PERPENDICULAR ELECTRON TRANSPORT THROUGH MAGNETIC MULTILAYERS

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This lecture is based on papers by the author and describes different aspects of the magnetic tunneling valve effect. In the section 1 [1] the role of interface in magnetic tunneling is discussed. Section 2 [2] deals with the current-driven excitation of magnetic multilayers. Some questions of a theory for interlayer exchange energy is presented in section 3 [3].

1. Role of interfaces in the magnetic tunneling valve effect

Experiments pioneered by Julliere [1, ref.3] show that the conductance of a ferromagnet-insulator-ferromagnet tunneling junction depends on the angle between the moments of the ferromagnetic electrodes. We call this dependence the magnetic-tunneling-valve (MTV) effect. In this section we interpret MTV experiments in the light of band theory and results of corresponding ferromagnet-to-superconductor tunneling experiments. We show how matching of spin-dependent wave functions at the interface between ferromagnet and insulator explain aspects of the existing data for the MTV effect. We shall designate the ferromagnet layers separated by insulating one as (FIF) and the ferromagnet and superconducting layers separated by insulating one as (FIS).

The strength of the spin-sensitive MTV effect observed in a FIF-junction, where both electrodes are ferromagnetic and a small external field suffices to produce spin-polarized effects is measured by the change in tunnel conductance $G$ when the relative moment orientation changes from parallel to antiparallel. A valve coefficient may be defined by the expression

$$
\Delta G / G = 2(G_{\uparrow\downarrow} - G_{\downarrow\uparrow}) / (G_{\uparrow\uparrow} + G_{\downarrow\downarrow})
$$

where $G_{\uparrow\downarrow}$ ($G_{\downarrow\uparrow}$) is the conductance for like (unlike) directions of magnetization in the two electrodes [1, ref.3]. The Fig. 1 illustrates the effect observed in a junction of composition Ni-NiO-Co [1, ref.4], in which the coercivity of Co is greater than that of Ni, at 4.2 K. As the field $H$ increases from - 100 oersted, the resistance $R$ varies from a minimum plateau (Ni and Co moments $\downarrow\downarrow$), through a maximum ($\uparrow\downarrow$) at about $H = 15$ 0e where Ni has switched, and finally arrives again at a minimum plateau ($\uparrow\uparrow$) for $H \geq 30$ 0e. after Co has switched. Row 5 in Table I shows the largest (lowest-
temperature) experimental $\Delta G/G$ values for the junction compositions Ni-NiO-f where f = Fe, Co. or Ni [1, ref.4]. Row 6 gives the corresponding experimental temperatures.

Table 1. Interpretation of magnetic valve data for Ni-NiO-f junctions

<table>
<thead>
<tr>
<th>f=</th>
<th>Fe</th>
<th>Co</th>
<th>Ni</th>
<th>inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$P_f$=</td>
<td>0.44</td>
<td>0.34</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>$k_f/k_n$ =</td>
<td>0.39</td>
<td>0.49</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>$A_{hf}$ =</td>
<td>-0.23</td>
<td>-0.32</td>
<td>-0.54</td>
</tr>
<tr>
<td>4</td>
<td>$\Delta G/G =$</td>
<td>1.1%</td>
<td>1.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>5</td>
<td>$\Delta G/G =$</td>
<td>0.5-1%</td>
<td>2%</td>
<td>0.4%</td>
</tr>
<tr>
<td>6</td>
<td>$T(K)$ =</td>
<td>$\leq 4.2$</td>
<td>4.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

One can base a simple valve theory solely on the bulk itinerant-electron spin-polarization factor $P_f$ of electrode f:

$$P_f = (\rho_{f+} - \rho_{f-}) / (\rho_{f+} + \rho_{f-}) \quad (2)$$

where $\rho_{f\pm}$ is the majority(minority)-spin bulk density of states of the highly itinerant sub-bands with energy equal to the fermi energy $E_F$. Then the relation $\Delta G/G = 2P_fP_{f'}$ follows from transfer-matrix tunneling theory [1, ref.3]. It predicts $\Delta G/G = 9.7$, 7.5, and 2.4% for the three junctions listed in Table 1, respectively [1, ref.4]. To account for the disagreement between these numbers and those of row 5, one is tempted to think of spin depolarization due to inelastic non-spin-conserving effects. Consider a level rectangular potential barrier with a very small transmission coefficient. (Fig. 2.) In the absence of spin, one defines the transmission factor $D(k_L,k_R)$ as the fraction of incident probability current transmitted through the barrier as a function of the fermi wave vectors of the left ($k_L$) and right ($k_R$) electrodes. For the rectangular barrier, Harrison [1,ref.10] has obtained such an expression for the transmission factor

$$D(k_L,k_R) = \frac{16k_Lk_Rk^2e^{-2kd}}{(k_L^2 + k^2)(k_R^2 + k^2) \quad (3)$$

where ik is the imaginary wave vector inside the barrier.

Now we let $k_f$ and $k_n$ be the majority- and minority-spin fermi wave vectors, respectively, for a ferromagnet of composition f (= Fe, Co, or Ni) whose energy bands are shifted by the local Stoner molecular field $h_f$ (Fig. 3) which has generally different directions in the two electrodes having compositions f and f' (Fig. 2). The conductance $G$ is calculated by summing the electron transmission over transverse momenta of the electrons. We use the fact that $G$ is proportional to $D$ and depends on $k_L$ and $k_R$ only.