Spin-filter tunneling detection of antiferromagnetic resonance with electrically tunable damping

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[Ques] Antiferromagnetic spintronics offers the potential for higher-frequency operations and improved insensitivity to magnetic fields compared to ferromagnetic spintronics. However, previous electrical techniques to detect antiferromagnetic dynamics have utilized large, millimeter-scale bulk crystals. [关键问题] 如何在微米尺度器件中实现对反铁磁共振的高灵敏度电学探测，并同时实现对阻尼的电控调节。

[Sum] 本文构建了一种基于 $PtTe_2$/双层 CrSBr/石墨的三端范德华异质结隧道器件，利用自旋过滤隧道效应直接电学探测到了 CrSBr 中的反铁磁共振，并利用 $PtTe_2$电极产生的自旋轨道力矩，首次实现了对反铁磁共振线宽（阻尼）的电学调控。

[亮点 1] 工作利用自旋过滤隧道效应在微米级器件中实现高信噪比的反铁磁共振电学探测，比传统依赖毫米级大块晶体的技术更易集成、更具器件化潜力。该方法显著降低了尺寸限制，为发展紧凑型高频反铁磁器件奠定关键技术基础。

[亮点 2] 实验结合理论模拟揭示自旋轨道力矩可选择性作用于特定子晶格，使研究者能够独立调控某一子晶格的阻尼系数。这种界面选择性效应表明异质结边界在反铁磁动力学中扮演关键调控角色，为构建子晶格级别的精细操作与信息编码提供可能。

[思考] 未来可探索该隧道探测方案是否能拓展至其他范德华反铁磁体，实现通用化、高带宽、高灵敏度的纳米尺度反铁磁共振检测平台。同时，选择性操控单个自旋子晶格的机制有望进一步发展为尼尔矢量的电切换，实现新一代反铁磁存储器件的高稳定度与低功耗操作。

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[拓展阅读 1] 什么是自旋过滤隧道效应？

[拓展阅读 1] 自旋过滤隧道是一种在携带自旋信息的电子通过磁性势垒时，自发选择某一自旋方向透射的量子效应。当一个反铁磁体作为隧道势垒时，尽管其无净磁化，但不同子晶格具有方向相反的局域磁矩，因此可形成对自旋敏感的隧道通道。通过测量隧道电流随频率的变化，可以直接接收到反铁磁共振导致的电导振荡，从而实现全电学探测。与传统光学或大尺度微波测量相比，自旋过滤隧道方式更适合集成化器件与片上高频应用。

[拓展阅读 2] 为什么能电控反铁磁阻尼？

[拓展阅读 2] 阻尼决定反铁磁共振线宽，是描述能量耗散的重要参数。$PtTe_2$ 具有强自旋轨道耦合，可在电流驱动下向 CrSBr 注入自旋流，形成自旋轨道力矩。由于界面耦合具有子晶格选择性，该力矩可精准调控靠近界面那一子晶格的阻尼强度，进而调节整体共振线宽。这种机制不仅揭示了界面在反铁磁动力学中的关键作用，也为通过外加电流构筑可编程阻尼与可调谐高频元件提供了新方案。

[introduction]

Manipulation of spin dynamics within antiferromagnets is attractive for future applications owing to the potential for high-frequency (gigahertz to terahertz) operation and insensitivity to small magnetic fields, but, because antiferromagnets have no net magnetic moment, it is challenging to efficiently detect and control these dynamics (1–3). The field of antiferromagnetic spintronics has made recent progress in demonstrating that the antiferromagnetic Néel vector can be reoriented using current pulses (4–12) and in achieving large magnetoresistance in tunnel junctions made with metallic antiferromagnet electrodes (13–15). High-frequency antiferromagnetic resonance modes have been detected using resonant absorption (16–18), optical (19–22), and spin-pumping techniques (23–25). However, the previous electrical approaches of resonant absorption and spin pumping focused on millimeter-scale or larger samples. To utilize gigahertz to terahertz antiferromagnetic dynamics for applications such as radiation sources, modulators, and detectors, it will be necessary to develop much more compact electrical devices that are capable of both detecting and manipulating these dynamics in low-damping antiferromagnets. In this study, we demonstrate micron-scale three-terminal platinum ditelluride (PtTe2)/bilayer chromium sulfide bromide (CrSBr)/graphite tunnel junctions that realize both functions. The devices achieve direct read-out of antiferromagnetic resonance in the CrSBr tunnel barrier using spin-filter tunneling (26–28) and, at the same time, allow the resonance damping to be tuned through spin-orbit torque (29–32) from the PtTe2 electrode (33, 34). The measurements reveal that the spin-orbit torque acts selectively only on the spin sublattice within the CrSBr layer adjacent to the PtTe2 electrode.

