wavelengths, in different parts of the actuating element.

To achieve complex motion beyond simple contraction and extension, the Eindhoven group used an ingenious alignment configuration: the direction of mesogen orientation changes smoothly and continuously from parallel to the surface on one face of the actuator element to perpendicular on the other. Photoexcitation causes contraction of the material on one surface and expansion on the other, as in a bimetallic or birubber[5] strip. This architecture allows large bend deformations even if the photoexcitation is uniform everywhere in the actuator material. More complex motion is made possible by the use of different azo dyes in different regions of the actuator strip. Illuminating the entire strip with light of a given wavelength results in bending only where the light is absorbed. Bend in different regions can be controlled independently by simply changing the wavelength.

One of the proposed applications for these actuators is pumping and mixing in microfluidic systems. Here, small length scales result in flow in the Stokes regime, where viscosity dominates and inertial effects are negligible. As shown by Purcell in 1976, this is the domain of the scallop theorem, in which swimming — or equivalently, the pumping of fluid — is impossible with motion where the sequence of configurations is indistinguishable from the time-reversed sequence[6]. As Purcell put it, "a scallop opens its shell slowly and closes its shell fast, squirting out water" to swim, but in the Stokes regime, "it can't swim"; the scallop gets nowhere if it tries to swim in treacle.

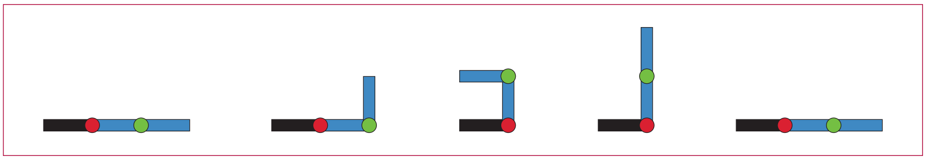

Figure 2 | Non-reciprocal motion made possible by two bend regions of the actuator. The black segment is attached to the substrate.

The cilia proposed for pumping by van Oosten and collaborators have two distinct and separately addressable regions for bend (Fig. 2). Activating these in sequence means the motion is non-reciprocal, and the cilia are therefore capable of pumping fluid.

The elegant solutions to the problems of realizing effective actuators proposed by the Eindhoven group are orientational order that varies spatially, the incorporation of different azo compounds in different regions of the active material and careful control of actuator shape. These stringent requirements would seem to make practical production prohibitively complicated. Evidently, this is not the case. The Eindhoven group used inkjet printing with self-assembling liquid-crystal inks on substrates and patterned sacrificial layers to produce the required spatially varying orientational order and composition. These printed liquid structures are then crosslinked through photopolymerization, and, on dissolving the sacrificial layers, become photoactive cilia attached to the substrate. Because of this remarkable demonstrated versatility, printing with liquid-crystal inks holds the promise of enabling the production of a variety of other new active polymeric microdevices. ❐

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References

1. Madden, J. D. W. *et al. IEEE J. Oceanic Eng.* **29,** 706–728 (2004).
2. van Oosten, C. L., Bastiaansen, C. W. M. & Broer, D. J. *Nature Mater.* **8,** 677–682 (2009).
3. de Gennes, P. G. *C. R. Seances Acad. Sci.* **281,** 101–103 (1975).
4. Finkelmann, H., Kock, H. & Rehage, G. *Makromol. Chem. Rapid Commun.* **2,** 317–322 (1981).
5. Assfalg, N. & Finkelmann, H. *KGK Kaut. Gummi Kunst.* **52,** 677–678 (1999).
6. Purcell, E. M. *Am. J. Phys.* **45,** 3–11 (1977).

IRON-BASED SUPERCONDUCTORS

Vital clues from a basic compound

Investigation of the phase diagram of the structurally simple compound FeSe may prove instrumental in raising the transition temperature in Fe-based superconductors and in understanding magnetic-mediated superconductivity.

