CONDENSED-MATTER PHYSICS

Excitons surf the waves

Directional control of the diffusion of excitons is desired for excitonic devices, but being neutrally charged they can't be transported by applying a bias voltage as for conventional electronic transport. It is now shown that surface acoustic waves can direct the flux of excitons over micrometre distances, even at room temperature.

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Conventional electronic devices rely on the transport of electron charge carriers to transmit information. However, the growing need for energy-efficient devices has recently led to the exploration of alternative approaches for developing logic devices where information is encoded in different particles (such as photons and magnons) or quantum numbers (for example spintronics and valleytronics). In recent years, excitons — bound states between an electron and a hole — have progressively gained relevance in the scientific community, owing to their great potential for interfacing light-based and electron-based devices to create exciton-based electronics[1,2]. Moreover, owing to their bosonic nature, excitons are appealing candidates for use in quantum information technologies.

Although the concept of excitons can be traced back to 1930, when it was first proposed by Yakov Frenkel, the possibility of using excitons as information carriers has only been explored very recently. Excitonic devices operate through the generation, diffusion and detection of excitons within a given material platform and, although generation and detection of excitons can be achieved relatively easily by optical methods, controlling their diffusion has remained a technically challenging task for many years. In particular, one of the main hurdles of excitonic devices is to achieve sufficiently large exciton diffusion lengths to be able to transmit information over a sizable distance[3]. One potential approach to overcome this limitation is to provide excitons with momentum, so that they can drift over longer distances before dissociating. However, owing to their charge neutrality, a directed flux of excitons cannot be achieved by simply applying an electric field.

The recent isolation of two-dimensional semiconductors with a high exciton diffusivity and a large exciton binding energy has renewed the hope for devices featuring excitonic transport at room temperature. In fact, atomically thin layers of transition metal dichalcogenides (TMDs) recently showed exciton diffusion lengths of up to several hundreds of nanometres[3]. Further, even larger exciton diffusion lengths can be achieved in TMD-based devices, either by separating electrons and holes in real space, like interlayer excitons in type-II heterostructures where electrons and holes are localized in different layers[1], or by using inhomogeneous strain profiles to funnel excitons[4,5,10], largely reducing exciton–phonon scattering[6].

Another appealing strategy to control and enhance exciton transport relies on the use of surface acoustic waves to generate a time-varying inhomogeneous strain profile[7]. This results in excitons preferentially accumulating into the (moving) tensile-strained regions of the waves, acquiring a net momentum in the propagation direction of the waves in the process. In particular, transport of excitons in GaAs quantum wells up to hundreds of micrometres was recently demonstrated using the moving strain field of a surface acoustic wave, but only at cryogenic temperatures[8].

Now, writing in *Nature Photonics*, Datta and co-workers demonstrate control of exciton transport at room temperature with dynamic strain[9].

To carry out their experiments, Datta et al. transferred a mechanically exfoliated tungsten diselenide (WSe$_2$) monolayer (a semiconductor with a strong exciton binding energy) onto the surface of a LiNbO$_3$ piezoelectric generator operating at ~745 MHz (Fig. 1) The semiconducting WSe$_2$ flake was encapsulated between hexagonal boron nitride flakes to suppress non-radiative recombination processes and scattering centres, as well as to moderate the dielectric environment to increase the mobility and binding energy of the excitons. Spatially resolved photoluminescence measurements allowed for monitoring the propagation of exciton densities temporally at room temperature.

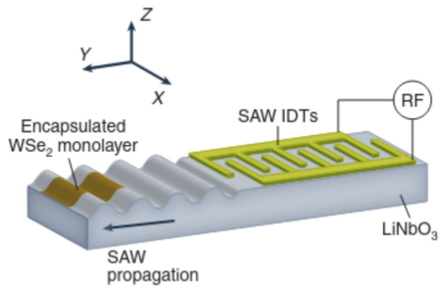

Fig. 1 | Schematic representation of a device for surface acoustic wave-driven transport of excitons in a WSe$_2$ monolayer. The inhomogeneous strain profile, generated through surface acoustic waves (SAWs), can locally modify the energy landscape felt by the excitons, thus creating a net flux of excitons in monolayer WSe$_2$ in the wave propagation direction. RF, radiofrequency; IDT, interdigital transducer. Figure adapted from ref. [9], Springer Nature Ltd.

When the surface acoustic waves are excited by feeding a radiofrequency signal to the piezoelectric actuator, the exciton density distribution shifts along the propagation direction of the waves, leading to a net transport of excitons in a user-defined direction over a distance in the 1 μm range. Based on their experiments, the neutral exciton drift velocity reaches 600 m s^{-1}, with an estimated exciton mobility of 900 cm^2 eV^{-1} s^{-1}. The speed of the excitons is sizably slower than that of the acoustic waves (which are almost six times faster), and leads to oscillations in the spatial density of excitons. This is an indication of weak coupling between the travelling acoustic waves and the drifting excitons, and thus there is plenty of room to improve the exciton transport.

The results of Datta and co-workers show a moderate spatial drift of the excitons of the order of 1 μm, most likely due to scattering with defects and phonons, and to the relatively short radiative lifetime of the neutral excitons in WSe$_2$. Although this travelling distance may suffice for certain applications, a longer diffusion length for neutral excitons is highly desired to ensure more mature and technologically relevant applications for excitonic devices. This should motivate further work to solve the issues leading to moderate travel distances. Improving the mobility of the excitons might be very challenging, as the authors have already fully encapsulated their monolayer WSe_2 in between hexagonal boron nitride layers to reduce the presence of scattering centres. One interesting avenue is to engineer the piezoelectric actuator to achieve higher strain gradients, which could eventually lead to reaching the strong coupling regime between the acoustic waves and the drifting excitons. The radiative lifetime could also be increased dramatically by using type-II heterostructures between dissimilar TMD semiconductors to separate the electron and hole, thus offering a longer lifetime. ❐

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Competing interests

The authors declare no competing interests.