Anomalous Hall Effect in Magnetic bilayers

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Collaboration with Eugene

• 1991-1997: Univ. of Barcelona
  Ph.D. Thesis: Macroscopic Quantum Tunneling of Magnetization

• My first Physical Review paper in my life was co-authored with Eugene

• Eugene has help me so much in my whole career.
Ordinary & Anomalous Hall Effect (AHE)

\[ \rho_{xy} = \frac{1}{nq} H = R_o H \]

\[ \rho_{xy} = R_o H + 4\pi R_s M \]
Mechanisms/origins of AHE

• **Intrinsic**
  
  Karplus and Luttinger: spin-orbit coupling in Bloch bands
  
  Berry phase effects on Bloch electrons

• **Extrinsic:**
  
  Imperfection scattering of electrons in ferromagnetic materials
  
  1) Skew Scattering
  2) Side jump
Experiment for Intrinsic mechanism

Experiments support the theory of Berry phase

• CMR manganites
  (PRL, 83, 3737 (1999); 84, 757 (2000)).

• Half metallic CrO$_2$
  (PRL 89, 187201(2002)).

• Gd single crystal
  (PRB 74, 104407(2005)).
AHE in SrRuO4

- The non-monotonic temperature dependence of AHE (even changes the sign) in SrRuO4 was ascribed to Berry Phase by Fang et al.
  

- A careful measurements near the temperature at which AHE changes sign seems to contradict the Berry Phase mechanism.
  
  PRB70, 180407(2004)
Extrinsic mechanism of the AHE

(a) Skew scattering
(b) Side jump

Both introduce a transverse momentum component—AHE origin.
AHE and longitudinal resistivity

Same origin: electron scattering by imperfections

\[ R_S = a \rho_{xx} + b \rho_{xx}^2 \]

Skew Scattering  Side jump
If \( n \approx 1 \), Skew Scattering

If \( n \approx 2 \), Side jump

If \( 1 < n < 2 \), both contribute
AHE in multilayers

- **Fe/Cr multilayers, \( n \approx 2 \) to 2.6**

- **Co-Ag granular films, \( n=3.7 \)**

- **Zhang’s study using the Kubo formalism.**
  The Scaling law is always invalid for superlattice structures, because the electron mean free path is always much larger than the layer thickness in these systems.
Issues in Multilayers/bilayers

• Short-circuit of AHE

• Shunting effect
Short-circuit of AHE

- Nonmagnetic layer
- Ferromagnetic layer

$+V_{AHE}$ $-V_{AHE}$

$I_c$ $H$ $I$
Shunting effect

\[ I_{\text{whole}} = I_{Fe} + I_{Cu} \]

\[ R_{AHE} = \frac{V_{AHE}}{I_{\text{whole}}} \quad \Rightarrow \quad V_{AHE} \propto I_{Fe} \]
Fe(200nm)/Cu (x)
Verify the existence of the SCE

Fe/Cu bilayer samples were prepared, the only difference is that there is a very narrow opening in the Cu layer in the left sample. Deposited by sputtering and measured simultaneously.
Short-circuit effect in Cu/Fe bi-layer

![Graph showing the short-circuit effect in Cu/Fe bi-layer with FeCu and FeCu Opening curves.](image)

Fe2000A,Cu150A @5K, 9.2% Opening
Shunting and Short – circuit effect

\[ \rho_{xyA, \text{bilayer}} = \rho_{xyA, \text{Fe}} \cdot \frac{1}{\left( \frac{\rho_{Fe}}{\rho_{Cu}} \cdot \frac{t_{Cu}}{t_{Fe}} + 1 \right)^2} \]
Cu layer dependence

FeCu bilayers
Fe = 1400 Å
Cu thickness varying
H = 30K Oe

AHE Resistivity ($\mu\Omega\text{cm}$)

Cu layer thickness (nm)
Cu layer dependence

![Graph showing Cu layer dependence]

- Red line: Shunting effect only
- Blue line: both effects
- Experimental data points

\[ \rho_{xyA} (\mu\Omega\cdot\text{cm}) \]

\[ t_{\text{Cu}} (\text{nm}) \]
Microstructure of Cu film
$R_s \propto \rho_{xx}^n$

![Graph showing the relationship between Cu layer thickness and $\rho_{xy}$ and $\rho_{xx}$](image)

$log\log$ scale

pure Fe

$n=4.18$ er:0.06
FM/FM bilayer--- Fe/Gd

1. Fe and Gd are simple ferromagnetic materials.
2. The signs of AHE are opposite each other in Fe and Gd single layers.
3. Gd has a much lower Curie temperature, which can be achieved by PPMS.
4. Some interesting phenomenon may be observed.
AHE in Single Layers

Fe single layer

Gd single layer
Positive + Negative = ?

@5K
Fe=150 nm
Gd=210 nm

@300K
Fe=150 nm
Gd=210 nm
Temperature dependence of AHE

Fe single layer

Gd single layer
Non-monotonic temperature dependence
Conclusions

The scaling law can not be applied to the multilayer systems.