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BOOK OF ABSTRACTS

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Structure predict ion for low-dimensional materials

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Until mid-2000s it was thought that crystal structures are fundamentally unpredictable. This has changed, and a special role in this was played by our evolutionary method/code USPEX (http://uspex-team.org). This method can be viewed as a type of artificial intelligence, and routinely allows one to predict stable crystal structures for a given chemical composition], predict all stable compounds formed by given elements, and even predict among all possible compounds the structure and composition that have desired combination of properties. Here I will discuss:

1. Its extension to 2D-systems (2D-crystals, surfaces, thin films, grain boundaries) and examples of its application.
2. Its extension to nanoclusters and examples of its application.

References

[1]Lepeshkin S.V., Naumova A.S., Baturin V.S., Oganov A.R. (2022). “Magic” molecules and a new look at chemical diversity of hydrocarbons. J. Phys. Chem. Lett. 13, 7600-7606.

[2]Lepeshkin S.V., Baturin V.S., Uspenskii Yu.A., Oganov A.R. (2019). Method for simultaneous prediction of atomic structure of nanoclusters in a wide area of compositions. J. Phys. Chem. Lett. 10, 102-106.

[3]Mazitov A.B., Oganov A.R. (2021). Grain boundaries in minerals: atomic structure, phase transitions, and effect on strength of polycrystals. Zapiski RMO (Proc. Russ. Mineral. Soc.) 150, 92-102.

[4]Zhou, X.F., Oganov, A. R., Shao, X., Zhu, Q., and Wang, H.T. (2014). Unexpected reconstruction of the α-boron (111) surface. Phys. Rev. Lett. 113 , 176101.

[5]Wang, Q., Oganov, A. R., Zhu, Q., & Zhou, X.-F. (2014). New reconstructions of the (110) surface of rutile TiO2 predicted by an evolutionary method. Phys. Rev. Lett. 113 , 266101.

[6]Zhu Q., Li L., Oganov A.R., Allen P.B. (2013). Evolutionary method for prediction of surface reconstructions with variable stoichiometry. Phys. Rev. B87, 195317.

[7]Yue C., Weng X.-J., Gao G., Oganov A.R., Dong X., Shao X., Wang X., Sun J., Xu B., Wang H.-T., Zhou X.-F., Tian Y. (2021). Formation of copper boride on Cu(111). Fundamental Research 1, 482-487.

[8]Wang Z.H., Zhou X.F., Zhang X., Zhu Q., Dong H.F., Zhao M., Oganov A.R. (2015). Phagraphene: A Low-Energy Graphene Allotrope Composed of 5–6–7 Carbon Rings with Distorted Dirac Cones. Nano Letters 15, 6182-6186.

[9]Zhou X.F., Dong X., Oganov A.R., Zhu Q., Tian Y. and Wang H.T. (2014). Semimetallic two-dimensional boron allotrope with massless Dirac fermions. Phys. Rev. Lett.112, 085502.

Aslamazov-Larkin effect and photogalvanic transport in 2D materials

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This talk encompasses nonlinear response theory effects in 2D materials close to the critical temperature of superconducting transition Tc, in particular, the photogalvanic effect (PGE) in 2D superconductors based on transition mental dichalcogenide (TMD) monolayers in the vicinity of Tc [1]. The PGE transport is characterized by the stationary and uniform electric current as a second-order response to an external electromagnetic field.

It turns out that superconducting fluctuations – emerging Cooper pairs before the system reaches the critical temperature – contribute to the PGE transport in nontrivial ways. Additional contributions to PGE arise due to the presence of i) trigonal warping in the system or ii) Rashba-type terms in the Cooper-pairs dispersion. Indeed, in a 2D noncentrosymmetric Ising superconductor in the fluctuating regime under the action of a uniform external electromagnetic field there emerge two contributions to PGE due to the trigonal warping of the valleys [2]. The first contribution stems from the current of the electron gas in its normal state, while the second contribution is of Aslamazov-Larkin nature. The valley degeneracy is lifted by the application of a weak out-of-plane external magnetic field producing a Zeeman effect.

Furthermore, in the system emerges a coherent PGE as a third-order response of the 2D material to an external EM field in superconductors with isotropic dispersion of Cooper pairs [3].

References

[1] K. Sonowal, V.M. Kovalev, I.G. Savenko, New J. Phys 23, 093009 (2021).

[2] A.V. Parafilo, M.V. Boev, V.M. Kovalev, I.G. Savenko, arXiv:2206.04322 (2022).

[3] V.M. Kovalev, K. Sonowal, I.G. Savenko, Phys. Rev. B 103, 024513 (2021)

Anisotropic photonics with van der Waals materials

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Large optical anisotropy observed in a broad spectral range is of paramount importance for efficient light manipulation in countless devices. Although a giant anisotropy has been recently observed in the mid-infrared wavelength range, for visible and near-infrared spectral intervals, the problem remains acute with the highest reported birefringence values of 0.8 in $BaTiS_3$ and h-BN crystals [1, 2]. This issue inspired an intensive search for giant optical anisotropy among natural and artificial materials [3, 4].

Here, we demonstrate that layered van der Waals materials provide an answer to this quest owing to their fundamental differences between intralayer strong covalent bonding and weak interlayer van der Waals interaction. To do this, we made correlative far- and near-field characterizations validated by first-principle calculations that reveal a huge birefringence in a broad spectral range for different van der Waals materials.

From a wider perspective, our result provides a path for next-generation nanophotonics based on van der Waals materials, for example, in tunable Mie-nanoresonators, nanophotonics waveguides and exciton-polariton physics.

References

[1]Niu, S. et al. Giant optical anisotropy in a quasi-one-dimensional crystal. Nat. Photonics 12, 392–396 (2018).

[2]Segura, A. et al. Natural optical anisotropy of h-BN: highest giant birefringence in a bulk crystal through the mid-infrared to ultraviolet range. Phys. Rev. Mater. 2, 1–6 (2018).

[3]Kats, M. A. et al. Giant birefringence in optical antenna arrays with widely tailorable optical anisotropy. Proc. Natl Acad. Sci. USA 109, 12364–12368 (2012).

[4]Ermolaev, G. A. et al. Giant optical anisotropy in transition metal dichalcogenides for next-generation photonics. Nat Commun 12, 854 (2021)

Anomalous optical response of graphene on hexagonal boron nitride substrates

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Graphene/hBN heterostructures can be considered as one of the basic building blocks for the next-generation optoelectronics mostly owing to the record-high electron mobilities. However, currently the studies of optical properties of graphene are limited to the standard substrates (SiO_2/Si, glass, quartz) despite the growing interest in graphene/hBN heterostructures. This can be attributed to a challenging task of the determination of hBN's strongly anisotropic dielectric tensor in the total optical response. In this study, for the first time, we overcome this issue through imaging spectroscopic ellipsometry utilizing simultaneous analysis of hBN's optical response with and without graphene monolayers. Our technique allowed us to retrieve the optical constants of graphene from graphene/hBN heterostructure in a broad spectral range of 250 - 950 nm. Here, we demonstrate an emergence of anomalous optical constants from monolayer graphene on top of a thick hBN and compare our results with the ones on one of the standard substrates (SiO_2/Si) from the literature and of our own. We also demonstrate a novel and highly sensitive approach to the detailed analysis of ellipsometric parameters and total optical response of graphene, which can potentially be easily extended to other two-dimensional materials.

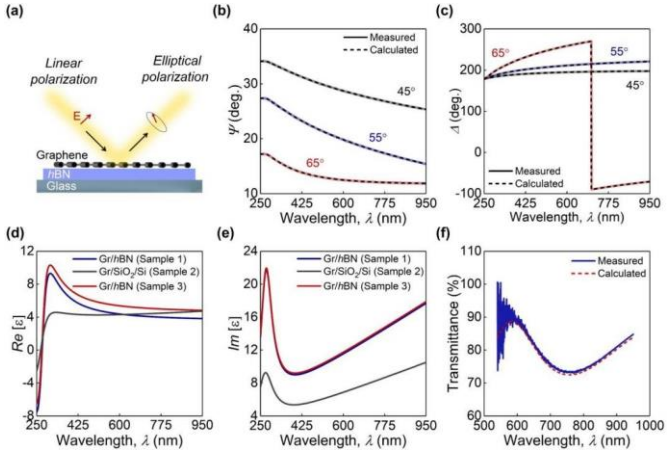

Figure 1: Imaging spectroscopic ellipsometry of monolayer graphene on hBN/glass substrate. (a) Schematic illustration of the measurement setup. Ellipsometric parameters Ψ (b) and Δ (c). Real (d) and imaginary (e) parts of the obtained dielectric function. Grey lines correspond to real and imaginary parts of dielectric function obtained for monolayer graphene on SiO_2/Si substrate. (f) Micro-transmittance spectra of graphene on hBN/glass substrate. Solid (dashed) line represents the measured (evaluated) case.

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Resonant transition metal dichalcogenide nanoparticles for nanophotonic applications

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An emerging field of all-dielectric nanophotonics implies the utilization of dielectric nanoparticles with a high refractive index exhibiting a resonant optical response due to Mie resonances [1]. Currently, traditional semiconductor materials such as silicon [2], germanium [3] and others are mainly used for the implementation of optical devices based on nanostructures with Mie resonances. However, a fixed value of the dielectric constant of these materials imposes fundamental restrictions on the development of optical devices operating at a strict selectivity of resonant frequencies. One of the ways to improve the properties of modern photonic devices is to use materials with anisotropic dielectric properties. Recent results on the optical properties of nanoparticles synthesized from transition metal dichalcogenides [4] demonstrate their unique applied potential associated with their internal layered structure [5]. An important feature of these materials is their strong dielectric anisotropy. Along homogeneous layers with a strong interatomic bond, the dielectric constant is a real value and does not exceed the value 10. Across the layers, the dielectric constant increases sharply, acquiring the imaginary part. Moreover, the value of its real part can reach values of more than 30 units in the visible part of the spectrum. Optical properties of nanoparticles made of such a layered material, can strongly depend on the irradiation conditions combining Mie resonance with electron-hole behavior in semiconductor layers. For example, a high field concentration at the resonant condition can provide a strong coupling between the Mie modes of the nanoparticle and its exciton resonances.

