Long-Range Propagation of Indirect Excitons in $MoSe_2/WSe_2$ van der Waals Heterostructure

L.H. Fowler-Gerace*, D.J. Choksy, L.V. Butov
Department of Physics, University of California at San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA
*lefowler@physics.ucsd.edu

We realize long-range propagation of indirect excitons in a $MoSe_2/WSe_2$ heterostructure. The data show that the long-range propagation of indirect excitons is possible in van der Waals heterostructures with the predicted moiré superlattice potentials.
OCIS codes: 160.4236 (materials – nanomaterials), 230.5590 (optical devices – quantum-well, wire, dot devices)

Spatially indirect excitons (IXs), also known as interlayer excitons, can form the medium for excitonic devices whose operation is based on controlled propagation of excitons. The realization of excitonic devices relies on meeting the requirements of (i) long-range IX propagation over lengths exceeding the in-plane dimensions of excitonic devices and (ii) in situ control of IX energy and IX propagation, in particular, by voltage. These requirements were met with IXs in GaAs heterostructures (Ref. [1] and references therein) and a proof of principle for excitonic devices was demonstrated in GaAs heterostructures [2]. However, the low binding energy of IXs in GaAs heterostructures limits the operation of excitonic devices in this materials platform to low temperatures.

IXs in van der Waals transition-metal dichalcogenide (TMD) heterostructures are characterized by high binding energies offering an opportunity to create excitonic devices operating at high temperatures [3,4]. However, a characteristic feature of TMD heterostructures is the presence of moiré superlattice potentials, which are predicted to cause strong modulations of IX energy [5,6]. These in-plane energy landscapes localize IXs, making IX propagation fundamentally different in TMD and GaAs heterostructures and making uncertain if long-range IX propagation can be realized in TMD heterostructures. A relatively short-range IX propagation in TMD heterostructures, with the 1/e IX luminescence decay distance reaching ~ 3 microns, has been reported [7-11]. Control of IX luminescence by voltage within these distances was also reported in TMD heterostructures [9,10].

In this work, we realize the long-range IX propagation with the 1/e IX luminescence decay distances reaching 13 microns in a $MoSe_2/WSe_2$ heterostructure. We also realize control of the long-range IX propagation: the IX luminescence signal in the drain of an excitonic transistor is controlled within 40 times by gate voltage.

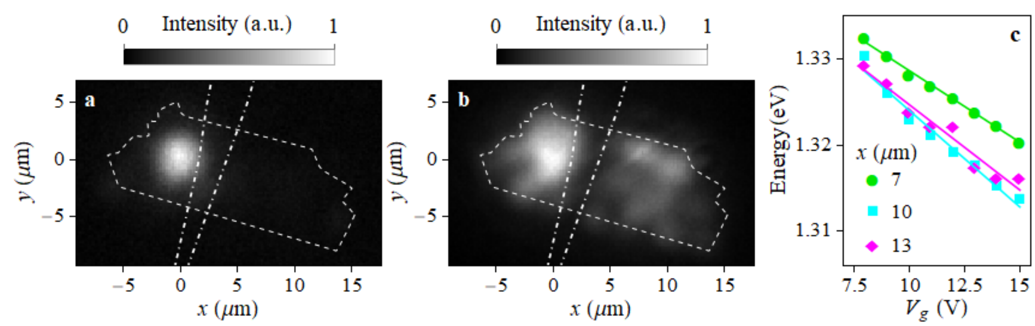

FIG. 1: (a,b) $x - y$ images of IX luminescence in the off (a) and on (b) state of the excitonic transistor. The dashed and dot-dashed lines show the boundary of the $MoSe_2/WSe_2$ heterostructure and graphene gate. The gate voltage V_g controls the IX propagation from the laser excitation spot at $x = 0$ through the device. A lower IX luminescence intensity is seen in the region covered by the graphene gate. $V_g = 10$ V (a), 0 (b). (c) IX energy vs V_g for positions in the drain region $x = 7$, 10, and 13 μm. $P_{ex} = 4$ mW, $T = 1.7$ K.

The $MoSe_2/WSe_2$ heterostructure is assembled by stacking mechanically exfoliated 2D crystals on a graphite substrate. The $MoSe_2$ and WSe_2 monolayers are encapsulated by hexagonal boron nitride (hBN). IXs are formed from electrons and holes confined in adjacent $MoSe_2$ and WSe_2 monolayers, respectively. The bias across the heterostructure is created by the gate voltage V_g applied between the narrow graphene top gate (Fig. 1a,b) and the global graphite back gate. The heterostructure region to the left of the graphene gate is referred to as the source and the heterostructure region to the right of the gate is referred to as the drain. IXs are optically generated by laser excitation focused in the source region (Fig. 1a,b).

In the off state of the device, IXs are localized in the laser excitation spot (Fig. 1a). In the on state, IXs spread out away from the excitation spot and propagate through the device, the 1/e IX luminescence decay distance reaches 13 microns (Fig. 1b). The total IX luminescence intensity in the drain region increases by 40 times as the gate voltage switches from off to on.

At voltages, which allow for IX propagation across the device, the IX luminescence energy is controlled by voltage in the entire drain region (Fig. 1c). This shows the basic IX property – IX energy control by voltage: IXs have dipole moments *ed* (*d* is the separation between the layers) and gate voltage controls the electric field F_z and changes the IX energy by edF_z. This verifies that the propagating luminescence signal corresponds to the IX luminescence. The IX luminescence spectra are traced over the entire drain region (Fig. 2a,b).

