Conference materials
UDC 535.016
DOI: https://doi.org/10.18721/JPM.183.141

Mechanical scanning probe lithography of van der Waals antiferromagnetic CrSBr for fabrication of high-index waveguides and resonators

I.E. Kalantaevskii [1] ✉, T.D. Gorelkina [1], K.A. Gasnikova [2], N.V. Glebov [1], A.I. Chernov [3, 4], P.A. Alekseev [2], V.A. Kravtsov [1]

[1] ITMO University, St. Petersburg, Russia;
[2] Ioffe Institute, St. Petersburg, Russia;
[3] Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Russia;
[4] Russian Quantum Center, Skolkovo, Moscow, Russia
✉ i.kalantaevskii@metalab.ifmo

Abstract. Recently emerged van der Waals antiferromagnetic CrSBr provides new opportunities for developing compact integrated photonic and optoelectronic devices since it exhibits high refractive index, strong excitonic response, and magnetic ordering. However, experimental methods for nanostructuring CrSBr to tailor its photonic properties are not yet well developed. Here we demonstrate photonic dispersion engineering in subwavelength-thick CrSBr slabs through patterning and creating slab photonic crystal structures. Using mechanical scanning probe lithography – a non-destructive technique benefiting from piezostage precision – we fabricate nanostructured CrSBr flakes of controlled geometry. Back-focal-plane reflectance spectroscopy measurements reveal modified photonic dispersion characteristics, with the photonic crystal dispersion tuned close to the CrSBr exciton resonance. The demonstrated engineering of the photonic dispersion in CrSBr, with tunable alignment between the photonic crystal resonance and the exciton energy, provides a base for further studies of exciton-photon interaction in 2D magnetic materials.

Keywords: scanning probe lithography, van der Waals magnetics, photonic crystal slab

Funding: This study was funded by Russian Science Foundation grant No. 25-22-20038. This study was funded by St. Petersburg Science Foundation grant No. 25-22-20038.

Citation: Kalantaevskii I.E., Gorelkina T.D., Gasnikova K.A., Glebov N.V., Chernov A.I., Alekseev P.A., Kravtsov V.A., Mechanical scanning probe lithography of van der Waals antiferromagnetic CrSBr for fabrication of high-index waveguides and resonators, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.1) (2025) 204–208. DOI: https://doi.org/10.18721/JPM.183.141

Материалы конференции
УДК 535.016
DOI: https://doi.org/10.18721/JPM.183.141

Механическая сканирующая зондовая литография Ван-дер-Ваальсова антиферромагнетика CrSBr для изготовления высокоиндексных волноводов и резонаторов

И.Э. Калантаевский [1] ✉, Т.Д. Горелкина [1], К.А. Гасникова [2], Н.В. Глебов [1], А.И. Чернов [3, 4], П.А. Алексеев [2], В.А. Кравцов [1]

[1] Университет ИТМО, Санкт-Петербург, Россия;
[2] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия;
[3] Московский физико-технический институт (национальный исследовательский университет), г. Долгопрудный, Россия;
[4] Российский квантовый центр, Сколково, Москва, Россия
✉ i.kalantaevskii@metalab.ifmo

Аннотация. Новый Ван-дер-Ваальсов антиферромагнетик CrSBr открывает перспективы для компактных фотонных и оптоэлектронных устройств благодаря сочетанию высокого показателя преломления, сильного экситонного отклика и магнитного упорядочения. Однако методы наноструктурирования CrSBr для управления его фотонными свойствами пока недостаточно развиты. В данной работе мы демонстрируем управление фотонной дисперсией в CrSBr путем создания фотонно-кристаллических структур. Используя механическую зондовую литографию – неразрушающую методику с прецизионным пьезопозиционированием – мы создаем наноструктурированные фотонные кристаллы в CrSBr с контролируемой геометрией.

Ключевые слова: сканирующая зондовая литография, Ван-дер-Ваальсовы антиферромагнетики, фотонные кристаллы

Финансирование: Данное исследование было профинансировано грантом Российского Научного Фонда № 25-22-20038. Данное исследование было профинансировано грантом Санкт-Петербургского Научного Фонда № 25-22-20038.