In this work we demonstrate nearly spherical nanoparticles of molybdenum and tungsten disulfide (MoS_2, WS_2) produced by femtosecond pulsed laser ablation of bulk target in deionized water. Structural and optical investigations have shown that that for all the NPs its structure is formed by polycrystalline inner part covered by fullerene-like outer shell. As a result, the preserved layered crystalline structure of laser ablated NPs combined with its variable size in the range 10-150 nm ensure the Mie-excitonic behavior of its optical response. Such nanoparticles demonstrate exciting optical and electronic properties inherited from the TMDC crystals, due to preserved crystalline structure, which offers a unique combination of pronounced excitonic response and high refractive index value, making possible a strong concentration of electromagnetic field in nanoparticles.

The work was supported by the Russian Science Foundation (grant № 21-79-00206).

References

[1]A.B. Evlyukhin et. al., Nano Lett. 12, 3749-3755 (2012).

[2]I. Staude et. al., Nature Photonics, 1, 274 (2017).

[3]G. Grinblat et. al. Nano Lett., 16, 4635-4640 (2016).

[4]R. Verre et. al. Nature Nanotech. 14, 679-684 (2019).

[5]S. Manzeli et. al. Nat Rev Mater., 2, 17033 (2017).

Topological darkness in ultrathin films of transition metal dichalcogenides and other high-refractive-index materials

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Layered materials present a promising platform for immobilization of biological molecules and their enhanced sensing in biosensors [1]. However, mainly they serve as a functional layer and only increase sensor performance [2]. In contrast, our biosensor design relies solely on atomically thin transition metal dichalcogenides, which strong dielectric response results in topological phase singularities [3]. Around these singularities, an optical phase has a rapid variation, which we leveraged for label-free sensing. It allows us to achieve a very stable two-dimensional biosensor with an enormous sensitivity of 7.5·104 degrees per refractive index unit. Additionally, singular points can be used for any atomically thin layers of high refractive index materials and provide enhanced absorption in these layers. Therefore, proposed topological phase singularities represent a universal platform for next-generation biosensors and nanophotonics.

References

[1]Y. Stebunov, O. Aftenieva, A. Arsenin, V. Volkov, Highly Sensitive and Se-lective Sensor Chips with Graphene-Oxide Linking Layer, ACS Appl. Mater. Interfaces, 7, 21727-21734, (2015).

[2]G. Ermolaev et al., Optical constants and Structural Properties of Epitaxial MoS2 Monolayers, Nanomaterials, 11, 1411, (2021).

[3]G. Ermolaev et al., Topological Phase Singularities in Atomically Thin High-Refractive-Index Materials, Nature Communications, 13(1), 1-9 (2022).

Spectroscopic ellipsometry of two-dimensional materials and Van der Waals heterostructures

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The discovery of a new class of materials, two-dimensional (2D) materials, has led to increasing interest in the application of these materials in photonics and optoelectronics [1]. While graphene has already been sufficiently studied, the optical properties of other 2D materials, even the well-known 2D transition metal dichalcogenides (TMDCs), remain unknown or do not satisfy researchers in terms of accuracy or consistency [2]. In addition, various hybrid structures that combine two or more 2D materials (van der Waals heterostructures) have attracted much attention in recent years. The lack of data on the optical properties of hybrid materials significantly limits researchers and developers in the design of new photonic and optoelectronic devices based on them.

Here we present the main approaches to the study of the optical properties of monolayer, multilayer (up to 10 layers) TMDCs and Van der Waals heterostructures using spectral ellipsometry in the ultrawide spectral range from ultraviolet to near-infrared wavelengths. Results are presented for a number of two-dimensional and atomic-thin materials such as PtS_2 and $PtSe_2$ (figure 1) [3], SnS_2, $SnSe_2$ [4], $PdSe_2$, MoS_2, WS_2 and WSe_2. Analysis of ellipsometry spectra was carried out, taking into account the excitonic nature of dispersion. We present the results of measurements of the optical constants of MoS_2 and WS_2 monolayers on graphene and hBN monolayers. It is noted that the graphene monolayers significantly affect the optical properties of TMDCs.

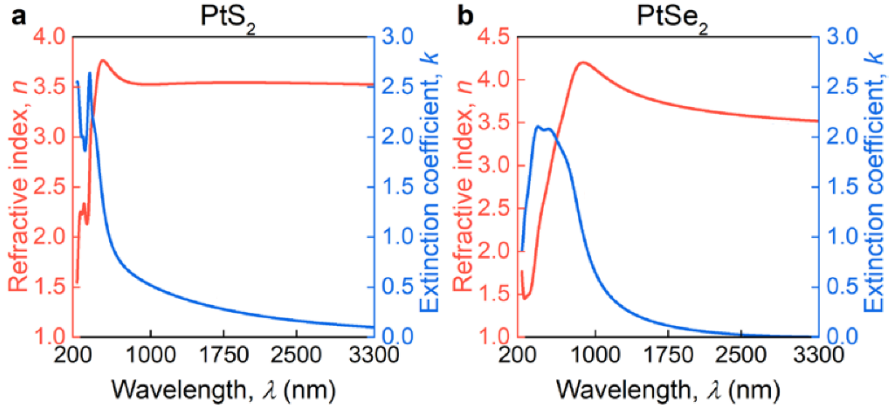

Figure 1: Optical constants of (a) PtS_2 and (b) $PtSe_2$ on SiO_2/Si substrates.

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References

[1] K.F. Mak, J. Shan, Nature Photonics 10, 216 (2016).

[2]G. Ermolaev et al, npj 2D Materials and Applications 4, 21 (2020).

[3]G. Ermolaev et al, Nanomaterials 11, 3269 (2021).
[4]G. Ermolaev et al, Nanomaterials 12, 141 (2022).

Spin noise in birefringent media

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Spin noise spectroscopy (SNS) is a proven powerful optical method for detecting paramagnetic resonance based on the measurement of Faraday rotation noise. At present, this technique is widely used to study spin systems in various media [1, 2], including low-dimensional semiconductor systems [3, 4, 5].

In the present work [6], the effect of linear birefringence in a medium on the spin noise spectrum was studied. Birefringent media with a large optical anisotropy almost completely suppress the static Faraday rotation [7]. Therefore, linearly birefringent media have not previously been studied by the SNS method. However, we demonstrate an unexpected result: despite the fact that regular Faraday rotation is suppressed by an optically anisotropic medium, Faraday rotation fluctuations caused by spatially uncorrelated spin fluctuations are practically not suppressed. This effect was demonstrated on rare-earth-doped birefringent crystals.

The measurements were performed on two uniaxial crystals $CaWO_4$:Nd^{3+} (1 at.%) with the linear birefringence $\Delta n \approx 0.016$ and $LiYF_4$: Nd^{3+} ($\sim$ 0.5 at.%) with the birefringence $\Delta n \approx 0.022$. Spin noise measurements in these crystals confirmed the absence of the effect of optical anisotropy on the Faraday rotation noise; in both crystals, ion spin noise spectra were detected 3+. In a more general case, it can be argued that the Faraday rotation noise is also not affected by spatially inhomogeneous birefringence. Provided that the studied paramagnetic particles are magnetically isotropic or their magnetic anisotropy is not related to the optical anisotropy of the medium.

In conclusion, for the first time, the absence of Faraday rotation noise suppression in optically anisotropic media, in contrast to the regular Faraday rotation, was discovered. This demonstrates the applicability of the SNS technique to a wide class of birefringent materials, including low-dimensional ones. When studying media with a spatial correlation between fluctuations of individual spins, using SNS, one can obtain information about the spin correlation length and the spin-diffuse coefficient.

The work was financially supported by RSF grant No. 21-72-10021.

References

[1]S. A. Crooker, and others, Nature 431, 49–52 (2004).

[2]S. Cronenberger, and others, Nat. Commun. 6, 8121 (2015).
[3]G. M. Müller, and others, Phys. Rev. Lett. 101, 206601 (2008).
[4]S. V. Poltavtsev, and others, Phys. Rev. B 89, 081304(R) (2014).
[5]M. M. Glazov and E. Y. Sherman, Phys. Rev. Lett. 107, 156602 (2011).
[6]V. O. Kozlov, and others, Phys. Rev. Lett. 129, 077401 (2022).
[7]S. Ramaseshan, Proc. Indian Acad. Sci. - Section A 34, 32 (1951).

Design of Stacking of Graphene-Silver Nanoparticles heterocompound for Near-infrared absorbers

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The optical properties of the physical-vapor-deposited silver thin film with a thickness of less than 10 nm have attracted much attention due to its high absorptive properties in the visible and near-infrared regions, which has wide applications ranging from biochemical sensing, and enhanced visible absorbers to solar cells [1]. The extinct properties of such a "thin" silver film result from the formation of the randomly distributed plasmonic nanoparticles, where their localized surface plasmon resonances can be excited by the incident light over a wide frequency range. However, such a particle-shaped film has a thickness limitation. Once, its thickness is larger than 10 nm, its high absorption properties change to high reflective due to the flat surface morphology, same as bulk metals.

In this work, we propose a way to take advantage of the mechanical properties of a two-dimensional graphene layer, which is composed of a one-atom-thick layer of carbon atoms arranged in a hexagonal lattice, to unlock the thickness limitation of particle-shape silver thin films for near-infrared absorbers. This can be designed by staking graphene and silver thin film on a substrate through a combination of a graphene transfer method and a magnetron sputtering technique. We design the stacking of graphene-silver nanoparticle heterocompound on a classical metal-insulator-metal configuration, which consists of a top-layer graphene/silver heterocompound layer and a bottom thick silver layer separated by a spacer SiO_2 layer. The low surface energy and strongest hardness of the graphene layer maintain the particles-shape of the silver thin film while keeping improving the durability of the staking films. Our experimental and numerical analysis points out that nearly 100 % absorptance can be achieved in the near-infrared region. In addition to the enhanced light absorption characteristics, such an amorphous heterocompound can be used for surface-enhanced Raman scattering applications. Meanwhile, the proposed graphene-metal heterocompound relies solely on CMOS-compatible, low cost, and large-area processing, which can be flexibly scaled up for mass production.

