Magnon transport in antiferromagnetic strained $SrMnO_3$ thin films

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PRB 2024

https://doi.org/10.1103/PhysRevB.110.144446

[Ques] This study demonstrates long-distance magnon transport in strained antiferromagnetic $SrMnO_3$ thin films with easy-plane anisotropy, detecting both electrically and thermally generated magnons up to 2.3 μm, and reveals the critical role of Néel vector reorientation and magnon mode coupling.

[关键问题] 该研究在具有易平面各向异性的应变反铁磁 $SrMnO_3$薄膜中实现了长距离磁子输运，探测到电生和热生磁子可达 2.3 μm，并揭示了奈尔矢量重取向和磁子模式耦合的关键作用。

[Sum] This work establishes $SrMnO_3$ as a promising platform for antiferromagnetic magnonics, demonstrating efficient magnon transport influenced by strain-induced magnetic anisotropy and revealing complex distance dependencies that suggest multiple transport regimes.

[亮点 1] 在应变调控的易平面反铁磁 $SrMnO_3$薄膜中实现了长达 2.3 微米的电生与热生磁子输运，展示了反铁磁体中高效自旋信号传输的可行性。

[亮点 2] 揭示了磁子输运信号的距离依赖性存在两个特征区间，反映出由应变诱导的各向异性与磁子模式耦合共同决定的多机制输运行为。

[思考 1] 在短距离下信号增强的现象是否意味着磁子相干干涉或自旋超流行为？未来可通过变温与磁场角度依赖测量进一步探究其物理起源。

[思考 2] 能否利用电场或应变调控 Néel 矢量取向，实现对磁子极化与传播特性的电控调制，从而构建可编程反铁磁磁子逻辑器件？

[拓展阅读 1] 应变工程在复杂氧化物磁子学中的作用

[拓展阅读 1] 应变通过外延生长过程中的晶格失配引入，可显著调控复杂氧化物的磁各向异性、交换相互作用及轨道占据。对于 $SrMnO_3$这类反铁磁钙钛矿，应变不

仅改变磁各向异性轴方向，还可能影响磁子能隙与色散关系，从而调节其输运长度与衰减机制。随着应变幅度的可控化发展，研究者可通过改变衬底或层厚精确设计磁子特性，实现可调谐的反铁磁自旋传输器件，为应变磁子学（strain magnonics）提供实验与理论基础。

[拓展阅读 2] 易平面反铁磁中的磁子模式耦合与自旋传输

[拓展阅读 2] 易平面反铁磁（如 $SrMnO_3$）中磁子通常为线性极化态，不携带净角动量，因此难以直接与自旋电流耦合。实验观测到的长距离磁子输运表明，线性模式之间的耦合可通过外场或界面自旋注入诱导，形成等效的圆极化分量，实现自旋—磁子间的有效转换。该机制的效率依赖于磁各向异性、交换能与磁场方向。未来可借助非弹性中子散射或太赫兹光谱精确测定不同模式能隙的磁场演化，以理解反铁磁中“隐藏”的自旋动力学，并为低损耗、自旋绝缘体型逻辑元件奠定理论基础。
[Introduction]

The ultrafast magnetization dynamics of antiferromagnetic (AFM) materials is complex due to their intricate magnetic order and excitation modes. The study of AFM spin dynamics is performed by neutron scattering [1,2], coherent driving in the THz regime [3,4], and AFM spintronics [5,6]. For potential device applications, driving magnons by application of a charge current is favored. This can be achieved by diffusion of thermal magnons, manipulated by an injected spin current.

