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Investigation of self-hybridized waveguide exciton-polaritons in the two-dimensional antiferromagnet CrSBr at room temperature

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Abstract. The interaction between light and excitons in van der Waals materials offers new avenues for exploring strong coupling in quantum systems. Exciton-polaritons, arising from the coherent hybridization of excitons and photons, provide a unique platform for studying collective interactions, optical anisotropy, and tunable responses in low-dimensional structures. This work investigates the self-hybridization of photonic and excitonic modes in a waveguide based on the two-dimensional antiferromagnetic semiconductor CrSBr. Using angle-resolved photoluminescence and numerical modeling, we demonstrate that the pronounced anisotropy of exciton localization along the crystallographic *b*-axis leads to strong interaction with the waveguide mode. The observed anticrossing of dispersion curves is quantitatively described by a coupled oscillator model with a coupling strength of ~185 meV, providing direct evidence for the formation of self-hybridized exciton-polaritons. In the orthogonal polarization, no such interaction occurs, and only directional waveguide emission is detected. These findings pave the way for miniaturized polaritonic devices based on van der Waals magnets, where light matter interaction can be controlled by both waveguide geometry and magnetic order.

Keywords: two-dimensional semiconductors, exciton-photon coupling, self-hybridization, angle-resolved photoluminescence

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Исследование самогибридизованных волноводных экситон-поляритонов в двумерном антиферромагнетике CrSBr при комнатной температуре

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Аннотация. Взаимодействие света с экситонами в ван-дер-ваальсовых материалах открывает новые пути для исследования сильной связи в квантовых системах. Экситон-поляритоны, возникающие при когерентной гибридизации экситонов и фотонов, представляют собой уникальную платформу для изучения коллективных взаимодействий, оптической анизотропии и управляемых откликов в низкоразмерных структурах. В данной работе исследована самогибридизация фотонной и экситонной мод в волноводе на основе двумерного антиферромагнитного полупроводника CrSBr. Методами спектроскопии угло-разрешённой фотолюминесценции и численного моделирования продемонстрировано, что выраженная анизотропия экситонной локализации вдоль кристаллографической оси *b* приводит к сильному взаимодействию с волноводной модой. Наблюдаемое антипересечение дисперсионных кривых количественно описано моделью связанных осцилляторов с энергией связи ~185 мэВ, что прямо подтверждает образование самогибридизованных экситон-поляритонов. В перпендикулярной поляризации подобное взаимодействие отсутствует, и регистрируется только направленная волноводная эмиссия. Полученные результаты открывают перспективы создания миниатюрных поляритонных устройств на основе ван-дер-ваальсовых магнитов, в которых взаимодействие света с веществом может контролироваться как геометрией волновода, так и магнитным порядком.

Ключевые слова: двумерные полупроводники, экситон-фотонная связь, самогибридизация, угло-разрешённая фотолюминесценция

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Introduction

The interaction between light and excitons in van der Waals semiconductors has established these materials as a versatile platform for strong light–matter coupling and polaritonic phenomena [1 – 3]. In particular, materials combining a high refractive index, strong in-plane optical anisotropy, and large excitonic oscillator strength are especially attractive for realizing waveguide-based and cavity-free polariton systems operating at room temperature [4 – 6]. Chromium sulfide bromide (CrSBr) has recently emerged as a unique two-dimensional semiconductor in this context. Owing to its large refractive index and pronounced birefringence, CrSBr supports strongly confined optical modes with polarization-dependent dispersion, while simultaneously hosting robust excitons with large binding energies and strong oscillator strength [7].

Optical studies have demonstrated that the excitonic response of CrSBr dominates the dielectric function along one crystallographic axis, leading to extreme optical anisotropy and highly directional light propagation [8]. This combination of high-index dielectric response and strong excitonic resonances enables efficient hybridization between excitons and confined photonic modes, giving rise to a variety of polaritonic phenomena. Recent works have reported waveguide and cavity exciton polaritons in CrSBr, including strong and ultrastrong coupling regimes, polarization-selective polariton modes, and self-hybridized exciton–photon states arising from the intrinsic optical properties of the material [9 – 11]. More broadly, strong excitons in van der Waals semiconductors have enabled nonlinear polariton effects and, in suitably engineered systems, signatures of polariton Bose–Einstein condensation [12, 13].

Despite the rapid progress in understanding exciton polaritons in CrSBr, the behavior of these hybrid modes within the light cone remains largely unexplored. This regime is particularly important because it governs the interplay between guided near-field excitations and radiative far-field modes, and is directly relevant for the design of integrated polaritonic devices. Understanding how strong excitonic resonances in CrSBr hybridize with waveguide modes in this regime is therefore essential for developing compact, room-temperature polariton platforms based on anisotropic van der Waals semiconductors.