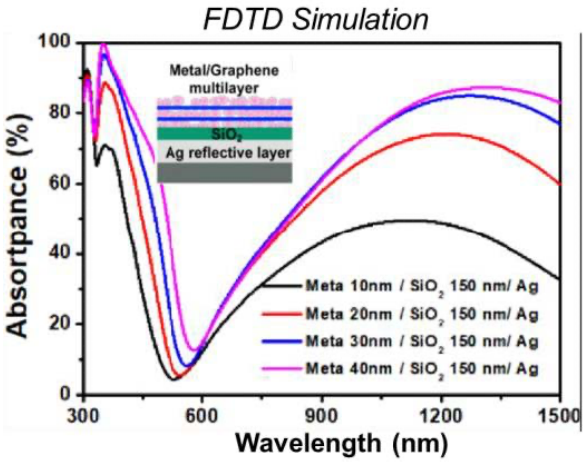

Figure 1: Finite difference time domain simulation of a graphene/silver nanoparticles heterocompound absorbers

References

[1]X. Long, W. Yue, Y. Su, W. Chen, and L. Li, Nanoscale Res. Lett., 14(1), 1-8 (2019).

Pairing of 2D bosons under spin-orbit coupling and a transverse magnetic field

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Bright excitons in 2D semiconductors experience effective momentum-dependent magnetic fields $\vec{\Omega}(\vec{p})$ due to the exchange interaction of the constituent electrons and holes. These fields lie in the structure plane and, as such, do not conserve the projection of the total spin S_z of two bosons on the transverse direction. Combined with the parity of the fields with respect to the time reversal, i.e. $\vec{\Omega}(\vec{p})=\vec{\Omega}(-\vec{p})$, this property results in coherent coupling of a spin-singlet (S_z=0) biexciton to the continua in the triplet (S_z= ±2) scattering channels. In this talk we shall discuss the ensuing phenomena for monolayers and bilayers placed into an ordinary perpendicular magnetic field. We predict giant biexcitonic halos possessing synthetic angular momenta $L_z=\pm 2\hbar$ [1] and biexciton Mott supercurrent. We shall discuss affinity of these phenomena to the polarized exciton superstripe emerging at zero transverse magnetic field in the equilibrium many-body phase diagram of dipolar excitons in bilayers at sufficiently large inter-layer distances, where the biexciton becomes weakly bound [2].

References

[1]S. V. Andreev, arXiv:2111.08782 (2021).

[2]S. V. Andreev, Phys. Rev. B 103, 184503 (2021).

Full computational model for quasi 2D excitons in magnetic eld in GaAs based heterostructures

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The magnetic field behavior in GaAs-based quantum wells (QWs) is particularly interesting for the light-hole (lh) exciton. Best theoretical efforts so far [1], revealed high sensitivity of the lh g-factor to the QW width. The reason for that being close proximity of the excited heavy-hole state to the lh state. Coupling of these two states heavily affects the g-factor, with calculation putting its value as high as g = 21. However Coulomb coupling has to be taken into account to compare these findings with the experiment.

A hydrogen-like particle in a quantum well has non-analytical wave function. It therefore must be calculated numerically. This calculation is hampered by the anisotropic valence band structure, internal heterostructure strain, and other complications of the real-life materials. Computers have only recently reached the ability to model two particles in a square potential coupled by the Coulomb interaction. New computational capabilities provide solutions for the previously unresolved problems, reviving interest to the seemingly well studied systems, such as QWs.

We have developed a numerical model [2], capable of obtaining exciton wave functions in a QW in the presence of an external magnetic field. It accounts for the complex valence band of the GaAs-based heterostructure using the Luttinger Hamiltonian. In our report we will present the results of our calculations, and address the effect of slight variation of the problem parameters on the exciton magnetic field behavior. The variation includes QW depth and width, Luttinger parameters, and additional coupling resulting from the symmetry breaking on the QW boundaries.

We compare calculation results with the experimental data, showing good agreement as shown in figure 1. Re- flectance spectra from 14-nm GaAs/Al0.03Ga0.97As QW are shown at various magnetic fields. Key parameters of the magnetic field behavior are shown on the right panel in the figure.

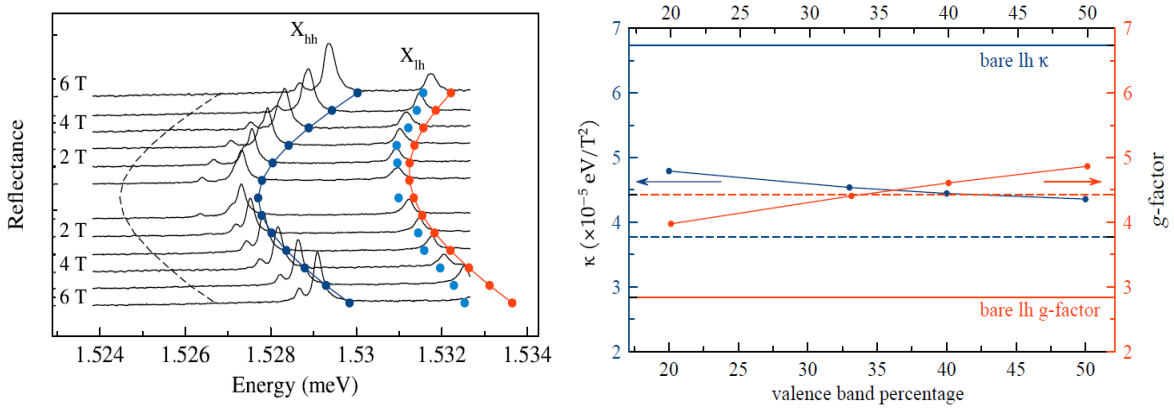

Figure 1. (left) Reflectance spectra in comparison with calculation at nominal parameter (dashed line), and with calculation with QW width set to L_{QW} = 11.35 nm (blue and red connected dots). Light blue dots correspond to the lh exciton position extracted from nonradiative broadening excitation spectra. For the nominal parameter calculation only the hh curve is shown to avoid cluttering, as the lh curve overlays the hh peaks in experimental spectra. (right) g-factor and the diamagnetic shift constant κ of the lh exciton as a function of the valence band mismatch percentage from the whole band mismatch value for the QW. Dashed grid lines correspond to the experimental values, while solid grid lines represent the parameters values without hh-lh coupling.

Financial support from RSF grant 21-72-00037 is acknowledged.

Bibliography:

[1] M.V. Durnev, M.M. Glazov, E.L. Ivchenko, Phys. E, 44, 797 (2012),

[2] P.S. Grigoryev, O.A.Yugov, S.A. Eliseev, et al. , Phys. Rev. B 93, 205425 (2016).

Spatially-indirect exciton-exciton interaction in MoS2 bilayers

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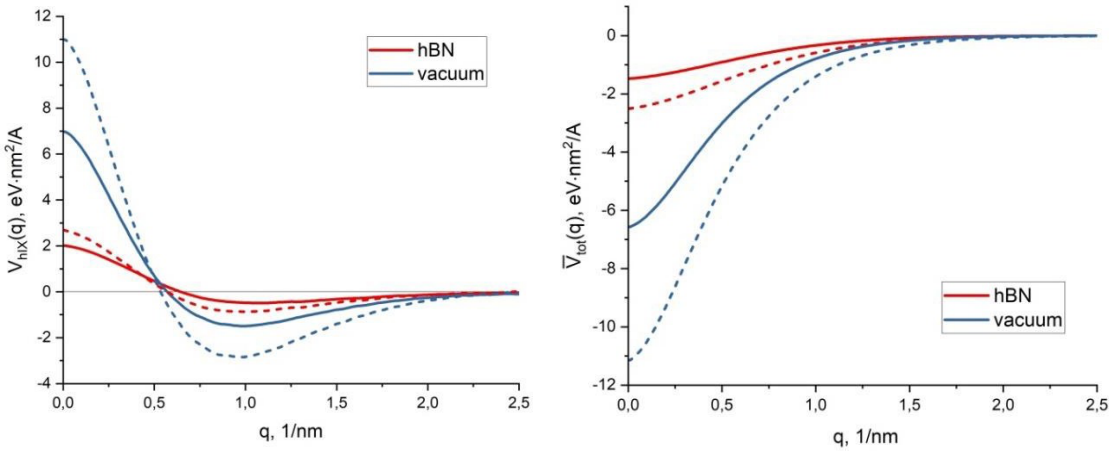
Interlayer excitons hosted in transition metal dichalcogenide (TMD) bilayers and their hybridization with direct excitonic species are opening the way to strong nonlinearity and hence to observation of many-body quantum phenomena [1]. The interaction between different types excitons in such structures is however not yet studied in detail, as they feature attraction and repulsion subject to reduced screening due to the structure dimensionality, and the interaction between the charge carriers is different both from Coulomb and Rytova-Keldysh descriptions [2].

In this work we study the interaction between dipolar excitons in the MoS2 homobilayer, which represent a hybridized state of indirect A-type excitons and direct B-type excitons. Using variational wave functions, we carry out the calculation of the matrix element of interaction taking into account both direct and exchange interaction processes. Numerical integration is used to obtain the dependence of the total interaction for indirect and hybridized dipole excitons on the transferred momentum (Fig. 1). It can be seen that the interaction of dipolar hybridized excitons is weaker than the interaction of indirect excitons due to the admixture of a direct B exciton, but remains rather strong. Notably, the interaction potential matrix element displays a nonmonotonic dependence on the transferred momentum, and at a certain value of the momentum repulsion is replaced by attraction. In the low density limit, the obtained dependencies make it possible to estimate the interaction constant of hybridized dipolar excitons in bilayers: $\mathrm{V}_{\mathrm{hIX}}^{\mathrm{hBN}}(0) \approx 2.0\ \mathrm{eV}\cdot\mathrm{nm}^2$, $\mathrm{V}_{\mathrm{hIX}}^{vac}(0) \approx 7.0\ \mathrm{eV}\cdot\mathrm{nm}^2$, $\overline{\mathrm{V}}_{\mathrm{hIX}}^{\mathrm{hBN}}(0) \approx -1.5\ \mathrm{eV}\cdot\mathrm{nm}^2$, $\overline{\mathrm{V}}_{\mathrm{hIX}}^{\mathrm{vac}}(0) \approx -6.6\ \mathrm{eV}\cdot\mathrm{nm}^2$. These interaction constants can be directly probed by experimental observation of blueshift or redshift of the indirect exciton line in reflectance spectrum of a bilayer.

This work was financially supported by the RFBR Grant No. 21–52–12038.



a) b)

Figure 1: Matrix element of interaction of two hybridized dipolar excitons (solid line) in comparison with the matrix element of the interaction of two indirect (non-hybridized) excitons (dashed line) in the MoS_2 bilayer (a) with parallel dipole moments (b) with anti-parallel dipole moments. A is the system area; q represents the transfer momentum.

