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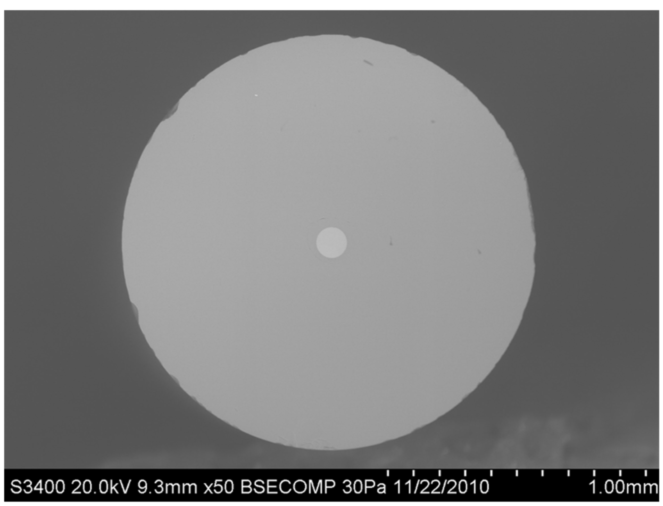

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Semiconductor Core Optical Fibers

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(Invited Paper)

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Abstract: Presented here is a review of recent efforts to date in the field of semiconductor core optical fibers. Various processing techniques have been employed to fabricate such fibers and control the degree of crystallinity achieved within the fiber cores. Following the brief review of recent progress is a more in-depth look at the molten core approach, which allows for long lengths of highly crystalline semiconductor core fibers to be achieved.

Index Terms: Optical fiber, semiconductor, silicon, germanium.

Recently, much progress has been made in the field of semiconductor core optical fibers, extending the field of silicon photonics from a planar waveguide form to an optical fiber-based technology. When combined with an appropriate cladding glass, such highly crystalline semiconductor core optical fibers have significant potential for Raman fiber devices, mid- and long-wave infrared sensing and power delivery, and terahertz guided wave structures. Their mid-infrared transmission capabilities have generated much interest in their use in the biomedical industry, where there is an unmet need for robust infrared waveguides in a variety of dental and medical procedures. Several techniques have been employed in the fabrication of silicon optical fiber. In addition to the work conducted at Clemson University (USA), researchers at Virginia Tech (USA), the Massachusetts Institute of Technology (USA), the University of Erlangen-Nuremberg (Germany), and collaborations between Pennsylvania State University (USA) and Southampton University (U.K.) have made significant contributions to this growing field.

The current state of the art includes several different techniques which have been employed in the fabrication of silicon optical fiber. Sazio *et al.* [1]–[6] have explored high-pressure microfluidic chemical deposition to deposit silicon inside pure silica microstructured optical fiber (MOF) templates for the fabrication of silicon fibers. MOFs are created by stacking and fusing glass capillary and rod arrays into performs which are subsequently drawn. The semiconductor deposition was performed by flowing a silane/helium mixture through the capillary hole. Since this is done at a temperature range where the material would remain amorphous (400 °C–500 °C), subsequent annealing is used to control the silicon polycrystallinity. Crystal grain sizes were reported to be around 0.5–1 μm. Initially, high optical transmission losses of around 50 dB/cm at 1550 nm have been reported for amorphous samples with losses decreasing with both increased annealing temperature and increasing wavelength. Transmission losses were also determined for polycrystalline samples. The

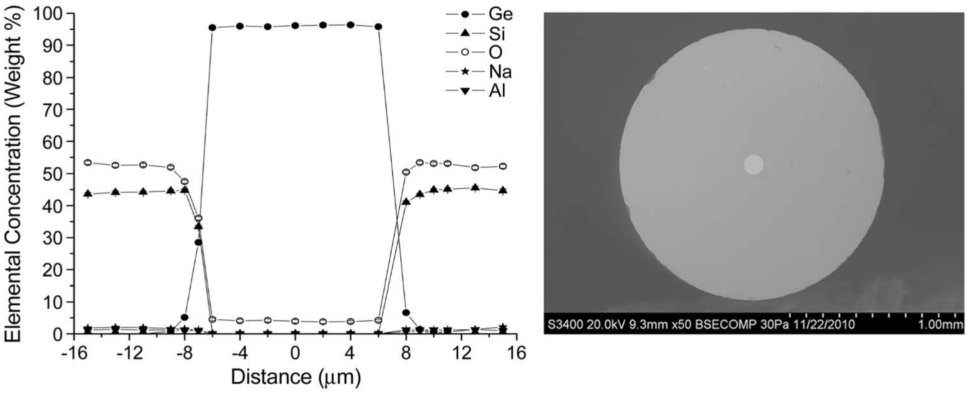

Fig. 1. (Left) Elemental analysis of the glass-clad germanium core optical fiber. (Right) Scanning electron micrograph showing the central silicon core and glass cladding.

lowest reported loss was approximately 5 dB/cm at 1550 nm [7]. Optical characterization revealed effective mode areas comparable with the effective area of a single mode fiber's fundamental mode. Effects such as tensile strain induced at the silicon core–silica cladding interface during cooling result in a red-shift of the Raman spectra of the silicon tubes with respect to that of single crystalline silicon [8].