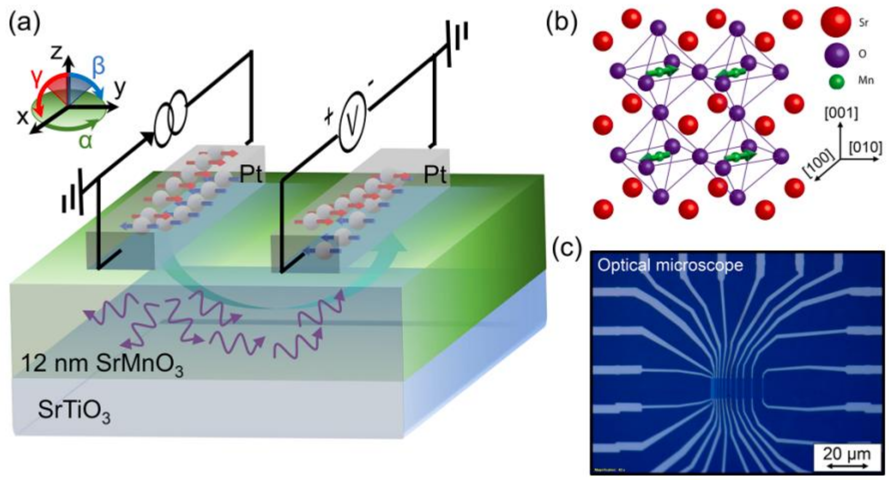
This diffusive magnon transport, driven by a magnon chemical potential, was pioneered on the low-damping ferrimagnetic material Yttrium iron garnet (YIG) [7,8] and their transport characteristics are extensively studied [9–11]. The first realization of magnon transport, driven both electrically and thermally, over long distances is demonstrated in the easy-axis AFM α-Fe_2O_3 [12]. Electrically generated magnons arise from the application of a charge current in an interfacial charge-to-spin layer, typically a heavy metal with a strong spin Hall effect. Thermally driven magnons are directed by a temperature gradient in the magnetic insulator, causing both a heat and magnon flow. However, the location of generation for thermal driven magnons is unclear and additionally the role of a multitude of other thermoelectric effects makes the resulting transport characteristics challenging, both to extract and interpret. Therefore, electrical control of magnons is more commonly pursued [13].\

Magnetic materials with a large net magnetization accommodate a single magnon mode represented by a precession of the net magnetization. Conversely, AFM materials exhibit magnon modes with circular and linear polarization, dependent on their magnetic anisotropy [14]. AFM materials with easy axis anisotropy have two degenerate magnon modes with a left-, and right-handed circular polarization which can carry spin information [12]. Thermally generated magnon transport in the quasi-two-dimensional easy-axis AFM MnPS3 has been observed around the spin flop [15] and electrically generated magnons in CrPS4 for applied magnetic fields above the spin-flip transition [16]. Additionally, spin currents have been studied in the easy-plane antiferromagnet Cr2O3 [17,18].

On the other hand, easy-plane AFMs have linearly polarized magnon modes which carry no spin angular momentum, and hence were initially not expected to display magnon transport signals [19,20]. However, α-Fe2O3 above the Morin transition temperature has an easy-plane magnetic anisotropy, and diffusive magnon transport has been observed in this phase [21,22]. Magnons with similar frequency can be coupled by the injected spin current, giving rise to a coupled mode which is circularly polarized. A distance and field-dependent coupling of the magnon modes results in a Hanle-like precession, which has been explained by a pseudospin representation [22,23].

Here we investigate magnon transport in a strongly correlated AFM material SrMnO3 (SMO), belonging to the complex oxide group. In bulk, SMO is G-type AFM with a Néel temperature of around 260 K [24,25], arising from superexchange interaction between Mn4+ ions. The magnetic order in SMO has a high degree of tunability with strain, brought about by the structural distortions of the oxygen octahedra. First principle calculations have predicted exchange anisotropy with varying strain, modifying the G-type AFM order to C type and A type. Additionally, a ferroelectric order is induced for strains above 2.6%, stabilizing a multiferroic phase with large magnetoelectric coupling [26–28]. The surface magnetic order of SMO has been studied by spin Hall magnetoeresistance measurements and the local spin Seebeck effect, revealing both a ferromagnetic surface order [29], and AFM surface order [30,31], depending on growth conditions and the stoichiometry of SMO. The magnetic anisotropy for SMO is calculated with density functional theory for 2.6% strained SMO grown on SrTiO3, revealing an easy-plane anisotropy with the hard-axis parallel to the [001] crystallographic direction (out-of-plane) for stoichiometric SMO.

In this work, we report magnon transport in the AFM insulator SMO, both electrically and thermally driven. We study the magnetic field and distance dependence of magnons driven by a spin current at 5 K in 2.6% epitaxially strained SMO grown on SrTiO3, caused by the lattice mismatch. A rotation of the magnetic field along the three directions reveals detectable nonlocal voltage modifications only for in-plane field rotations. Moreover, nonlocal voltages arising from thermal gradients are studied by detection of the second harmonic response. Finally, we also report on the decay of the magnon transport by using Pt strips with varying edge-to-edge distances.



SPELLs BeyondStory 编辑部

编辑：闫婷

投稿人：杨铸

日期：2025-11-06