Layer-dependent electro-optic effects and the brightening of dark excitons in few-layer black phosphorus

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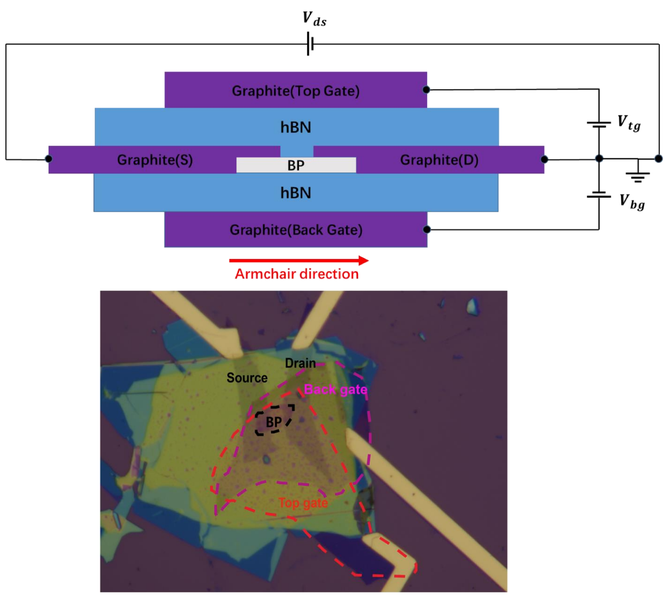
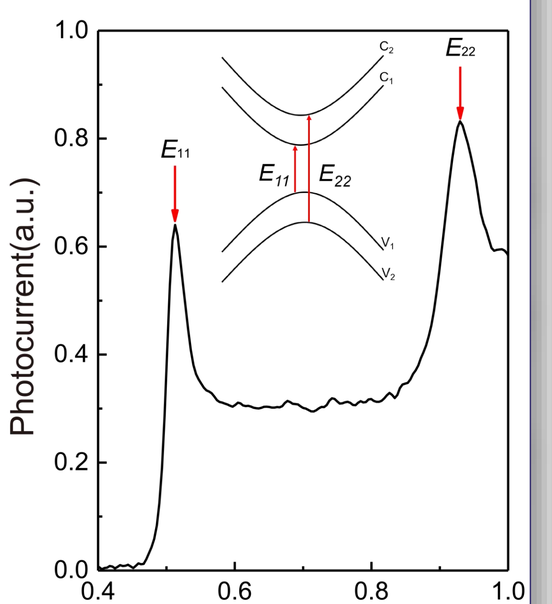
Introduction

Black phosphorus (BP) is rediscovered as an attractive material for infrared optoelectronic applications because of its anisotropic nature and a moderate bandgap which varies with thickness from 0.3 to 2 eV. Here we report that a vertical electric field can effectively tune the exciton absorption experimentally. The polarizabilities of E_{11} excitons are extracted, unravelling layer dependent Quantum Confined Stark Effect (QCSE), which is clearly explained by our screened Quantum Well (screened QW) calculations. We further show that transitions with different indices behave distinctly. Moreover, the influence of the external field also brightens transitions that are otherwise prohibited by the selection rule. Our study not only unleashes BP's potential as an alternative material whose optical gap could cover all mid-infrared range, but also may enable the possibility for integrated on-chip photodetectors and modulators with different modulating speed and range.

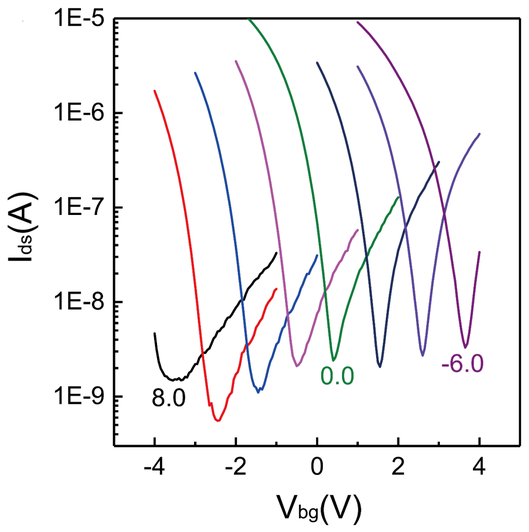
Characterization of the BP mid-IR photodetectors

