SCIENCE

Scientists Develop Ultra-Thin Semiconductor Fibers That Turn Fabrics Into Wearable Electronics

Scientists from Nanyang Technological University, Singapore (NTU Singapore) have developed ultra semiconductor fibres that can be woven into fabrics, turning them into smart wearable electronics.

To create reliably functioning semiconductor fibres, they must be flexible and without defects for stable signal transmission. However, existing manufacturing methods cause stress and instability, leading to cracks and deformities in the semiconductor cores, negatively impacting their performance and limiting their development.

NTU scientists conducted modelling and simulations to understand how stress and instability occur during the manufacturing process. They found that the challenge could be overcome through careful material selection and a specific series of steps taken during fibre production.

They developed a mechanical design and successfully fabricated hair-thin, defect-free fibres spanning 100 metres, which indicates its market scalability. Importantly the new fibres can be woven into fabrics using existing methods.

To demonstrate their fibres' high quality and functionality, the NTU research team developed prototypes. These included a smart beanie hat to help a visually impaired person cross the road safely through alerts on a mobile phone application; a shirt that receives information and transmits it through an earpiece, like a museum audio guide; and a smartwatch with a strap that functions as a flexible sensor that conforms to the wrist of users for heart rate measurement even during physical activities.

The team believes that their innovation is a fundamental breakthrough in the development of semiconductor fibres that are ultra-long and durable, meaning they are cost-effective and scalable while offering excellent electrical and optoelectronic (meaning it can sense, transmit and interact with light) performance.

NTU Associate Professor Wei Lei at the School of Electrical and Electronic Engineering (EEE) and lead-principal investigator of the study said, "The successful fabrication of our high-quality semiconductor fibres is thanks to the interdisciplinary nature of our team. Semiconductor fibre fabrication is a highly complex process, requiring know-how from materials science, mechanical, and electrical engineering experts at different stages of the study. The collaborative team effort allowed us a clear understanding of the mechanisms involved, which ultimately helped us unlock the door to defect-free threads, overcoming a long-standing challenge in fibre technology."

The study, published in the top scientific journal *Nature*, is aligned with the University's commitment to fostering innovation and translating research into practical solutions that benefit society under its NTU2025 five-year strategic plan.

Developing semiconductor fibre

To develop their defect-free fibres, the NTU-led team selected pairs of common semiconductor material and synthetic material — a silicon semiconductor core with a silica glass tube and a germanium core with an aluminosilicate glass tube. The materials were selected based on their attributes which complemented each other. These included thermal stability, electrical conductivity, and the ability to allow electric current to flow through (resistivity).

Silicon was selected for its ability to be heated to high temperatures and manipulated without degrading and for its ability to work in the visible light range, making it ideal for use in devices meant for extreme conditions, such as sensors on the protective clothing for fire fighters. Germanium, on the other hand, allows electrons to move through the fibre quickly (carrier mobility) and work in the infrared range, which makes it suitable for applications in wearable or fabric-based (i.e. curtains, tablecloth) sensors that are compatible with indoor Light fidelity ('LiFi') wireless optical networks.

Next, the scientists inserted the semiconductor material (core) inside the glass tube, heating it at high temperature until the tube and core were soft enough to be pulled into a thin continuous strand.

Due to the different melting points and thermal expansion rates of their selected materials, the glass functioned like a wine bottle during the heating process, containing the semiconductor material which, like wine, fills the bottle, as it melted.

First author of the study Dr Wang Zhixun, Research Fellow in the School of EEE, said, "It took extensive analysis before landing on the right combination of materials and process to develop our fibres. By exploiting the different melting points and thermal expansion rates of our chosen materials, we successfully pulled the semiconductor materials into long threads as they entered and exited the heating furnace while avoiding defects."

The glass is removed once the strand cools and combined with a polymer tube and metal wires. After another round of heating, the materials are pulled to form a hair-thin, flexible thread.

In lab experiments, the semiconductor fibres showed excellent performance. When subjected to responsivity tests, the fibres could detect the entire visible light range, from ultraviolet to infrared, and robustly transmit signals of up to 350 kilohertz (kHz) bandwidth, making it a top performer of its kind. Moreover, the fibres were 30 times tougher than regular ones.

The fibres were also evaluated for their washability, in which a cloth woven with semiconductor fibres was cleaned in a washing machine ten times, and results showed no significant drop in the fibre performance.

Co-principal investigator, Distinguished University Professor Gao Huajian, who completed the study while he was at NTU, said, "Silicon and germanium are two widely used semiconductors which are usually considered highly brittle and prone to fracture. The fabrication of ultra-long semiconductor fibre demonstrates the possibility and feasibility of making flexible components using silicon and germanium, providing extensive space for the development of flexible wearable devices of various forms. Next, our team will work collaboratively to apply the fibre manufacturing method to other challenging materials and to discover more scenarios where the fibres play key roles."

Compatibility with industry's production methods hints at easy adoption

To demonstrate the feasibility of use in real-life applications, the team built smart wearable electronics using their newly created semiconductor fibres. These include a beanie, a sweater, and a watch that can detect and process signals.

To create a device that assists the visually impaired in crossing busy roads, the NTU team wove fibres into a beanie hat, along with an interface board. When tested experimentally outdoors, light signals received by the beanie were sent to a mobile phone application, triggering an alert.

A shirt woven with the fibres, meanwhile, functioned as a 'smart top', which could be worn at a museum or art gallery to receive information about exhibits and feed it into an earpiece as the wearer walked around the rooms.

A smartwatch with a wrist band integrated with the fibres functioned as a flexible and conformal sensor to measure heart rate, as opposed to traditional designs where a rigid sensor is installed on the body of the smartwatch, which may not be reliable in circumstances when users are very active, and the sensor is not in contact with the skin. Moreover, the fibres replaced bulky sensors in the body of the smartwatch, saving space and freeing up design opportunities for slimmer watch designs.

Co-author Dr Li Dong, a Research Fellow in the School of Mechanical and Aerospace Engineering, said, "Our fibre fabrication method is versatile and easily adopted by industry. The fibre is also compatible with current textile industry machinery, meaning it has the potential for large-scale production. By demonstrating the fibres' use in everyday wearable items like a beanie and a watch, we prove that our research findings can serve as a guide to creating functional semiconductor fibres in the future."

For their next steps, the researchers are planning to expand the types of materials used for the fibres and come up with semiconductors with different hollow cores, such as rectangular and triangular shapes, to expand their applications.
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