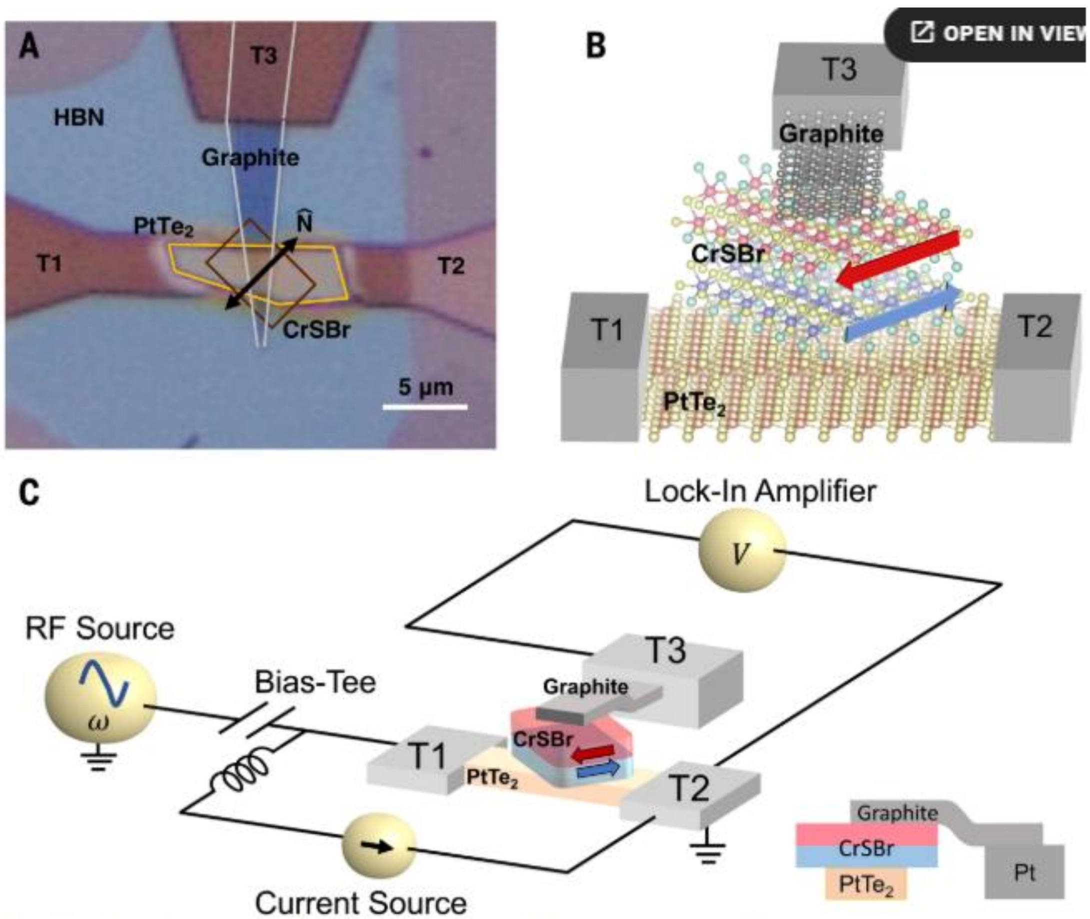

Fig. 1. $PtTe_2$/CrSBr/graphite three-terminal device and measurement configuration.

Identification of phonon symmetry and spin-phonon coupling in van der Waals antiferromagnetic $FePSe_3$

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[Ques] For engineering of van der Waals antiferromagnetic material FePSe3 and expanding its potential technological promise in spintronic fields, a detailed knowledge of the underlying physics of vibrational phonon modes and their coupling with the spin degree of freedom are undoubtedly needed.