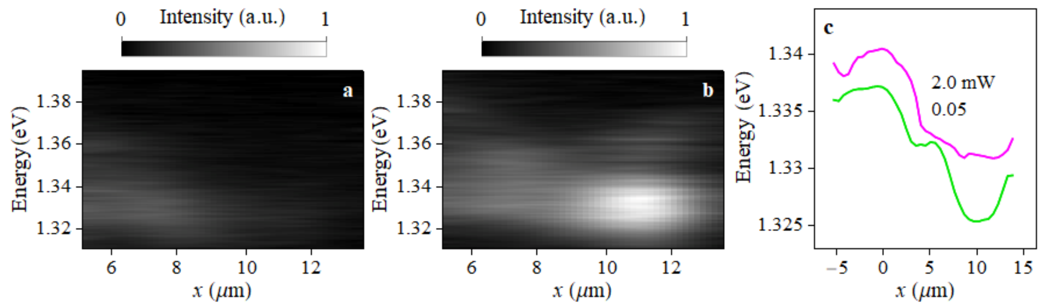

FIG. 2: (a,b) *x* – energy images of IX luminescence in the drain region for P_{ex} = 0.05 mW (a) and 2 mW (b). (c) IX energy vs position for P_{ex} = 0.05 mW (green) and 2 mW (magenta). Laser excitation is focused and centered at x = 0 μm, V_g = 10 V, T = 1.7K.

The overall IX energy reduction is observed with increasing separation from the IX optical generation spot and with reducing P_{ex} (Fig. 2c). The IX energy reduction with reducing IX density is consistent with repulsive interaction between IXs [1]. The IX energy variations due to the moiré superlattice are not resolved in the optical experiment.

The IX propagation is different in GaAs and TMD heterostructures. The moiré superlattice potentials are strong in TMD and vanishing in GaAs. Furthermore, the control of IX propagation by voltage in TMD presented in this work is different from that in GaAs heterostructures [2]. The screening of in-plane potential landscapes plays an essential role in the long-range IX propagation in TMD heterostructures.

We thank E.V. Calman, M.M. Fogler, S. Hu, A. Mishchenko, and A.K. Geim for valuable discussions and contributions in earlier studies of IXs in TMD heterostructures. This work was supported by DOE award DE-FG02-07ER46449. The heterostructure fabrication and data analysis were supported by SRC and NSF grant 1905478.

[1] C.J. Dorow, J.R. Leonard, M.M. Fogler, L.V. Butov, K.W. West, L.N. Pfeiffer, Split-gate device for indirect excitons, Appl. Phys. Lett. 112, 183501 (2018).

[2] G. Grosso, J. Graves, A.T. Hammack, A.A. High, L.V. Butov, M. Hanson, A.C. Gossard, Excitonic switches operating at around 100 K, Nature Photonics 3, 577 (2009).

[3] M.M. Fogler, L.V. Butov, K.S. Novoselov, High-temperature superfluidity with indirect excitons in van der Waals heterostructures, Nature Commun. 5, 4555 (2014).

[4] Thorsten Deilmann, Kristian Sommer Thygesen, Interlayer Trions in the MoS_2/WS_2 van der Waals Heterostructure, Nano Lett. 18, 1460 (2018).

[5] Fengcheng Wu, Timothy Lovorn, A.H. MacDonald, Topological Exciton Bands in Moiré Heterojunctions, Phys. Rev. Lett. 118, 147401 (2017).

[6] Hongyi Yu, Gui-Bin Liu, Jianju Tang, Xiaodong Xu, Wang Yao, Moiré excitons: From programmable quantum emitter arrays to spin-orbit–coupled artificial lattices, Sci. Adv. 3, e1701696 (2017).

[7] Pasqual Rivera, Kyle L. Seyler, Hongyi Yu, John R. Schaibley, Jiaqiang Yan, David G. Mandrus, Wang Yao, Xiaodong Xu, Valley-polarized exciton dynamics in a 2D semiconductor heterostructure, Science 351, 688 (2016).

[8] Luis A. Jauregui, Andrew Y. Joe, Kateryna Pistunova, Dominik S. Wild, Alexander A. High, You Zhou, Giovanni Scuri, Kristiaan De Greve, Andrey Sushko, Che-Hang Yu, Takashi Taniguchi, Kenji Watanabe, Daniel J. Needleman, Mikhail D. Lukin, Hongkun Park, Philip Kim, Electrical control of interlayer exciton dynamics in atomically thin heterostructures, Science 366, 870 (2019).

[9] Dmitrii Unuchek, Alberto Ciarrocchi, Ahmet Avsar, Zhe Sun, Kenji Watanabe, Takashi Taniguchi, Andras Kis, Valley-polarized exciton currents in a van der Waals heterostructure, Nature Nanotechnology 14, 1104 (2019).

[10] Yuanda Liu, Kévin Dini, Qinghai Tan, Timothy Liew, Kostya S. Novoselov, Weibo Gao, Electrically controllable router of interlayer excitons, Sci. Adv. 6, eaba1830 (2020).

[11] Zumeng Huang, Yuanda Liu, Kévin Dini, Qinghai Tan, Zhuojun Liu, Hanlin Fang, Jin Liu, Timothy Liew, Weibo Gao, Robust room temperature valley Hall effect of interlayer excitons, Nano Lett. 20, 1345 (2020).