Introduction

Dielectric screening plays an essential role in semiconductor physics. It modifies the interactions between electronic carriers and therefore strongly impacts not only transport phenomena, but also optoelectronic properties via its influence on both the size and binding energy of bound electron-hole pairs (excitons). In 3D bulk semiconductors that are characterized by a single dielectric constant $\varepsilon$, exciton radii and binding energies scale simply as $\varepsilon$ and $1/\kappa^2$, respectively. For example in bulk GaAs, the large dielectric constant ($\varepsilon$~13), together with the light electron mass, leads directly to large excitons (~15nm radius) with small binding energy (~5meV).

In new 2D semiconductors such as monolayer MoS$_2$, WSe$_2$, phosphorene, and germanene -- the recent discoveries of which have sparked tremendous interest -- dielectric screening from the semiconductor itself is generally much weaker and is lengthscale-dependent. For example, a well-separated electron and hole are essentially unscreened (because electric field lines connecting the two lie mainly outside the 2D slab), while for electron-hole separations of order the slab thickness many more field lines lie within the slab which partially screens the electrostatic potential. These ‘non-local dielectric screening’ phenomena in 2D semiconductors lead to markedly non-hydrogenic electrostatic potentials $V(r)$ and to excitons with very large binding energies (100s of meV) and correspondingly very small radii (~1nm), both in significant contrast to their bulk counterparts.

Crucially, because excitons in 2D semiconductors necessarily reside near a surface, their fundamental properties (size, binding energy, oscillator strength) are expected to be strongly influenced by any additional screening from the dielectric environment surrounding the monolayer. These exciton parameters are currently of significant interest, particularly in the monolayer semiconductors. Understanding and quantifying the role of the dielectric environment on 2D semiconductors is therefore of critical importance for future 2D optoelectronic devices.

Experimental

However, studies exploring this role in 2D materials are both scarce and challenging, in part because the most readily accessible property of an exciton -- its optical transition energy -- is largely unaffected by the surrounding dielectric. This is because the expected reduction in exciton binding energy due to the dielectric environment is nearly exactly compensated by an equivalent reduction in the free-particle bandgap, resulting in an unchanged exciton energy.

Here we show that the role of the dielectric environment is revealed through its systematic influence on the size of the exciton, which can be directly measured via the diamagnetic shift of the exciton transition in high magnetic fields. Using exfoliated WSe$_2$ monolayers affixed to single-mode optical fibers, we tune the surrounding dielectric environment by encapsulating the flakes with different materials, and perform polarized low-temperature magneto-absorption studies to 65T. The systematic increase of the exciton’s size with dielectric screening, and concurrent reduction in binding energy (also inferred from these measurements), is quantitatively compared with leading theoretical models. These results demonstrate how exciton properties can be tuned in future 2D optoelectronic devices.

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[1] Stier, A.V. et al., Nano Letters 16, 7054 (2016).