Ссылка при цитировании: Калантаевский И.Э., Горелкина Т.Д., Гасникова К.А., Глебов Н.В., Чернов А.И., Алексеев П.А., Кравцов В.А. Механическая сканирующая зондовая литография Ван-дер-Ваальсова антиферромагнетика CrSBr для изготовления высокоиндексных волноводов и резонаторов // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.1. С. 204–208. DOI: https://doi.org/10.18721/JPM.183.141

Introduction

In recent years, enhanced light-matter interaction in novel van der Waals materials has attracted significant attention as a promising approach for developing nonlinear optical and optoelectronic devices. In the regime of strong light-matter coupling, exciton-polariton quasiparticles can be formed, which are manifested in the energy spectrum as Rabi splitting between material and optical dispersions. A promising platform for realizing exciton-polaritons with additional degrees of freedom is the two-dimensional van der Waals magnetic semiconductor CrSBr. Its optical response is dominated by an excitonic resonance, with excitons exhibiting high oscillator strength, stability under ambient conditions, and strong anisotropy — making CrSBr a promising candidate for room-temperature polaritonic devices with enhanced functionality [1]. Typically, strong light-matter interaction is achieved by coupling excitonic resonances in thin-layer materials to resonant optical modes supported by external cavities, such as distributed Bragg reflectors [2] and subwavelength gratings [3]. CrSBr is also a high-refractive-index semiconductor (refractive index of ~5), enabling its use as a waveguide for self-hybridized polaritons [4].

Additionally, since CrSBr excitons are sensitive to magnetic order [5], this provides a new degree of freedom for tuning the optical response. However, nanostructuring this material for creating waveguides and photonic crystal slabs remains largely unexplored. In this work, we investigate photon dispersion engineering in CrSBr to align the photonic crystal resonance with the exciton energy via scanning probe lithography.

Materials and Methods

To fabricate photonic crystals in CrSBr, we employed mechanical probe lithography, a technique chosen for its non-degradative impact on the material, simplicity, and dynamic tunability via high-precision piezostages. To enhance contrast and photonic crystal quality factor (Q), we selected samples with 50–100 nm thicknesses supporting only a single transverse electric (TE) mode. The required thickness was achieved via iterative mechanical exfoliation from bulk crystals with low-residue Nitto tape monitored via optical microscopy. Atomic force microscopy (AFM) was used to precisely determine sample thickness after dry transfer onto SiO_2/Si substrates with oxide thickness of 1000 nm.

Results and Discussion

Crystal orientation was determined via polarization-resolved photoluminescence revealing the excitonic easy axis (b-axis), which is critical for dispersion control. Photonic crystals were fabricated via mechanical probe lithography. The method is schematically illustrated in Fig. 1, *a*. Designs for 4 photonic crystals were calculated via Fourier modal method (FMM) and implemented via scanning probe. Fig. 1, *b* and Fig. 1, *c* show the AFM maps and profiles of the resulting photonic crystals. Atomic force microscopy measurements confirmed that the spatial parameters of the fabricated photonic crystals closely match the designed values.

