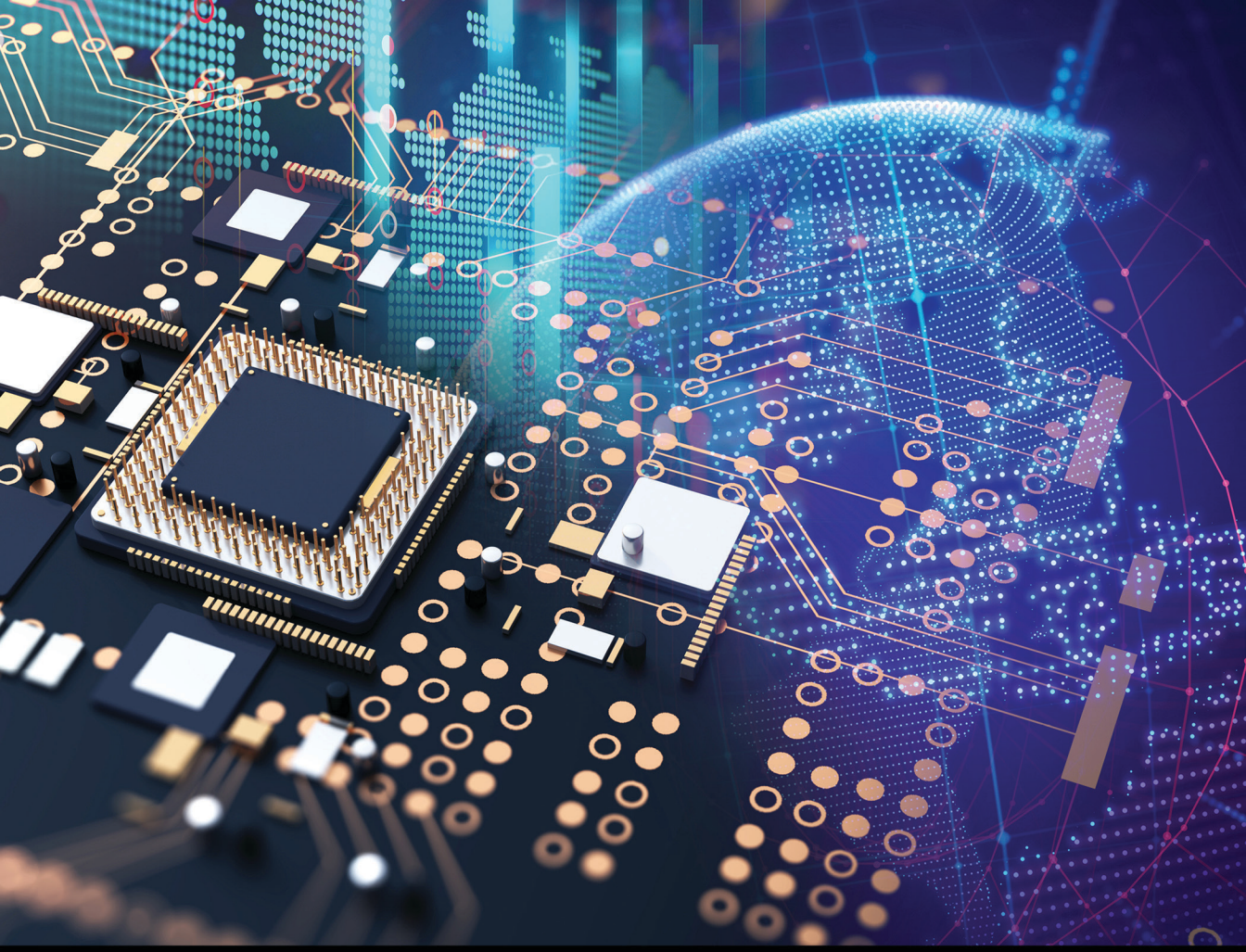


Semiconducting Fibers

Preparation, Advances, and Applications

Edited by
Ram K. Gupta

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Semiconducting Fibers

Semiconducting Fibers: Preparation, Advances, and Applications is a comprehensive study of the properties and emerging applications of semiconducting fibers. These nanomaterials have unique optoelectronic properties: they are flexible, one-dimensional, and lightweight, and can grow in bulk, thin films, and nano-dimensions (0D, 1D, 2D, 3D). Written by experts from around the world, this book covers the fundamentals of semiconducting fibers, their fabrication, and emerging applications in electronics, optoelectronics, energy, and healthcare. Various approaches to fabricating semiconducting fibers, their characteristics, and the working principles of nano-dimensional devices are covered.

Key features:

- Expert scientists across the world present state-of-the-art progress on semiconducting fibers for emerging applications, including flexible and wearable electronics.
- Provides details of novel methods and advanced technologies used in energy applications of semiconducting fibers.
- Provides fundamentals of electrochemical behavior and their understanding of optoelectronics, photovoltaics, batteries, fuel cells, sensors, and supercapacitors.
- Presents fabrication, characterization, and applications of semiconducting fibers for energy conversion and storage.

This book will be a key resource for students, academics, and industry professionals interested in the fabrication, device technologies, and applications of semiconducting fibers.