References

[1] C. Gerber et al., Phys. Rev. B 99, 035443 (2019).

[2] N. A. Asriyan et al., Phys. Rev B 99, 085108 (2019).

Ti_3C_2 nanoparticles for photonic biomedical applications

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Since the isolation of graphene in 2004, the palette of novel 2D materials has been growing rapidly. One of the more recent additions are the family of MXenes [1], which, owing to the excellent ion storage capacity, are promising for making batteries and supercapacitors. Optical applications remain much less explored, with the lowered expectations due to significant absorption losses in the optical region.

Here, we present the accurate optical constants of ultrathin Ti_3C_2 "paper" of various thicknesses measured by spectroscopic ellipsometry and verified via transmittance measurements. We find that the absorption peak at about 800 nm, which is widely considered plasmonic, in fact originates from interband transitions (Figure 1a), while the plasmonic optical response should be expected at wavelengths above 1400 nm, where the real part of the dielectric permittivity falls below zero.

The material's optical properties make it a promising candidate for biomedical applications. We show that nanoparticles made of Ti_3C_2 have higher absorption cross-section than gold and silicon nanoparticles of similar size and reaching that of TiN nanoparticles in the first biological therapeutic window of 700–980 nm. In the second window 1100–1700 nm, owing to the localized plasmonic resonance within this range the absorbance vastly exceeds all other types of nanoparticles. Combined with good biocompatibility of Ti_3C_2, these properties become very attractive.

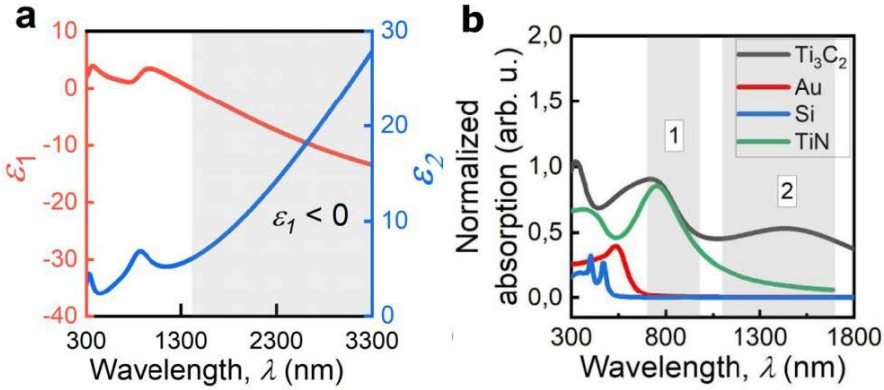

Figure 1: a) Measured dielectric functions of Ti_3C_2; b) Calculated absorption cross-section spectrum of Ti_3C_2 nanospheres with a diameter of 100 nm and its comparison with the other materials.

This work is supported by the Russian Science Foundation (22-79-10312).

References

[1] M. Naguib et al., Adv. Mater. **23**, 4248–4253 (2011).

Non-classical optics and transport of two-dimensional excitons

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Two-dimensional (2D) semiconductors based on transition metal dichalcogenides (TMDCs) form building blocks for emerging platform of van der Waals heterostructures [1]. Strong spin-orbit and Coulomb effects make TMDC monolayers (MLs) and bilayers (BLs) particularly attractive for fundamental physics of 2D systems.

Optical response of 2D TMDC is dominated by tightly bound excitons; hBN encapsulation makes excitonic transitions particularly narrow making it possible to address fine details of excitonic spectra and study Bose-Fermi mixtures of excitons and resident charge carriers [2]. It is also possible to observe exciton propagation in optical experiments opening prospects of bridging optical and transport effects in 2D [3].

In my plenary talk, several key aspects of excitonic physics in 2D TMDCs will be covered. I will focus on the unconventional effects where the specifics of TMDC-based heterostructures is brightly manifested.

1. Control of exciton radiative and spin-valley lifetime via the Purcell effect by tailoring the environment [4,5].
2. Exciton-electron interaction: trions and Fermi-polarons in excited states [6,7].
3. Non-classical propagation of excitons in the presence of exciton-exciton interactions and phonon-induced weak localization [3,8,9].
4. Spin and valley Hall effects on 2D excitons [10,11].

Theoretical models will be illustrated by the experimental results.

The author is grateful to T. Amand, B. Urbaszek, A. Chernikov, Z.A. Iakovlev, X. Marie, and M.A. Semina for fruitful discussions. Financial support from RSF Grant 19-12-00051 is gratefully acknowledged.

References

[1] A. K. Geim and I. V. Grigorieva, Nature 499, 419 (2013).

[2]G. Wang, A. Chernikov, M. M. Glazov, T. F. Heinz, X. Marie, T. Amand, and B. Urbaszek, Rev. Mod. Phys. 90, 021001 (2018).

[3]M. Kulig, J. Zipfel, P. Nagler, S. Blanter, C. Schueller, T. Korn, N. Paradiso, M. M. Glazov, and A. Chernikov, Phys. Rev. Lett. 120, 207401 (2018).

[4]H.H. Fang, B. Han, C. Robert, M.A. Semina, D. Lagarde, E. Courtade, T. Taniguchi, K. Watanabe, T. Amand, B. Urbaszek, M.M. Glazov, and X. Marie, Phys. Rev. Lett. 123, 067401 (2019).

[5]A. I. Prazdnichnykh, M. M. Glazov, L. Ren, C. Robert, B. Urbaszek, and X. Marie, Phys. Rev. B 103, 085302 (2021).

[6]M.M. Glazov, Optical properties of charged excitons in two-dimensional semiconductors J. Chem. Phys. 153, 034703 (2020).

[7]K. Wagner, E. Wietek, J. D. Ziegler, M. A. Semina, T. Taniguchi, K. Watanabe, J. Zipfel, M. M. Glazov, and A. Chernikov, Phys. Rev. Lett. 125, 267401 (2020).

[8]M.M. Glazov, Phys. Rev. Lett. 124, 166802 (2020).

[9]K. Wagner, J. Zipfel, R. Rosati, E. Wietek, J. D. Ziegler, S. Brem, R. Perea-Causin, T. Taniguchi, K. Watanabe, M. M. Glazov, E. Malic, and A. Chernikov, Phys. Rev. Lett. 127, 076801 (2021).

[10] M. M. Glazov and L. E. Golub, Phys. Rev. Lett. 125, 157403 (2020)

[11] M. M. Glazov, 2D Mater. 9, 015027 (2022)

Spin physics of two-dimensional colloidal nanoplatelets

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A survey of our studies on spin-dependent phenomena in colloidal nanoplatelets based on CdSe semiconductor will be given. Several experimental techniques are used: polarized photoluminescence, two-photon excitation spectroscopy, spin-flip Raman scattering, optically-detected magnetic resonance, and pump-probe Faraday rotation with picosecond time resolution. Measurements were performed at low temperatures and in strong magnetic fields. Spin structure of neutral and charged excitons and spin dynamics, including coherent spin dynamics are investigated. We evaluate the exciton and carrier g-factors, characteristic spin relaxation times and receive information on spin relaxation mechanisms. Magneto-optical study provides information on type of nanoplatelet charging and its dynamics. These studies are extended for CdSe/CdMnSe nanoplatelets with magnetic Mn ions, which presence strongly modify spin properties and dynamics of charge carriers.

One of the surprising result of our study is the discovery that the surface of diamagnetic CdSe nanoplatelets has very pronounced paramagnetic properties, being provided by the spins of the dangling bonds. Interaction of the surface spins with the excitons confined in nanocrystals accelerates radiative recombination of the dark ground exciton state and strongly modify polarization properties of emitted light.

References

[1] E. V. Shornikova et al., Electron and hole g-factors and spin dynamics of negatively charged excitons in CdSe/CdS colloidal nanoplatelets with thick shells, NANO Letters 18, 372 (2018).

[2] E. V. Shornikova et al., Addressing the exciton fine structure in colloidal nanocrystals: the case of CdSe nanoplatelets, Nanoscale 10, 646 (2018).

[3] D. Kudlacik, et al., Single and double electron spin-flip Raman scattering in CdSe colloidal nanoplatelets, NANO Letters 20, 517 (2020).

[4] D. Feng, et al., Charge separation dynamics in CdSe/CdS core/shell nanoplatelets addressed by coherent electron spin precession, ACS Nano 14, 7237 (2020).

[5] E. V. Shornikova et al., Surface spin magnetism controls the polarized exciton emission from CdSe nanoplatelets, Nature Nanotechnology 15, 277 (2020).

[6] E. V. Shornikova et al., Negatively charged excitons in CdSe nanoplatelets, NANO Letters 20, 1370 (2020).

[7] E. V. Shornikova, et al., Magneto-optics of excitons interacting with magnetic ions in CdSe/CdMnS colloidal nanoplatelets, ACS Nano 14, 9032 (2020).

[8] D. O. Tolmachev, et al., Optically detected magnetic resonance in CdSe/CdMnS nanoplatelets, Nanoscale 12, 21932 (2020).

[9] E. V. Shornikova, et al., Exciton binding energy in CdSe nanoplatelets measured by one- and two-photon absorption, NANO Letters 21, 10525 (2021).

Density-dependent dynamics and effective temperature of nonradiative exciton reservoir in quantum wells

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Optically dark or nonradiative excitons with large wave vector exceeding the wave vector of light play important role in the dynamics of excitons and polaritons in semiconductor heterostructures. The interaction of bright and dark excitons plays particularly important role in formation of polaritons and their dynamics in structures with microcavities [1]. In high quality structures, the reservoir excitons can persist for a long time (tens of nanoseconds [2]) and they can be accumulated up to large densities.

We report here on density-dependent dynamics of excitons in the nonradia-tive reservoir. The method of the study is based on detection of the photo-induced broadening of exciton resonances in a reflectance spectrum [2]. An example of the broadening dynamics measured by the pump-probe technique for the heavy-hole exciton resonance (Xhh) in a GaAs/AlGaAs quantum well (QW) is shown in Fig. 1.