Results and Discussion

This article investigates a waveguide based on the two-dimensional van der Waals magnetic semiconductor CrSBr. A multilayer CrSBr sample was prepared by mechanical exfoliation from a bulk crystal and subsequently dry-transferred onto a SiO$_2$ substrate patterned with cylindrical pedestals etched using hydrofluoric acid. The thickness of the CrSBr layer, which governs the formation of a single optical waveguide mode, was controlled and verified via atomic force microscopy.

The waveguide layer thickness was selected based on simulations of the guided mode within the material, ensuring its spectral proximity to the exciton resonance at approximately 1.3 eV. The mode distribution, calculated using the transfer matrix method, is shown in Fig. 1, *a*. To understand the waveguide mode formation, we took refractive index data from the work of our colleagues [7] (inset in Fig. 1, *a*). The results reveal a strong localization of the excitonic resonance along the *b*-axis.

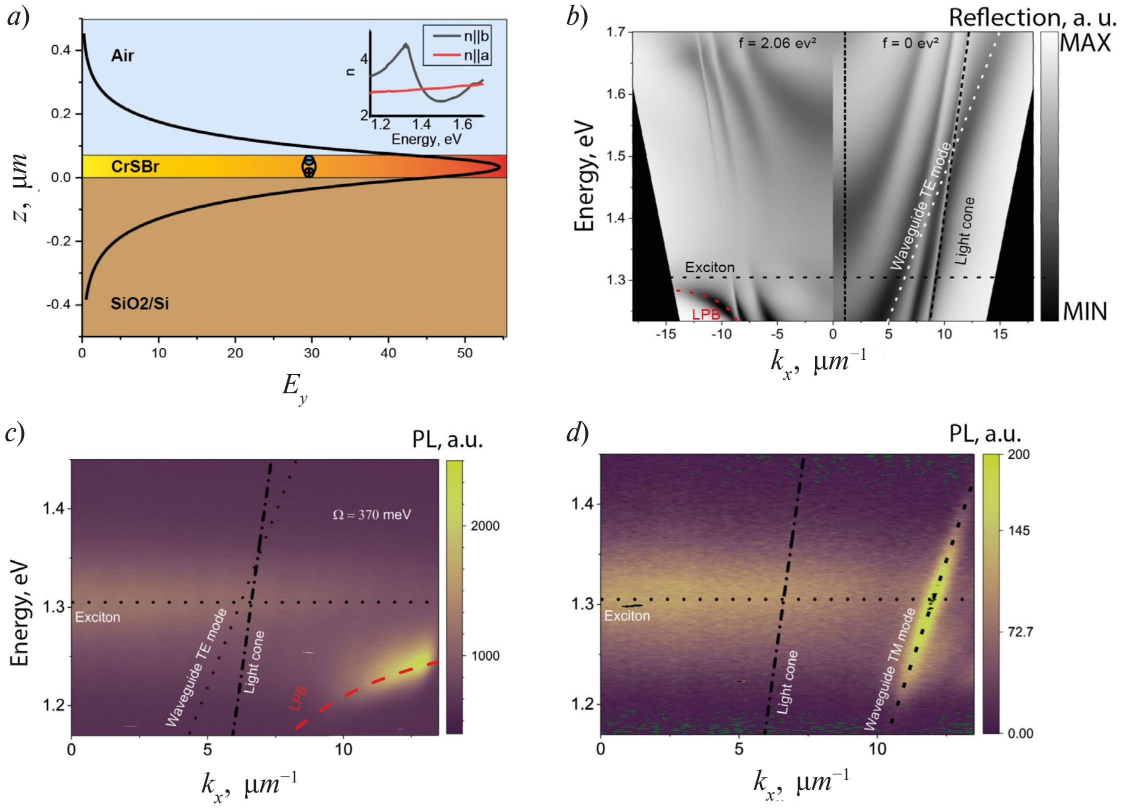

Fig. 1. Schematic representation of the sample (*a*);
transfer matrix method results for oscillator strength 2.06 eV2 and 0 eV2 (*b*);
angle-resolved photoluminescence spectra for TE (*c*) and TM (*d*)

First, we conducted a simulation of waveguide modes. We used the refractive index data featuring the exciton resonance, fitted it, and extracted an oscillator strength of 2.06 eV^2. Subsequently, we simulated reflectance spectra in the presence of a high index GaP layer for two cases: using the measured refractive index and using a background refractive index (~3.4) without the excitonic resonance. The simulation results are shown in Fig. 1, *b*. The figure shows the calculated reflection spectra. The figure is divided into two parts, which differ in the strength of the exciton resonance oscillator. The figure on the right shows a waveguide mode with an exciton resonance oscillator strength equal to zero. The white dotted line shows the dispersion of the waveguide mode, the black horizontal dotted line shows the position of the exciton resonance, the oblique black dotted line labeled with a grid cone shows the boundary of the wave vectors freely propagating into the open space. The red dotted line on the left side of the drawing shows the lower polariton branch. A clear anticrossing between the photonic and waveguide modes within the excitonic resonance region is observed, indicative of self-hybridized exciton-polaritons.

