vascular structures with complex functions, including vasodilation and vasoconstriction. In addition to vascular function, the scaffold needs to be compatible with parenchyma function. For example, electrical coupling between implanted cardiac tissue and the host heart is important for the therapeutic application of cardiac tissue scaffolds. The scaffold developed by Radisic and colleagues should establish the basis for further control of vascular angiogenesis and arteriogenesis, and allow for the fast and accurate recapitulation of complex organs. Further developments of this technology will advance our understanding of complex biological questions concerning tissue-scale biology and vascular-network–parenchyma interactions, and promote the generation of implantable tissues on a therapeutically relevant scale. ❐

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EXCITON–POLARITON CONDENSATES

Exciton-mediated superconductivity

Laser-generated exciton–polariton condensates in transition metal dichalcogenide heterostructures may trigger Cooper pairing of electrons and induce high-temperature superconductivity.

Alexey Kavokin and Pavlos Lagoudakis

Superconducting currents in metals are carried by Cooper pairs of electrons. According to the original Bardeen–Cooper–Schrieffer (BCS) theory[1], electrons may attract each other and form couples due to their exchange by lattice vibration quanta — acoustic phonons. In conventional superconductors, phonon coupling is relatively weak and thus Cooper pairs (given their small binding energy) survive only at cryogenic temperatures. In a recent publication, Ataç Imamoğlu and coworkers[2] discuss an alternative electron pairing mechanism, mediated by excitons in 2D monolayers of transition metal dichalcogenides. This work indicates a pathway to realize light-induced superconductivity in 2D semiconductor crystal structures.

Already in the 1970s, excitons (Coulomb-bound electron–hole pairs) were proposed as promising binding agents for electron pairing in metal–semiconductor structures; compared to phonons, they would be able to provide stronger binding and, consequently, higher critical temperatures of superconductivity[3]. A possible experimental implementation in this direction would be multilayer metal–semiconductor sandwiches, to maximize coupling between free electrons and excitons[4]. However, no firm experimental evidence for the excitonic mechanism of superconductivity has ever been reported. An important fundamental obstacle towards confirmation of this mechanism lies in the parabolic dispersion of excitons, which is in contrast to the linear dispersion of acoustic phonons. Excitons would acquire a velocity close to the Fermi velocity in metals (of the order of 10^6 m s^{-1}) as a result of elastic scattering with electrons situated at the Fermi surface. On the other hand, acoustic phonons in crystals propagate with a speed of sound that is at least three orders of magnitude lower than the Fermi velocity. This is why electrons attract each other at long distances if they exchange slow phonons, but they must be much closer to each other if they couple via the exchange of fast excitons. The smaller-sized Cooper pairs that are expected to be formed through the excitonic mechanism tend to be unstable due to repulsive Coulomb interactions.

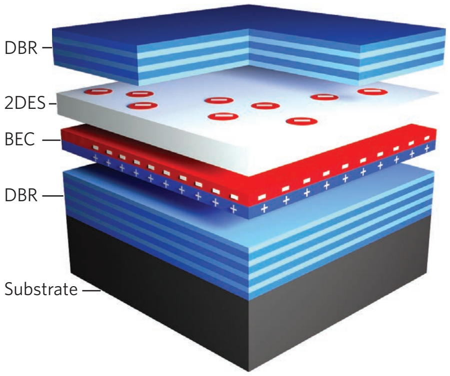

Figure 1 | Schematic structure proposed for the observation of the exciton-mediated superconductivity[2]. An atomic monolayer containing a two-dimensional electron system (2DES) is separated by a thin barrier from an excitonic bilayer, in which a Bose–Einstein condensate (BEC) of excitons may be formed by resonant laser pumping. The structure is sandwiched between two high reflectivity mirrors (distributed Bragg reflectors, DBRs) that lead to strong exciton–photon coupling. Figure reproduced with permission from ref. 2, APS.

Exciton–polaritons are half-light, half-matter quasiparticles, the result of the strong coupling between excitons and photons, trapped inside a high-finesse optical cavity. Recent discoveries of the condensation of exciton–polaritons[5] and polariton lasing[6] inspired a plethora of theories regarding exciton-mediated superconductivity. It has been argued that the strength of exciton–electron coupling increases proportionally to the occupancy of the polariton condensate[7]; the exciton-mediated attraction may become so strong that even small-sized Cooper pairs would remain stable. First estimations have shown that critical temperatures of the order of a few tens of Kelvin can be achieved in GaAs-based microcavity structures with embedded modulation-doped quantum wells[8]. In the case of superconductivity mediated by a polariton condensate, the critical temperature is governed by the density of bosonic quasiparticles in the condensate. However, by increasing the exciton density, one inevitably approaches the Mott transition, where excitons dissociate into electrons and holes. The Mott transition threshold corresponds to the exciton density of the order of 10^{10} cm^{-2} in GaAs-based quantum wells[9]. On the other hand, in 2D semiconductor crystals based on transition metal dichalcogenides, for example, MoSe$_2$ or WS$_2$, Mott densities are expected to be three orders of magnitude higher due to the small exciton Bohr radius[10], whereas strong light–matter coupling in such 2D atomic layers is readily achievable[11].