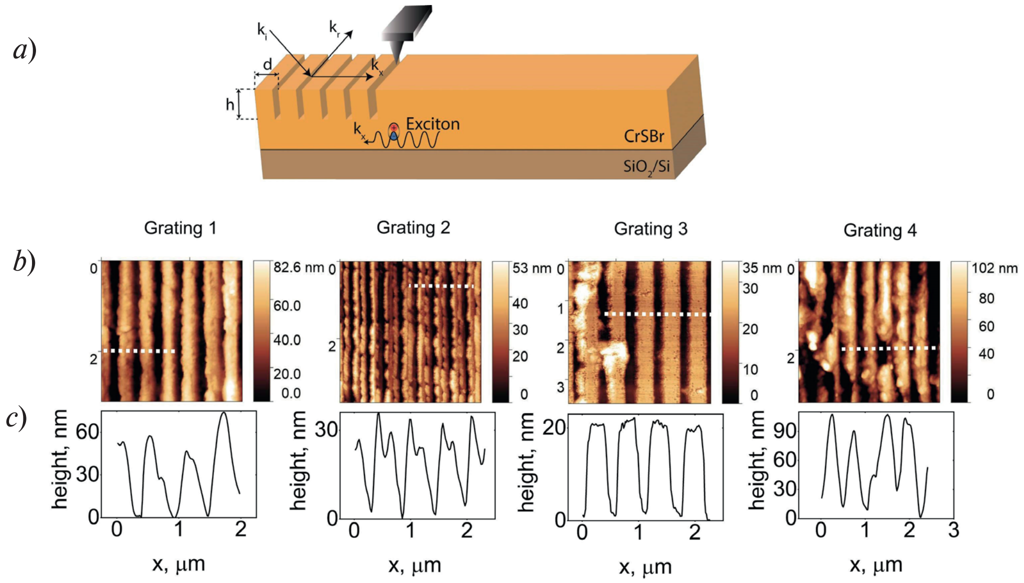

Fig. 1. Schematic illustration of the scanning mechanical probe lithography method (*a*), AFM images of fabricated photonic crystals (*b*), AFM profiles of the obtained photonic crystals (*c*)

Using the FMM method, the dispersion relations of the fabricated photonic crystals were calculated as angle-resolved reflectivity spectra. Fig. 2, *a* shows the simulation results for the 4 structures with thickness of 105 nm, duty cycle of, 0.3, and different grating periods indicated above each plot. The optical dispersions of the fabricated nanostructured CrSBr films were experimentally investigated through back-focal-plane (BFP) photoluminescence measurements with angular resolution in the polarization channel corresponding to TE modes. The experimental dispersion characteristics are shown in Fig. 2, *b* and exhibit good agreement with the results of FMM simulations.

In Fig. 2, *b*, the red line indicates the exciton resonance position, while the orange dashed line shows the lower polariton branches calculated using the coupled oscillator model. From the plots, we observe increasing bending of the dispersion curve away from the exciton resonance as they approach each other for gratings with smaller periods. This is due to increase of the exciton-photon interaction, which can be described by a coupled oscillator model with parameters including the coupling strength and excitonic/photonic relaxation rates. The exciton-photon coupling strength g values were derived from curve fitting for all gratings. It was found to be in a range of 35–45 meV, indicating a sizeable interaction between the photonic and excitonic modes. The results showed that the photonic-crystal dispersion can be sensitively controlled via the pitch and duty cycle of the grating fabricated in the CrSBr flake and thus can be brought into resonance with CrSBr exciton at 1.34 eV. The demonstrated coupling strength (g = 35–40 meV) significantly exceeds the polariton linewidth ($\gamma \approx 20$ meV), which suggests that the system operates in the strong light-

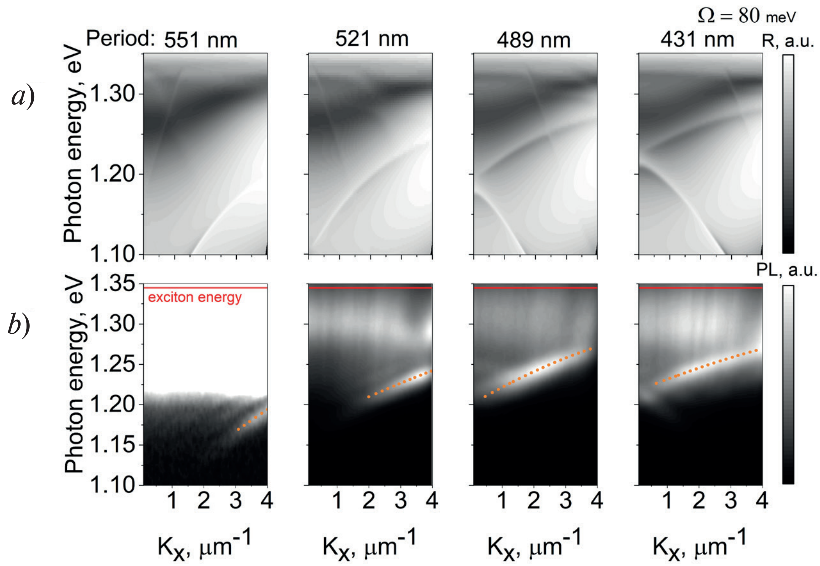

Fig. 2. Simulated grating dispersions using FMM (*a*) and experimentally measured photoluminescence spectra in the back focal plane from fabricated CrSBr gratings (*b*)

matter coupling regime. Future studies should characterize temperature-dependent linewidth narrowing to fully exploit the light-matter hybridization for polaritonic devices.

