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Van der Waals thin films of WTe_2 for natural hyperbolic plasmonic surfaces

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A hyperbolic plasmonic surface supports highly directional propagating polaritons with extremely large density of states. Such plasmon polaritons have been realized in artificially structured metasurfaces. However, the upper bound of the achievable plasmon wave vector is limited by the structure size, which calls for a natural hyperbolic surface without any structuring. Here, we experimentally demonstrate a natural hyperbolic plasmonic surface based on thin films of WTe_2 in the light wavelength range of 16 to 23 microns by far infrared absorption spectroscopy. The topological transition from the elliptic to the hyperbolic regime is further manifested by mapping the isofrequency contours of the plasmon. Moreover, the anisotropy character and plasmon frequency exhibit prominent temperature dependence. Our study demonstrates the first natural platform to host 2D hyperbolic plasmons, which opens exotic avenues for the manipulation of plasmon propagation, light-matter interaction and light emission in planar photonics.

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Longitudinal Spin Excitations and Magnetic Anisotropy in Antiferromagnetically Ordered $BaFe_2As_2$

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We report on a spin-polarized inelastic neutron-scattering study of spin waves in the antiferromagnetically ordered state of $BaFe_2As_2$. Three distinct excitation components are identified, with spins fluctuating along the c axis, perpendicular to the ordering direction in the ab plane and parallel to the ordering direction. While the first two ''transverse'' components can be described by a linear spin-wave theory with magnetic anisotropy and interlayer coupling, the third ''longitudinal'' component is generically incompatible with the local-moment picture. It points toward a contribution of itinerant electrons to the magnetism that is already in the parent compound of this family of Fe-based superconductors.

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Among very different classes of materials, including the Fe-based superconductors (FeSCs), the cuprates, and the heavy-fermion compounds, a striking feature of unconventional superconductivity is that it commonly appears close to an antiferromagnetic (AF) phase [1]. Since magnetism may be a common thread for the pairing interaction in unconventional superconductors [2], it is important to determine the microscopic origin of the AF order. For the cuprates, it is well accepted that their Mott-insulating parent compounds have localized moments, and the spin waves can be well described by a Heisenberg model [3–5]. In the case of iron-pnictide families of FeSCs, there is no consensus on the origin of the colinear AF order in the parent compounds [6–9]. On the one hand, the parent compounds of FeSCs are semimetals with hole- and electronlike Fermi pockets at the Brillouin-zone center and zone corners, respectively [Fig. 1(a)] [10–13], and the AF order [Fig. 1(b)] may arise from nesting between the hole and electron Fermi pockets [10], much like the spin-density-wave (SDW) order in chromium [14]. On the other hand, the bad-metal phenomenology of iron pnictides [15] suggests that these materials are near a Mott transition with magnetism arising from localized moments, much like in the cuprates [16–18].

If the AF order in the iron pnictides arises entirely from localized moments on Fe, spin waves from these moments should be purely transverse spin excitations (TSEs), with moments fluctuating perpendicular to the staggered magnetization, keeping an unchanged magnitude. In contrast, if Fermi-surface nesting and itinerant electrons contribute significantly to the AF order, one would expect the presence of longitudinal spin excitations (LSEs) with fluctuating moment sizes [19–22], similar to the LSEs seen in the SDW state of chromium [23]. Although unpolarized inelastic neutron-scattering (INS) experiments have mapped out spin waves in the iron-pnictide parent compounds $CaFe_2As_2$ [8,24], $BaFe_2As_2$ [25], and $SrFe_2As_2$ [26], the spectra can be described by either local-moment [8,25] or itinerant models [21,24,26]. To conclusively determine if itinerant electrons contribute to the magnetism, one needs to perform spin-polarized INS experiments to search for LSEs in the AF ordered state. In spite of considerable efforts in this direction on $BaFe_2As_2$ [27] and NaFeAs [28], no clear evidence for LSEs has been found. While the lack of LSE signal has been suggested in the previous spin-polarized INS study on $BaFe_2As_2$ [27], the

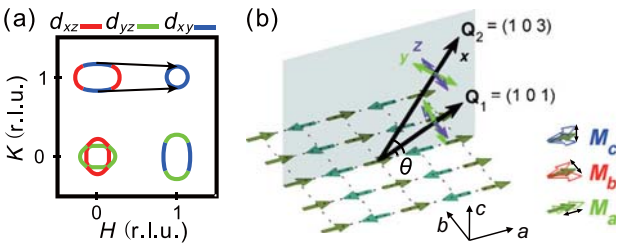

FIG. 1. (a) Fermi surface of $BaFe_2As_2$, reproduced from Ref. [40] using the band structure from Ref. [42]. Arrows indicate nesting vectors. (b) Spin arrangement and fluctuation directions in the AF phase of $BaFe_2As_2$. Coordinate systems for neutron polarization are indicated for two examples $\mathbf{Q}_1$ and $\mathbf{Q}_2$.

