increase of couplings between the incident waves and the resonance mode, thereby rendering the 2D photonic crystal layer the Laplacian function for transmission. This physical mechanism might explain why such 2DOIDs have a large numerical aperture of ~0.32, one order of magnitude larger than that of previous theoretical work[8].

The structure of the 2DOIDs designed by Zhou and colleagues is remarkably simple. A 2D photonic crystal composed of silicon nanorods is embedded in polymethyl methacrylate on a silicon dioxide substrate (Fig. 1). The architectural simplicity reduces the burden of nanofabrication. As exemplified by the team, the device can be fabricated by employing either electron-beam lithography or self-assembly-based nanosphere lithography. In particular, self-assembly-based nanosphere lithography facilitates large-scale nanofabrication, and the team successfully fabricated centimetre-scale 2DOIDs.

Another advantage of such 2DOIDs is compactness. The whole device is fabricated on a single glass chip without using any bulky optical elements. As a result, the 2DOIDs can be combined with conventional imaging systems, conveniently adding edge detection to their existing functionalities. For instance, it is shown that a 2DOID, with a size of ~3.5 mm × 3.5 mm, fabricated with electron-beam lithography can be integrated into a commercial optical microscope (Axio Vert.A1) by simply placing the 2DOID below the sample stage on top of the microscope objective. Using the integrated microscope, the authors applied edge detection to image microscale biological cells including onion epidermis, pumpkin stem and pig motor nerve, and they observed high-contrast cell boundaries that are less discernible with bright-field microscopy.

Besides this, the authors also integrated a 2DOID, with a size of ~1 cm × 1 cm, fabricated with self-assembly-based nanosphere lithography into a near-infrared camera for edge detection of centimetre-sized plastic flower moulds, outlining potential application in machine vision. As a further step towards a monolithic image processing system, Zhou and colleagues successfully combined the 2DOID with a flat metasurface lens on a single chip.

Although these results represent substantial progress, the limitation that the 2DOIDs work only for one polarization cannot be overlooked. The limitation relates to the physical mechanism discussed earlier. The BIC and its evolved leaky modes only couple with *p*-polarized waves due to the modal symmetry. The spatial differentiation is thus carried out only on *p*-polarized waves, while the *s*-polarized waves are completely blocked in transmission. Therefore, for imaging applications that use coherent polarized light, the light polarization requires an object-dependent optimization to attain maximal image brightness and a higher signal-to-noise ratio, while for those that use incoherent unpolarized light, only half of the light is utilized for edge detection. A 2DOID with polarization insensitivity and further improved transmission efficiency is thus highly desirable. This remains to be developed in the near future.

In addition, unitizing the 2DOIDs for edge detection in practical problems, for example biological imaging and machine vision, should be comprehensively explored in order to derive qualitative conclusions about the advantages and disadvantages of optical image differentiation. Compared with electronic-computing-based image processing, optical image processing, for example, with the 2DOIDs, has the advantages of higher computation speed and lower energy consumption, but at a cost of lower image quality. However, with the rapid progress of artificial intelligence in this decade, image processing with electronic digital computing has been substantially improving in terms of computation speed, especially for difficult problems, and, accordingly, energy consumption per task has been reduced significantly. This naturally begs the question of to what extent the envisioned significant gain of employing optical imaging processes can be kept up?

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EXCITONICS

Strain creates a trion factory

Exciton funnelling due to non-homogeneous strain was previously thought of as an efficient neutral exciton transport mechanism. New findings suggest that exciton funnelling might be negligible compared with another strain-dependent process, the conversion of neutral excitons into trions.

Riccardo Frisenda and Andres Castellanos-Gomez

Strain engineering of the electronic properties of two-dimensional (2D) materials is a strategy of interest made possible by the exceptional mechanical resilience of 2D materials, due mostly to the absence of dangling bonds at their surfaces[1]. In fact, strain engineering has already led to the observation of ultra-large pseudo-magnetic fields in graphene and it has been used to tune the bandgap of 2D semiconductors[2,3]. Moreover, unlike in strain engineering experiments with conventional 3D materials, where the strain is typically applied by forcing the epitaxial growth of a material on top of another

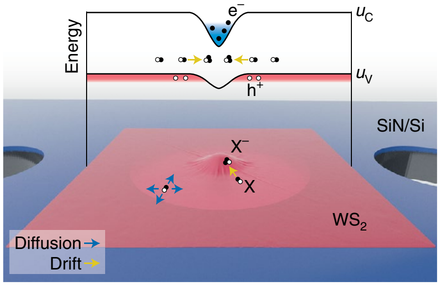

Fig. 1 | Strain-induced conversion of neutral excitons into trions in monolayer WS_2. The WS_2 flake suspended on top of a hole in the SiN/Si membrane is indented from the bottom by an AFM cantilever. The non-uniform strain profile generated favours the drift of neutral excitons (X) towards the point of highest strain where they get converted into charged trions (X^-) with high efficiency. The band structure modified by the application of strain is schematically depicted (u_C and u_V are the bottom of the conduction band and the top of the valence band, respectively). e^-, electrons; h^+, holes.

material with a certain lattice parameter mismatch, in 2D materials strain can be applied in a more flexible way, allowing one, for example, to apply localized strains or to vary the strain level in time.