In Fig. 3, *a*, the expected energy of the original photonic mode without coupling to the exciton resonance is shown as extracted from fitting the experimental data with the coupled oscillator model. In Fig. 3, *b*, the actual experimentally observed energy is shown, when coupling to the exciton resonance is present. The overall energy is lower in the coupled case (Fig. 3, *b*) due to anticrossing, while the photonic mode (Fig. 3, *a*) can actually reach the exciton energy at 1.34 eV and cross it. The difference in energy for 2 selected wavevectors (empty and filled symbols, corresponding to 0.5 μm^{-1} and 3.5 μm^{-1}) is smaller in the coupled case (*b*), which is due to the increased fraction of excitons in the polaritons at higher *k*.

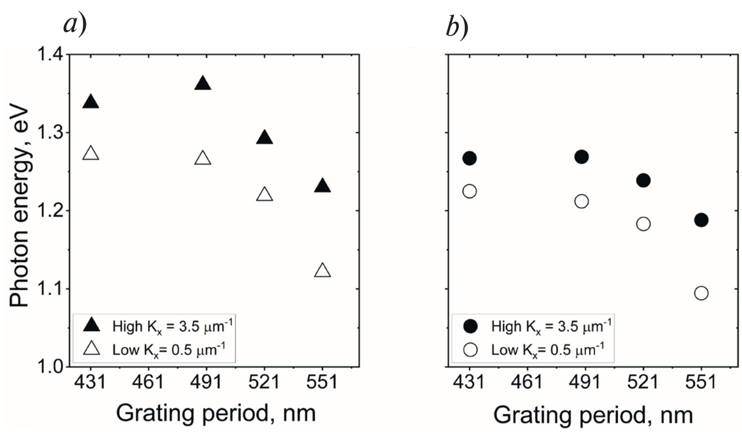

Fig. 3. Photonic dispersion energy in (*a*) in the absence of exciton-photon coupling. Polaritonic dispersion energy in (*b*) in the presence of exciton-photon coupling

Conclusion

Using mechanical scanning probe lithography, we successfully patterned subwavelength thick flakes of van der Waals antiferromagnetic CrSBr and engineered its photonic dispersion, achieving tunable alignment between the photonic crystal resonance and the excitonic transition energy. The coupling strength between the excitonic and photonic modes was evaluated and determined to lie in the range of 35–40 meV. These results create further opportunities for achieving enhanced light-matter coupling in nanopatterned CrSBr for developing novel compact photonic and optoelectronic devices.

Acknowledgments

This study was funded by Russian Science Foundation grant No. 25-22-20038. This study was funded by St. Petersburg Science Foundation grant No. 25-22-20038.

REFERENCES

1. **Li C., et al.,** 2D CrSBr Enables Magnetically Controllable Exciton-Polaritons in an Open Cavity, Advanced Functional Materials. 34 (51) (2024) 2411589.
2. **Wang T., et al.,** Magnetically-dressed CrSBr exciton-polaritons in ultrastrong coupling regime, Nature Communications. 14 (1) (2023) 5966.
3. **Li Q., et al.,** Two-dimensional magnetic exciton polariton with strongly coupled atomic and photonic anisotropies, Physical Review Letters. 26 (133) (2024) 266901.
4. **Dirnberger F., et al.,** Magneto-optics in a van der Waals magnet tuned by self-hybridized polaritons, Nature. 7974 (620) (2023) 533–537.
5. **Komar R., et al.,** Colossal magneto-excitonic effects in 2D van der Waals magnetic semiconductor CrSBr, arXiv preprint arXiv:2409.00187. (2024).

THE AUTHORS

KALANTAEVSKII Ivan E.
royal37lol@gmail.com

GORELKINA Tatiana D.
tatiana.gorelkina@metalab.ifmo.ru

GASNIKOVA Ksenia A.
k.gasnikova@metalab.ifmo.ru

GLEBOV Nikita V.
nikita.glebov@metalab.ifmo.ru
ORCID: 0000-0002-9026-6106

CHERNOV Alexander I.
a.chernov@rqc.ru
ORCID: 0000-0002-6492-9068

ALEKSEEV Prokhor A.
npoxep@gmail.com
ORCID: 0000-0002-8143-4606

KRAVTSOV Vasily A.
vasily.kravtsov@metalab.ifmo.ru
ORCID: 0000-0002-3555-1027

Received 25.08.2025. Approved after reviewing 02.09.2025. Accepted 05.09.2025.