In this context, the work of Imamoğlu and colleagues[2] clearly suggests that multilayer structures based on transition metal dichalcogenide monolayers are among the most promising candidates for the observation of exciton-mediated superconductivity. The schematic structure that they propose[2] is a microcavity with an embedded n-doped layer containing a two-dimensional electron system (2DES) placed in close proximity to the double quantum layer (Fig. 1), where the generation of spatially indirect excitons is controlled by pumping of the external laser. The structure design is crucial: excitons and free electrons must be placed as close as possible to each other in order to maximize the scattering probability, but tunnelling between 2DES and the excitonic layer must be excluded to prevent exciton dissociations.

The proposed light–matter hybridization of transition metal dichalcogenide monolayers in the vicinity of two-dimensional electron systems demonstrates new pathways in the quest for exciton-mediated superconductivity. All-optical control of superconductivity in semiconductor heterostructures goes beyond the excitement of replacing phonons with excitons to couple electrons in Cooper pairs. It could bridge superconductivity, lasing and exciton condensates, and unleash a plethora of previously inconceivable devices. ❐

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MATERIAL WITNESS

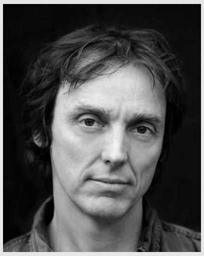
ENGINES OF IMAGINATION

When does analogy become ontology? Or to put it in a less grandiose fashion, what's the difference between saying a physical system is 'like' X and saying that it 'is' X? That question is surely prompted by the report from Roßnagel *et al.* of a 'single-atom heat engine'[1]. By moving a single calcium ion through a cyclic process within an asymmetric electrical trap, the researchers can get it to absorb heat from a hot reservoir (where it consists of electrical noise) and do mechanical work while dissipating some of the heat into a cold reservoir (a beam of laser photons, which cool the ion). This work can be stored and used to drive an oscillator. Thus the device satisfies all the reasonable criteria for a heat engine, with the single ion acting as a kind of piston.

Any practical applications are unclear — the engine produces a power output of just 3.5×10^{-22} W, although its near 0.3% efficiency is respectable enough for such a minuscule system. The point is more fundamental: to show that thermodynamics, although arguably not really operating here at a 'single-atom' level (the input and output are many-particle quantities), can be applied even with atomic-scale components.

All the same, to cast this system as an engine is to tell a particular story about it. That's not a criticism, but rather recognition of how science is done. This account of manipulations of an atom via its interactions with electromagnetic fields would have little meaning without the analogy with the machines of the Industrial Revolution.

And this is no more than we do for pretty much any complex system: we must 'chunk' it, as cognitive scientists would say, into elements from which we can build a story. Consider quasiparticles such as holes, phonons, plasmons and heavy electrons, which are so indispensible to condensed-matter physics. Apply too much reductionism and there's nothing to see. Does this mean that the quasiparticles are somehow illusory, or do they have some more profound ontological status? Some physicists, such as Brian Greene, have argued that emergent structures are just a convenience imposed by our inability to calculate everything from first principles[2] (although that inability, given the combinatorial possibilities, is not just a matter of principle). With reference to the concepts of condensed matter, Stephen Blundell argues in contrast that emergent narratives are a valid and efficient way to describe complex reality, with a "non-trivial relationship to the underlying microphysics"[3].



PHILIP BALL

For one thing, not every emergent narrative will correctly describe reality. Thermodynamics is one that does, but how this essentially classical theory tallies with the quantum aspects of microscopic physics is an area of active study[4]. And that, perhaps, is one of the best justifications for casting energy exchanges between a trapped ion and its environment within the narrative of the classical functions of a heat engine — because the system then looks very promising for examining the connections between these two topics. Or to put it another way: there's a big difference between giving a prosaic result some canny packaging to help it sell, and (as here) finding a story that offers fruitful purchase for the mind. ❐

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