Conference materials
UDC 538.9
DOI: https://doi.org/10.18721/JPM.183.208

Electrostatic control of correlated phases in spatially inhomogeneous two-dimensional moiré structures

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Abstract. Two-dimensional moiré structures are a promising platform for quantum simulations. In 2D van der Waals twisted bilayers, a moiré superlattice acts as a periodic potential for capturing interlayer excitons, which opens new possibilities for constructing quantum correlated phases. In addition, precise control of electronic states in such structures is possible via electrostatic doping and application of out-of-plane electric fields. However, effects related to spatial inhomogeneity, which is often present in experimental samples of van der Waals heterostructures, are currently not well studied. Here we experimentally investigate correlated phases in a spatially inhomogeneous twisted WSe_2/WS_2 bilayer with electrostatically controlled free charge carrier density. Using photoluminescence (PL) spectroscopy, we locally detect multiple correlated phases and demonstrate continuous tuning of their energies via electric bias. Our results contribute towards the development of quantum simulators based on correlated phases in twisted van der Waals heterostructures.

Keywords: moiré superlattice, 2D semiconductors, strongly correlated electronic states

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: Abramov A.N., Chiglintsev E.O., Oskolkova T.O., Bandurin D.A., Iorsh I.V., Chernov A.I., Kravtsov V.A., Electrostatic control of correlated phases in spatially inhomogeneous two-dimensional moiré structures, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.2) (2025) 49–52. DOI: https://doi.org/10.18721/JPM.183.208

Материалы конференции
УДК 538.9
DOI: https://doi.org/10.18721/JPM.183.208

Электростатическое управление коррелированными фазами в пространственно неоднородной двумерной муаровой структуре

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Аннотация. Двумерные муаровые структуры являются многообещающей платформой для создания квантовых симуляторов. В двумерных Ван-дер-Ваальсовых скрученных бислоях муаровая сверхрешетка действует как периодический потенциал для захвата межслоевых экситонов, что открывает новые возможности для формирования квантово-коррелированных фаз. Кроме того, точный контроль электронных состояний в таких структурах возможен с помощью электростатического допирования и приложения внеплоскостных электрических полей. Однако эффекты, связанные с пространственной неоднородностью, которая часто присутствует в экспериментальных образцах Ван-дер-Ваальсовых гетероструктур, в настоящее время изучены недостаточно. В данной работе мы экспериментально исследуем коррелированные фазы в пространственно неоднородном скрученном бислое WSe_2/WS_2 с электростатически контролируемой плотностью свободных носителей заряда. Используя фотолюминесцентную спектроскопию (ФЛ), мы локально обнаруживаем множество коррелированных фаз и демонстрируем непрерывную перестройку их энергий с помощью электрического смещения. Наши результаты важны для разработки квантовых симуляторов на основе коррелированных фаз в скрученных Ван-дер-Ваальсовых гетероструктурах.

Ключевые слова: муаровая сверхрешетка, двумерные полупроводники, сильно коррелированные электронные состояния

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

Ссылка при цитировании: Абрамов А.Н., Чиглинцев Э.О., Осколкова Т.О., Бандурин Д.А., Иорш И. В., Чернов А.И., Кравцов В.А. Электростатическое управление коррелированными фазами в пространственно неоднородной двумерной муаровой структуре // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 3.2 № .18. С. 49–52. DOI: https://doi.org/10.18721/JPM.183.208

Introduction

Moiré structures are a powerful platform for studying solid state physics, with prospective applications for developing novel quantum simulators. Heterostructures based on two-dimensional materials make it possible to create moiré superlattices and control electronic states with unique degrees of freedom such as the twist angle, lattice mismatch, deformation, doping by charge carriers, as well as external electric and magnetic fields. This makes it possible to implement and study various fundamental multiparticle quantum models of condensed matter physics [1]. In addition, the strong optical response of excitons in such structures allows straightforward optical

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readout [2]. By now, correlated electronic phases have been observed in WSe_2/WS_2 heterostructures, and corresponding exciton dynamics have been studied [3]. Here we study the behavior of strongly correlated phases in a spatially heterogeneous structure.

Results and discussion

We investigate a moiré superlattice device based on WSe_2 and WS_2 monolayers in R stacking and with contact, top and bottom gates (Fig. 1, *a*). We can apply voltages V_{tg} and V_{bg} to the top and bottom gates for independent control of the free carrier density and displacement electric field. The contacts and gates are made of atomically thin graphite and gold electrodes fabricated by electron beam lithography. The interlayer exciton (IX) is generated by optical excitation, while the impurity electron and hole are in different monolayers (Fig. 1, *b*).

