was obtained under assumption that the interfaces are ideally flat However interfaces can exhibit roughness, which can modify the interlayer coupling. Let us consider two magnetic (rough) interfaces F_1 and F_2 of average thickness d. We assume that interfaces are populated with ferromagnetically ordered magnetic moments S_i , which interact via RKKY exchange, i.e. the coupling is given by $H(r_{ij}) = J(r_{ij})\, S_i\, S_j$. The magnetic interlayer coupling is obtained by summing $H(r_{ij})$ over all pairs ij, with i and j running over F_1 and F_2. The energy of coupling $E_{1,2}$ per unit area can be written as [1] $E_{1,2}= I_{1,2}\cos\theta_{1,2}$ where $\theta_{1,2}$ is the angle between saturation magnetizatios of F_1 and F_2. The interlayer coupling constant $I_{1,2}$ is given by [1].

$$I_{1,2} = J_o\frac{d}{V_o}S^2\sum_{j\in F_2}J(r_{oj}) = I_o\sum_{j\in F_2}J(r_{oj}), \tag{5}$$

where 0 labels one site of F_1 taken as the origin. If both interfaces are rough we can expand the exchange integrals in power series of the deviations $\xi_i = z_i - z_i^o$, $\xi_j = z_j - z_j^o$ from the positions expected for the case of ideally flat interfaces we have

$$E_{1,2} = E_{1,2}^o + \Delta E_{1,2} = J_o\sum_{i\in F_1}\sum_{j\in F_2}J(r_{ij})S_iS_j + J_o d\sum_{i\in F_1}\sum_{j\in F_2}\frac{1}{r_{ij}}\Delta J(r_{ij})(\xi_i-\xi_j)S_iS_j \tag{6}$$

where

$$\Delta J(r_{ij}) = \frac{dJ(r_{ij})}{dr_{ij}} \tag{7}$$

Under assumption that all spins within layer are oriented ferromagnetically we can replace S_i by their average i.e. $S_i \sim m_1$ and $S_j \sim m_2$ (for any i and j), where m_k is the in layer magnetization. The first term of Eq. (6) describes the interlayer coupling when both interfaces are ideally flat and provided that aforementioned assumption holds can be written as

$$E^{\circ}_{1,2} = I^{\circ}_{1,2} m_1 m_2 \tag{8}$$

The interlayer coupling parameter $I_{1,2}$ can be calculated by direct integration over interfaces leading to [6].

$$I^{\circ}_{1,2} = I_o \frac{d^2}{d^{\alpha-2}} \{J_{v-1}(k_F d) Y_{v-1}(k_F d) + 2J_v(k_F d) Y_v(k_F d) + J_{v+1}(k_F d) Y_{v+1}(k_F d)\} \tag{9}$$

with d being the average spacer thickness.

The second term of the Eq. (6) accounts for the interface roughness. If we account that in the case of α=3D electron gas the exchange integral is given by the classical RKKY formula [8]

$$J(r) = \frac{1}{r^4}[k_F r \cos(k_F r) - \sin(k_F r)], \tag{10}$$

If we take into account the formula (7) one can easily find that the leading term of $\Delta E_{1,2}$ behaves as

$$\Delta E_{1,2}(k_F r) \approx J(k_F r - \tfrac{\pi}{2}), \tag{11}$$

this means that the interface roughness generates contribution to the interlayer coupling which exhibits phase shift $\Delta\varphi=\pi/2$ with respect to the case of ideally flat interfaces. From this results that the roughness contribution has a maxima for this values of spacer thickness for which the leading term vanishes (nodes of the oscillations).

In conclusion, we have shown that in the magnetic SL the interface roughness is the source of a contribution to the effective magnetic coupling, which shows conventional oscillatory behaviour. However, contrary to the case of ideal interfaces this contribution exhibits a phase shift, which in the case of a system with effective spectral dimensionality $\alpha=3$ equals $\Delta\varphi=\pi/2$.

ACKNOWLEDGEMENT.

Financial support from the State Committee for scientific Research (KBN) through University grant is gratefully acknowledged.

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