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Preface

Fibers originating from either natural or manmade materials have significantly improved the quality of our lives. On the other hand, semiconducting materials govern electronic, optoelectronic, and energy sectors due to their unique optoelectronic properties and ability to grow in various dimensions. They can be grown in bulk, thin films, and nano-dimensions (3D, 2D, 1D, 0D). Among the various dimensions, 1D semiconductors possess properties that can be integrated into many emerging technologies. Semiconducting fibers are particularly attractive due to their unique and tunable properties which can find applications in various areas such as optoelectronic devices, photonics, energy production and storage, and biomedicals. The flexible nature of such materials makes them very suitable for flexible electronics. The one-dimensional shape and light weight of fibers make them very suitable for wearable electronics.

The main objective of this book is to provide current, state-of-the-art knowledge on semiconducting fibers. This book not only covers the fundamentals of semiconducting fibers but also their fabrication and emerging applications. Various approaches to fabricating semiconducting fibers, their characteristics, and the working principles of nano-dimensional devices are covered. The emerging applications of semiconducting fibers in the areas of electronics, optoelectronics, energy, etc. are also covered. All chapters are written by experts in these areas from around the world, making this a suitable textbook for students and providing new guidelines to academicians, researchers, and industries.

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1

Semiconductor Fibers: An Introduction

Svetlana Nikolaevna Khonina, Nikolay Lvovich Kazanskiy, and Muhammad Ali Butt

1.1 Introduction

Silica glass fibers have become pervasive due to their exceptional transparency and versatile design options, facilitating the swift and dependable transmission of modern communications [1–4]. These characteristics of silica-based glass have spurred numerous supplementary applications. While silica boasts remarkable qualities like ultra-low loss and natural abundance, it does come with certain constraints in terms of its functional capabilities. Consequently, silica fibers primarily serve as passive conduits for information transmission, with signal processing and light generation occurring at different places. Lately, the utilization of silica in certain specialized contexts has faced challenges from what are known as 'multi-material' or 'hybrid' fibers, where disparate material families are co-processed within a single fiber [5]. Unlike conventional fibers that typically feature a core and cladding of compositionally similar materials (e.g., silica cladding with doped silica core), multi-material fibers exploit the vast diversity of elements in the periodic table to a greater extent. This broader range of core and cladding materials yields a more extensive array of intriguing and practical properties. Remarkable examples include 'omniguide fibers' combining polymers and chalcogenide glass, as well as glass laser fibers derived from YAG (yttrium aluminum garnet) [6,7].

Semiconductor fibers are crafted to possess semiconductor characteristics, typically hewn from materials like silicon, gallium arsenide, or similar compounds. These fibers serve diverse purposes, primarily within the realm of photonics and optoelectronics, where they excel in the controlled manipulation and transmission of light owing to their inherent semiconductor traits [8]. One extraordinary attribute of these fibers lies in their adjustability of bandgap, accomplished through precise manipulation of semiconductor material composition and doping levels. This capability empowers them to govern the specific wavelengths of light absorption and emission, rendering them invaluable for applications such as light emission, exemplified by lasers, and light detection, as seen in photodetectors [9].

When meticulously engineered, semiconductor fibers are capable of manifesting optical gain, signifying their capacity to amplify light signals. This property finds practical utilization in semiconductor optical amplifiers (SOAs), essential components within optical communication systems for enhancing signal strength [10]. Very similarly to conventional fiber optics, these semiconductor counterparts are adept at guiding and manipulating light. They accommodate diverse modes of light propagation, with their waveguiding characteristics being indispensable for a spectrum of applications, including integrated photonics and optical communication [11].

In recent times, there has been a growing trend toward the adoption of silicon core fibers for MIR applications. These fibers have demonstrated propagation losses of less than 2 dB/cm at wavelengths up to 4 μm, and 1.62 dB/cm within the range of 4.7 μm to 4.9 μm, as reported in Ref. [12]. Furthermore, germanium (Ge) core fibers have also shown promise in the mid-IR (MIR) spectrum. The first proof of concept of their potential occurred in 2007, utilizing the high-pressure chemical vapor deposition (HPCVD)

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approach [13]. It's worth noting that, in this study, the optical properties were not evaluated. Notably, semiconductor fibers seamlessly integrate with other semiconductor components, including diode lasers, waveguides, and photodetectors. This integration facilitates the creation of compact and highly efficient photonic devices. Their applicability spans a wide array of fields, encompassing telecommunications, fiber optics, sensors, and medical devices. In practice, they contribute to the development of optical communication systems, as well as optical sensors catering to various constraints, for instance, temperature, pressure, and chemical composition [3]. Moreover, they serve as essential light sources in medical and scientific instrumentation.

Nonetheless, it is imperative to acknowledge that the manufacturing of semiconductor fibers can be a formidable endeavor, necessitating meticulous control over material properties and dimensions. Additionally, efficient management of heat dissipation assumes paramount importance, particularly in the context of high-power laser applications.

1.2 Working Mechanism of Optical Fibers

Fibers operate by exploiting the principle of total internal reflection (TIR), enabling the efficient transmission of light signals over extended distances while minimizing signal degradation [14]. Fibers are composed of two primary components: the core and the cladding. The core, situated at the fiber's center, is crafted from a highly transparent material, often glass or plastic, possessing a higher refractive index than the surrounding cladding. The cladding envelops the core and features a slightly lower refractive index. The working mechanism of fiber optics is depicted in Figure 1.1.

