The dawn of ultralong flexible semiconductor fibers

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Inorganic crystalline semiconductors are foundational to the field of solid-state electronics.[1,2] Among ample examples, elemental semiconductors such as silicon (Si) and germanium (Ge) are the cornerstone of the modern electronics industry. Moving into the new era of flexible electronics, the intrinsic rigidity of both Si and Ge has largely limited the applications of these exemplary semiconductors. Although multiple organic semiconductors are developed based on their favourable soft nature, the demands for high-performance semiconductors have inspired studies of making inorganic crystalline semiconductors flexible. Due to the brittle nature of these crystalline semiconductors, the strategies to enable their flexibility mostly address the mechanics in the geometrical forms of the material—in other words, dimension reduction. For example, zero-dimensional (0D) dots, 1D fibers, and 2D films have been exploited to achieve flexible electronic systems. On the device level, both dots and films have been used in the assembly of monolithic devices, whereas fibers are mostly used in the form of a nanowire bundle or a nanowire forest to assemble a planar-type device, which does not exercise the fiber form but seeks the advantage of high surface area-to-volume ratio from the nanostructure. Micron-sized fibers are the more favorable candidates for fabricating devices in the fiber form from the processing perspective. However, successful reports on semiconductor microfibers are lacking due to the challenges in production. Several melt growth techniques, such as the micro-pulling technique, have been used in producing semiconductor microfibers. Nonetheless, the accessible fiber diameters are constrained in the range of hundreds of microns, and the growth rates and fabrication lengths are largely limited to within a few centimeters per hour and tens of centimeters, respectively. To fundamentally promote fiber-based electronics, a scalable production of semiconductor fibers is urgently needed.

A potential alternative is the fiber thermal drawing method, which was originally applied to the production of optical fibers and gained unprecedented success in telecommunications. This single-material fiber drawing process was then introduced to the fabrication of multimaterial fibers, including semiconductor fibers in glass claddings.[3] The raw semiconductor material is placed inside a glass tubing. Then, the combination is drawn into the fiber dimension after being heated. This modified thermal drawing method is also called the molten-core method because the semiconductor core is shaped into fiber form in the molten state. Similar to conventional optical fiber production, the draw speed of semiconductor fibers via the molten-core method is in the range of a few meters per minute, resulting in hundreds-to kilometers-long single strands of fiber, the diameter of which can be controlled in the range of submicrons to hundreds of microns. The process shares some similarities to the micro-pulling technique but with a "deformable glass crucible." Although this deformable glass crucible allows fast draw rate, extended length, and controllable size of the fiber, it also poses challenges to the understanding of the core-shell interface, which is critical

