FLEXIBLE ELECTRONICS

Tiny lamps to illuminate the body

Biocompatible light-emitting structures based on high-performance inorganic compound semiconductors on flexible substrates open the path to futuristic therapeutic devices, instrumented surgical gloves and many other applications.

Takao Someya

The advantages of optoelectronic devices in the life sciences are widely exploited, particularly for medical diagnostics and treatment. A fascinating extrapolation of optoelectronic devices would be to imagine a future in which medical devices comprising photodetectors and light sources can be significantly miniaturized and then fabricated on biocompatible elastic electronic materials for implantation in a living body. Imagine how versatile and sensitive they could be in collecting biological information for diagnosis, and the innovative medical treatments that would become possible.

Such visions might become reality very soon. In this issue of *Nature Materials*, Rak-Hwan Kim and colleagues describe how mechanically flexible and stretchable optoelectronic systems can be fabricated by attaching inorganic semiconductors to a wide range of unconventional substrates such as rubber, paper and metal foil[1]. As an example, they describe how two-dimensional arrays of very small light-emitting diodes (LEDs) and photodetectors can be integrated on elastomer sheets by material-transfer printing. They also present a numerical analysis to optimize the device layout and demonstrate that the implantable LED arrays are compatible with biological fluids, catheter balloons and surgical gloves.

Their device geometry is outlined in Fig. 1. The key step that enables the fabrication of such films is a technique Kim and colleagues developed previously that transfers single-crystal thin films of inorganic semiconductors on to unconventional substrates[2]. Indeed, the integration of photodetectors and LEDs on elastic substrates represents a good example of the potential use of this technology for new applications. One of their main advances in realizing these new devices lies in optimized mechanics design, including the use of multilayer geometries to realize high fill factors and an elastic response. Another advance is in the use of low modulus, biocompatible encapsulation layers that serve as effective water barriers without degrading the mechanics of the substrates.

The benefit of the approach by Kim and colleagues becomes apparent if one considers how optoelectronics on flexible substrates could potentially be realized using existing technology. One could for example envisage how light could be easily guided by optical fibres and optical waveguides, both of which can be made of plastic. And uniform light emission across a wider area of membrane could be realized by the same light-guiding plates widely used as backlights for liquid-crystal displays. However, at the same time it would be very difficult to maintain light transmission over a large area when these light-guiding plates or fibres would be squeezed or crumpled on flexible substrates.

To avoid such complexities, the team's solution is to distribute active devices such as photodetectors and LEDs over a large area while using mechanically durable wavy wiring to transmit signals electrically. Interestingly, even greater mechanical flexibility could be achieved by replacing the inorganic semiconductors with organic materials, but this would require improvements in the long-term stability of current organic devices for any practical purpose.

The devices made by Kim and colleagues exhibit simultaneously impressive mechanical durability, excellent electric performance and biocompatibility. For example, their integrated LED array sheets show no mechanical or electric degradation even when twisted by 720° or stretched diagonally by up to 46%. The current–voltage characteristics are invariant even after 100,000 cycles of stretching by 75% along the horizontal direction. The biocompatibility was demonstrated by implanting the arrays under the skin of a mouse, on top of the muscle tissue. Furthermore, a biocompatible encapsulation technique allows them to operate the photonic devices even in soapy water and other solutions of relevance to clinical medicine.

The recent developments[2,3] in stretchable electronics[4] support the prospect for many other applications such as robotic sensory skins[5], ambient displays[6] and stretchable solar panels[7]. In particular, applications in medicine and healthcare are receiving considerable attention focusing on applications as wearable and implantable devices. The goal for wearable devices is that they should be able to non-invasively collect biological information such as the oxygen concentration in blood or the heart rate using light and other properties. However, devices that are to be implanted inside the human body must also be compatible with living tissue, and this, for many years, has remained a significant problem.

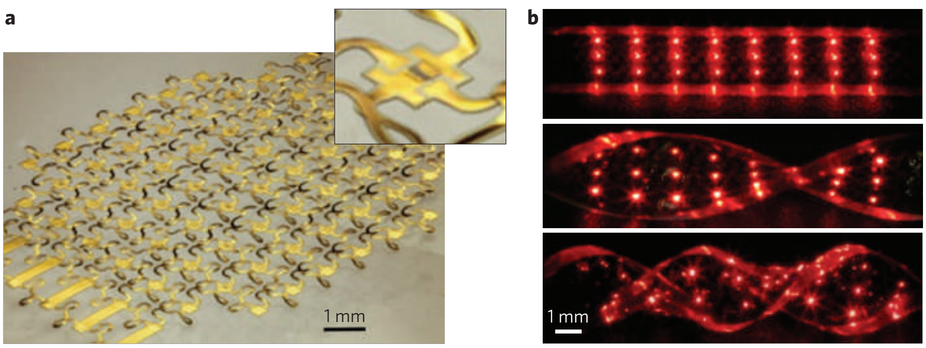

Figure 1 | Flexible light-emitters — photographs of the device layout[1]. **a**, A 6 × 6 array of small LEDs is addressed by flexible, wavy connectors. **b**, The structures continue operating even if twisted by 720°.