The foundational concept behind fibers hinges on TIR. When light travels from a medium with a higher refractive index (the core) to one with a lower refractive index (the cladding) at an angle surpassing the critical angle, it wholly reflects into the higher refractive index medium instead of refracting outward. This phenomenon effectively confines the light within the core. To transmit information, a light source, typically a laser diode or LED, injects light into the core which experiences multiple internal reflections as it traverses the fiber's length. Information is imparted onto the light signal by modulating its intensity or phase. This modulation serves as a means of representing data, either through binary encoding (on/off) or analog modulation (variations in intensity).

Fibers are meticulously engineered to minimize signal loss during transmission. Thanks to TIR, the light signal can traverse substantial distances without significant attenuation. This unique property empowers fibers to transmit data across continents without requiring frequent signal amplification. At the receiving end of the fiber optics, a photodetector, usually a semiconductor-based device, detects the incoming light signal. The photodetector converts the optical signal back into an electrical form, which can subsequently undergo processing, amplification, and decoding to recover the original data. The electrical signal derived from the photodetector is usually directed to electronic devices for further processing and decryption. This process enables the transmission of various types of data, such as voice, video, and digital information, across extensive distances at high speeds and with exceptional reliability.

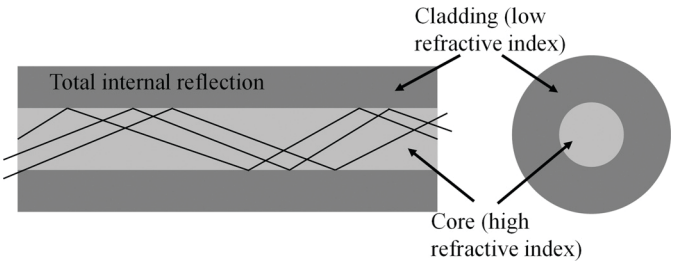


FIGURE 1.1 Schematic representation of fiber optics. Lateral view (left), cross-sectional view (right). TIR takes place between core and cladding resulting in the smooth propagation of light.

1.3 Advances in Optical Fiber Communication

Fiber optics technology serves as the backbone of contemporary communication systems, playing a pivotal role in various applications, including telecommunications, defense, remote sensing, and biomedicine [15,16]. Recent advancements in fiber optics technology have transformed fibers from mere passive waveguides into versatile mediums for the modulation, generation, and manipulation of optical radiation [17,18]. Two primary approaches harness the advantages of semiconductor materials within the realm of fiber optics: (i) Semiconductor fiber optics: In this approach, lengthy strands of silica glass fibers are doped or coated with semiconductor materials such as silicon, germanium, or other crystalline semiconductors; and (ii) Electronics based on planar chips: Planar chips are intricately crafted through lithography techniques and then interconnected with intermediate optics and packaging. These chips offer a wide array of functionalities, including detectors, amplifiers, modulators, and lasers.

In contemporary communication systems, semiconductor fiber optics and planar optoelectronic devices coexist in synergy. The overarching goal is to seamlessly incorporate planar optoelectronic capabilities into fiber-based infrastructure, obviating the necessity for separate, diverse, and expensive optoelectronic components in communication networks. The outcome is the creation of highly efficient communication systems that achieve optical radiation generation and modulation within the fiber structure, all while lowering costs.

Since the advent of light guidance through semiconductor fibers less than two decades ago, these fibers have attracted extensive attention. This interest has not been limited solely to their optical properties but has also extended to their thermoelectric, optoelectronic, and photovoltaic capabilities. We can anticipate even more diverse applications for semiconductor fibers soon. Figure 1.2 provides an overview of the currently industrialized fibers, encompassing solid-core and semiconductor-infilled variations. While the optical losses in semiconductor fibers are akin to those in planar semiconductor waveguides, they still present relatively high losses that constrain broader applications. Researchers are keenly exploring techniques like core recrystallization, graded-index profiling, and tapering to further enhance the optical performance of these fibers. However, it's worth mentioning that even with their current optical performance, semiconductor fibers may serve as suitable contenders for various applications [19].

These include solid-core semiconductors, which encompass single components, alloys, and compounds, as well as semiconductor-infilled fibers, each showcasing different materials and design variations. Looking ahead, the next generation of fibers is poised to introduce innovations like graded-index structures and the integration of semiconductor materials into photonic crystal fibers (PCFs). These advancements promise to further expand the capabilities and applications of semiconductor fibers.

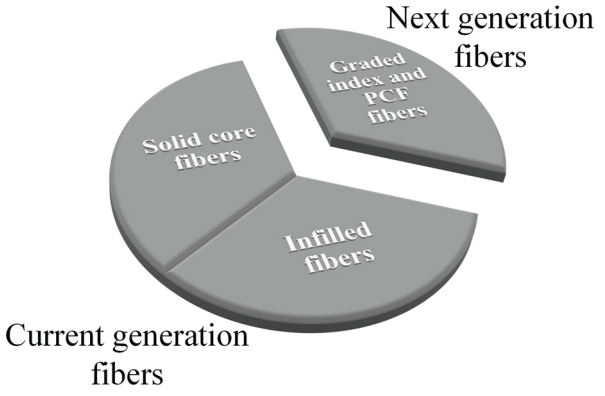


FIGURE 1.2 The current state and prospects of semiconductor fibers encompass a diverse range of developments.

