energy level with respect to the Fermi levels of the electrodes. Indeed, the researchers observe switching from cooling to heating when they reverse the bias voltage, and there exists a bias voltage value at which the net cooling effect is maximized. This behaviour can be interpreted as a competition between the Q_J and Q_P terms. The same switching occurs when the molecules in the molecular junctions are switched from biphenyl-4,4′-dithiol to 4,4′-bipyridine, in which the carrier tunnelling occurs mainly in the lowest unoccupied molecular orbital (LUMO), rather than the highest occupied molecular orbital (HOMO) (that is, Π switches from positive to negative).

From a theoretical point of view, one needs to take into account the quantum-mechanical nature of Q_{tot} in the charge transport and introduce the Landauer formalism in which the transport is dictated by an energy-dependent transmission probability spectrum of the molecules in the junction. Cui et al. validate their experimental results by computing the transmission probabilities for the three investigated molecules, and confirm that the switching of Q_{tot} from heating to cooling for biphenyl-4,4′-dithiol and 4,4′-bipyridine arises from the conduction in the HOMO and LUMO, respectively.

The molecular-scale Peltier effect observed by Cui et al. may not be of immediate practical relevance. But one could optimize the thermoelectric energy conversion efficiency, which would boost Π, using molecules that have been predicted to have greater thermoelectric figure-of-merit due to quantum interference effects in the molecular transport[2,9]. Subsequently, one could envisage integrating these molecular junctions in a dense array to increase the total power output — that is, the refrigerating power (Fig. 1b). However, this conventional array structure is far from an ideal design for refrigeration for molecular junctions, because it would be challenging to maintain a large temperature difference in nanoscale gaps, owing to considerable thermal conduction through the molecules; such heat flow would introduce a lossy channel for the hypothetical molecular junction cooling devices. Although the work of Cui et al. is an important first step, many advances and optimizations are needed before thinking of any practical implication. ❐

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TWO-DIMENSIONAL MATERIALS

Tunable confinement of charges and excitations

Electrical control over quantum confinement opens a new avenue for spatial manipulation of charge carriers and bound excited states for quantum opto-electronics.

Deep Jariwala

Two-dimensional (2D) semiconductors that can be isolated from van der Waals layered materials such as the transition metal dichalcogenides (TMDCs) provide a unique material system for opto-electronics and condensed-matter physics. The structural and electronic confinement in two dimensions brings with it several new physical properties, such as a transition from indirect to direct bandgap upon isolation from bulk to monolayer, and strongly bound excitons that are stable up to room temperature[1,2]. These properties have enabled the demonstration of atomically thin electronic and photonic components[3,4]. But one of the most promising features of 2D van der Waals materials is their ability to be tuned electrostatically. These properties, in combination, give rise to new physical phenomena and applications that are difficult to achieve in other quantum material systems.

Writing in *Nature Nanotechnology*, Wang et al.[5] have made a critical advance in using electrostatic tuning to induce 0D quantum confinement within the 2D plane of ultrathin MoS_2 and $MoSe_2$. Using nanofabricated metallic electrostatic gates, the authors have achieved spatial variation of the potential at a length scale of 50 nm, enabling the formation of quantum dots. Even though quantum confinement in electrostatically gated TMDCs has been reported before, their work demonstrates several developments in fabrication and contact engineering, yielding high-quality samples with mean free paths of around 100 nm for the carriers. As a result, the

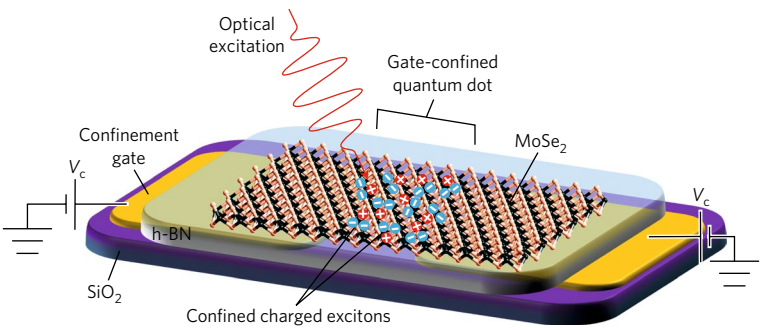

Fig. 1 | Schematic of a gate-defined monolayer $MoSe_2$ quantum-dot device, with negatively charged excitons localized in the gate-confined region. h-BN, hexagonal boron nitride.

authors can clearly observe signatures of conductance quantization through their quantum point contacts (QPC), formed using the local electrostatic gates in a tri-layer MoS_2 device. Another key feature of the device is the tunable, monotonic control over the QPC channels — that is, the tunnel couplings between the quantum dot and charge reservoir. Consequently, resonant tunnelling peaks appear in the conductance spectra when the energy level in the quantum dot is aligned with the Fermi energy and vanish when out of resonance, a clear signature of quantum confinement.

Besides tightly bound neutral excitons, TMDCs also support charged excitons or trions whose fraction varies as a function of doping or gate-voltage[6,7]. Charged excitons can be optically detected because they recombine and emit light at energies lower than the neutral exciton, owing to the lower binding energy in the charged state[7]. In the present work using gate-induced electrical confinement, the authors have also demonstrated 0D and 1D spatial confinement of charged excitons in a monolayer $MoSe_2$ device (Fig. 1). This result is particularly noteworthy because charged excitations can be optically induced and detected by measuring photoluminescence. Thus, it is possible to spatially map the luminescence originating only from the negatively charged exciton state, and this luminescence signal is found to be localized to the quantum-dot region of the $MoSe_2$ confined by means of the electrostatic gates. This localization or confinement of charged excitons is observed only for a gate potential that corresponds to a purely tunnelling transport regime. For other gate potentials, the luminescence signal of the charged excitons is delocalized. The gate-induced spatial confinement of the luminescence is not observed for neutral excitons.

The spatial confinement of charged excitons opens interesting opportunities for the study of collective behaviour and many-body physics[8,9] of such charged excited states in quantum-confined semiconductors. With top-down control over spatial confinement and electrically tunable control over the quantization of excited states, TMDCs and other excitonic 2D materials offer an experimental platform for investigations of charge and energy transfer in quantum-confined channels, with potential for broad-ranging impacts, from on-chip communication of classical and quantum information to energy sciences. ❐

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