As discussed in detail by Kim and his co-authors, achieving biocompatibility in photonic devices that can be integrated together with soft microfluidic devices, tubes and related platforms will play an important role in clinical medicine. For instance, they could be applied to instrumented catheters for advanced surgical procedures or be used to realize light-emitting structures. In addition, although the present device relies on a single colour of light, other wavelengths could be made available, in principle, by using different kinds of semiconductors, allowing for spectroscopic analysis. The integration of biocompatible microelectromechanical systems will also open up a wide range of new applications.

Although the achievement by Kim and colleagues is a true milestone, further major hurdles await. One important challenge is long-term biocompatibility, as certain applications will require devices to remain in the body for years. And solutions to power these devices during such long-term implantation would also be critical. The key technologies for the latter include wireless power transmission, implantable batteries and electronics with ultra-low power consumption. But regardless of these remaining issues, this study will trigger extensive discussion on the fascinating possibilities of implantable optoelectronic devices. ❐

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SPIN SEEBECK EFFECT

Thinks globally but acts locally

Experiments on magnetic insulators and semiconductors imply that the spin Seebeck effect is conceptually different from the standard thermoelectric effect, launching new challenges for both theorists and experimentalists in spintronics.

Jairo Sinova

Thermopower, also known as the Seebeck effect, is the ability of conductors to generate electric voltages from thermal gradients. This and other closely related thermoelectric effects are the basis for nanoscale heat-management devices, which are considered key factors for the continuation of Moore's law: as charge-based logic devices shrink in size, the Joule heating generated by charge currents becomes too high for them to operate reliably[1]. One route around this problem is to search for different logic variables that may require lower power consumption, as is done in the field of spintronics where the spin of the electron, instead of its charge, is the variable being manipulated[2]. An alternative route was suggested recently by the discovery of the spin Seebeck effect, where a thermal gradient in a ferromagnetic metal was found to generate a spin accumulation over long distances[3]. This effect occupies a central role in a new subfield of spintronics, termed spin caloritronics[4], which explores the possibility of controlling spin currents by means of heat currents and *vice versa*. Now, as reported in *Nature Materials*, two independent teams have uncovered important findings on this effect. Uchida *et al.* show that it is not limited to conductors, as in the case of the charge Seebeck effect, but that it also occurs in ferromagnetic insulators[5], opening a possible new frontier in this field. Jaworski *et al.* study the effect in ferromagnetic semiconductors and prove experimentally that the spin Seebeck effect observed in metals does not originate from charge flow[6]. The spin Seebeck effect, which at first seemed to behave as a global thermal transport effect, seems instead to be acting locally with regard to spin diffusion.

The two teams used similar set-ups to study different materials. Uchida *et al.*[5] focused on the insulating ferromagnet $LaY_2Fe_5O_{12}$ (known as YIG), whereas Jaworski *et al.*[6] studied the ferromagnetic metallic semiconductor GaMnAs. The essentials of the spin Seebeck effect are shown in Fig. 1a, where a ferromagnetic sample is subject to a thermal gradient. Platinum strip contacts are placed across the sample at intervals along the channel; a voltage is observed across these contacts, and this changes monotonically along the channel. This voltage originates from the inverse spin Hall effect, which is a direct measure of a spin-current flowing into the contact. The original interpretation of the spin Seebeck effect observed in NiFe speculated[3] that a spin-accumulation was generated by the thermal gradient, which flowed down the channel and was then measured directly by the platinum contacts. This raised exciting new possibilities for thermoelectric spin-current generation and magnetic cooling devices. But one fundamental point was unclear: how the spin accumulation survives for distances much larger than the spin-dephasing length in NiFe.

Uchida *et al.* now show that the spin Seebeck effect is not restricted by charge flow but that it also occurs in insulators[5]. This separates the spin Seebeck effect conceptually and practically from standard thermopower, as the charge Seebeck effect does not occur in insulators. The authors argue that the heat flow is carried by the long-lived spin-waves in the YIG (which can be of the order of millimetres), and the induced spin accumulation is then detected by the platinum contacts which are out of equilibrium with the spin-wave bath temperature. This imbalance in local temperature then leads to a spin-current in the contact through the spin-pumping effect, where a time-varying magnetization at an intersection between a ferromagnetic and a normal metal generates a spin-current into the normal metal[7]. The plausibility of this explanation is further supported by a recent experiment in YIG where the spin-waves are excited by microwaves and detected coherently across long distances[8]. This opens new possibilities for magnetic insulating interconnects in spintronics devices based on spin-currents, which could lead to new logic architectures with low power consumption.

But the new result leaves another unanswered question. If the physics behind