1.4 Fabrication Method of Semiconductor Fibers

In the early development of semiconductor-core fibers, a technique known as high-pressure chemical vapor deposition (HPCVD) was employed within pre-existing micron-sized pores of glass capillaries [20]. The illustration is shown in Figure 1.3(a) [19]. This method is particularly useful for growing or depositing materials with specific optical properties or for functionalizing fibers for various applications. This method offers several advantages, including the attainment of high material purity through gas precursor reactions and the proficiency to deposit substances that would otherwise vaporize during conventional methods like MCD (molten core draw) [21]. The use of lower temperatures, significantly below the deposit material's melting point, results in the formation of either amorphous or small-grain polycrystalline materials, which can prove advantageous for specific purposes. Fibers created using this approach are typically several centimeters in length and require considerable growth durations because of the inherent challenges of material transport through the narrow pore diameters. Additionally, laser annealing has been employed to transform these materials into single crystal cores, further enhancing their optical properties.

A replacement to the HPCVD technique is the pressure-assisted melt filling (PAMF) method for fiber fabrication [22]. Illustrated in Figure 1.3(b), this process involves the injection of molten material into a capillary under elevated pressure. Unlike HPCVD, PAMF allows for the rapid production of long centimeter-scale fibers within a short timeframe, often just a matter of hours. PAMF was initially showcased in the creation of Ge cladding inclusions within microstructured fiber optics. Since then, this methodology has been expanded to encompass various materials, including glasses and metals. An intriguing application involves the incorporation of gold to commence plasmonic capabilities into microstructured fiber optics. Impressively, the research team succeeded in melting and forcing gold into pore sizes as small as 120 nanometers in diameter, highlighting the remarkable precision achievable with this method.

However, there are certain limitations associated with PAMF. One such constraint is the necessity to select a core material with a lower melting temperature than the softening temperature of the cladding material. For instance, depositing silicon into a silica capillary is not feasible due to the semiconductor's

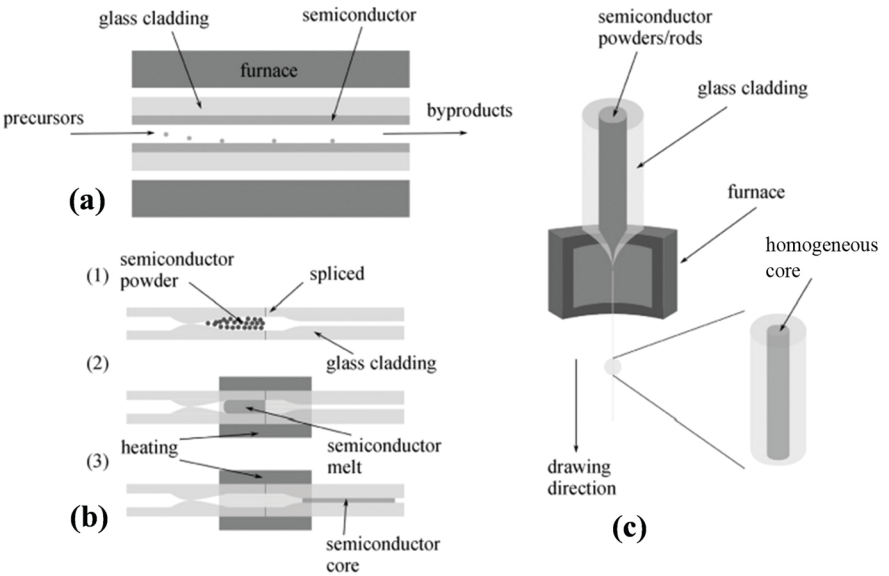


FIGURE 1.3 Illustrations depicting different semiconductor fiber fabrication techniques are as follows: (a) HPCVD method, (b) PAMF method, (c) MCD method. Adapted with permission from Ref. [19]. CC by 4.0 DEED Attribution 4.0 International.

high melting temperature of 1414°C, whereas silica's softening temperature is only 1200°C. Another challenge lies in controlling the cooling process, often resulting in core materials with suboptimal crystallinity. Nevertheless, researchers have demonstrated that these challenges can be addressed through post-processing techniques, as illustrated by Chen et al. [23].

The MCD technique originated from the powder-in-tube method, initially developed for manufacturing OFs containing core materials that tend to be unstable when subjected to standard optical fiber drawing conditions. In this process, a glass tube serves a dual role as both a container and the outer layer for the fiber. It is loaded with the semiconductor core material of choice, typically in the form of powder, a rod, or a combination of both. Subsequently, this prepared structure is subjected to heating at temperatures surpassing the glass's transition temperature and the semiconductor's melting point. The fiber optics are then drawn using the same techniques applied to conventional glass fibers, as illustrated in Figure 1.3 (c). As the drawn optical fiber gradually cools, the molten material transforms into a polycrystalline core, while the glass tube effectively becomes the cladding. One notable advantage of the MCD method is its ability to produce kilometer-long fibers with centimeter-scale single-crystal grains. This characteristic is crucial for achieving low-loss optical transmission. Moreover, the assembly process is comparatively straightforward when compared to HPCVD.

Nonetheless, it is essential to highlight that the elevated processing temperatures in this method pose a potential risk of oxygen or other elements migrating from the cladding into the core, which may result in contamination and the creation of defects [24]. To tackle this challenge, several remedies have been devised. One effective solution entails the inclusion of an alkaline oxide modifier at the interface between the core and cladding. This modifier serves to impede diffusion and mitigate interfacial stress arising from the thermal expansion mismatch between the core and cladding materials [25].