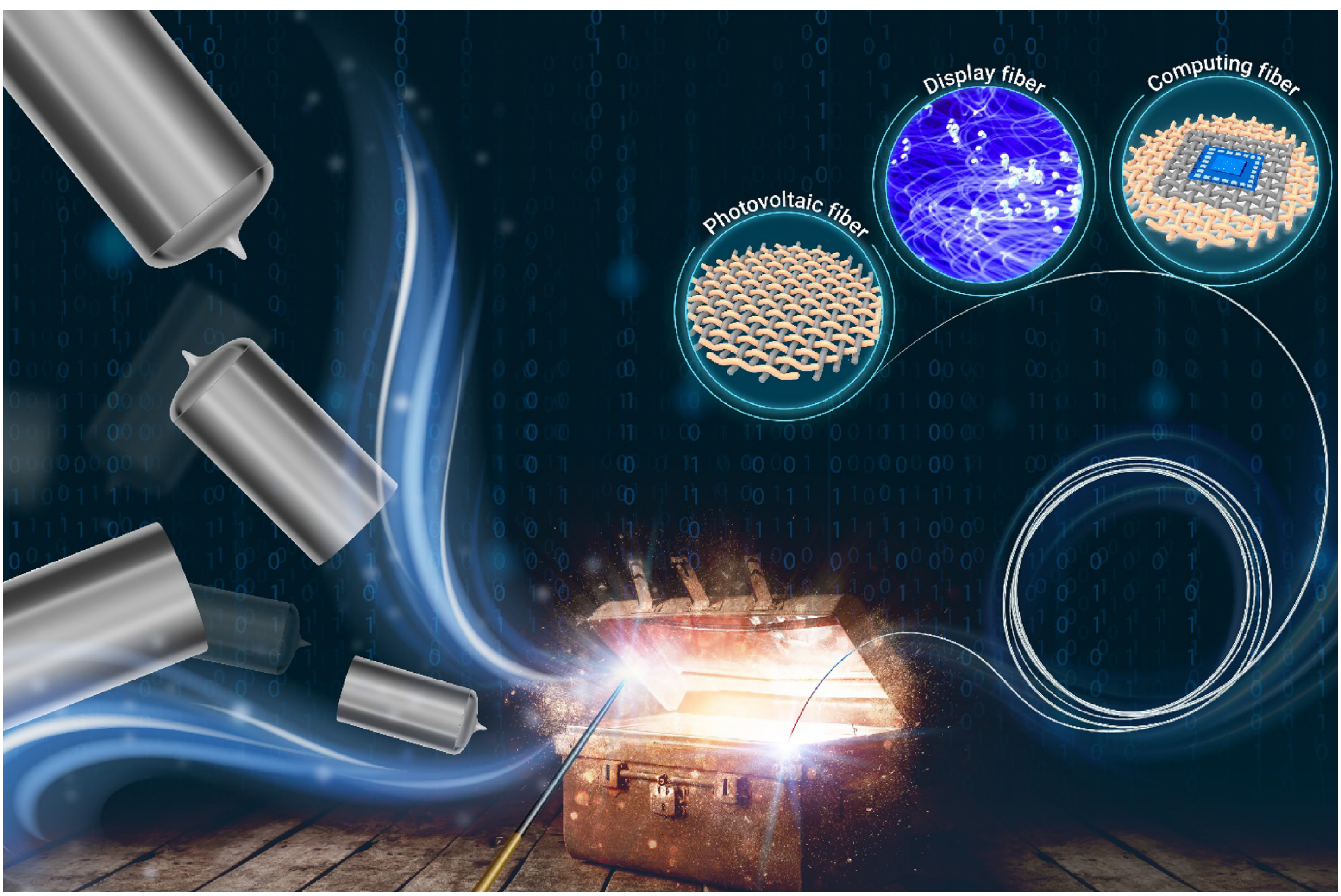

Figure 1. Semiconductor optoelectronic fibers and and potential applications

to the fiber fabrication, because any defects caused by the thermal, rheological, or mechanical mismatch between the glass cladding and semiconductor core could break the fiber continuity, especially at the extremely high processing temperature (as high as 2,000°C).

To address these challenges, a study published in *Nature* by Wang et al. reported exciting progress in understanding the thermomechanical basis of the molten-core method.[4] Taking Si and Ge as examples, a thorough analysis of the molten-core method was introduced by dividing the whole process into three stages according to the status of the semiconductor core, namely the viscous flow (molten semiconductor), the crystallization (semiconductor being crystallized), and the cooling stage (crystallized semiconductor). Key considerations for each stage were emphasized. At the viscous flow stage, the glass cladding and the semiconductor core were either softened or melted, governed by the fluid mechanics. Therefore, a growth factor of the capillary instability was raised to guide the proper processing window for an unperturbed liquid semiconductor fiber. Upon fiber formation, the whole assembly cooled down and entered the crystallization stage of the semiconductor. It is worth noting that Si and Ge went through an anomalous volume expansion similar to the water-ice change, resulting in stress formation. The last stage was the solid-phase fiber assembly cooled down to ambient temperature, in which thermal contraction mismatch was the major contributor to potential defects. A combination of theoretical and finite element analyses was developed for each stage to address these issues. The results suggest that cladding glasses with an annealing point similar to the melting point of the semiconductor core and with a coefficient of thermal expansion matching the semiconductor should be used to reduce the stress formed during fabrication. Moreover, the cladding glass should have a softening point that is not much lower than the melting point of the semiconductor core to suppress capillary instability. Based on these considerations, the authors proposed the material selection and process optimization strategy. They verified it experimentally by demonstrating ultralong, perturbation-free, and crack-free Si and Ge microfibers. In addition, the authors demonstrated a photodetector in the fiber form made of the Si and Ge microfibers, the performance of which was on par with planar-type devices and was integrated into textiles for wearable optoelectronics.

Semiconductor fibers offer a new platform for electronics because their form provides unique features that are inaccessible in traditional wafers (Figure 1). Notably, Si and Ge fibers, the alternative form of the most widely used semiconductor materials, are compatible with modern CMOS technology. From cleaning and doping to lithography, the techniques for wafer treatment can in principle be applied to the fibers by simply adding a rotating mechanism dealing with the curved surface. The advances in the molten-core method could address the accessibility issue caused by the production rate, which is three to four orders of magnitude faster than traditional melt growth techniques. There are some open questions regarding the possible fiber cross-sectional shapes, impurities, clad peeling method, and compatibility with other promising semiconductor materials such as fourth-generation semiconductors. Nonetheless, this innovation in the molten-core method may lead to unprecedented potential for fiber-based devices. For example, transistors, logic gates, and complex digital circuits could be integrated within a hair-thin structure and further knitted into daily apparel, providing a digital path toward a human-centered information system.[5]

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DECLARATION OF INTERESTS

The author declares no competing interests.