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The Optical Properties and Plasmonics of Anisotropic 2D Materials

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In the fast growing 2D materials family, anisotropic 2D materials, with their intrinsic in-plane anisotropy, exhibit a great potential in optoelectronics. One such typical material is black phosphorus (BP), with a layer-dependent and highly tunable bandgap. Such intrinsic anisotropy adds a new degree of freedom to the excitation, detection, and control of light. Particularly, hyperbolic plasmons with hyperbolic *q*-space dispersion are predicted to exist in BP films, where highly directional propagating polaritons with divergent densities of states are hosted. Combined with a tunable electronic structure, such natural hyperbolic surfaces may enable a series of exotic applications in nanophotonics. Herein, the anisotropic optical properties and plasmons (especially hyperbolic plasmons) of BP are discussed. In addition, other possible 2D material candidates (especially anisotropic layered semimetals) for hyperbolic plasmons are examined. This review may stimulate further research interest in anisotropic 2D materials and fully unleash their potential in flatland photonics.

1. Introduction

The past decade has witnessed significant progress in the field of 2D materials. Strong interactions with light have been demonstrated in atomically thin 2D materials.[1–12] For example, single-layer graphene can absorb 2.3% of the incident light in the visible to near-IR spectral range, which is associated with interband transitions.[1,2] More surprisingly, for intraband transitions in the terahertz range, the light extinction for doped single-layer graphene can even reach 60%.[4] Such strong optical absorption in 2D materials provides promising platforms for future optoelectronic applications, such as photodetectors,[13–16] light emitters,[17,18] and optical modulators.[19,20]

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Beyond graphene, transition metal dichalcogenides (TMDCs) (e.g., MoS_2, $MoSe_2$, WS_2, and WSe_2) are also important members of the 2D materials family. They possess many intriguing properties, such as spin–valley coupling,[21–24] strong many-body interactions,[7–9] and indirect-to-direct bandgap transition in the monolayer limit.[25,26] Their optical absorption is mainly in the visible spectral range, and inherently isotropic (identical to that of graphene). In addition, hexagonal boron nitride (hBN), with an insulating bandgap of ≈6 eV, is another well-known 2D material that is widely used as an excellent dielectric in 2D-material-based electronics.[27] Although anisotropic light emission from monolayer hBN has been demonstrated in the visible range, this anisotropy is not intrinsic and is instead due to vacancy-related defects.[28]

Recently, anisotropic 2D materials with intrinsic in-plane band anisotropy, summarized by Li et al.,[29] have attracted significant attention. Among them are black phosphorus (BP), ReX_2 (X = S, Se), MX (M = Sn, Ge; X = S, Se), etc., with reduced crystal symmetry. Compared to graphene and TMDCs, one of the landmark features for anisotropic materials is their capability to detect and control light polarization. As an elemental 2D material beyond graphene, BP has been widely studied due to its tunable direct bandgap and relatively high mobility. In 2014, Li et al. reported the pioneering work on 2D BP transistors, with the carrier mobility reaching ≈1000 cm^2 $(V\ s)^{-1}$ at room temperature, showing very encouraging device performance.[30] BP has a direct bandgap that exhibits a strong layer dependence, ranging from 0.3 eV (bulk) to 1.7 eV (monolayer).[31–34] It covers a broad frequency range from visible to mid-IR, filling up the gap between the most popular graphene and TMDCs. Moreover, the bandgap can be further tuned by strain[31,35–40] and electric fields,[41–44] and even fully closed with a semiconductor-to-metal transition.[37,41] The sizeable and highly tunable direct bandgap, combined with the relatively high carrier mobility, makes BP a promising candidate in IR photonics and optoelectronics.