The semiconductor fiber platform has demonstrated remarkable versatility, with various optical fiber material systems emerging over the past decade. Each of these material systems brings unique functionalities to the table, such as enabling transmission in the MIR, possessing robust nonlinear optical coefficients, facilitating light emission, and supporting optical-to-electrical conversion capabilities. While there have been instances of microstructured optoelectronic fibers, the predominant design has been the step-index fiber optics. A significant portion of investigation efforts have been directed toward the integration of novel materials and the reduction of light propagation losses in these optical fibers.

Due to its relatively modest melting point, which sits at around 940°C, Ge has been subjected to comprehensive scrutiny through the exploration of alternative manufacturing approaches. In the initial stages of research, photonic crystal fibers (PCFs) were devised, involving the injection of molten Ge into the hollow capillaries embedded within the fiber structure [23]. This methodology yielded composite fibers characterized by filled cores extending up to several centimeters in length, showcasing temperature-dependent optical losses determined by analyzing light transmission within the glass structure. Additionally, pressure-assisted melt-filling techniques were utilized to produce hybrid fiber segments ranging from 3 mm to 7 mm in size, wherein a Ge core was positioned near a conventional fiber optics core. These hybrid fibers exhibited a linear response to a wavelength of 1.3 μm [24]. Recent experiments have reported single-core fibers produced through pressure-assisted melt-filling followed by CO_2 laser annealing to enhance grain size and mitigate core stresses via recrystallization. These laser-treated fibers boasted core diameters of approximately 2 μm and extended over 8 mm in length, constrained by the available equipment [20]. The fabrication of Ge core fibers has been accomplished through MCD, utilizing both borosilicate and silica cladding glasses. Silica-clad Ge core fibers exhibited optical losses of 0.7 dB/cm at 3.39 μm, while Ordu et al. stated an average optical loss of 5.1 dB/cm across the wavelength range of 5.82–6.28 μm [25]. Notably, Ge cores clad with borosilicate glass and featuring 20 μm cores were produced in quantities of 100 m using a double-draw method. These optical fibers established high-speed photodetection capabilities. The double-draw process was associated with a slight reduction in stress, and the electrical resistivity of the material measured approximately twice that of the initial material, possibly due to interactions with the cladding.

Several post-fabrication processing techniques have been employed with Ge core optical fibers, encompassing tapering, oven annealing, and argon and CO_2 laser annealing. Tapering experiments revealed initial indications of selective crystal orientation during recrystallization, yielding single crystal segments extending up to 4 mm in length. Oven annealing, although not yielding functional properties

in the specific study, led to an increase in grain size and a reduction in stress within Ge core fibers. The limited interaction between Ge and silica has been strategically utilized in fusion splicer annealing, allowing for the creation of microsphere temperature detectors. Additionally, employing 488 nm laser treatment on HPCVD Ge core fibers encased in silica produced a remarkable 9 mm single crystal with optical losses measuring just 1.33 dB/cm at a wavelength of 2 μm [26]. Utilizing a CO_2 laser annealing approach on a Ge core fiber, with an axially symmetric beam (albeit slightly off-axis), resulted in the alleviation of stress and a reduction in optical losses. Raman studies were conducted to investigate the extent of interaction between the core, which ranged from 30 μm to 60 μm in diameter, and the surrounding silica cladding. It's worth noting that although the study identified a minimum in optical losses concerning CO_2 laser power using a scan rate of 3 mm/s, no data regarding grain size were presented [27].

1.5 Main Structures of Semiconductor Fibers

The most general structures for semiconductor fiber optics, including semiconductor core fibers, metal-semiconductor-insulator fibers, multi-structured optical fibers (MOFs), and photonic bandgap structured (PBG) fibers are discussed in this section.

1.5.1 Semiconductor Core Fibers

Silicon has garnered the most extensive research attention as a core material in fibers to date [28]. This is primarily due to its transparency within telecom wavelengths and the significant expertise accumulated through the development of planar silicon photonics [29]. Numerous reviews on this core material have already been published. Here, we will spotlight a few additional studies in this field. Most MCD fabrication of silicon core fibers has been carried out using bulk silica as the cladding material. Post-processing techniques have resulted in substantial enhancements in optical losses and the grain size of the core material. Some studies have reported high-quality fibers using only the silicon/silica combination, while others have introduced an interface layer to reduce stress during the drawing of cane and fiber and to minimize oxygen incorporation in the core. Stress, stemming from the expansion of silicon upon solidification, plays a crucial role and can limit the maximum core size achievable through drawing. It was observed that rapidly cooling microspheres formed by locally heating silicon-core fiber optics resulted in lower tensile stress compared to both the as-drawn fiber and spheres created with gentler temperature cycles. The relaxation of the glass surrounding the silicon core likely contributes to this difference, highlighting the importance of selecting the appropriate glass or interface layer to maintain a deformable material during the semiconductor's solidification. It's worth noting that silicon undergoes nearly a ten percent increase in volume when transitioning from the molten state to room temperature. Extensive efforts in the advancement of silicon core fibers have propelled this material to the forefront of potential commercial applications. Furthermore, these accomplishments have provided invaluable insights into the processing and material characteristics applicable to a diverse array of other materials. While some research suggests the feasibility of achieving pure silicon optical fiber with a single crystal core spanning meters in length, no such accomplishment has been reported to date. Nevertheless, it's worth noting that current applications have not necessitated the development of such an extended optical fiber.