Scott *et al.* [9], [10] have used powder-in-tube fabrication methods in which powder silicon is packed into a silica tube, pulling a vacuum and evacuating the preform, in order to minimize silicon oxidation. This powder-in-tube technique produced fibers, drawn at around 1600 °C, which averaged an overall length of approximately 7 cm. Thermal expansion induced microcracks, and other such irregularities, at the boundary between the core and the cladding materials resulted in high optical losses. Based on results of electron dispersive spectroscopy (EDS), silicon and oxygen were both present in the cladding glass. However, silicon was the sole element confirmed throughout the core. Electron backscatter diffraction (EBSD) confirmed large grained polycrystallinity aligned with the fiber axis, along with several crystalline orientations throughout the fiber.

Our group at Clemson University employs a more conventional draw tower fabrication process which has shown success in fabrication of long lengths of optical fibers [11], [12]. The "molten core" technique employed requires that the core semiconductor material melt at a temperature where the cladding glass softens and draws into the optical fiber. In order to achieve this, a semiconductor rod is sleeved inside a tube of cladding glass, the draw temperature of which is greater than the melting temperature of the core. The molten semiconductor core is therefore contained within the constraints of the inner walls of the cladding glass tube. Efforts have primarily been focused on silicon [11], germanium [12], [13], and indium antimonide [14] cores and their respective cladding glass selections. To date, more than 250 m of crystalline germanium core fiber have been fabricated. Fig. 1 provides the compositional profile along a line crossing the full diameter of the core, as well as the interface into the cladding. Also shown is a cross-sectional view of a silicon core fiber.

As crystallographic strain can be induced by thermal expansion mismatch between the core and the cladding materials, crystallographic orientation data have been obtained on glass clad germanium optical fibers in order to determine the nature of the crystallinity of the material. These data were obtained by single crystal X-ray diffraction (XRD) and EBSD. Reflection profiles of initially obtained axial photographs revealed a local single crystalline character in the fibers, as seen in Fig. 2, with sufficiently large grain sizes to reliably determine orientation. A preference for alignment in the ⟨100⟩ and ⟨110⟩ directions was exhibited close to the longitudinal axis of the fiber, while ⟨100⟩ orientations were likely to align with the fiber axis. This preference toward ⟨100⟩ and ⟨110⟩ orientations has often been observed in dendritic crystals of cubic symmetry.

The ability to achieve high crystallinity over fairly long lengths of fiber begs the question as to the rate at which these crystals can be grown. The interplay between kinetics and thermodynamics also plays a strong role here, as crystallization of the core occurs without a seed crystal from which

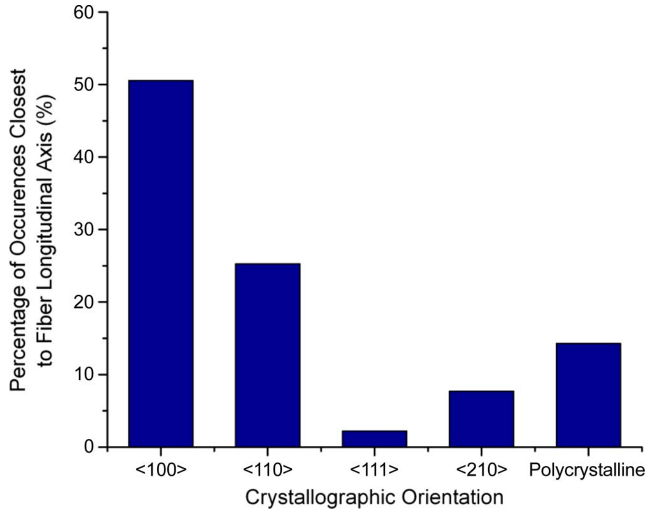

Fig. 2. Histogram of germanium crystallographic orientations nearest to the fiber longitudinal axis (from [13]).

nucleation may occur. A spontaneous nucleation event must then occur during the draw process as the fiber cools, which gives an indication that there must exist a range of draw speeds and temperatures over which crystallization can occur over long distances. While crystalline core fibers have been achieved at draw rates of about 1 m/s, it is very likely that the draw speeds can be considerably higher [15].

Much progress has been made to this emerging field in a fairly short period of time. While several different methods, which have been reviewed here, have been employed to create these semiconductor core fibers, such fibers have proven to be of some difficulty to create. Future work aims to lower the attenuation of the fibers to below 1 dB/m, which will require reducing the amount of both scattering and absorption. Cladding glasses are being developed to better control the dissolution of oxide impurities and improve the thermal expansion mismatches, which should further reduce the losses. A significant amount of work remains in order to develop a more complete understanding of the role of diffusion, kinetics, thermodynamics, and thermomechanics in the optimization of these novel optical fiber material systems.

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