Electric-Field Effect on Photoluminescence of Single Colloidal Lead-Halide Perovskite Nanowires

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Abstract

Single colloidal perovskite nanostructures have emerged as a promising class of photonic sources, offering both classical and quantum light emission capabilities. Notably, they can be heterogeneously integrated with CMOS circuits, paving the way for advanced optoelectronic and photonic device applications . In this study, we investigate single excitons in individual $CsPbBr_3$ nanowires, demonstrating how their photoluminescence properties are modulated by an external electric field at cryogenic temperatures.

Author Keywords

Perovskite; $CsPbBr_3$; Quantum Confined Stark Effect (QCSE); Semiconductor nanowires; Photoluminescence

1. Introduction

All-inorganic lead-halide perovskite (LHP) nanostructures ($CsPbX_3$, X = Cl, Br, or I) have emerged as a highly promising platform for diverse optoelectronic applications, such as light-emitting diodes (LEDs) with narrow emission spectra and quantum light sources [1][2]. The local dielectric environment, the band structure of LHP, and their combined interaction with external electric fields significantly influence the formation and recombination processes of excitons within LHP, playing a crucial role in determining their optoelectronic performance [3][4].In this study, we conduct an electric-field-dependent photoluminescence (PL) investigation on single $CsPbBr_3$ nanowires (NWs) with lengths of approximately 100 nm and widths of ~ 10 nm at cryogenic temperatures. The Quantum Confined Stark Effect (QCSE) reveals that the overlap of electron and hole wave functions can be effectively modulated by an external electric field [4][5], resulting in significant shifts in exciton recombination energy, reaching up to ~ 4.33 meV in single perovskite NWs. These findings offer valuable insights into the impact of electric fields on exciton recombination properties in lead-halide perovskite nanostructures, which are crucial for advancing both classical and quantum optoelectronic devices.

2. Results and discussion

The colloidal $CsPbBr_3$ NWs have been synthesized by the method developed by Jing et al. [6] with lengths of approximately 100 nm and widths of ~ 10 nm from the transmission electron microscopy image as shown in Figure 1(a). For the optical studies of single $CsPbBr_3$ NWs, we employed a picosecond 405 nm laser operating at 5 MHz with a power density of ~ 1 W/cm^2. As shown in Figure 1(b), the PL peak is observed around 2.412 eV at room temperature, within the visible color. The Schematic of the electrode is shown in Figure 2. The electrodes were fabricated using photolithography and e-beam evaporation, with each electrode having a width of 10 μm and a spatial separation of 5 μm between adjacent electrodes. The electrode consists of a 5 nm thick chromium (Cr) layer and an 80 nm thick gold (Au) layer. Monodisperse NWs were randomly distributed between the finger electrodes using a spin-coating method. Single-particle spectroscopy was performed at ~ 4 K, the sharp exciton PL[7] of a single NW under the influence of an applied electric field was obtained. The electric filed is generated by Keithley 2636B source meter.

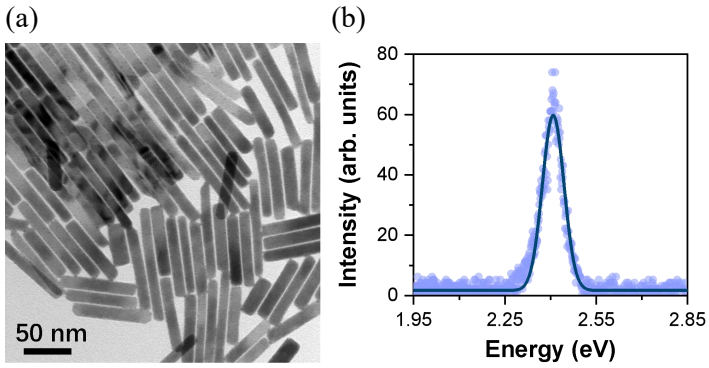

Figure 1. (a) Transmission electron microscopy (TEM) image of $CsPbBr_3$ nanowires. (b) PL spectrum of a single $CsPbBr_3$ NW at room temperature.

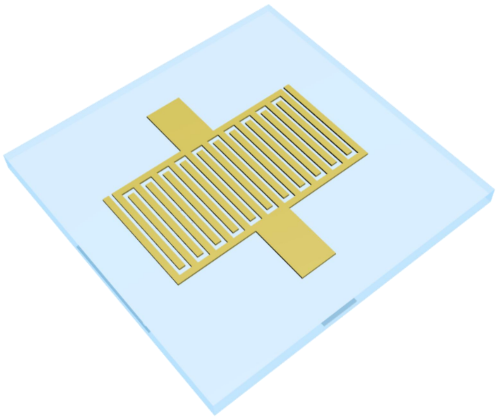

Figure 2. The finger electrode had a width of 10 μm, with the two nearby electrodes separated by a spatial distance of 5 μm.

