Vectorial Observation of Spin Seebeck Effect in NiFe$_2$O$_4$ Thin Films

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**Introduction**

The spin Seebeck effect (SSE), which generates spin current via temperature gradient through thin films (e.g. Y$_3$Fe$_5$O$_{12}$, NiFe$_2$O$_4$), has been an active research area of spin caloritronics. We have grown NiFe$_2$O$_4$ thin films on different substrates and studied the effect of lattice mismatch, and found that decreasing lattice match between thin film and substrate enhances thermally generated spin current from Pt/NiFe$_2$O$_4$ thin films. Moreover, we find that two perpendicular simultaneous SSE measurements can be used for vectorial magnetometry, visualizing the magnetization process in the thin film.

**Motivation**

- Optimize the deposition conditions for nickel ferrite (NiFe$_2$O$_4$ or NFO) thin films
- Enhance thermally generated spin voltage at NFO/Pt interface
- Explore a new alternative vectorial magnetometry technique to observe magnetization reversal

**Methodology**

- Pulsed laser deposition (PLD)

<table>
<thead>
<tr>
<th>Target Substrates</th>
<th>Fluence (J/cm$^2$)</th>
<th>O$_2$ Pressure (mTorr)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiFe$_2$O$_4$</td>
<td>~1000</td>
<td>10</td>
<td>700</td>
</tr>
<tr>
<td>MgGa$_2$O$_4$ (110 or 100)</td>
<td>~1000</td>
<td>10</td>
<td>700</td>
</tr>
<tr>
<td>CoGa$_2$O$_4$ (110 or 100)</td>
<td>~1000</td>
<td>10</td>
<td>700</td>
</tr>
</tbody>
</table>

- Structural characterization by X-Ray Diffraction (XRD), X-Ray Reflectivity (XRR) and Rocking Curve (RC) measurements
- Vibrating Sample Magnetometry (VSM)
- Ferromagnetic resonance (FMR)
- Spin Seebeck effect (SSE) measurements

**Experimental setup**

- (a) Longitudinal SSE setup. The sample is sandwiched between two copper blocks and a temperature gradient ΔT is applied. (b) The geometry for four-point vectorial SSE measurements. (Diagonal direction SSE measurement also can be done besides X and Y directions.)

**References**


**Acknowledgments**

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**Results and discussion**

- Standard θ-2θ diffraction patterns of NFO films (1) and different substrates (MGO (110), MGO (100), CGO (110), CGO (100))(2), respectively.
- Normalized in-plane (IP) magnetization versus magnetic field for NFO/MGO (110) (a), NFO/CGO (110) (b) and NFO/MGO (100) (c), respectively. The magnetization is measured with the external in-plane magnetic field applied in two perpendicular directions for all samples.
- LSSE measurements at various angles for Pt/NFO/MGO (110) with voltage is measured (a) along the hard axis direction (AC), and (b) along the easy axis direction (BD), respectively.
- LSSE measurements at various angles for Pt/NFO/CGO (110) with voltage is measured (a) along 0° direction (AC), and (b) along 90° direction (BD), respectively.

**Conclusions**

- Two perpendicular SSE measurements were carried out simultaneously for the first time.
- The lattice mismatch between the film and the substrate leads to strain anisotropy in the NFO thin film, which is higher for MGO than CGO substrate.
- The voltages obtained from two perpendicular SSE measurements reveal the complete reversal process of magnetization, which has potential for a new alternative vectorial magnetometry for magnetization reversal.

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