Most importantly, BP exhibits a unique in-plane anisotropy, originating from the puckered atomic structure. Inside each BP layer, which consists of two sublayers, P atoms are covalently connected to three neighboring atoms to form the puckered hexagonal unit, while the BP layers are held together by weak van der Waals (vdWs) interactions. The low lattice symmetry of BP leads to two distinct in-plane directions: armchair (AC,

Observation of magnetoelastic effects in a quasi-one-dimensional spiral magnet

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We present a systematic study of spin and lattice dynamics in the quasi-one-dimensional spiral magnet $CuBr_2$, using Raman scattering in conjunction with infrared and neutron spectroscopy. Along with the development of spin correlations upon cooling, we observe a rich set of broad Raman bands at energies that correspond to phonon-dispersion energies near the one-dimensional magnetic wave vector. The low-energy bands further exhibit a distinct intensity maximum at the spiral magnetic ordering temperature. We attribute these unusual observations to two possible underlying mechanisms: (1) formation of hybrid spin-lattice excitations and/or (2) "quadrumerization" of the lattice caused by spin-singlet entanglement in competition with the spiral magnetism.

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I. INTRODUCTION

Multiferroic spiral magnets [1–4] offer a useful test ground for us to gain insight into the coupling between the spin and lattice degrees of freedom. While an extensive understanding of magnetoelastic effects has been attained in the static regime [5–10], investigation of their counterparts in the dynamic regime has proved a more demanding task. The challenge is in part brought about by a rich yet diverse set of experimental observations in both spiral [11–21] and colinear [22–25] magnets, for which a unified theory is still lacking. To make progress in this direction, it is desirable to study materials with simple crystal and magnetic structure, so that the lattice and spin dynamics can be separately determined and compared.

An even more interesting case is when spiral magnetism meets low dimensionality. In reduced dimensions, long-range magnetic order becomes unstable against thermal and/or quantum fluctuations, whereas local entanglement of spins (i.e., spin singlets) becomes more favorable since each spin has only a small number of interacting neighbors. Competition between Néel-type long-range magnetic order and spin-singlet formation has been widely explored in one-dimensional (1D) antiferromagnetic chains, with in-depth investigations both in theory [26–29] and in experiments, particularly for the case of spin-$\frac{1}{2}$ systems [30–32]. Low-dimensional spiral magnets, which commonly host frustrating spin interactions, are particularly interesting because magnetic frustration may further promote spin-singlet formation [33–35]. As spin-singlet valence bonds and lattice dimerization are often two sides of the same coin in real materials [36–38], this provides a second route to magnetoelastic coupling, distinct from the one related to spiral magnetism which requires explicit consideration of spin-orbit interactions [2–4].

The recently discovered multiferroic material $CuBr_2$ [39] presents an interesting case in this regard. $CuBr_2$ has a simple crystal structure that belongs to the monoclinic space group $C12/m1$ (no. 12), with only three atoms in the primitive cell. The structure consists of edge-sharing CuBr4 squares that form ribbons running along the b axis. Each ribbon constitutes a spin-$\frac{1}{2}$ chain with dominating next-nearest-neighbor antiferromagnetic spin interactions, whereas the nearest-neighbor (ferromagnetic) and interchain spin interactions are considerably weaker [40], rendering the system as quasi-1D. Because of the frustrating intrachain interactions and the presence of interchain interactions, an incommensurate spiral magnetic order develops below $T_N = 73.5$ K with a propagating wave vector $\mathbf{Q}_{AF} = (1, 0.235, 0.5)$ in reciprocal lattice units (r.l.u.) [39–41]. The component $q_M = 0.235$ along the $\hat{\mathbf{b}}^*$ direction corresponds to about 85° spin rotation between adjacent Cu along the chain. A sketch of the crystal and spin structure can be found in the Supplemental Material (SM [42]). Such a spin pattern breaks the inversion symmetry and gives rise to spontaneous ferroelectric polarization below T_N via the inverse-Dzyaloshinskii-Moriya mechanism [43]. Here, we report a systematic characterization of dynamic signatures of magnetoelastic coupling in $CuBr_2$ that are likely related to the spiral magnetism and/or the low dimensionality of the system.

II. EXPERIMENTS AND RESULTS

Throughout our presentation, the polarization geometries of infrared (Raman) experiments are indicated by one (two) italic letter(s) that specifies the incoming (incoming and scattered) photon polarization with respect to crystallographic directions. A detailed description of our experimental methods can be found in the SM [42]. Figures 1(a) and 1(b) display Raman spectra obtained in the *aa* geometry over a wide temperature (T) and energy range. Upon cooling, a broad signal develops with an increasing characteristic energy, and intensities averaged over three representative spectral ranges (R1–R3), which are calculated by integrating the areas, all show clear anomalies at T_N [Fig. 1(c)]. The T dependence, together with the distribution of spectral weight primarily in

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Polarization of the edge emission from Ag/InGaAsP Schottky plasmonic diode