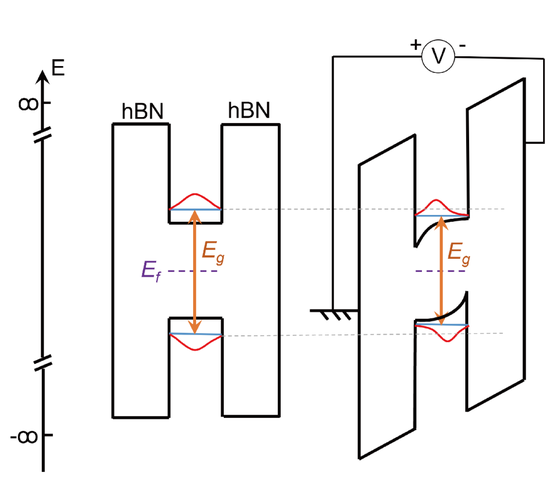


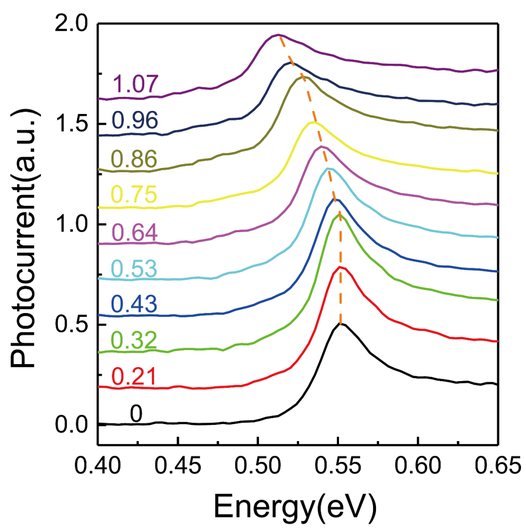


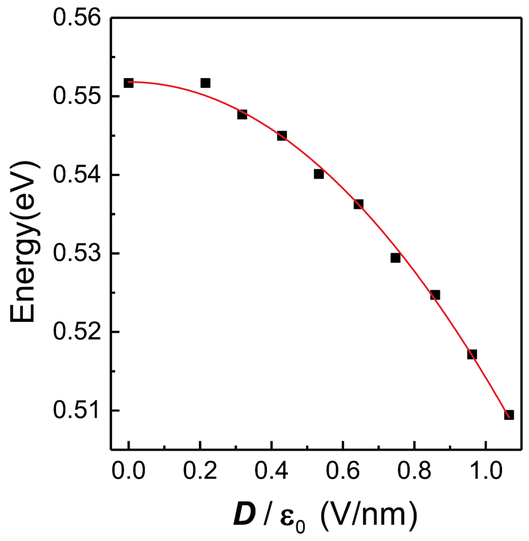
Electrical characterization and photocurrent spectrum

- The E_{11} positions shift quadratically: typical quantum confined stark effect (QCSE).