Ge was among the pioneering semiconductor core materials explored for fiber optics, employing the HPCVD technique. Seminal research papers emphasized the prospects of cores composed of both Ge and supplementary components. Initially, the amorphous germanium optical fibers exhibited optical losses exceeding 15 dB/cm at a 3.5 μm wavelength, which subsequently decreased to 4.8 dB/cm at 10.6 μm. Subsequent investigations into crystallized cores have revealed the promising potential of this material for MIR devices. While Ge has received less optical scrutiny due to its small bandgap, rendering it incompatible with conventional telecom testing equipment, efforts have been made to reduce losses in the material and explore its nonlinear behavior. Whispering gallery modes have been characterized in microspheres created from Ge core fibers. Furthermore, Ge has garnered interest as an infrared Raman source with a 5.62 μm pump, paving the way for further research and applications in this material.

Other elemental semiconductors have been efficaciously fused into the cores of optical fibers clad with glass, and selenium (Se) has garnered particular interest due to its low melting point of 220°C, which makes it compatible with polymeric cladding materials [30]. Reports exist of glass-clad OFs with Se cores exhibiting optical losses as minimal as 1.5 dB/cm at a wavelength of 1.3 μm, achieved through a two-stage oven annealing process applied to amorphous-core starting material [31]. Additionally, tellurium has been drawn into glass-clad fibers; however, initial experiments yielded significant optical losses attributed to the incorporation of cladding components into the core. Chalcogenide materials, including selenium and tellurium, possess higher vapor pressures [32]. Consequently, they are often drawn within lower-temperature claddings, such as polymers or borosilicate glasses, where thermally driven vapor pressure effects are mitigated. Strategies like using thicker cladding or arranging the chalcogenide material spatially before the drawing process may further alleviate issues associated with vapor pressure. A conventional optical fiber drawing process was employed to create a glass-clad fiber with a flexible length of 250 meters. This fiber boasts a crystalline and phase-pure germanium core measuring 15 μm in diameter, encased within a 150 μm diameter as shown in Figure 1.4(a).

1.5.2 Metal–semiconductor–insulator Fibers

The operation of most practical electrical and optoelectronic devices necessitates the utilization of conductors, semiconductors, and insulators, all meticulously arranged with defined geometries and precise length scales, while ensuring intimate surface interactions. Traditionally, manufacturing these components involves intricate wafer-based techniques, capable of producing microscopic features but limited to planar configurations and constrained coverage areas. In contrast, the process of drawing fiber optics from a pre-existing reel or tube offers a more straightforward approach, yielding longer, highly uniform fibers with controlled geometries and exceptional optical transport properties. Although initially restricted to specific materials and larger features, thermal drawing has emerged as a versatile method. It enables the creation of fiber photodetectors, featuring an amorphous semiconductor core enveloped by metallic microwires, rendering the fiber light-sensitive along its entire length, spanning tens of meters. This configuration serves as a one-dimensional photodetection element and can be interwoven to form grids of fibers able of pinpointing the location of an incident light source [33].

The diverse array of metal–semiconductor–insulator fiber structures allows for multifunctional fibers. The schematic of the metal–semiconductor–insulator fiber is shown in Figure 1.4(b). By integrating optical, electrical, and thermal components, these fibers can function as self-monitoring optical transport devices [34]. Hollow-core multilayer cylindrical photonic bandgap fibers are employed within the fiber transmission element to efficiently direct high-power radiation along the fiber axis [35]. Concurrently, long metal wires, interconnected by a semiconductor layer at their ends, respond to variations in the fiber's temperature by transmitting a current to the fiber's terminals, thereby facilitating real-time temperature monitoring along the fiber's length. These self-monitoring, high-power optical transmission lines possess the capability to predict and prevent potential failures. This is achieved through the semiconductor material's electrical conductivity, which exhibits exponential sensitivity to temperature fluctuations, allowing for instantaneous differentiation between normal transmission conditions and conditions indicative of localized defect formation.

1.5.3 Multi-structured Optical Fiber (MOF)

MOF (multi-structured optical fiber) represents an innovative breakthrough featuring an intricate network of nanoscale to microscale capillaries deliberately engineered to harness light through photonic bandgap effects [36]. To expand the capabilities and applications of these optical fiber devices, a range of physical techniques, including drawing and fluid infiltration, are being employed. These methods facilitate the incorporation of various substances, including gases, liquid crystals, polymers, as well as low-melting-point materials like metals, compound glasses, and semiconductors into MOFs. The significance