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Electrical plasmonic sources with compact sizes are a fundamental component in plasmonics. Here, we report a simple plasmonic diode having an Ag/InGaAsP quantum well Schottky structure. The polarization ratio (TM:TE) of the edge-emission photoluminescence for the quantum wells is about 2:1 and increases to about 3:1 after covered by Ag. As contrast, the electroluminescence polarization ratio exceeds 10:1 at a low current, indicating a high plasmon generation efficiency but drops gradually as current increasing; simultaneously, the peak wavelength red shifts evidently, which are attributed to the recombination zone shift and quantum confinement Stark effect. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4792508]

Surface plasmon polaritons (SPPs) show unique properties such as great field enhancement and sub-wavelength field localization and so have attractive application prospects in nanophotonics,[1] imaging,[2] metamaterials,[3] bio-sensing,[4] and other fields. In these applications, SPPs are generally excited by light or e-beam illumination at present; however, the electrical SPP sources are more practical and in urgent need.[5] Recently, several types of them are investigated based on special organic light-emitting diodes (LEDs),[6,7] metal-insulator-semiconductor,[8] metallic slot waveguide,[9] and quantum-well (QW) LEDs.[10–13] One of the fundamental issues of the electrical excited SPP diode is its metallic electrical contact.[5] In order to most efficiently couple the radiation power into the SPP modes, the active region should be placed as close as possible (normally <100 nm) to the metal component which is regularly used as the electrode. Thus, the tiny separation between the active region and the metal causes difficulty in the fabrication of conventional ohmic contact due to the diffusion of metallic elements into the active region when heated for metallization. Considering that the noble metals like Ag (or Au) are frequently used both in Schottky junctions and plasmonic structures,[14] we here demonstrate a simple Ag-QWs Schottky plasmonic diode, which has an efficient SPP generation efficiency and highly polarized electroluminescence (EL) when the diode is forward biased. This work shows that the simple and fundamental metal-semiconductor structure can be a candidate for an efficient electrical plasmonic diode and indicates a significant progress to an electrical Schottky SPP laser or amplifier.[15,16]

The schematic configuration of the Schottky plasmonic diode is illustrated in Fig. 1(a). The InGaAsP tensile strain multiple (7 x)- QW structure for 1.55 μm wavelength was grown on a p-type InP substrate, similar to that for conventional InP lasers. Here, the tensile strain is for yielding a higher transverse-magnetic (TM) mode gain relative to the transverse-electric (TE) mode. The electric fields for TM and TE modes are normal to and parallel to the QW plane, respectively, as defined in Fig. 1(c). Noticeably, the shown upper InGaAsP separate confinement heterostructure (SCH, 1.2 Q) has been thinned to 30 nm by wet etching to guarantee sufficient coupling between SPPs at Ag/SCH interface and the QW emitters while the metal loss is not heavy. After the formation of back side Ohmic contacts, Schottky contact was formed by evaporation of about 100 nm Ag film on top of the thinned SCH layer. This is a modified Schottky structure. The QWs in close proximity to metal are introduced to confine the carriers and then their recombination zone. Ag has a work function close to the electron affinity in InGaAsP, beneficial for electron injection from it to semiconductor. Finally, the samples were cleaved into 300 μm $\times$ 600 μm pieces by a lancet to form well-defined edges. Polarization-resolved photoluminescence (PL) or EL signals were collected from the sample edge, from which we can deduce the SPP generation inside the device if any. Figure 1(b)

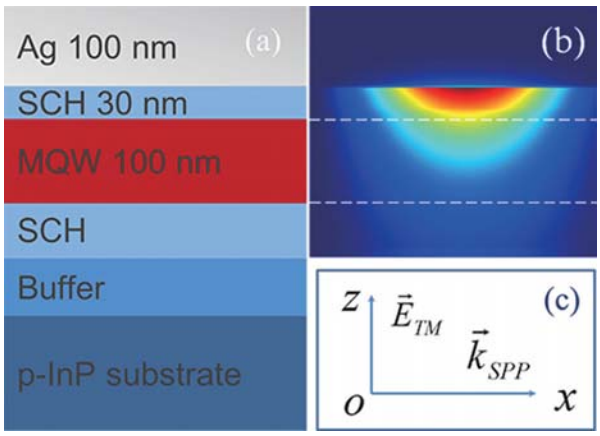

FIG. 1. (a) The schematic configuration of the Ag/InGaAsP Schottky SPP-emitting diode. MQW: multiple-QW. (b) The electric-field distribution of the fundamental surface plasmon mode. (c) The electric field direction for the TM modes and the propagation direction of SPPs.

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Spectroscopic studies of plasmons in topological materials

Wang Chong Xing Qiao-Xia Xie Yuan-Gang Yan Hu-Gen

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