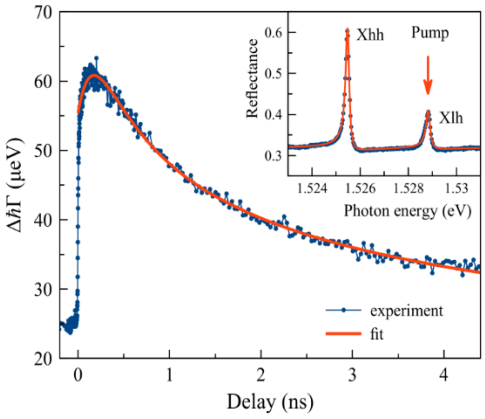

Figure 1. Dynamics of the photoinduced nonradiative broadening of the Xhh resonance under excitation into the Xlh resonance. Experimental data are shown by the blue dots, simulation by the red curve. The inset shows the reflectance spectrum with no pumping.

The areal density and the dynamics of quasi-particles in the reservoir are controlled by several processes. The reservoir is populated via scattering of the photocreated excitons into the states with large in-plane wave vector. The exciton density in the reservoir depends on the depleting processes. In high-quality heterostructures, the main mechanism of depletion of the reservoir at low temperatures is the scattering of excitons into the light cone, where they quickly recombine with the emission of photons. We found that the exciton-carrier scattering dominates over other depleting processes [2].

Strong optical excitation leads to heating of the exciton reservoir and activation of other processes. The heating is accompanied by a shift in the dynamic equilibrium of excitons ↔ free charge carriers towards the latter. This leads to an acceleration of the scattering of excitons from the light cone and a reduction in their lifetime in the reservoir. In addition, the states of the light-hole excitons (Xlh), which are higher in energy than the Xhh exciton states, are populated in the reservoir. Experiments show that, at low temperatures, the Xlh resonance broadening is approximately twice smaller than that of the Xhh resonance [2]. This is due to peculiarities of the exciton-exciton exchange interaction [3]. When the reservoir temperature increases the interaction strength of excitons in the reservoir with the Xlh and Xhh bright excitons levels out. In the experiment, this is observed as equalization of the photo-induced non-radiative broadening of the Xlh and Xhh exciton resonances. The ratio of the broadenings can serve as a kind of thermometer for the reservoir. We found that, at the excitation power density of about 10 W/cm^2, the reservoir temperature increases by about 7 K and then it slowly relaxes down with characteristic time 9 ns, see Fig. 2. We developed a model of dynamic processes in the exciton system, which quantitatively describes the observed dynamics.

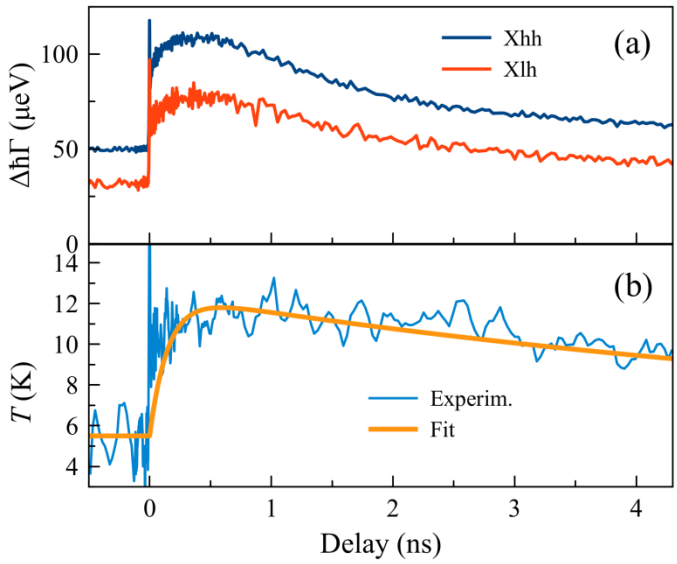

Figure 2. (a) Dynamics of the nonradiative broadening of the Xhh and Xlh excitons measured at the excitation power P = 1.6 mW. (b) Dynamics of reservoir temperature extracted from the experiment (noisy curve). Smooth curve is the fit by a two-exponential function with parameters: T_0 = 5.5 K, ΔT = 7 K, t_{decay} = 7 ns, and t_{rise} = 0.15 ns. Sample temperature T = 4.5 K.

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References

[1] A. V. Kavokin, J. J. Baumberg, G. Malpuech, and F. P. Laussy, Microcavities (Oxford University, New York, 2017).

[2] A. S. Kurdyubov, A. V. Trifonov, I. Ya. Gerlovin, B. F. Gribakin, P. S. Grigoryev, A. V. Mikhailov, I. V. Ignatiev, Yu. P. Efimov, S. A. Eliseev, V. A. Lovtcius, M. Assmann, M. Bayer, A. V. Kavokin, Phys. Rev. B 104, 035414 (2021).

[3] B.F. Gribakin, E.S. Kramtsov, A.V. Trifonov, I.V. Ignatiev, Phys. Rev. B 104, 205302, 2021.

Quantization of exciton polaritons in shallow optical traps

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The growth technology of semiconductor microcavities was significantly improved in the last ten years. Modern samples with microcavities have polariton lifetime more than ten picoseconds, and the polariton diffusion length of tens of microns. The long diffusion length of polaritons makes it possible to study polariton condensates, which are spatially separated from optical pumping. In this case, the properties of the condensate turn out to be closer to ideal quantum system, since the interaction of the condensate with noisy reservoir of excitons is strongly suppressed. Various geometries are used to create trapped condensates, including sample etching, application of stress, etc. [1] One of them is an optical confinement, when pumping is done with multiple pump spots or concentric rings. In this case, photoproduced excitons work both as a confining potential and as a source of polaritons. Hot excitons in the reservoir have a very short diffusion length and the confining potential almost repeats the shape of the optical pump. While excitons relax in energy and become more photon-like, they can travel to large distances and reach the condensate, but the efficiency of this process is low.

As an example of new phenomena originated from far polariton diffusion, it is possible to create condensate in the form of a narrow strip sandwiched between the outer and inner rings of optical pumping. Such condensates are interesting, in particular, because they can have nonzero orbital angular momentum (AOM), just like their light emitted by them. Moreover, as our studies have shown, a simpler trap geometry with one outer ring can also be used to form a condensate with a nonzero AOM. We have observed that at the optical pumping of a sample with a microcavity by a narrow ring with a diameter of about 15–20 micrometers, radiation of a polariton condensate of a quite definite shape is observed. When the pump power is just above the threshold of a polariton laser, spectrally narrow radiation is observed, corresponding to the occupation of single quantum state. Depending on the diameter of the trap, this state can either be the lowest, for traps with a smaller diameter, or one of the excited ones for traps with a larger diameter. As the pump power is increased, several quantum states with energy spacing less than 1 meV begin to shine simultaneously.

By scanning the projected image of the sample across the slit of the spectrometer and measuring the spectrum with vertical resolution, we can separately obtain the spatial distribution for all emitting states. By the observed spatial shape of the radiating states, it can be assumed that they are the levels of radial quantization of the polariton condensate, since the number of minima increases for each next level. Moreover, the spatial distribution of levels coincides very closely with what one-

particle quantum-well levels should look like in a cylindrical trap! The height of the potential created by optical pumping in our experiment is such that, depending on the pump power, from one to four size-quantization levels exists in the trap. It is interesting to note that, depending on the diameter of the trap, when the condensation threshold is exceeded, or the ground state, or one of the excited states can light up first. We attribute this to the different overlap for different states between the exciton reservoir and the size- quantized state, than leads to the different pumping rates. This overlap is always maximum for the highest level in the trap. At a certain pump power, the second level turns out to be upper and the state with nonzero angular orbital momentum begins to shine. Thus, the trap diameter allows us to change the relative efficiency of optical pumping at different levels while the peak power allows you to change the height of the potential barrier and the number of quantum-well levels within the trap. This creates an effective basis for further study of polariton currents in optical traps.

Remains unclear whether the observed behavior can be called a polariton condensation? If single polaritons have a discrete spectrum of states in the trap, and the coherence length of the polariton exceeds the size of the trap, then it is rather a quantum dot than a condensate. But this is more a matter of definition, rather than observable phenomena.

References

[1] P. Cristofolini, A. Dreismann, G. Christmann, G. Franchetti, N. G. Berloff, P. Tsotsis, Z. Hatzopoulos, P. G. Savvidis, and J. J. Baumberg, Phys. Rev. Lett. 110, 186403 (2013)

Strongly Quantum Confined CsPbBr3 Nanocrystals: from dark excitons to hot electron generation

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Metal halide perovskite nanocrystals have gained explosive interest as a superior source of photons and charges with high luminescence quantum yield and long carrier diffusion length compared to many other semiconductor nanocrystals. The integration of metal halide perovskite nanocrystals into the technological applications, such as solar cells and light emitting devices, has driven intensive research on characterization and structural control of the properties of excitons. Two important features of metal halide perovskite nanocrystals are accessible strongly quantum confined regime as well as possibility to work with various nanocrystal structure – it could be 0D (quantum dots), 1D (nanowire) or 2D (nanoplatelets) structure, each having its own advantages.

Dark exciton as the lowest-energy exciton state in metal halide perovskite nanocrystals is a subject of much interest. This is because the superior performance of perovskites as the photon source combined with long lifetime of dark exciton is very attractive for the applications such as quantum information processing. In our research we able to directly observation of intense and long-lived photoluminescence with 1-10 μs lifetime from dark exciton state in strongly quantum confined CsPbBr3 nanocrystals with large bright-dark energy splitting. Due to large splitting the dak exciton dominates emission of nanocrystals already at 4 K and can be spectrally addressed. Furthermore, intense dark exciton PL was observed regardless of the dimensionality of the confinement, making all strongly confined 0D (quantum dot), 1D (nanowire) and 2D (nanoplatelets) nanocrystals viable nanostructures to exploit dark exciton's longevity.

Dark exciton applications go way beyond possible computational application. For example, dark excitons can assist hot electron generation, which play a crucial role in enhancing the efficiency of photon-to-current conversion or photocatalytic reactions. In semiconductor nanocrystals, energetic hot electrons capable of photoemission can be generated via the upconversion process involving the dopant-originated intermediate state, currently known only in Mn-doped cadmium chalcogenide quantum dots.

Here, we report that Mn-doped $CsPbBr_3$ nanocrystals are an excellent platform for generating hot electrons via upconversion that can benefit from various desirable exciton properties and the structural diversity of metal halide perovskites. It appears that in this case 2-dimensional Mn-doped $CsPbBr_3$ nanoplatelets are particularly advantageous due to the strong exciton-dopant interaction mediating the upconversion process. Nanoplatelets indeed reveal evidence for the hot electron upconversion via long-lived dark exciton in addition to bright exciton that may enhance the upconversion efficiency.