As illustrated in Figure 3a, the PL spectrum of a single $CsPbBr_3$ NW excited at an exciton density of $\langle N \rangle$ ~ 0.1 (where $\langle N \rangle$ represents the number of excitons generated per pulse[8]) shows a shift in the single-exciton peak from ~ 2.3796 eV to ~ 2.3787 eV as the electric field decreases from 0 to - 89.6 kV/cm . This phenomenon is attributed to the QCSE. In a typical QCSE process, the exciton peak generally undergoes a redshift when a positive or negative electric field is applied. However, as the electric field increases from 0 to 133 kV/cm, the built-in electric

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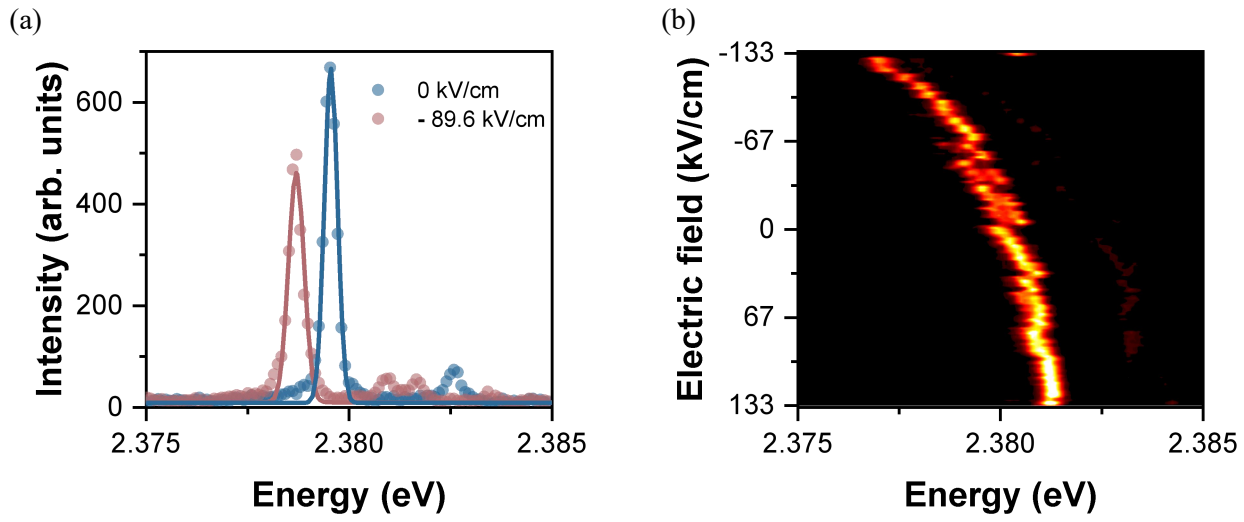

Figure 3. (a). PL spectral of a single $CsPbBr_3$ NW showing the single-exciton peak at the electric fields of 0 and -89.6 kV/cm. (b). PL spectral image of the same single-exciton peak shifts as a function of the external electric field.

field is progressively compensated, leading to a blueshift in the single-exciton peak, as depicted in Figure 3b. With an external electric field (E), the induced change of the exciton recombination energy can be described as $\alpha E + \beta E^2$ [5], where α represents the permanent dipole moment associated with the built-in electric field, and β corresponds to the exciton polarizability. In this NWs system, the PL peak exhibits a shift of up to ~ 4.33 meV as the electric field varies from -133 to 133 kV/cm. And compared to single perovskite nanocrystals (NCs), single NWs are larger in size, with a greater length (L). It is believed that as the size increases, the surface tension of the crystal decreases, symmetry improves, and the permanent dipole moment reduces. As a result, the PL shift range decreases[4].

From our measurement of electric-field effect on single 1D perovskite NWs, we observe significant modulation of their PL properties, demonstrating that they can serve as highly sensitive nanomaterials for electro-optical modulation applications. Due to its compatibility with any substrate via spin coating, it holds significant potential for CMOS device applications[9].

3. Conclusion

To summarize, we applied external electric fields to single perovskite $CsPbBr_3$ NWs with weak quantum confinement and demonstrated that their PL spectra shift in response to variations in the electric field. Notably, the Stark shift range is smaller than that observed in single NCs. This electric-field-dependent behavior highlights the modulation of exciton dynamics within the nanostructures and reveals the influence of the electric field on recombination energy. The observed spectral shifts offer valuable insights into the interaction between excitons and the applied electric field, enhancing our understanding of the optoelectronic properties of perovskite NWs. These findings contribute to the development of perovskite-based optoelectronic devices, including tunable light sources and quantum photonic applications, including silicon-based compatible electro-optic modulator.

4. Acknowledgments

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