In 2012, Feng and co-authors[3] proposed the use of localized biaxial tensile strain in single-layer MoS_2 to generate an inhomogeneous potential landscape for the excitons. Photogenerated excitons would drift towards the region with largest strain, creating a so-called 'exciton funnel'. It was proposed that this process could help to increase the efficiency of solar cells based on these 2D materials by spatially concentrating the photogenerated charges to be collected. Fingerprints of this control of the exciton dynamics have been experimentally observed in refs. [4] and [5] using different experimental configurations from the one originally proposed by Feng and co-authors[3]. These previous experimental configurations involved changes in the dielectric environment and/or chemical composition of the strained 2D material under study and as such are not ideal demonstrations of the funnelling process.

Now, writing in *Nature Photonics*, Harats and co-workers[6] report a comprehensive experimental study of the role of localized biaxial strain, reproducing experimentally the configuration proposed by Feng and co-workers[3] that can help to unambiguously determine the role of strain-induced funnelling in the exciton dynamics. By performing optical spectroscopy in a 2D semiconductor subjected to non-uniform biaxial strain, the authors managed to reveal the dynamics of the photoexcited carriers. They found that the drift of the neutral excitons towards the point of largest strain, due to 'exciton funnelling', is a highly inefficient process at room temperature. Conversely, the dominant effect is the conversion of neutral excitons into charged excitons (trions), which can be carried out with efficiencies close to 100%. These results can pave the way to novel optoelectronics devices based on the electrical control of trions.

To achieve these findings, the authors presented an experimental set-up based on an all-electrical[7] operated atomic force microscope (AFM) coupled with an inverted optical microscope micro-photoluminescence (PL) system. This configuration allows them to achieve full dynamical control of the magnitude and symmetry of the spatial strain profile in optically interrogated 2D semiconducting WS_2 monolayers without disturbing the optical spectroscopy measurements with stray light coming from the AFM (as conventional AFMs are based on a laser beam deflection system). The non-homogeneous strain profile is applied by indenting the tip of the AFM on a WS_2 monolayer flake that was transferred onto a SiN/Si membrane substrate with micrometre-sized holes, as shown in Fig. 1. The authors probed the role of strain on the optical properties of the single-layer WS_2 through micro-PL.

Similar to previous studies, Harats and co-workers found that at zero strain the PL spectrum can be described by a non-symmetric Gaussian peak, which is composed of a neutral exciton peak (resulting from the recombination of neutral excitons, marked as X in Fig. 1) and a charged exciton peak (from the recombination of trions, formed by two electrons and one hole, marked as X^-). However, after applying tensile strain to the WS_2, the authors observed an initial redshift and broadening of the Gaussian peak (at small strain values) and the development of a two-peak structure for large strain.

Using a drift–diffusion model, the authors show that the changes observed in the PL spectra are consistent with the highly efficient conversion of neutral excitons to trions. Although the strain modification of the band structure induces the drift of neutral excitons towards the maximum strain position (funnelling), its efficiency is much lower than previously predicted. The local conduction band minimum created by the strain profile also leads to the accumulation of free electrons that leads to the conversion of photogenerated neutral excitons into trions in this region of the sample. The two-peak structure in the PL spectra is then mostly due to exciton and trion recombination, and not to pure exciton funnelling (as was previously thought). This experiment by Harats and co-workers indicates that the neutral exciton funnelling process is not as efficient as was initially thought, even for high strain values. The authors estimate that at room temperature, the efficiency of exciton funnelling is ~4%, while the exciton-to-trion conversion can reach 100% efficiency. Importantly, strain-dependent exciton-to-trion conversion produces experimental signatures that may appear similar to those of neutral exciton funnelling.

The results of Harats and co-workers imply that a careful reinterpretation of previously reported non-uniform strain engineering experiments[4,5] may be needed to determine the real contribution of the exciton funnelling process in those experimental configurations. Moreover, these new results seem to indicate that the photoconversion mechanism proposed by Feng and co-authors[3], which was especially promising for photovoltaics, may not be feasible, at least at room temperature. The good news is that the strain-dependent exciton-to-trion conversion observed by Harats and co-workers may constitute an alternative, more efficient photoconversion mechanism. In contrast to neutral excitons, charged trions can be easily moved by an electric field, making the collection of photo-generated trions a more straightforward task than the collection of neutral excitons. Moreover, the electrical control of the trion density may also lead to the fabrication of excitonic devices and circuits that operate at room temperature in the context of exciton-based electronics[8].

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