The results from this study demonstrate the potential of strongly quantum confined metal halide perovskite nanocrystals as the excellent material platform to utilize dark exciton, combining the benefits of the superb properties of metal halide perovskite as the source of photons and charges with large confinement-enhanced large bright-dark energy splitting. This study also establishes the feasibility of hot electron upconversion in Metal halide perovskite host and demonstrates the potential merits of 2-dimensional MHP nanocrystals in hot electron upconversion.

Thermally stimulated mechanisms of the defect-related luminescence in hexagonal boron nitride

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Hexagonal boron nitride (h-BN) is a two-dimensional widegap material demonstrating a unique set of electrophysical characteristics, what proves its perspectives to be used for fabrication of van der Waals heterostructures in optoelectronics and nanophotonics, and for development of solid-state nuclear track detectors for luminescence dosimetry of ionizing radiation. It is known that intrinsic and impurity defects form the system of electron and hole trapping levels within the bandgap of h-BN. At the same time, carbon and oxygen are considered to be main technological impurities in h-BN replacing boron and nitrogen atoms in corresponding crystal sublattices and creating point defects and associated complexes. Moreover, intrinsic and impurity defects play the role of recombination centers and to a large extent define the mechanisms of radiation stimulated response and dosimetric properties of h-BN [1 – 4]. In this connection, a combination of photoluminescence (PL) quenching [1, 2] and spectrally resolved thermally stimulated luminescence (TSL) [3, 4] techniques allow to analyze in details multistep mechanisms of recorded photo- and thermoactivated emission and give a possibility to selectively stimulate, excite and study trapping and recombination centers of a specific type.

In present work the regularities of luminescence response are studied for the irradiated micro- and nanostructured powders of h-BN with different concentration of carbon and oxygen impurities. Spectral and kinetic characteristics of photostimulated luminescence processes are analyzed in a wide temperature range 7 – 900 K. Numerical analysis for the measured PL curves in the terms of the Mott relation for thermal quenching with two independent channels and consideration of the TSL process contribution is performed. It is shown that the calculated values of quenching energy correlate with the position of the CN-center levels in the forbidden gap relative to the top of the valence band for two possible energy configurations in the M- and K- valleys.

Particulars of spectrally resolved TSL following ultraviolet and electron beam irradiation are studied. Using curve fitting, peak shape, various heating rates and initial rise methods an estimation of kinetic parameters (activation energy, effective frequency factor and kinetics order) for the optically active capture centers, forming the complex multitrap system, is performed. The consideration of temperature quenching of luminescence in the evaluation of traps activation energy is analyzed. It is found that, under the thermal activation of electron (1B- and 3B-centers) and hole

(CN-centers) traps, TSL processes of first and second kinetics order dominate respectively. Energy-level diagram, describing the features of thermally stimulated redistribution of charge carriers, is proposed for the irradiated h-BN. Mechanisms of radiative and non-radiative relaxation of the excited energy states in the bandgap of h-BN are discussed.

References

[1]A. Vokhmintsev et al. J. Luminescence 208, 363-370 (2019).

[2]A. Vokhmintsev et al. Radiat. Meas. 124, 35-39 (2019).

[3]A. Vokhmintsev et al. Radiat. Meas. 106, 55-60 (2017).

[4]A. Vokhmintsev et al. Measurement 66, 90-94 (2015).

Effects of exciton fine structure in moiré quantum dots

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Excitons dominate the optical properties of transition metal dichalcogenide (TMDC) monolayers and even their heterobilayers with type II band alignment despite the spatial separation of electrons and holes. The moiré potential and structure reconstruction in TMDC heterobilayers lead to the exciton confinement and effective formation of quantum dot (QD) ensembles. In this work we predict the two resonant effects related to the exciton fine structure tuning by external magnetic field, which were later confirmed experimentally: dynamic valley polarization [1,2] and valley-magnetophonon resonance [3].

The four lowest interlayer exciton states in moiré QDs form two doublets of optically active intravalley excitons and inactive intervalley excitons split by the electron hole short-range exchange interaction. Application of magnetic field splits the doublets and can lead to the crossing of the intervalley and intravalley exciton levels at the resonant field Bexch. Our analysis of the exciton valley dynamics under unpolarized and nonresonant optical excitation shows that at the crossing of the exciton levels [1] (i) photoluminescence (PL) intensity resonantly increases, (ii) PL gets circularly polarized, and (iii) resident charge carriers in moiré QDs become strongly valley polarized, see Fig. 1(a). This provides a useful tool to orient valley pseudospin in small magnetic fields of the order of a few tens of millistesla by unpolarized light [2]. This effect was recently observed in WS_2/WSe_2 moiré QDs [4].

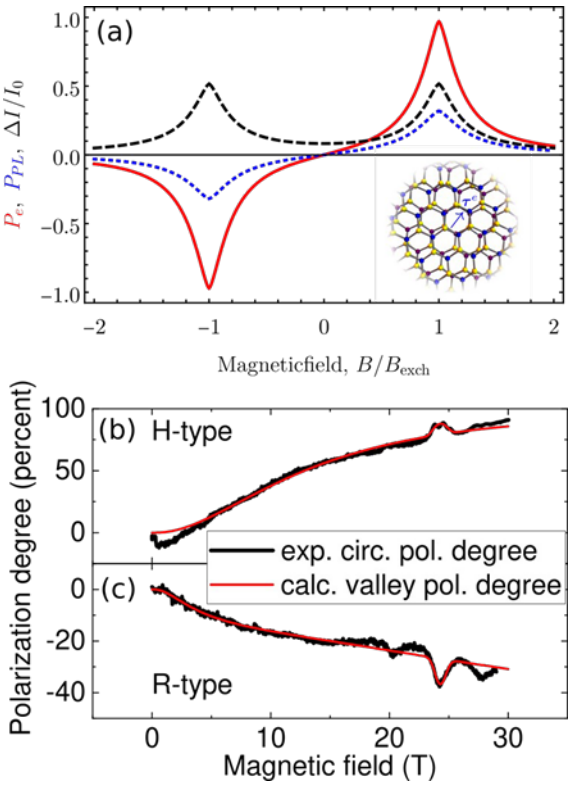

Figure 1: (a) PL intensity (black), PL polarization (blue) and resident electron valley polarization (red) in magnetic field. (b+c) Localized exciton valley polarization in $MoSe_2/WSe_2$: experiment and theory.

Another resonance is realized in much stronger magnetic fields of a few tens of Tesla, when the Zeeman splitting of one of the charge carriers equals to the chiral phonon energy at the corner of the Brillioin zone. In these conditions, the exciton

valley polarization resonantly increases as a result of the efficient scattering between intravalley and intervalley exciton states [3]. Such valley-magnetophonon resonance was detected for localized excitons in $MoSe_2/WSe_2$ heterobilayers with H-type and R-type stackings at 24.2 T, see Fig. 1(b) and (c), respectively. The dominant mechanism of valley-magnetophonon resonance is the electron-spin-conserving scattering between the excitonic states mixed by the long-range electron hole exchange interaction with chiral TA-phonon of $MoSe_2$ monolayer.

The resonant effects related to the interplay between intravalley and intervalley excitons can be used to manipulate valley pseudospin of excitons and charge carriers in moiré QDs.

References

[1]D. S. Smirnov et al., Phys. Rev. Lett. 125, 156801 (2020).

[2]D. S. Smirnov, Phys. Rev. B 104, L241401 (2021).

[3]D. S. Smirnov et al., 2D materials (2022).

[4]X. Wang, et al., Nature 604, 468 (2022).

MBE grown Mg substituted fluorite dielectric layers for 2D-electronics

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The exponentially growing interest to the 2D-electronics is highly justified by the exciting physical properties of 2D materials and their applicability in perspective device applications, [1]. A thin high-quality insulating layer forming a perfect interface with a semiconductor is often a critically important element in such devices. Among other materials, the single crystal fluoride films are highly suitable candidates to be used in 2D electronics. Their highly attractive insulating properties have been recently demonstrated on the example of $MoS_2/CaF_2/Si(111)$ field effect transistors [2]. Noteworthy, despite the low leakage current and high breakdown voltage observed in CaF_2/Si layers, the film/substrate mismatch is still considerable in this system which may result in an undesirable strain and potential generation of defects, deteriorating the dielectric properties. As the next step of the fluoride based insulating technology, we introduce here magnesium substituted fluorite layers that are almost perfectly lattice matched to Si, exhibit high crystal quality, low surface roughness and improved dielectric strength. The thin $Ca_{1-x}Mg_xF_2$ films with $x=0\div0.3$ have been grown on Si(111) substrates by means of MBE. The oscillating temporal evolution of electron diffraction (RHEED) intensity both in specular and off-specular conditions (Fig. 1 A,B) have been used to optimize the layer-by-layer growth mode and to determine magnesium concentration. It was found that at x=0.1-0.15 the RHEED oscillations become most pronounced, indicating the optimal fluoride-to-silicon lattice matching, Fig. 1A. The analysis of the RHEED patterns has shown that the $Ca_{1-x}Mg_xF_2$ solid solution crystallizes in a fluorite lattice structure up to x=0.2, Fig. 1 C,D. Measured by atomic force microscopy the surface roughness of the $Ca_{1-x}Mg_xF_2$ layers is 0.18 nm, which is about twice smoother than the pure CaF_2 films of the same thickness. As a confirmation of high insulating properties of the Mg substituted fluorite layers, Fig.2 demonstrates the I-V characteristics of $Au/Ca_{1-x}Mg_xF_2/n\text{-}Si$ MIS structures. The above findings open the door for creation of advanced fluoride- based devices for 2D-electronics. This work was supported by RFBR Grant No 21-52-14007.