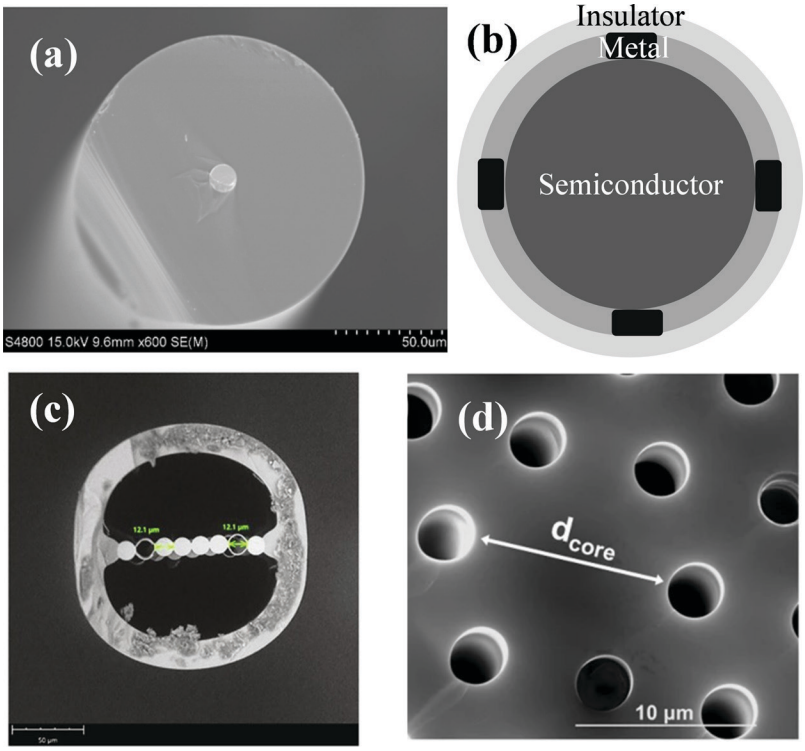


FIGURE 1.4 Structures of optical fibers. (a) Semiconductor core fiber. Adapted with the permission from Ref. [24]. Copyright (2009) OSA. (b) Metal–semiconductor–insulator fiber. (c) MOF. Adapted with permission from Ref. [36]. Copyright (2021) Elsevier Inc. (d) PBG structured fiber. Adapted with permission from Ref. [40]. Creative Commons Attribution 4.0 International License.

of high-performance semiconductors and junctions cannot be overstated in the realms of advanced optoelectronics and photonics [37]. Components such as transistors, light-emitting diodes/lasers, and high-speed photodetectors rely on the precise creation of p–n junctions, a feat achieved through carefully controlled impurity doping.

MOFs can be effectively deposited using the HPCVD, seamlessly integrating conformal semiconductor layers and void-free wires within micro-to-nanoscale-diameter pores [20]. The use of fibers as templates for crafting these semiconductor devices provides greater flexibility in geometric design compared to conventional planar fabrication methods. Consequently, this paves the way for the realization of all-fiber engineering approaches, harmoniously integrating optoelectronic and photonic devices with optical fiber infrastructure. Significantly, fiber optics devices based on junctions, with gigahertz bandwidth capabilities, can be produced using doped crystalline semiconductors, resulting in improved performance. In cases where it is not practical to draw amorphous hydrogenated silicon, fiber deposition techniques become prominent, enabling the utilization of its nonlinear optical characteristics. Eventually, the cores of fibers made from crystalline compound semiconductors hold substantial promise for high-power infrared applications, supporting light guidance and enabling subwavelength-resolution, wide-area infrared imaging capabilities.

A novel and straightforward fabrication method has been successfully employed to create a unique multi-structured flat fiber featuring dual airholes and doped with specific materials. This proof-of-concept fabrication technique utilizes a drawing tower equipped with a setup of solid rods and capillaries inserted into a preform using a simple holder. The resulting doped flat fiber with dual airholes has dimensions of 165 μm × 33 μm, with airhole diameters measuring 11.2 μm. A scanning electron microscopy (SEM) image of an MOF fiber is revealed in Figure 1.4(c) [36]. Optical characterization

confirms excellent light-guiding properties in the core, with no light leakage to the adjacent cores due to the integrity of the capillaries separating them. This innovative fabrication technique is characterized by its simplicity, cost-effectiveness, and the capacity to arrange a flexible core structure using glass rods and capillaries with different refractive indices. This flexibility enables the creation of a wide range of complex multi-structured flat fibers and ensures precise control over core dimensions, making it ideal for future applications in light-guiding devices and optical sensors, such as biosensors requiring analyte flow through airholes.

1.5.4 Photonic Bandgap Structured (PBG) Fibers

A versatile omnidirectional dielectric mirror fiber was crafted through a thermal drawing process using a multilayered fiber precursor [38]. This involved the use of glassy materials characterized by distinct refractive indices but equivalent thermomechanical properties to construct 21 layers of alternating refractive indices, enveloping a robust polymer core. These remarkable optical fibers find application in diverse scenarios, for instance woven radiation shields, spectral analysis of textiles, and telecommunications filtration. These dielectric mirror fibers function as all-encompassing mirrors, capable of redirecting incident light from any angle and polarization. Subtle adjustments in the layer thickness, spanning just a few atomic layers, can yield transmission spectra that cover the entire electromagnetic spectrum. These fibers exhibit transmission peaks in the visible, ultraviolet (UV), near-infrared (NIR), and MIR segments of the optical spectrum, with the specific layer thickness influencing the spectral response. Thanks to their minimal material absorption, hollow-core, multi-material photonic bandgap (PBG) fibers hold potential for low transmission loss in lasers, achieving peak outputs of up to 11.4 MW at 1.55 μm, with a remarkable 97% of the laser's output energy retained in the fundamental mode [39].

An innovative tunable hybrid silica PCF has been developed, featuring integrated As_2S_3 glass nanolayers within its air capillaries using a solution-based glass fabrication method. An SEM image of a PCF fiber is shown in Figure 1.4(d) [40]. These deposited high-index layers exhibit anti-resonant transmission windows spanning from approximately 500 nm to around 1300 nm. Additionally, this study marks the first-time demonstration of the ability to thermally adjust these antiresonances, leveraging the high thermo-optic coefficient of the solution-processed nanolayers.

