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Engineering

Flexible fibres take fabrics into the information age

Xiaoting Jia & Alex Parrott

A technique for embedding fibres with semiconductor devices produces defect-free strands that are hundreds of metres long. Garments woven with these threads offer a tantalizing glimpse of the wearable electronics of the future. **See p.72**

Imagine a washable hat that can help a blind person to sense changes in traffic lights, or a dress that can act as a tour guide as its wearer moves through a museum. These technologies can be realized using smart flexible fibres equipped with semiconductor devices that detect and process signals, and the performance of such fibres has advanced rapidly over the past few years[1–8]. However, existing fabrication methods can produce threads with fractured, defective semiconductor cores. On page 72, Wang *et al.*[9] report an innovative approach in which tiny semiconductor components are fed into a fibre-pulling machine, resulting in continuous high-performance flexible fibres that can sense, communicate and interact with each other.

Humans have been using fibres since the Stone Age[10], but attempts to expand their functionality beyond simple thermal insulation are much more modern. One of the challenges associated with incorporating semiconductor devices into fibres involves wearability: the fibres must be flexible and twistable, so that they can be woven; washable, for repeated use; and breathable, so that they can be worn comfortably. Many researchers have prioritized these features by creating smart fibre devices made from amorphous semiconductor materials. However, incorporating conventional silicon-based semiconductors is expected to lead to superior electronic properties and performances[2].

An alternative approach involves generating a glass-clad fibre with a silicon core, but this technique, known as the molten-core method, often leads to fibres that fracture easily and contain defects. Wang *et al.* overcame this problem by first performing a detailed mechanical analysis of the fabrication process to identify the sources of stress that induce fracture. The molten-core method begins with a semiconductor wire made of silicon or germanium being inserted inside a glass tube (Fig. 1). Both materials are heated to at least 1,000 °C until they are soft enough to be pulled into a thin strand, which is then cooled.

Wang *et al.* identified stress formation in two stages: the point at which the core solidifies; and the subsequent phase, in which the fibre is cooled. Specifically, they found that mismatches in the viscous behaviour of glass and the melting point of the wire induced stresses in the core, as did differences in the thermal-expansion rates of the materials. The authors showed that both problems could be alleviated by choosing the right combination of materials: silicon cores worked well with cladding made from ultra-tough silica glass, whereas germanium cores performed better when clad in aluminosilicate glass.

The resulting fibres are fracture-free and of high quality, but the glass cladding compromises their applicability. For this reason, the cooled fibres are immersed in hydrofluoric acid to remove the outer layer of glass, leaving behind the semiconductor core. This core is then fed into a polymer tube together with electrically conductive wires. The whole structure is heated again, and pulled into a flexible fibre that can be hundreds of metres long. The resulting fibre takes the form of a p–n junction, which is the basic building block of modern electronics and can convert light signals into electrical currents. The process is reminiscent of making spun sugar — if the sugar were embedded with tiny, controllable, electronic components.

Wang *et al.* showed that their fibres could be used to make several devices. In one example, the authors knitted fibres into a hat that could be used to sense signals from traffic lights. The signal received by the hat was sent to a mobile phone, which then buzzed when the lights turned red or green. In another case, the fibre was woven into a sweater that served as a light-fidelity (Li-Fi) device, a technology that transmits data at light frequencies instead of the radio frequencies used by wireless networks such as 5G. The sweater detected image signals that were encoded as light pulses, and then a second device decoded these signals to

