Quantum interference effects in [Co/Bi]ₙ thin films

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Abstract. Magnetococonductivity (MC), Δσ(B), and Hall coefficient, R_H(B), measurements have been performed in polycrystalline thin films of Bi(15nm), Bi(10nm)/Co(1nm)/Bi(10nm) trilayer and [Co(0.7nm)/Bi(2nm)]₁₀ multilayer, grown by magnetron scattering. The temperature dependence of R_H(B) curves reveal the existence of a second conduction channel below 250K, that can be assigned to surface states. MC measurements between ±0.4T show at 5K an interplay between weak-antilocalization (WAL) in Bi and Bi/Co/Bi films and weak-localization (WL) in [Co/Bi]₁₀ multilayer.

1 Introduction

The quantum mechanical phase coherence length in certain thin films can be maintained over micron distances. As the size L (width or thickness) of these structures approaches the electron phase coherence length L₀, electron interference phenomena become evident. Electron quantum interference effects involve the interference of electron waves as they traverse a disordered solid. Different electron trajectories emanating from the same starting point can interfere constructively some distance later as long as they are in phase. Time-reversal invariance guarantees that the probability amplitudes $\overline{A}$ and $\overline{A}$ for clockwise and counterclockwise propagation around the closed loop are identical: $\overline{A} = \overline{A} = A$. The coherent backscattering probability $|A + \overline{A}|^2 = 4|A|^2$ is then twice the classical result. This enhanced probability for return to the point of departure reduces the diffusion constant and the conductivity, giving rise to weak localization (WL) effect in magnetococonductivity (MC), $\Delta \sigma(B) = \sigma(B) - \sigma(0)$, measurements. The WL effect can be studied experimentally by measuring the negative magnetoresistance (MR) or positive MC, peak associated with its suppression by a magnetic field B. The quantum correction to two dimensional $\Delta \sigma(B)$ can be approximated as [1,2]:

$$\Delta \sigma(B) = \frac{e^2}{\hbar} \left[ \psi \left( \frac{1}{2} + \frac{B}{2} \right) - \ln \left( \frac{B}{2} \right) \right] = \frac{e^2}{\hbar} \left[ \psi \left( \frac{1}{2} + \frac{L}{L_p} \right) - \ln \left( \frac{L}{L_p} \right) \right]$$

where $e^2/h$ is the quantum of conductance, $L_0 = (\hbar/2\pi e B)^{1/2}$ is the magnetic length, $L_p = (\hbar/2\pi e B_0)^{1/2}$ is the phase coherence length, and the coefficient $\alpha$ is: (i) $\alpha < 0$ in weak antilocalization (WAL) effect, (ii) $\alpha > 0$ in weak localization (WL) effect.

This study presents MC measurements of a pure Bi film, a Bi/Co/Bi trilayer and a [Co/Bi]₁₀ multilayer. The observed MC curves at 5K can be analysed with a two-band model [3] for fields $|B| < 0.4T$ and a WL formula [1,2] in the low-field region $|B| < 0.4T$. Here we focus only on the analysis of these MC curves in the low-field region, using a modified Hikami-Larkin-Nagaoka (HLN) function derived theoretically [1,2] for the case of a topological insulator (TI) with magnetic doping on the top surface.

2 Experimental Details

A series of thin film Co/Bi structures [4] were grown by magnetron sputtering on Si(100)/SiNₓ substrates with rectangular shapes of 5x5mm², using a base pressure of Ar-gas about $10^{-8}$ Torr, without to control the substrate temperature during film deposition. The nominal thickness values (fig.1) of Co and Bi layers were reduced to Co concentrations, c-Co, (0, 0.05, 0.26) by dividing the subtotal of Co layer thickness with total film thickness. The results in Fig.1 are tabulated with increasing order of c-Co. Resistivity and magnetococonductivity measurements were performed on the as-made films with a PPMS, using the Van der Pauw method in magnetic fields up to B=9T.

3 Results

Fig.1 shows the temperature dependence of Hall coefficient $R_H(B)$ curves for $c=0$, 0.05, 0.26. In fig.1a, pure Bi(15nm) film exhibits two different slopes below 250K, revealing a second conduction channel (probably with different concentration of charge carriers) at lower-T. Fig.1b shows that the insertion of a Co layer in between two Bi layers (trilayer) affects mainly the second
channel. The relative decrease observed in $R_H$ magnitude between $c=0$ and $c=0.05$ may imply that the effect of the second channel competes with the anomalous Hall effect (AHE) contribution. Fig.1c reveals that the competition between AHE and second channel contributions is more evident, decreasing farther the $R_H$ magnitude in a multilayer structure with larger Co concentration ($c=0.26$). Fig.2 shows the temperature dependence of $dR_H/dB$ slopes (in absolute values) obtained from linear fits in fig.1 at high fields (dash lines) and second channel (#2) field region (solid lines). All slopes in fig.2 tend to converge above 250K, indicating that the importance of the second conduction channel increases progressively below 250K. Since #2 channel appears at the intermediate field regime, there is no analytic expression between experimental $R_H$ values and charge carrier concentration or mobility values.