[关键问题] 如何厘清 $FePSe_3$ 中声子模态的对称性并揭示其与自旋之间的耦合机制，从而理解磁性与晶格动力学的关联？

[Sum] In this work, by angle-resolved polarized Raman spectroscopy in corroboration with first-principles calculation, the Raman modes of bulk FePSe3 have been rationally assigned, which clarify the ambiguity about symmetry identification of some Ramanactive modes in previous studies. Moreover, through detailed temperature-dependent Raman scattering experiments, the abnormal shift of the frequency, linewidth, and integrated intensity across the Neel temperature have been identified for phonon modes associating with a non-magnetic [P2Se6]4- cluster. This can be well explained with the assistance of the spin-phonon coupling mechanism that involves the variation of the d electron transfer with lattice vibration in magnetic materials. Our results are helpful for uncovering the rich physics in FePSe3 and also for enriching the further understanding of magnetic van der Waals materials down to the 2D limit.

[亮点 1] 研究系统建立了 $FePSe_3$ 的完整拉曼模态指认体系，结合第一性原理计算排除了先前文献中在对称性归属上的分歧。特别是声子色散无虚频表明该材料具有良好的动态稳定性，同时理论与实验的拉曼峰位高度一致，为进一步探讨其磁振动耦合奠定了可靠基础。

[亮点 2] 通过角分辨偏振拉曼光谱实现了对晶格振动对称性的高精度解析。实验中利用半波片调节入射光偏振覆盖完整 0–360°范围，而样品与散射光保持固定，使

角度依赖性仅反映晶体内部振动特征，大幅提升了对声子选择定则和对称性的判别能力。

[思考] 未来可进一步研究 $FePSe_3$ 在二维极限下的声子与自旋耦合是否会因维度降低、层间相互作用消失而产生新的模态分裂或能量重整化。同时，可考虑外加应变、电场或磁场对自旋-声子耦合强度的调控，探索其是否适合作为可编程声子器件或低维磁性调控平台中的功能单元。

[拓展阅读 1] 什么是自旋–声子耦合？

[拓展阅读 1] 在磁性晶体中，局域磁矩之间的相互作用依赖于原子间距与轨道重叠，当晶格振动改变这些微观参数时，会导致交换作用随振动同步变化，即形成自旋–声子耦合。在 $FePSe_3$ 中，Fe^{2+} 的 d 电子跃迁可通过非磁性的 $[P_2Se_6]^{4-}$ 团簇进行中介：当入射光激发某一 Fe 离子的电子到导带时，其邻近 Fe 离子的 d 电子可通过该团簇发生虚跃迁并产生特定声子模态。振动同时改变轨道重叠，使拉曼频率、线宽、强度在 Néel 温度附近出现异常。这类耦合不仅揭示了磁序对晶格动力学的影响，也为利用声子表征低维反铁磁材料提供了关键窗口。