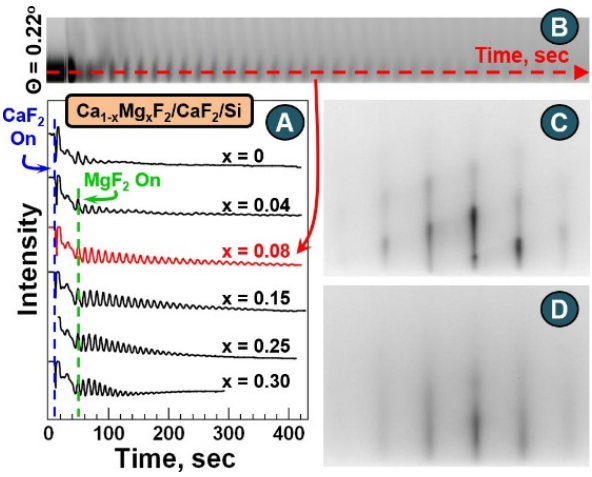

Figure 1: RHEED A) - intensity oscillations at different x; B) - pattern temporal evolution; C) pattern at x=0; D) - pattern at x=0.08

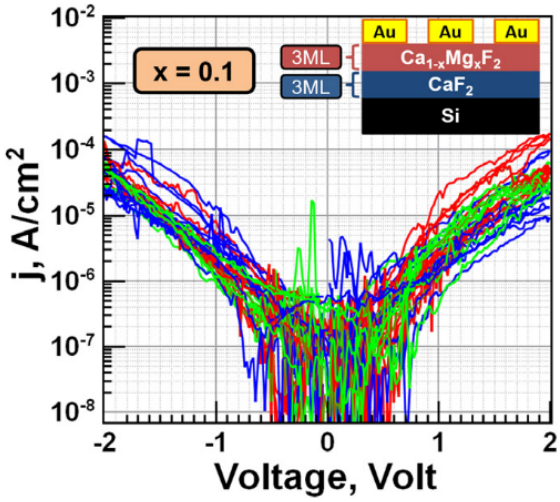

Figure 2: Typical I-V curves of MIS devices based on Au/ MgxCa1-xF2/n-Si heterostructures. Thickness of one fluorite monolayer is equal to 0.315 nm

References

[1]K. Novoselov et al., Science 306, 666 (2004).

[2]Yu. Illarionov et al., Nat. Electron. 2, 230 (2019)

Synthesis and exfoliation of 2D (Ti, Hf, Zr)S_3 solid solutions for thin-film electronics

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Recent reports on transition metal trichalcogenides (TMTCs) which have MX_3 composition, where M is a transition metal atom, such as Ti, Zr or Hf and X is S, Se or Te show, that this is a promising direction for novel thin-film semiconductor devices, such as thermoelectric converters [1 2], sensors [3] or even charge transport materials in solar cells [4]. This family of materials has $P2_1/m$ structure type, which could be described as covalently bonded 1D chains assembled into crystals through van der Waals-like interactions. The bond along crystallographic 'c' direction also have van der Waals nature. This kind of structure was successfully exfoliated by a simple scotch-tape method and as was shown recently, by liquid-phase ultrasonic treatment in organic solvents. Most of studied transition metal trichalcogenides could be separated into two groups: having a bandgap around 1 eV or less, as TiS_3, $TiSe_3$, $ZrSe_3$ and the second group with a bandgap higher than 2 eV, such as ZrS_3 and HfS_3. However, some applications for those materials require a control over the bandgap value in between 1 and 2 eV. Although such control can be achieved by varying the chalcogen, we tried a different approach – to vary the transition metals ratio in the precursor solid solution. Knowing that Ti-Zr and Ti-Hf systems have infinite solubility in one another, we prepared a number of Ti-Zr and Ti-Hf alloys with different Ti/Zr and Ti/Hf ratios and used them for preparation of $Ti_{1-x}A_xS_3$ crystals, where A is either Zr or Hf. To obtain the trichalcogenide structure we used conventional chemical vapor transport technique in vacuum-sealed quartz ampoules filled with flakes of the precursor alloy and elemental sulfur.

We studied the structure and composition of obtained crystals using SEM, Raman, XRD, EDX and UV-Viz spectroscopy and determined how the metal ratio in the precursor alloy could be used to control the bandgap of the resulting trichalcogenide and also studied how exfoliated in isopropyl alcohol $Ti_{1-x}A_xS_3$ ribbons can be used as photodetectors in drop-casted thin-film devices. Obtained solid solutions detectors showed a non-linear photocurrent behavior depending on applied bias and wavelength. We report a correlation between the photoresponse and titanium to hafnium ratio in drop casted $Ti_{1-x}Hf_xS_3$ devices.

This work has been supported by the grant of Russian Science Foundation (RSCF), project number 22-19-00812.

References

[1]Wang, C.; Zheng, C.; Gao, G. Bulk and Monolayer ZrS 3 as Promising Anisotropic Thermoelectric Materials: A Comparative Study . J. Phys. Chem. C, 124 (12), 6536–6543, (2020).

[2]Morozova, N. V.; Korobeinikov, I. V.; Kurochka, K. V.; Titov, A. N.; Ovsyannikov, S. V. Thermoelectric Properties of Compressed Titanium and Zirconium Trichalcogenides. J. Phys. Chem. C, 122 (26), 14362–14372, (2018)

[3]Rafiefard, N.; Iraji, A.; Esfandiar, A.; Sasanpour, P.; Fardindoost, S. A Graphene / TiS 3 Heterojunction for Resistive Sensing of Polar Vapors at Room Temperature, Microchimica Acta.,187:117, (2020).

[4]Island, J. O.; Biele, R.; Barawi, M.; Clamagirand, J. M.; Ares, J. R.; Sánchez, C.; Van Der Zant, H. S. J.; Ferrer, I. J.; D'Agosta, R.; Castellanos-Gomez, A. Titanium Trisulfide (TiS3): A 2D Semiconductor with Quasi-1D Optical and Electronic Properties. Sci. Rep. 2016, 6 (February), 1–7, (2016)

Advanced interface modification with low dimensional materials for stabilized nano-crystalline perovskite solar cells

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The hybrid perovskite (HP - APbX3, where X – iodine, bromine or chlorine) solar cells are emerging technology of thin-film optoelectronics. The outstanding intrinsic properties, such as big diffusion length, tunable bandgap, and sharp onset near the edge of the absorption, could be achieved in microcrystalline thin films with solution processing (inkjet, slot die etc)[1]. The power conversion efficiency of halide perovskite photovoltaics recently exceeded the value of 25 % being competitive to the benchmark of industry – crystalline silicone (Si). However, the long-term operation of PSCs is still far from the exploitation standards. The simplified fabrication processing with liquid-phase crystallization and hybrid organo-inorganic composition of perovskite tend to the formation of the ionic defects that initiates the corrosion at the hetero-junctions and interfaces in the device structure[2]. This intrinsic feature of HPs is a challenge for the development of advanced passivation methods, modification of the surfaces and technological transfer for up-scaling.

In this work, we developed the novel approach for the stabilization of the all slot die coated PSCs with passivation interlayers based on Ti_3C_2—Mxenes micro-flakes and nanoparticles. We found the functionalized low dimensional material effectively suppressed the migration of the ionic defects towards metal electrodes and reduces the dynamics of corrosion. The approach was successfully transferred to an industrial method of fabrication - slot die coating. The complex investigation of XRD and IR- Fourier spectroscopy identified the phase stabilization of halide perovskite absorber films and chemical stability of charge transporting layers. Other benefits were achieved with Cl-doping for perovskite thin-films. We found that Cl-doping suppressed[3] the formation of the antisite defect (I_{Pb}, I_{FA}) and iodine interstitials (I_i), that could trigger unfavorable phase transitions and degradation of the interfaces. Our investigation clearly showed that Cl-anion substitution changes the mechanisms of the defect formation and delays the dynamics of structural degradation in PCSs.

The authors gratefully acknowledge the financial support of the Russian science foundation (RSF) in terms of the project grant № 21-79-00299.

References

[1]M. Grätzel, “The light and shade of perovskite solar cells,” Nat. Publ. Gr., vol. 13, no. 9, pp. 838–842, 2014.

[2]N. N. Udalova et al., “New Aspects of Copper Electrode Metamorphosis in Perovskite Solar Cells,” J. Phys. Chem. C, vol. 124, no. 45, pp. 24601–24607, Nov. 2020.

[3]A. S. Shikoh et al., “On the relation between mobile ion kinetics, device design, and doping in double-cation perovskite solar cells,” Appl. Phys. Lett., vol. 118, no. 9, p. 093501, Mar. 2021.

Thin-film inverted perovskite solar cells on flexible substrates

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Halide perovskite (HP) photovoltaics (PV) is emerging technology showing promising performance with power conversion efficiency > 25% [1] for terrestrial applications. HP semiconductors demonstrate unique combination of optical and transport properties in micro-crystalline thin-films: diffusion length (>1 μm), lifetime (up to 1 ms), mobility of charge carriers (up to 10^2 $cm^2/V{\cdot}s$), direct-band gap structure. Fabrication of HP PV devices could be realized with solution processing via coating on the flexible substrates at low temperatures [2]. The advantages of flexible solar cells (FSCs) are light weight, portability, possibility of integration on curve surfaces. This potentially reduces capital expenditures (CAPEX) for the manufacturing of the solar cells and decreases cost estimates for generated electricity in comparison to the standard wafer devices based in silicone (Si).

Typically, flexible HP solar cells (SCs) fabricated on the light-weight plastic substrates– polyethylene terephthalate (PET), polyester etc. The conditions of the technological processes are limited with annealing at T <150 ºC due to the low thermal stability of plastics [3]. Accord to this, fabrication of charge transporting layers (CTLs) and absorber films should be adopted without negative impact on the output performance. Current challenges for the p-i-n structured HP SCs requires novel approaches for the modification of highly efficient hole transporting thin films based on Nickel oxide with surface termination, deposition of the small molecule semiconductors etc.

In this work we made complex investigation for the modification of the p-type CTLs with small molecules of bphenatroline (BPhen), plasma treatment and use of low dimensional materials for the interface engineering. The impact of the HTL type on the output characteristics of flexible solar cells was estimated under the light of a solar simulator. The benefits for the surface modification of CTLs for flexible HP SCs were discussed.

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References

[1] Narges Yaghoobi Nia, Danila Saranin, Alessandro Lorenzo Palma, Aldo Di Carlo Solar Cells and Light Management: Materials, Strategies and Sustainability: chapter 5 Perovskite solar cells – Elsevier (2020).

[2] M., & Druffel, T. (2020). Fabrication of Flexible Perovskite Solar Cells via Rapid Thermal Annealing. Materials Letters, 128215. doi:10.1016/j.matlet.2020.128215.