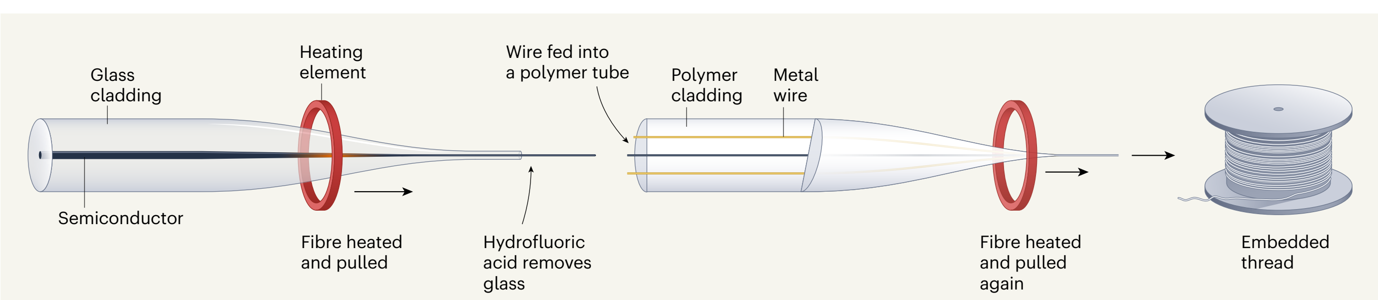

Figure 1 | A method for fabricating digitized fibres. Wang *et al.*[9] devised a way of embedding fibres with semiconductor materials to create long, flexible threads. A semiconductor wire is inserted inside a glass tube and both materials are heated until they are soft enough to be pulled into a thin strand, which is then cooled. Hydrofluoric acid is used to remove the glass. The wire is then fed into a polymer tube together with metal wires. The structure is heated again, and pulled into a flexible thread that can be hundreds of metres long, and can be woven into fabrics that detect and process signals.

reconstruct the image.

The authors also wove their smart fibres into a flexible wristband that outperforms similar devices for heart-rate monitoring. The devices that are currently available typically use a rigid sensor that doesn't flex to the shape of the wrist, and can therefore produce inaccurate measurements. The performance of Wang and colleagues' fibres is on a par with these commercial silicon devices, but they can also withstand high compression, such as that experienced at an underwater depth of 3,000 metres. The authors showed that their wristband could be used to detect visible light around a submarine.

Another key advantage of this technology is its industrial readiness. The instrument that fabricates the fibres includes a fibre-drawing device that is used to produce commercial optical fibres in the telecommunication industry. And once the fibres are generated, they can be knitted or woven into fabric using tools that are already used widely in the textile industry.

Wang and colleagues' work takes a leap towards embedding micro-computers into everyday clothing. An exciting future direction would be to equip the fibres with more-complex devices, such as transistors, and to increase the density of these functional components. One limitation of the current approach is that it requires a post-processing step to incorporate exceptionally high-quality (single-crystal) semiconductors into the fibre. Finding a way of embedding these materials during fabrication would broaden the scope of the fibres' electronic and optoelectronic applications.

Finally, because the wires embedded in Wang and colleagues' fibres are easily connected to existing computer hardware, this technology could prove useful in efforts to develop integrated human–machine systems. The work therefore allows us to imagine a generation of smart fibres and fabrics that enable individuals to engage seamlessly with their surroundings — and make their everyday experiences fully immersive.

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Bacterial prey turns the tables on predator

The bacterium *Myxococcus xanthus* is a voracious predator of other microorganisms. *M. xanthus* can form fruiting bodies (black dots, pictured) and swarm through colonies of prey (right-hand circle) by forming ripple-like travelling waves. However, writing in *PLoS Biology*, Vasse *et al*. report that the prey bacterium *Pseudomonas fluorescens* can slaughter *M. xanthus* to extinction under certain conditions (M. Vasse *et al*. *PLoS Biol.* **22**, e3002454; 2024).

Inspired by earlier observations, Vasse *et al*. investigated how the growth temperature of *P. fluorescens* affects its risk of predation. When this bacterium was grown in culture at 32 °C, the authors observed that it was largely killed by *M. xanthus*, as expected. But remarkably, when cultured at 22 °C, *P. fluorescens* became the predator — killing *M. xanthus* and growing on its remains.

This is a rare example of the reversal of a microbial predator–prey relationship triggered by a specific abiotic environmental factor — in this case, temperature. Intriguingly, the reversal depends on the temperature experienced before, rather than during, the predator–prey interaction. The authors speculate that most microbes might engage in predation to some extent.

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