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主　論　文　の　要　旨

論文題目　Device engineering for investigating optical properties of two-dimensional semiconductors

（デバイスエンジニアリングに基づく二次元半導体の光学特性の研究）

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論　文　内　容　の　要　旨

Light-matter interaction plays an instrumental role in helping humans understand the world and the underlying physics. In recent years, monolayer transition metal dichalcogenides (TMDs), a type of two-dimensional (2D) materials, have emerged as a platform for investigating light-matter interaction on atomic scale owing to their fascinating optical properties and strong light-matter interaction. Owing to the 2D structure of monolayer TMDs, screening is less pronounced, leading to strong Coulomb interaction. As a result, the binding energies of excitons, which are tightly bound electron-hole pairs, exhibit orders of magnitude higher values compared to those observed in conventional semiconductors. The optical properties of 2D TMDs are, therefore, dominated by excitonic effects, which provide intriguing optical responses and a broad range of tunability by applying external fields and electrostatic gating.

This work aims to combine the optics of 2D materials with device engineering to investigate new optical phenomena. We have developed various techniques for investigating the optical properties, particularly the exciton physics of 2D TMDs, through device design and fabrication. First, the author reports a reflectance spectroscopy method called gate-modulated reflectance (GMDR) spectroscopy to detect exciton states, specifically excited high-energy states of excitons (exciton Rydberg states), in 2D semiconductors. This method is based on measuring the change in exciton resonance induced by a carrier density change in a field-effect transistor. The results have successfully demonstrated an excellent sensitivity of GMDR to excitonic states, particularly the exciton Rydberg states that are difficult to observe in traditional reflectance measurements. For example, the author has successfully observed trion 2s states in a GMDR spectrum at around 2.2 eV, in addition to the exciton 2s state. Second, the author introduces a nanofabricated metal mask for exploring moiré excitons in TMD heterostructures. Due to the inhomogeneity of Moiré excitons, PL spectra of moiré systems often exhibit numerous peaks, which complicates the understanding of their origin. The metal mask effectively blocks the majority of incident excitation light and PL signals emitted by the sample, while simultaneously permitting the excitation and collection of PL signals from a specified area through a central aperture with a diameter of 200 nm. Therefore, the metal mask with the 200 nm aperture is expected to enhance the homogeneous photon emission from the moiré superlattice. Indeed, the PL spectra show a reduced number of peaks and a narrowed linewidth when using the metal mask. This method does not introduce any damage or pollution to the TMD bilayer. Furthermore, the metal mask can act as a top gate, providing great potential for various device integration in the future. Finally, the author presents a strategy to visualize the Valley Hall effect in monolayer TMDs. The Valley Hall effect is a Hall effect that can appear without the application of a magnetic field. The Valley Hall effect has been observed by measuring Hall voltages in previous work, but direct visualization is challenging. The visualization is based on the luminescence of a MoS_2 transistor under a bias voltage and a light excitation. Split luminescent spots were observed around the MoS_2-electrode (bismuth) contact region when a biased MoS_2 channel was excited at 633 nm. Holes injected by the light excitation and electrons from the bismuth electrode recombine to emit the observed PL spots. The split PL spots observed indicate that the injected holes, driven by the bias voltage, experienced anomalous velocity due to the valley Hall effect.