Semiconductor Nano-filaments in Fiber

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ABSTRACT

One-dimensional structures with nanometre scale have achieved with substantial progresses for device applications in electronics, photonics, photovoltaics and biology. The fabrication for the well-ordered extended semiconductor wires remains highly desirable for the alignment and assembly. Here by relying on optical-fiber drawing technique, we report the semiconductor (Se and As_2Se_3) filament-arrays embedded in our multi-material fiber. These filaments can reach high aspect-ratio on the order of 10^6. This may offer new approach to produce wires with the capability of high-throughput and low-cost.

Keywords: fiber, nano-filaments, semiconductor, high aspect-ratio

1 INTRODUCTION

Optical-fiber thermal drawing from a viscous macroscopic preform is well established in the telecommunications industry and enables the rapid fabrication of kilometre-long silica-glass fibers with precise dimensions [1-3]. With these methods, in the last decade, microstructured fibers incorporating air enclaves have been created, resulting in a large set of novel fiber designs [4]. All these fibers, however, consist of a single material (silica glasses or polymers) with the possible addition of air cavities.

An altogether different class of fibers incorporating multiple materials (*e.g.*, amorphous semiconductor thin films, polymers, and metals) [0] in the same preform can be produced by thermal drawing. These fibers with novel designs and material combinations are enabling unique applications in sensing and flexible electronics [5-12]. However, nothing is known about the extent to which a feature size (such as film thickness) can be reduced in a multimaterial fiber using this fluid processing technique.

2 MULTI-MATERIAL FIBER FABRICATION

Thin films of As_2Se_3 or Se were thermally evaporated onto polyethersulphone (PES) or polysulphone (PSU) films, respectively. The macroscopic preform was fabricated by rolling the glass films and thick polymer claddings onto a PTFE mandrel and consolidating the structure under vacuum for approximately one hour, after which the mandrel was removed.

A conventional optical fiber draw tower consisting of a three-zone furnace to heat the preform to its processing temperature, a feeding mechanism to controllably introduce the preform into the furnace (downfeed speed of $0.003 mm \cdot s^{-1}$), and a capstan to pull the resulting fiber from the preform (set at was $\sim 0.1 m \cdot min^{-1}$) was used to draw tens of meters of fiber from cylindrical preforms measuring 160mm in length and 20mm in diameter. The drawing parameters were fixed to keep a constant draw-down ratio of about 20 between the features sizes of the initial preform and final fiber.

3 STRUCTURE SCALING DOWN

An example of such a fiber is sketched in Fig. 1a, where a solid macroscopic preform contains a micron-scale amorphous semiconductor glass film clad on both sides with a polymer. As in traditional thermal fiber drawing, this preform is heated to the viscous state and controllably stretched into a fiber by applying axial tension. The final fiber cross-section is simply a scaled down version of the initial preform (Fig. 1b, c). The results confirm that the layered structure is preserved

4 EXTENDED FILAMENT

However, as film thickness is reduced, the sub-100 nm layer is breakup in the fiber. We observe the filament arrays embedded in the fiber. Examples of the extracted filaments are given in Fig. 2. Figure 2a shows a 1-mm-long Se filament extracted from a fiber containing 100-nm-thick Se layer that has broken up. The filament is ribbon shaped, with width on the order of 10 μm and thickness on the order of 100 nm. Bundles of As_2Se_3 ribbons extracted from an As_2Se_3/PES fiber with 10-nm thickness are shown in Fig 2b. Individual ribbons have sub-100-nm width and 10-nm thickness. The longest achieved As_2Se_3 ribbons reach the aspect ratio on the order of 10^6.

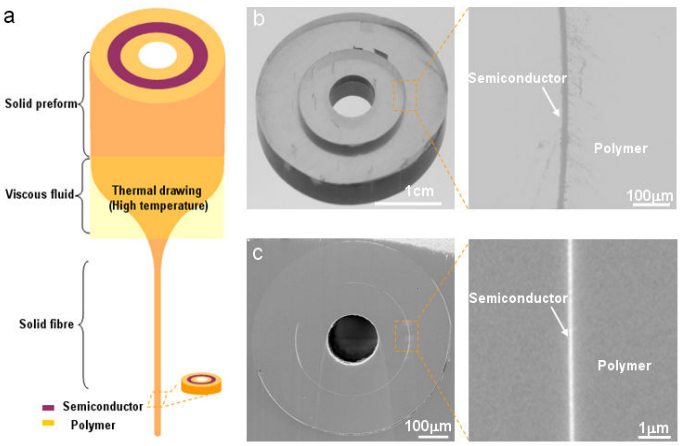

Figure 1 Fiber drawing. **a,** A hollow-core fiber preform is drawn down while maintaining the layer structure through the thermal processing. **b,** An optical microscope image of the layer structure in the preform is shown on the left, and a magnified section of the thin film on the right. **c,** SEM micrograph of the fiber cross section is shown on the left, and a magnified section of the intact semiconductor thin film, right, confirms that the layered structure is preserved.

