能谷电子学新进展：单层 WS_2 中的 K-Q 谷间三重子发光

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借鉴电子自旋自由度的研究思路，可以利用谷自由度作为信息载体，调控谷自由度设计并实现相关量子功能器件，即“能谷电子学”(valleytronics)。其中，二维体系中的能谷电子特性优异，受到了大量关注，包括对称性破缺的石墨烯、单层过渡金属二硫化物（MX_2）等。

近日，福州大学裴家杰副教授、深圳大学张晗教授以及清华大学熊启华教授联合团队通过使用高质量的 h-BN 封装的 WS_2 场效应晶体管调整费米能量来改变间接带 Q 谷的电子占据状态。通过改变场效应管的背栅压，可以控制导带中不同能谷内的电子浓度。结果，一个比传统的 K 谷三重子能量低 20 meV 的明显发射特征出现，并且与传统的 K 谷三重子发光强度呈竞争关系，二者的相互转化过程符合玻尔兹曼分布规律。进一步研究证明，这种发光特征是来自间接带 Q 谷三重子的发光，有别于先前报道的双激子或者带电双激子，虽然二者具有非常接近的能量，但是它们主要是在低掺杂的样品中出现，并且随电场变化的趋势应该是相反的。在高掺杂或高激发功率下，电子向 Q 谷的散射变得更加高效，有助于形成这种 Q 谷带电态，从而影响该发射特征的幂律响应。因此，能够通过栅压调制将其幂律响应从线性（α~0.95）调整为超线性（α~1.42）。通过时间分辨光致发光（TRPL）测量探测的这种激子态的载流子寿命也显示出很强的栅极依赖性。非线性功率和栅极响应是由于费米能级的变化引起的间接带 Q 谷带边激子数量的变化。

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Switching of K-Q intervalley trions fine structure in n-doped monolayer WS_2

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The anomalous spin and valley configurations at the conduction band edges in monolayer WS_2 give rise to even more fascinating valley many-body complexes. The coupling of charges, spins, energy valleys, and many-body complex quasiparticles offers opportunities to manipulate quantum information by an optical method.

The research group of Prof. Han Zhang and Qihua Xiong from Shenzhen University and Tsinghua University found that the indirect Q valley in the first Brillouin zone of monolayer WS_2 plays a critical role in the formation of a new excitonic state. By employing a high-quality h-BN encapsulated WS_2 field-effect transistor, it is able to switch the electron concentration within K-Q valleys at conduction band edges. Consequently, a distinct emission feature could be excited at the high electron doping region. This feature is competitive with the traditional K-valley trions and obeys the Boltzmann distribution law. Further studies have proved that this feature is from the luminescence of the indirect Q-valley trions. Such a feature differs from the previously reported trion-exciton complex (XX^-), which only appeared at the very low doping region of the sample, although they have very close energies. It is found that the actual doping level of the sample has a significant impact on the power-law response of this emission feature. With increasing Fermi level, the scattering of electrons to the Q valley becomes more efficient facilitating the formation of such a charged state. Consequently, it is able to tune its power-law response from linear (α~0.95) to superlinear (α~1.42), and radiative lifetime τ_2 from 880 ps to 250 ps efficiently by gate modulation.

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