PL spectra are measured at 8 K with 633 nm laser excitation, revealing a complex dependence on gate voltage. We observe an interlayer exciton at 1.38–1.42 eV and a shift in its energy near the electron filling factor $n = 1$ of the moiré superlattice. In the range between the filling factors $n = 0$ and $n = 1$,

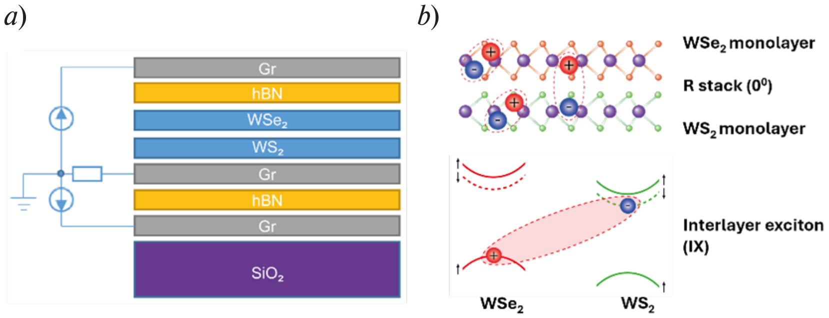

Fig. 1. Scheme of the sample (*a*), showing two monolayers in an R stack (top) and interlayer exciton formation in WSe_2/WS_2 heterostructure (bottom) (*b*)

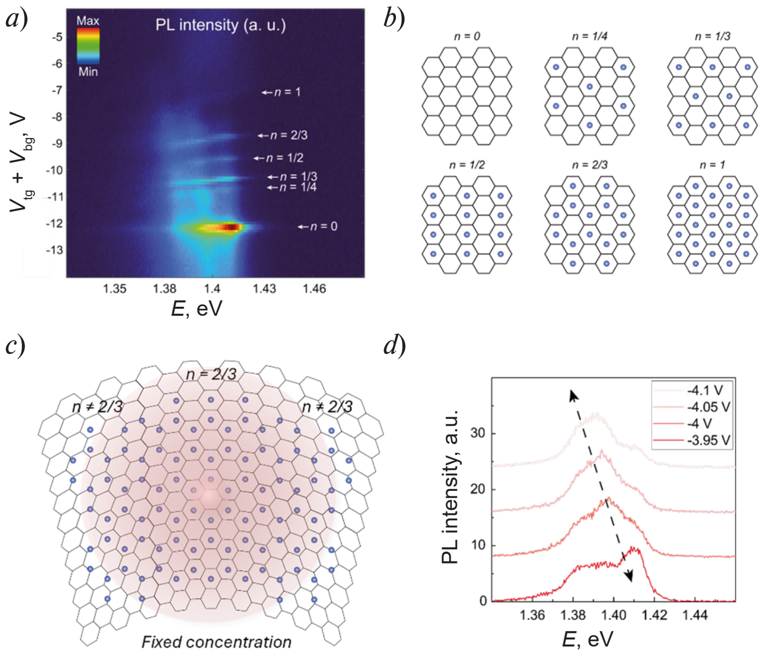

Fig. 2. Dependence of the photoluminescence spectrum of a WSe_2/WS_2 structure on gate voltage (*a*); localization of free electron charge carriers in a moiré superlattice (*b*); schematic illustration of a spatial distribution of both energy IX and the filling factor due to heterogeneity in the sample (*c*), the red-colored area indicates the laser spot; shift of the filling factor $n = 2/3$ with the applied voltage (the dotted line schematically shows the shift of the PL maximum) (*d*)

we clearly observe a number of maxima in the PL spectra, corresponding to fractional filling factors of the moiré superlattice [4, 5] (Fig. 2, *a*). The integer and fractional filling factors correspond to the state of the generalized Wigner crystal. In this case, the free charge carriers form an ordered periodic lattice and are localized at the points of symmetry of the moiré superlattice (Fig. 2, *b*). Interestingly, we also observe a continuous energy shift of the local photoluminescence maxima with voltage. This is attributed to the spatial inhomogeneity of the twist angle between semiconductor monolayers, where twist angle gradient within the excitation laser spot creates certain spatial distributions of both the IX energy and filling factor (Fig. 2, *c*). In addition, local tensile or compressive strain can also contribute to the observed effect. We note that the presence of such inhomogeneity in the heterostructure in principle allows us to manipulate the spatial position of the desired correlated state in the heterostructure within the excitation laser spot. In this case, the region of the structure with a certain filling factor shifts inside the laser spot when the concentration of charge carriers changes, which leads to a change in the energy of the interlayer exciton. Fig. 2, *d* shows such shift of the PL peak corresponding to the filling factor $n = 2/3$. Further studies of exciton dynamics in such structures will provide better understanding of the processes occurring in moiré superlattices for the development of 2D quantum simulators.

Conclusions

In this work, we fabricated and characterized moiré structures based on twisted WSe_2 and WS_2 monolayers. We observed a continuous energy shift of the PL peaks corresponding to certain filling factors, which is attributed to the spatial inhomogeneity of the twist angle and local strain of the heterostructure. This will allow for future research on Hubbard physics in spatially inhomogeneous structures. Our results are important for the development of quantum technologies using two-dimensional materials.

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Received 12.09.2025. Approved after reviewing 17.09.2025. Accepted 19.09.2025.