Bernd Büchner and Christian Hess

One of the greatest ambitions of solid-state physicists has been to obtain superconductivity — a macroscopic quantum effect leading to the flow of electrical currents without dissipation — at technically relevant temperatures. For more than 20 years, the efforts have focused on understanding the properties of the so-called cuprate superconductors. These compounds show superconductivity at temperatures that are in some cases higher than that of liquid nitrogen (77 K), and it is clear that the origin of superconductivity is different than in the case of low-temperature — or conventional — superconductors. Then suddenly, in the spring of 2008, the discovery of superconductivity below a critical temperature (T_c) at 26 K in $LaO_{1-x}F_xFeAs$ (ref. 1) gave birth to what many have already christened "the iron age of high-temperature superconductivity". Some 1,000 papers later, a whole class of iron-based high-temperature superconductors has been established.

The members of the iron-pnictide superconductors share a common structural motif, namely layers with edge-shared tetrahedra, whereby the central Fe atoms are surrounded by four As, P or Se atoms, respectively. The Fe_2X_2 (X = As, Se) layers are considered to be electronically active, whereas the other layers stabilize the structure and serve as charge reservoirs to dope the active layers. Many specific characteristics and problems observed in the pnictides, such as, for example, chemical complexity and phase separation, are closely related to these extra structural elements. Recently however, superconductivity was observed in the basic structure FeSe, which consists

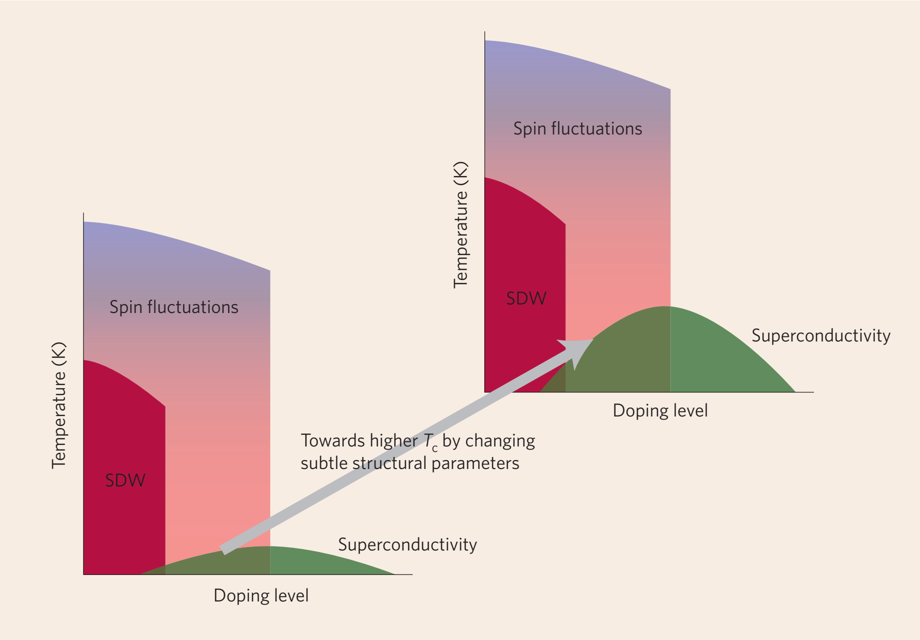

Figure 1 | Generic phase diagram of Fe-based superconductors. On doping or pressure, a spin density wave (SDW) order is suppressed and superconductivity appears. The maximum transition temperature T_c is not universal but depends on subtle structural differences.

only of a stack of electronically active layers[2]. As the transition temperature was only 8 K, it could be argued that this was a conventional superconductor. On page 630 of this issue, a paper by Medvedev and colleagues demonstrates that FeSe is truly a high-temperature superconductor[3].

Medvedev and colleagues studied the electronic and magnetic phase diagram of FeSe under pressure and found transition temperatures as high as 37 K. This observation, which is confirmed by a second experimental study reported by Margadonna and co-workers[4], not only places it among the highest reported T_c in a binary compound, but is also of the same order of magnitude as the transition temperatures found thus far in the other, chemically much more complex, Fe-based systems.