[3]Feng, J., Zhu, X., Yang, Z., Zhang, X., Niu, J., Wang, Z., Yang, D. (2018). Record Efficiency Stable Flexible Perovskite Solar Cell Using Effective Additive Assistant Strategy. Advanced Materials, 1801418. doi:10.1002/adma.201801418.

Heterodyne and direct detection at sub-terahertz wavelength with a superconducting niobium diselenide ($NbSe_2$)

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Thin superconducting films are used as the basis of various quantum detectors, such as superconducting nanowire single-photon detectors, SSPD (or SNSPD) and hot-electron bolometer, HEB, which are in demand for various applications such as astronomy and quantum communications. The significant parameter of these detectors is the thickness of the superconducting film which effects the detector sensitivity. One of the promising two-dimensional superconductors is $NbSe_2$ with a bulk critical temperature Tc = 7.3 K, in which a superconducting transition with a limit of 1 and 2 layers has already been demonstrated [1]. Moreover, the photoresponse at 1500-nm wavelength was reported [2] in this material, and the obtained characteristics for the optical NEP are commensurate with commercial photodiodes. In this work, we move into the long wavelength part of the electromagnetic spectrum and investigate $NbSe_2$ as a material for the development of bolometers in THz region.

Here we report the terahertz photoresponse of a thin $NbSe_2$ flake in a superconducting state under the 130 GHz radiation. The thicknesses of $NbSe_2$ flakes were 10 - 15 nm. The critical temperature was found to be in the range of 6.5 - 7.3 K. We have demonstrated both direct and heterodyne detection at frequency of 130 GHz. The responsivity of our detector reaches 125 V/W with NEP = 0.05 pW/ $Hz^{0.5}$ and the response time is about 160 ps at T = 5K. We believe that further optimization, namely the integration into the antenna and reduction in the number of $NbSe_2$ layers, may lead to the development of the next generation of THz bolometers.

References

[1] M. S. El-Bana, D. Wolverson, S. Russo, G. Balakrishnan, D. M. Paul and S. J. Bending, Supercond. Sci. Tech. 26, 125020 (2013).

[2] Gavin J et al.," Niobium diselenide superconducting photodetectors ", Appl. Phys. Lett. 114, 251103 (2019)

Highly stable GFETs with 2nm crystalline CaF_2 insulators

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Graphene is a promising material with numerous interesting properties [1] which can be exploited in optoelectronics [2] and sensors [3]. These devices typically require high-quality insulators to form graphene FETs (GFETs) [2,3]. However, previously used amorphous oxides contain numerous defects which cause severe hysteresis and thus degrade the device stability. As a promising alternative, here we demonstrate GFETs with 2nm thick CaF_2 insulators previously used in the most stable MoS_2 FETs reported so far [4].

Our GFETs fabricated by transferring CVD single-layer graphene onto epitaxially grown Si/CaF_2 substrates (Fig.1a) exhibit promising ID-VG characteristics within few Volts operation range (Fig.1b). While they have excellent thermal stability up to at least 175oC, annealing at this temperature allows to partially suppress the hysteresis (Fig.1c) which may be caused by adsorbates or defects at the Si/CaF_2 interface. The remaining hysteresis due to border traps in CaF_2 normalized by the insulator field is orders of magnitude smaller than in MoS_2 FETs with SiO_2 [5] and similar GFETs with SiO_2 and Al_2O_3 (Fig.1d). This confirms that our crystalline CaF_2 has low density of defects and thus can enable highly stable operation of GFETs. In summary, our results are valuable for the development of stable graphene sensors and optoelectronics.

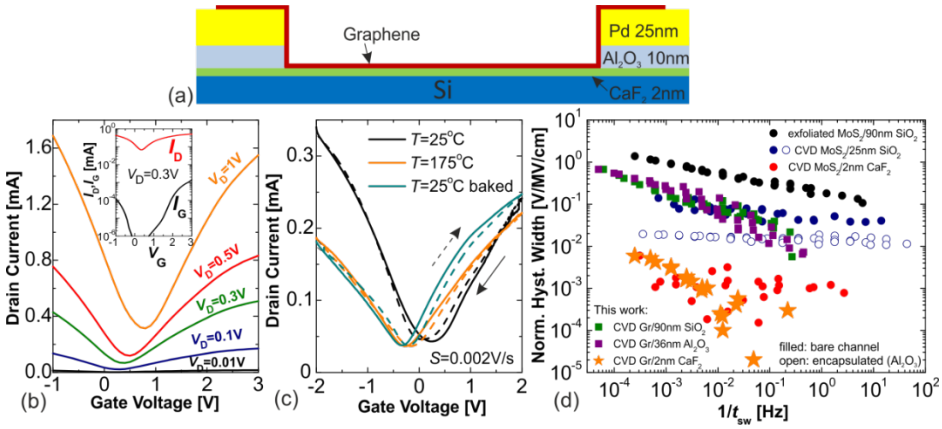

Figure 1: (a) Schematics of our GFETs with 2nm CaF_2 insulators. (b) Typical ID-VG characteristics of these devices. The inset shows that the gate leakage current through our thin CaF_2 layers is small compared to the drain current. (c) Double sweep ID-VG characteristics measured at different temperatures using slow sweep rates. (d) Comparison of post-annealing hysteresis in our GFETs with CaF_2 and other 2D devices.

References

[1] K. Novoselov et al., Science 306, 666 (2004).

[2] H. Geng et al., J. Mater. Chem. C 7, 11056 (2019).

[3] A. Béraud et al., Analyst 146, 403 (2021).

[4] Yu.Yu. Illarionov et al., Nat. Electron. 2, 230 (2019).

[5] Y. Illarionov et al., IEEE Electron. Dev. Lett. 38, 1763 (2017).

Conductivity of thin carbon-gold films

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We present an experimental demonstration of the photostimulation effect on the tunneling conductivity of free-standing thin carbyne-gold films [1]. To measure the current–voltage characteristics and to examine the photosensitivity of samples, we used Ntegra Aura scanning tunneling microscopy (STM) [2]. Figure 1 schematically illustrates the experimental set-up we used. We detected a significant increase in the tunneling current in the case of the laser illumination of the tunneling probe area. The observable current amplification is caused by the increase of the free charge carrier concentration due to the resonant absorption of the laser radiation of the 532 nm wavelength by gold nanoparticles.

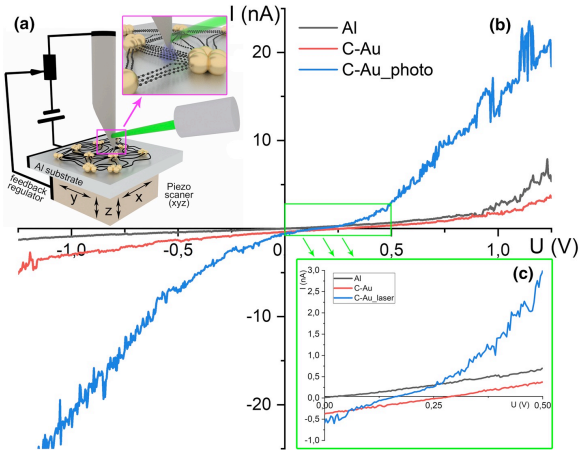

Figure 1: The tunneling current as a function of the voltage applied to the deposited free-standing C–Au films: a schematically illustrates the layout of the main elements of the STM set-up. b The current–voltage curves measured at various samples: the black line corresponds to the I/U curve of a pure aluminum substrate, the red curve corresponds to the C–Au thin film and the blue curve shows the I/U dependence of the C–Au thin film subjected to the excitation at the wavelength of 532 nm. c The inset presents the behavior of the tunneling at a low applied voltage level.

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References

[1] Kutrovskaya S. et al. Field-Induced assembly of sp-sp2 carbon sponges //Nanomaterials. – 2021 T. 11. – №. 3. – C. 763.

[2] Samyshkin V. et al. Photosensitive free-standing ultra-thin carbyne–gold films, Optical and Quantum Electronics. – 2019. – T. 51. – №. 12. – C. 1-9

Sound tuned non-classical light emission from atomic-scale defects in hexagonal boron nitride

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Among various available non-classical light sources, atomic defects based on monolayers, multilayers and crystals of hexagonal boron nitride (h-BN) have emerged as a promising physical system for quantum light emission. These luminescent defects, which most likely originate from midgap vacancy-related localized states, have been shown to behave as robust, high-temperature and ultra-bright multicolor single-photon sources [1,2]. However, identifying the exact nature of these emitters still remains a challenge for any practical future applications of h-BN in photonic quantum technologies. In this work, individual atomic-scale defects in h-BN are visualized using atomic force microscopy under ambient conditions [3]. This direct observation of the defects structure combined with density functional theory calculations of their band structures and electronic properties made it possible to associate the existence of several single-photon optical transitions to the observed defects, thus shedding light on the origin of quantum emitters in h-BN.

Furthermore, having single-photon emitters that can be operated on-demand and with the possibility of in situ control of the photon emission wavelength and time is a crucial prerequisite for on-chip quantum photonics. To date, spectral tuning of the optical emission from non-classical light sources in h-BN has only been demonstrated experimentally over a few-meV-wide range by static strain [2]. Here, we report on the dynamic real-time control of the photon emission wavelength from individual h-BN atomic defects subjected to the radio frequency surface acoustic waves (SAWs) [4]. When perturbed by the SAW-induced elastic vibration propagating at the acoustic frequency of ~330 MHz on the surface of a $LiNbO_3$ crystal equipped with an acoustic delay line onto which flakes of multilayer h-BN were mechanically transferred, the h-BN defects embedded in the dispersed flakes are periodically strained and their optical transitions are modulated by the acousto-mechanical coupling within a ~2 meV bandwidth [4]. This SAW- mediated spectral fine-tuning is further combined with spectral detection filtering for temporal control of the emitted photons [4]. In this way, both spectral tunability and on-demand emission of non-classical light are achieved simultaneously. Altogether, this study opens the door to the use of sound for scalable integration of h-BN emitters in nanophotonic and related quantum information technologies.

References

[1] T. Tran et al., Nat. Nanotechnol. 11, 37 (2016).

[2] G. Grosso et al., Nat. Commun. 8, 705 (2017).

[3] P. Areas et al., Adv. Electron. Mater. 7, 2001177 (2021).

[4] S. Lazić et al., Commun. Phys. 2, 13 (2019).