Fig.3a shows that the relatively large curvature, between $\pm 0.4T$, of perpendicular magnetoconductance (MG) in pure Bi(15nm) film, disappears above 5K. Fig.3b shows that the transverse MG can be separated in two regions at 5K: (i) The peak between $\pm 0.4T$ may imply a WAL contribution. (ii) At higher fields, the MG effect comes from a power-law function: $G(B) \propto B^{n(T)}$ ($1.4 \leq n(T) \leq 1.7$) that can be fitted with a two-band model.

Fig.4b reveals that at low fields the insertion of a very thin Co layer in between two Bi layers gives rise to anisotropic magnetoresistance (AMR) effect in transverse MG of the trilayer. The observed increase of field-peak, $H_{peak}$, values (where the AMR is maximum) with decreasing temperature provide evidence that the anisotropy of magnetization in Co layer is enhanced at lower-T. In addition, fig.5b shows that the $H_{peak}$ values in AMR curves are much lower in the multilayer structure, (with larger Co concentration $c=0.26$) than in trilayer (with $c=0.05$), indicating that the easy-axis of magnetization is lying in the film-plane for $c=0.26$.

Fig.4a shows that the two branches in perpendicular MG loops merge progressively at lower-T, whereas a negative MG peak emerges at 5K between $\pm 0.15T$. Such behavior is not consisted with an AMR effect only. Fig.5a shows that in multilayer structure both, the $H_{peak}$ values in AMR curves and the AMR effect (peak-height) decrease progressively from 300K to 50K, and a merging of the two MG branches occurs below 50K whereas a positive MG peak appears between $\pm 0.13T$ at 5K. Fig.6 shows a comparison among the perpendicular MC curves observed in 3 different samples ($c=0, 0.05, 0.26$) at 5K. It
reveals a behavior that is reminiscent of a crossover between WAL and WL effect observed [6] in a magnetically doped TI. However, in transverse MG loops (figs.4b, 5b) the AMR effect is predominant down to 5K, indicating that electron trajectories emanating from the same starting point cannot interfere constructively due to scattering at Co/Bi interfaces (note that the field is in film plane forcing charge carriers in trajectories across Co/Bi interfaces). Thus $L/g_{307}$ becomes indistinguishable from the elastic mean free path $L_e$ and the condition: $L/g_{307}/g_{167} L$, for WAL or WL effect is not satisfied ($L/g_{314}$ film thickness). In perpendicular MG loops an interplay between WAL and WL appears (fig.6) at 5K, evidencing that inelastic scattering of charge carriers forms closed paths inside Bi layers (since the field is bending their trajectories in film plane). It creates an $L/g_{307}>L_e$ and, thus, the condition: $L_g>\tilde{L}$, for WAL or WL effect is approached at 5K.

The observed change in $\Delta G(B)$, from negative peak in Bi/Co/Bi trilayer to positive peak in [Co/Bi]$_{10}$ multilayer (fig.6), indicates that the function in Eq.1 should become a sum of two such functions with two weight factors $\alpha_0$, $\alpha_1$ of opposite sign and two different phase coherence lengths $L_{g,0}$ , $L_{g,1}$ (see Eq.2) to reproduce the crossover from WAL to WL effect due to their competition [1,3].
The main results of this constrained fit are: (i) the observed (fig.6) increase of WAL effect from c=0 to c=0.05 comes from an increase of both $L_{o,0}$ and $L_{o,1}$ lengths, and (ii) the change from WAL at c=0.05 to WL effect at c=0.26 requires an increase of $L_{o,0}$ (or $L_0$) length by two times and a decrease of $L_{o,1}$ (or $L_1$) length by almost 2 times. This outcome is due to the single set of $a_0$ and $a_1$ values that, according to Ref.2, correspond to a common $\Delta 2E_F$ ratio for the three samples. Since the physical mechanism that creates WL and WAL in Bi films remains elusive, then Eq.2 can be considered only as a formula that may reproduce at the macroscopic level the change of $\Delta \sigma(B)$ peak from negative in Bi/Co/Bi trilayer to positive in [Co/Bi]$_n$ multilayer.

5 Conclusion

In summary, Hall coefficient loops, $R_H(B)$, reveal the existence of a second conduction channel below 250K, that can be assigned to surface states. The temperature dependence of $R_H(B)$ loops show that Co/Bi interfaces affect the contribution of the second conduction channel via the surface states in Bi layers. MC measurements between ±0.4T indicate that WAL and WL effects might be responsible for the observed peaks in $\Delta \sigma(B)$ curves at 5K. A macroscopic, $\Delta \sigma(B)$ formula (Eq.2) derived for TI can reproduce the observed change from WAL to WL in Fig.6. In this approximation, surface states may explain such behavior if they are considered inside a band gap in the bulk of Bi layers, whereas a three band model [10] for the surface states of Bi is not consisted with weak localization peaks in $\Delta \sigma(B)$ at 5K.

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