The work by Medvedev and co-workers may pave the way for the discovery of new superconductors with even higher T_c, which is one of the main driving forces of superconductivity research. At first glance, the pressure dependence of the T_c in FeSe is reminiscent of the superconducting dome observed in many unconventional superconductors, such as cuprates, heavy fermions and, of course, pnictides[5–9]. There is, however, a clear difference: the disappearance of superconductivity in FeSe at very high pressure is connected to a structural phase transition to a hexagonal, more densely packed phase. This suggests that, if a way could be found to avoid this structural phase transition, the transition temperature could be raised even higher than 37 K. A possible strategy would be to use thin films of FeSe on appropriate substrates; such experiments on artificially designed materials could open a completely new direction in iron-based superconductor research.

Apart from the high T_c observed, the results on FeSe provide intriguing insight into the origin of superconductivity, and in particular its relationship with magnetism. A close relationship between the two phenomena is common in iron-pnictides. The parent compounds — that is, the versions with no doping — are usually magnetic. On the contrary, no static magnetism is observed throughout the phase diagram of FeSe. This is really surprising, because the FeSe layers are isoelectronic with the parent compounds of other Fe-based superconductors, such as LaOFeAs and $BaFe_2As_2$. Instead, FeSe is already superconducting in the parent phase. On the other hand, clear signatures of slow spin fluctuations have recently been revealed by NMR data[10], and these signatures point to an incipient magnetic phase transition, accumulated under pressure[10]. In other words, both magnetic instability and T_c increase simultaneously with pressure. But the pronounced pressure-induced increase of T_c in FeSe does not follow the general trends of the generic phase diagram, whereby the static magnetism in the parent compounds is suppressed by carrier doping or pressure in favour of the superconducting state[5–9,11] (Fig. 1).

The rise of the superconducting transition temperature up to 37 K must be due to something other than the suppression of a competing magnetic-order phenomenon. It is instead connected to the variation of a so far unknown parameter, most likely connected to the structural deformation of the Fe_2X_2 layers (Fig. 1). The fact that a variation of the structure in FeSe enhances both magnetic instability and superconducting T_c provides strong experimental evidence that spin fluctuations have a crucial role in superconducting mechanism in pnictides. The importance of this point is that the influence of structure is actually present in other compounds. For example, the differences in the transition temperatures and normal-state properties[7–9] of $LaO_{1-x}F_xFeAs$ (ref. 7) and $SmO_{1-x}F_xFeAs$ (ref. 8) are most likely connected to details of the structure within the Fe_2As_2 layers. Hence, not only is FeSe the prototypical new iron-based high-temperature superconductor, but it also seems to yield a simple and clear-cut example of "magnetism mediated superconductivity"[12], whereby the attractive interaction between electrons is not mediated by phonons — as in conventional superconductors — but is caused by spin fluctuations.

"The iron age of high-temperature superconductivity" is not only providing a new class of high-T_c compounds, it could also provide the clearest examples of magnetism-mediated superconductivity. ❐

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References

1. Kamihara, Y., Watanabe, T., Hirano, M. & Hosono, H. *J. Am. Chem. Soc.* **130,** 3296–3297 (2008).
2. Hsu, F. C. *et al. Proc. Natl Acad. Sci. USA* **105,** 14262–14264 (2008).
3. Medvedev, S. *et al. Nature Mater.* **8,** 630–633 (2009).
4. Margadonna, S. *et al.* <http://arxiv.org/abs/0903.2204> (2009).
5. Rotter, M. *et al. Angew. Chem. Int. Ed.* **47,** 7949–7952 (2008).
6. Rotter, M. *et al. New J. Phys.* **11,** 025014 (2009).
7. Luetkens, H. *et al. Nature Mater.* **8,** 305–309 (2009).
8. Drew, A. J. *et al. Nature Mater.* **8,** 310–314 (2009).
9. Hess, C. *et al. Europhys. Lett.* (in the press); available at http://arxiv.org/abs/0811.1601.
10. Imai, T., Ahilan, K., Ning, F. L., McQueen, T. M. & Cava, R. J. *Phys. Rev. Lett.* **102,** 177005 (2009).
11. Alireza, P. L. *et al. J. Phys. Condens. Matter* **21,** 012208 (2009).
12. Monthoux, P., Pines, D. & Lonzarich, G. G. *Nature* **450,** 1177–1183 (2007).