5 DISCUSSIONS

The mechanism for these long nano-filaments is not clear so far. What would determine the lower limit of layer scaling down? Why dose break of layer occur? How are these filaments formed? What is the dynamical process during the thermal drawing? All these questions definitely demand more theory efforts.

There are several promising applications for these semiconductor wires. The semiconductors used in this work have attractive optical properties such as a high nonlinearity, high refractive indices, and wide transmission window in the near- and mid-infrared regimes. Additionally, they exhibit intriguing properties such as a high photoconductivity, large piezoelectric and thermoelectric coefficients, and low thermal conductivity.

Exciting directions for future work include crystallizing the amorphous semiconductor nano-ribbons and assembling more diverse materials together in the same fiber.

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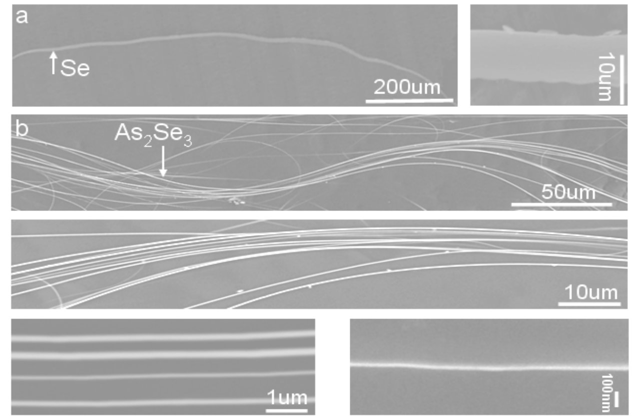

Figure 2 Semiconductor nano-filaments. **a,** SEM micrograph of a Se filament and a magnified section. **b**, (i) A bundle of As_2Se_3 filaments. (ii) Magnified section showing parallel filaments. (iii) A section of a single filament.

REFERENCES

[1] Maurer, R.D. & Schultz, P.C. Fused silica optical waveguide. US patent 3,659,915 (1972).
[2] Keck, D. B., Maurer, R. D. & Schultz, P. C. Ultimate lower limit of attenuation in glass optical waveguides. Appl. Phys. Lett. 22, 307-309 (1973).
[3] Agrawal, G.P. Fiber-optic communication systems 3rd edn (Wiley-Interscience, New York, 2002).
[4] Knight, J. C. Photonic crystal fibers. Nature 424, 847-851 (2003).
[5] Abouraddy, A. F. *et al*. Towards multimaterial multifunctional fibers that see, hear, sense and communicate. Nature Mater. 6, 336-347 (2007).
[6] Bayindir, M. *et al*. Kilometer-long ordered nanophotonic devices by preform-to-fiber fabrication. IEEE J. Sel. Top. Quant. 12, 1202-1213 (2006).
[7] Yeh, P., Yariv, A. & Marom, E. Theory Of Bragg fiber. J. Opt. Soc. Am. 68, 1196-1201 (1978).
[8] Fink, Y. et al. A dielectric omnidirectional reflector. Science 282, 1679-1682 (1998).
[9] Fink, Y. et al. Guiding optical light in air using an all-dielectric structure. J. Lightwave Technol. 17, 2039-2041 (1999).
[10] Hart, S. D. *et al*. External reflection from omnidirectional dielectric mirror fibers. Science 296, 510-513 (2002).
[11] Temelkuran, B., Hart, S. D., Benoit, G., Joannopoulos, J. D. & Fink, Y. Wavelength-scalable hollow optical fibers with large photonic bandgaps for CO_2 laser transmission. Nature 420, 650-653 (2002).
[12] Abouraddy, A. F. *et al*. Large-scale optical-field measurements with geometric fiber constructs. Nature Mater. 5, 532-536 (2006).