1.6 Applications of Semiconductor Fibers

Scientists are currently exploring the potential of semiconductor optical fibers, which offer substantial benefits compared to the prevalent silica-based fiber optics technology used for the transmission of nearly all digital data. Silica, or glass, fibers are limited to transmitting electronic data once it has been converted into light data. This necessitates the use of costly external electronic devices that consume substantial amounts of electricity. On the other hand, semiconductor fibers possess the capability to transmit both light and electronic data, and there is potential for them to perform real-time conversion from electrical to optical data during transmission, potentially enhancing delivery speeds.

The pronounced nonlinearity exhibited by semiconductors, surpassing silica glasses by several orders of magnitude, is poised to play a pivotal role in shaping the future of optical fibers. Recent endeavors have underscored the immense potential of these fibers in nonlinear optical applications. Take, for instance, the case of supercontinuum generation in solid-core silica PCFs, which typically necessitates several meters of fiber to achieve a broad spectrum. In stark contrast, a mere couple of centimeters of semiconductor-core fiber can yield a similar spectral bandwidth. To date, semiconductor-core fibers have successfully demonstrated a range of nonlinear phenomena, including detuning oscillations [41], supercontinuum generation [42], stimulated Raman amplification [43], and frequency comb generation [44].

Nonlinear optics has matured into a well-established field with significant technological importance across a range of applications, including laser technology, communications, quantum optics, and imaging. Within this context, semiconductors are noteworthy for their robust higher-order optical nonlinearities, rendering them a compelling element in the landscape of semiconductor optoelectronic fibers. It is

important to highlight that, despite the potential for second-order nonlinearities in materials such as ZnSe, most demonstrations showcasing nonlinear behavior in semiconductor optical fibers have been observed in centrosymmetric crystal systems, primarily on the silicon fiber platform. As we progress in the development of these fibers, it is certain that further exploration of additional nonlinear effects will be facilitated.

The core functionality of many semiconductor-based detection and energy-harvesting optoelectronic technologies revolves around the conversion of optical energy into electrical power. This capability stands as one of the most appealing attributes of the semiconductor optoelectronic fiber platform which has been effectively leveraged to create in-fiber detectors and innovative 'solar threads' [45]. What sets this platform apart from other fiber technologies is the exciting prospect of integrating optoelectronic functionality directly into the core material of the waveguiding fiber.

Semiconductor optoelectronic fibers present an exciting and innovative alternative to the conventional fiber laser platform. One of their notable advantages is the ability to extensively manipulate host materials, thereby enabling access to previously unexplored wavelength ranges and shorter device configurations. Despite the vast potential, there have been relatively few instances of fiber lasers within this platform. Notably, ZnSe has emerged as a well-regarded host material for transition metal ions, facilitating light emission. For instance, demonstrations of Cr^{2+}:ZnSe and Fe^{2+}:ZnSe lasers have successfully produced light at wavelengths around 2–3 μm and 3.7–5 μm, respectively [46].

1.7 Challenges Associated with the Development of Semiconductor Fibers

Current semiconductor fiber research focuses on two main areas: advancements in fiber materials and compositional structuring. Manufacturing kinetics analysis and post-processing techniques are crucial for performance enhancements. However, producing semiconductor core fibers involves complex challenges, requiring specialized techniques like precise doping. Harmonizing compatibility among core, cladding, and coating materials is crucial to prevent structural and operational issues. Semiconductor core fibers are sensitive to temperature fluctuations, impacting optical performance. Effective thermal management is vital, especially in high-power applications. While they can handle high optical power, managing core heat is challenging, as excessive heat can damage materials and reduce device lifespan. Ensuring a high-quality laser beam profile is critical, as imperfections in the core can limit performance.

Long-term reliability and stability are essential for mission-critical applications like telecommunications and medical devices. Minimizing signal attenuation and degradation over time is imperative. However, development and manufacturing costs, along with complex integration into devices, pose challenges. Precise packaging and alignment are crucial for optimal performance. At high power levels, semiconductor core fibers may exhibit nonlinear optical effects, requiring mitigation strategies. Material choices for core fibers are somewhat limited, and ongoing research aims to expand options. Despite challenges, semiconductor core fibers have made significant advancements, providing solutions in telecommunications, laser technology, and sensing. Ongoing research works to overcome obstacles and unlock their full potential.

1.8 Concluding Remarks

Semiconductor fiber optics is a groundbreaking innovation incorporating semiconductor materials into glass-clad fibers, introducing optoelectronic capabilities, and enhancing nonlinear performance. One approach embeds crystalline and amorphous semiconductors into the fiber, as seen in semiconductor core fibers, eliminating the need for electrical-to-optical conversion in communication systems. Advancements in fabrication and post-processing have led to high-quality semiconductor core fibers, primarily using silicon or germanium.

Manufacturing processes like MCD and HPCVD create specialty fibers with unique properties. The choice depends on specific fiber requirements and intended applications. Initial showcases of MIR supercontinuum generation and semiconductor optoelectronic fiber lasers have paved the way for applications in sensing, spectroscopy, and medical fields.

Semiconductor fiber optics is expected to play a crucial role in quantum optics, telecommunications, wearable electronics, and more. The technology boosts bandwidth, efficiency, and delivery speed while reducing costs, making it applicable in optical data communications, automotive, artificial intelligence, biomedical, astronomy, and aerospace systems. This overview highlights rapid advancements, sparking a revolution in global data and signal transmission.

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