Novel fabrication and optoelectronic property of semiconductor filaments by optical-fiber thermal drawing

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.
Novel fabrication and optoelectronic property of semiconductor filaments by optical-fiber thermal drawing

D. S. Deng a, b, N. Orf a, b, A. F. Abouraddy a, Y. Fink a, b

a Research Laboratory of Electronics,

b Department of Materials Science and Engineering,
Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA

One dimensional nanostructure such as nanowires is typically fabricated by the wafer-based approach. Here we report nanowires are fabricated by thermal drawing of fiber. A thin viscous semiconductor film internal to the fiber undergoes filamentation driven by a fluid instability while retaining longitudinal structural integrity. Arrays of centimeter-long crystalline nanowires by post-drawing crystallization process are electrically contacted and yield a two-order-of-magnitude change in conductivity between dark and illuminated states. These results hold promise for the nanowire-detector arrays that may be integrated with large-area electronics.

Keywords: fiber, thermal drawing, nanowires, semiconductor, photoconductivity

1. INTRODUCTION

Optical-fiber thermal drawing from a viscous macroscopic preform is a well-established process for producing kilometer-long silica fibers with uniform dimensions in the telecommunication industry. In the last decade, microstructured fibers incorporating air enclaves have been created with these methods, resulting in novel fiber designs. All these fibers, however, consist of a single material with the possible addition of air cavities. The fact that these fibers consist of a single dielectric material limits their usage to optical-transport related applications.

An altogether different class of fibers incorporating multiple materials (e.g., semiconductors, insulators, and metals) thermally drawn from a macroscopic preform has recently emerged [1]. These fibers, by virtue of their novel designs and material combinations, are enabling unique applications in sensing and flexible electronics. However, nothing is known about the extent to which a feature size (such as film thickness) can be reduced in a multimaterial fiber.

Fig. 1 Novel fabrication of filament arrays using the optical-fiber thermal drawing technique. a) Schematic diagram of break-up of a thin cylindrical shell into a periodic array of filament arrays; b, c, Photograph of centimeter-long preform and of meter-long fiber.
2. FABRICATION

Our approach to achieve extended nanofilaments is illustrated in Fig. 1a. A macroscopic preform is composed of a thin cylindrical semiconductor selenium shell encapsulated in a polymer matrix (Fig. 1b). During thermal drawing, the preform is heated at elevated temperature into a viscous fluid and controllably stretched by the application of axial tension into an extended fiber (Fig. 1c). Upon reaching a characteristic thickness, a shell undergoing a scaling process evolves into an ordered array of filaments with breakup in the cross-section while maintaining uniformity in the axial direction [2].

Several intriguing features are offered by this new approach. Filaments are produced in a high-throughput fashion with unprecedented length. Filaments are hermetically sealed in a protective polymer matrix, thus avoiding problems associated with the mechanical fragility of these nanostructures. Additionally, the methods should be compatible with other materials such as metals and other semiconductors.

3. EXTENDED FILAMENTS

As film thickness is reduced, the sub-100 nm layer breaks up in the fiber and we observe 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$_2$Se$_3$ ribbons extracted from an As$_2$Se$_3$/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$_2$Se$_3$ ribbons reach an aspect ratio on the order of $10^6$.

![Fig. 2](image_url)

**Fig. 2** Semiconductor nanofilaments. **a**, SEM micrograph of a Se filament and a magnified section. **b**, (i) A bundle of As$_2$Se$_3$ filaments. (ii) Magnified section showing parallel filaments. (iii) A section of a single filament.

4. PHOTOCONDUCTIVITY

The entire nanowire array after post-drawing crystallization can be easily connected to external circuitry by contacting the two fiber ends with a conductor. For example, an in-fiber array of polycrystalline nanowires was contacted by applying silver paint to both ends of a fiber segment and then wrapping thin wire around the silver-painted ends. The 2-cm-long nanowire array behaves ohmically under applied bias (Fig. 3), and the electrical conductivity of the nanowires in dark can be estimated from the applied voltage, measured current, and array dimensions. The nanowire arrays exhibit enhanced photoconductivity under illumination from a 500 mW/cm$^2$ broadband white-light source (red line in Fig. 3). An array of amorphous nanowires was contacted and measured in the same way (gray line in Fig. 3) but no current was recorded owing to its very low conductivity [3].
Fig. 3 Current-voltage characteristics of an array of 2-cm-long $c$-Se nanowires in the dark (blue line) and under illumination (red line). No detectable current was observed in the $a$-Se nanowires (gray line), owing to their large resistivity.

5. OUTLOOK

This top-down methodology is a unique approach to producing nanofilaments with several attractive features. These filaments may be produced in a high-throughput and low-cost fashion. The arrays are well-ordered with parallel alignment. Furthermore, these filaments are encapsulated in a protective polymer matrix, which lends itself to manual manipulation until the need to extract filaments arises. We thus bypass the fragility of these nanostructures during handling that plagues other approaches. Most importantly, the nanofilaments are produced with exceptionally long lengths. Nanofilament bundles of these or other materials may be potentially useful in enabling large-area applications including renewable energy and bioengineering. Directions for future work include producing high-density filament bundles using a multiplicity of layers in the fiber preform, and assembling metal and semiconductor structures in the same fiber.

REFERENCES