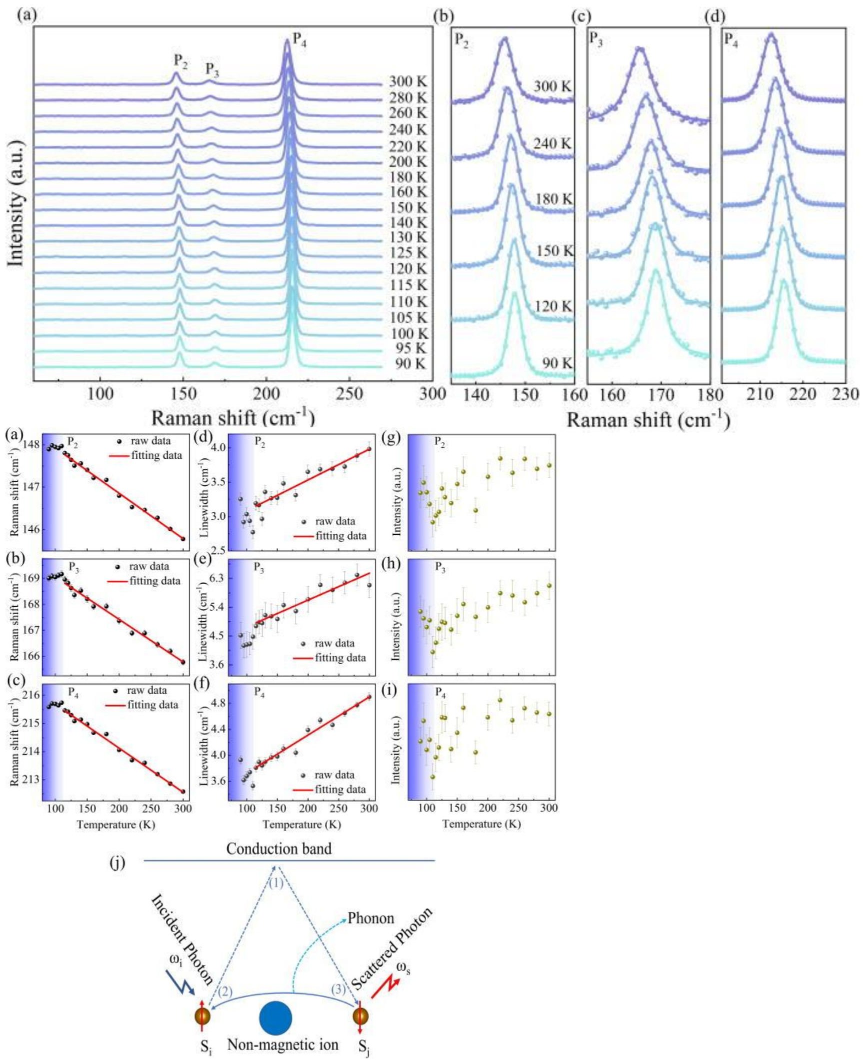
[拓展阅读 2] 为什么 $FePSe_3$ 的声子模式能反映磁性变化？

[拓展阅读 2] $FePSe_3$ 属于蜂窝状的范德华反铁磁体，磁性 Fe^{2+} 离子构成二维磁性网络，而非磁性的 $[P_2Se_6]^{4-}$ 团簇嵌于其中并承担电子跃迁与振动传播的桥梁角色。当温度接近 Néel 点时，自旋有序逐渐消失，使得 d 电子间的交换通道发生剧烈变化，从而影响声子模式的频率漂移与线宽展宽。尤其是与 $[P_2Se_6]^{4-}$ 团簇相关的振动模态，对自旋有序非常敏感，因此在温度扫描拉曼谱中表现出显著异常。这种现象反映了低维磁性体系中自旋与晶格的互相牵引关系，是研究磁性重整化、交换作用变化及其对声子动力学影响的重要实验手段。

[introduction] Recently, magnetic van der Waals (vdW) materials have attracted widespread interest around the world, since the discovery of intrinsic low-dimensional magnetism in atomically thin systems such as FePS3,1 CrI3,2 Cr2Ge2Te6,3 and Fe3GeTe2,4 laying the foundation for developing next-generation of spintronic devices. Among these materials, transition metal phosphorus trichalcogenides MPX3 (M are generally 3d elements such as Mn, Fe, Co, Ni, etc., X = S or Se) is an important family, which has been widely investigated both in theoretical5,6 and experimental7,8 aspects. Most MPX3 materials are vdW antiferromagnetic (AFM) semiconductors with magnetic properties and band gaps displaying strong dependence on the choice of M and X atoms in the host.9 Multiple types of AFM orders have been reported thus far, including Ising-type in FePS3/FePSe3,10,11 Néel-type in MnPS3/MnPSe3,12 and XYZ-type in NiPS3.13 In addition, by specific element combinations of M and X, the bandgap can be adjusted from 1.3 to 3.5 eV,14 further contributing to the optoelectronic application needs in a broad wavelength response.

Currently, compared with the sulfides, it seems that the studies on selenides have just started. FePSe3 is known as one of the important vdW antiferromagnetic semiconductors, and there have been extensive studies covering the observations from the emergence of superconductivity under high pressure,15 revealing the wide spectrum photocurrent in the FePSe3-based photodetector,16 serving as a bifunctional electrocatalyst for efficient zinc-air batteries,17 and to the modulation of magnetic order by Mn doping.18 In spite of these available interesting works, the lattice vibrations, as well as possible coupling between magnetic order and phonon (quanta of lattice vibrations) in FePSe3 have not yet been fully studied, which is highly imperative for this emerging material.

Raman spectroscopy, being highly sensitive to minute lattice vibrations, has been proven to be an effective, popular, and powerful tool for investigating the fundamental properties of vdW magnets.19,20 Polarized Raman spectroscopy is generally used to characterize the vibration symmetry and even the crystallographic orientations. While by temperature-dependent Raman scattering studies, the rich information on spin-related properties can be determined, generally through analyzing the peak splitting8 or phonon anomalies of specific modes.21 Therefore, in the present work, combining the angle-resolved polarized Raman spectroscopy characterizations with first-principles calculation, the Raman modes in FePSe3 are rationally assigned. Moreover, through carefully analyzing the temperature-dependent Raman spectra, the spin-phonon coupling effect is demonstrated due to the spin-dependent Raman scattering process. Our work provides an important step for future spin physics studies of FePSe3 down to the 2D limit.



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