Following this, we conducted a series of angle-resolved photoluminescence experiments using a solid immersion lens. Measurements were performed in an Otto geometry with a high-index GaP solid immersion lens [14]. This configuration, combined with a high-aperture objective, enabled access to large wavevectors beyond the light cone ~16 μm^{-1}. Data were acquired for two orthogonal polarizations.

Fig. 1, *c* clearly shows the anticrossing between the waveguide and excitonic modes. Fitting this dispersion with a coupled oscillator model yields a coupling strength of ~185 meV and Rabi splitting of ~370 meV, which indicates that there is a strong coupling. In contrast, Fig. 1, *d* shows no anticrossing; instead, the photoluminescence is coupled directly into the transverse magnetic (TM) waveguide mode. The difference in behavior indicates the essential role of polarization properties and symmetry of modes in the interaction process.

To better understand the formation of exciton polaritons and their relationship to the waveguide mode in the material, angle-resolved reflectance measurements were performed on samples with different thicknesses. Fig. 2, *a* shows the measured angle-resolved reflectance maps for various thicknesses. It can be observed that the polariton branches shift to lower energies with decreasing thickness. Numerical simulations were also conducted for the measured thicknesses; Fig. 2, *b* shows a similar behavior of the waveguide polariton modes. Unlike the experiment, where the low-energy part exhibits weak contrast due to the spectral sensitivity of the silicon CCD detector, the simulation provides a clearer picture. For the two largest thicknesses, the lower polariton branch becomes visible. In general, the observed and modeled data show that the selection of the sample thickness can control the position of the polariton dispersion.

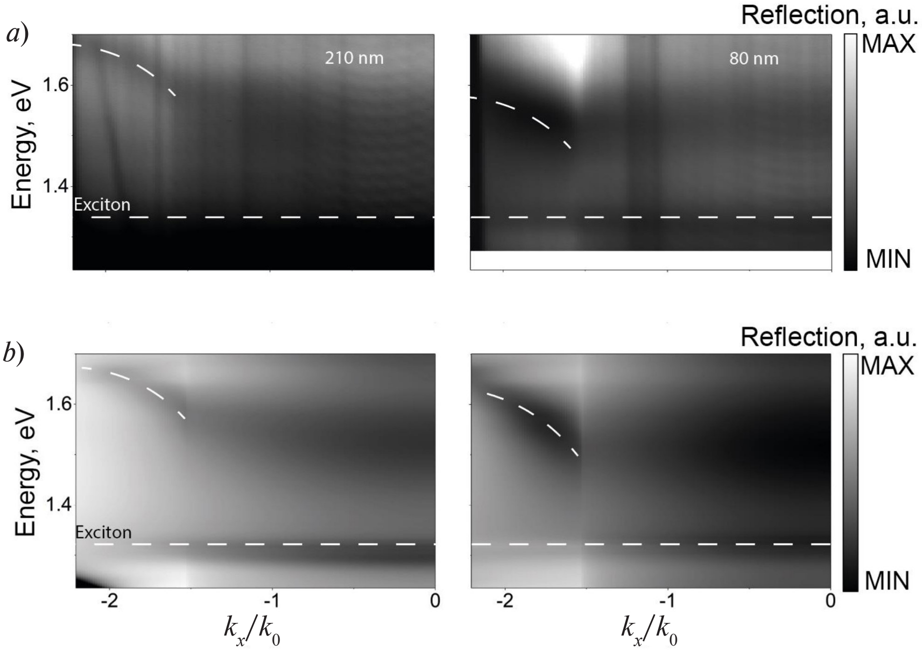

Fig. 2. Experimental angle-resolved reflectance maps for thicknesses of 210 and 80 nm (*a*); angle-resolved reflectance maps obtained using the Transfer Matrix Method (TMM) for the same thicknesses (*b*)

Conclusion

Our study directly demonstrates the formation of guided polaritons below the light line in a CrSBr-based waveguide, achieving strong light-matter coupling (~185 meV) mediated by the material's intrinsic optical anisotropy. This waveguide geometry provides a robust, cavity-free platform for polariton generation and control. Furthermore, by varying the waveguide thickness, we achieve tuning of the polariton branches, highlighting an additional degree of freedom for device design. These results establish CrSBr as a promising material platform for integrated, tunable polaritonics operating at room temperature.

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