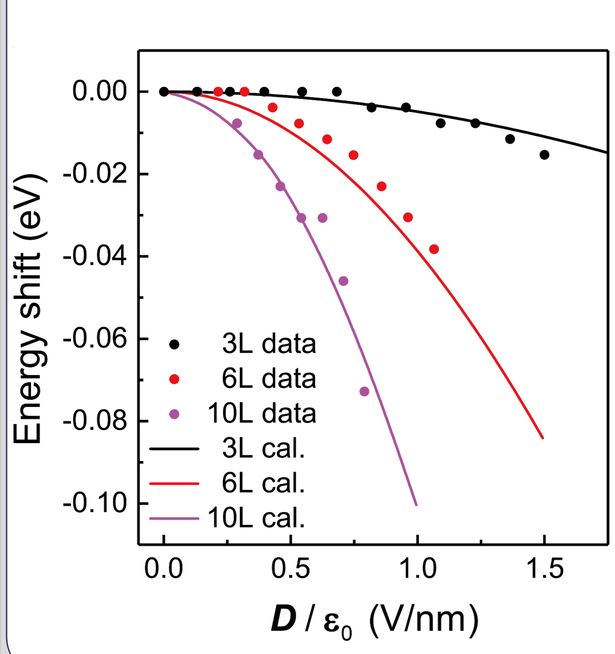


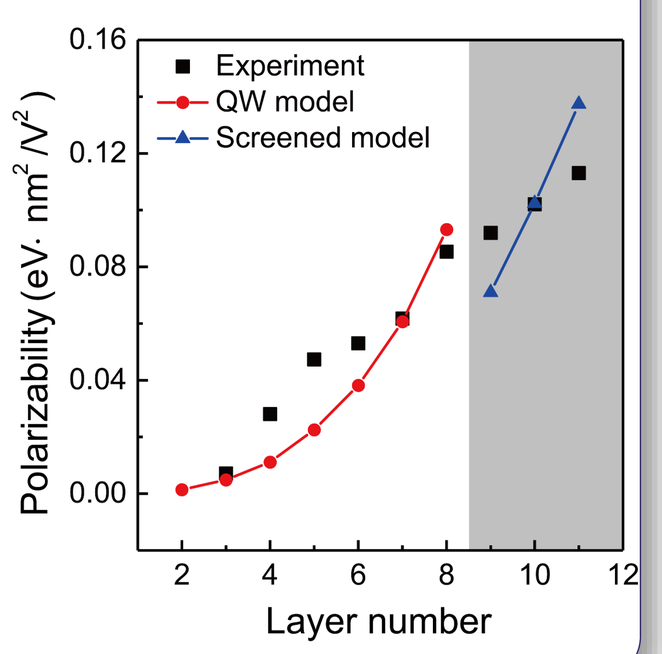




The layer dependent QCSE of E_{11} in BP FETs

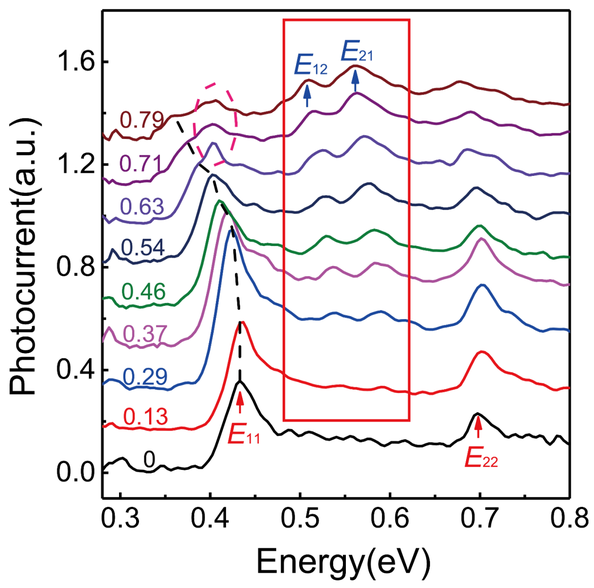
- Layer dependent polarizabilities of E_{11}
  thicker sample has larger polarizability
- The emergence of electrostatic screening effect

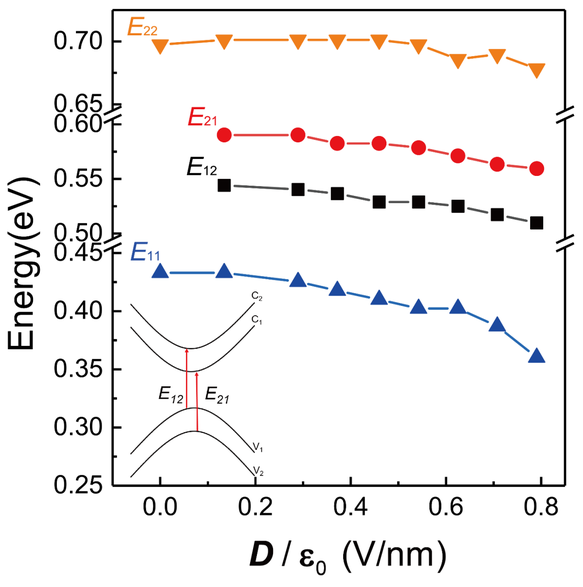


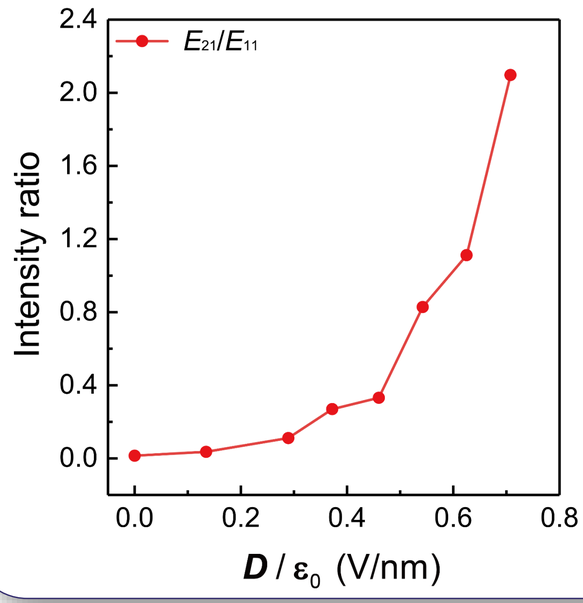


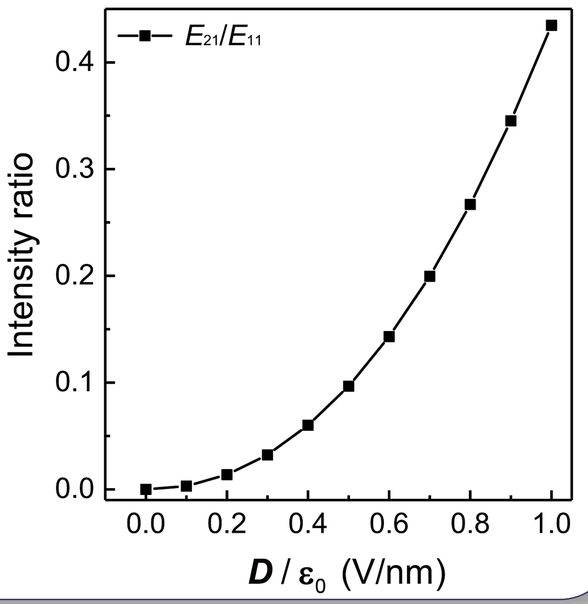
Index-dependent QCSE and the brightening of dark excitons

- Index dependent QCSE
  E_{11} shows stronger QCSE: wave function is more sensitive
- Dark excitons become brighter: symmetry is broken









Conclusion

In summary, widely tunable mid-IR photodetector based on hBN encapsulated BP has been demonstrated for mid-IR photonics applications. We have observed the QCSE and the emerge of forbidden transitions under a symmetry-breaking electric field, which are originated from optical transitions between different subbands and show strong layer and gate voltage dependence. Moreover, the intensity of forbidden transitions enhance as the field enlarges, which could provide a platform for other new applications.