

Photonic Materials for Optical Communications

Hartmut Hillmer and Roland Germann,
Guest Editors

Abstract

An overview of key materials for optical communications, including semiconductors, dielectrics, glasses, and organics, is presented in this issue of *MRS Bulletin*. Materials quality is in all cases crucial for advanced device and system performance. Materials properties and important problems are reviewed, and their impact on the performance of state-of-the-art optical devices is assessed and demonstrated by means of selected examples.

Keywords: dielectrics, glasses, optical communications, organic materials, photonics, semiconductors.

The 20th century can be considered the century of electronics. The invention of the field-effect transistor in 1926 and the bipolar transistor in 1947, and the development of integrated circuits since 1958, have opened up our information age. As for the 21st century, many experts believe that it will be devoted to optics and nanostructures. Thus, we probably stand at the entrance to a century of photonics and nanosystems technology. Recent advances in modern photonics have always been strongly related to advances in materials fabrication and the understanding of the physics involved. Today's application of photonic devices, components, and systems has recently spread to an enormously wide field, encompassing communications technology (datacom and telecom); illumination technology; indicator elements (i.e., control LEDs in the automotive field, measurement equipment, audio components, etc.); self-illuminating displays; projection displays such as digital micromirror technology and laser TV; optical-storage technology; medical technology in diagnostics, health monitoring, and surgery; devices and systems for sensing and high-precision measurements, including environmental control as well as gas and liquid detection; high-precision alignment and distance control, collision-avoiding

mobile systems; and finally, direct laser applications for cutting, welding, soldering, and drilling.

This issue is devoted to photonic materials for optical communications. A broad set of active and passive devices is used in today's optical communications systems. The optical part of such systems consists of light emitters and receivers, a medium for the light transmission, and devices for manipulating light in the optical domain.

Light emitters are usually lasers or LEDs made of III-V semiconductor materials. Wavelengths around 1550 nm have become standard for long-haul applications in optical backbone networks because of the minimum propagation loss of optical fibers in this wavelength window. Shorter-range applications in local networks, optical interconnects, optical backplanes, and even on-board and on-chip communications are using shorter wavelengths, in the range of 1310 nm, 980 nm, 850 nm, or below. The writing and reading of information in storage devices, such as compact disks and digital versatile disks, can be considered a special kind of shorter-range optical communication that makes use of even shorter wavelengths, ranging from 850 nm to less than 400 nm.

The optical receiver in optical communications systems is also dominated by

semiconductor materials, such as silicon and compound semiconductors. Different types of photodiodes cover the wavelength range between 1600 nm and the near-UV region.

The vast majority of optical communications systems use optical fibers as the transmission medium. Optical free space communication in air is used in special cases, such as short-distance data links or short-range optical interconnects. Glass has evolved as the material of choice for optical transmission, with doped silica being the dominant material used in single-mode fibers (SMFs) for long-haul applications. Silica multimode fibers are used for shorter-range data communications, and plastic optical fibers have gained interest as an alternative for low-cost applications.

During the last few years, we have seen an increasing demand for optical devices that can be used to manipulate light in the optical domain. Optical functions such as splitting and combining of light, switching of channels in the space domain, multiplexing and demultiplexing of channels in the wavelength domain, and filtering are very important building blocks toward the construction of all-optical networks. The advantage of these fully transparent optical networks is that the signals stay in the optical domain without the need to convert them from the optical to the electrical domain and back to perform switching operations electrically. Different technologies are used to construct such passive optical devices. Fusion of silica fibers is used to build simple devices such as power splitters and combiners. Miniature optics, such as gratings, lenses, beam splitters, prisms, mirrors, and interference filters, are used to fabricate bulk optic devices with the functionality of wavelength multiplexers and demultiplexers, switches, and filters. Although these devices exhibit very good optical properties, their future potential for certain applications may be limited because of the complicated packaging and fiber-alignment schemes, their size, and limits in integration density. Planar lightwave circuits (PLCs) based on layers of glass, polymers, or other materials deposited on a planar substrate are a promising alternative, with the potential for low-cost manufacturing and high integration density by using well-established fabrication technologies from the silicon industry.

A big industry, consisting of companies with a broad portfolio of different materials technologies and smaller niche players, has been built to supply the huge variety of devices for the optical communications sector. Although the optical device indus-

try has been hit hard economically by the bursting of the Internet bubble, we think that the whole sector will move back to steady and healthy growth after a consolidation phase.

Because of the huge variety of different materials systems (element, III–V, and II–VI semiconductors; organic conducting, semiconducting, and insulating materials; inorganic and organic glasses; LiNbO₃; dielectrics, garnets, and metals) used in the optical device industry, it is impossible to cover all materials systems and relevant materials aspects in this issue of *MRS Bulletin*. We have tried to review a broad set of materials that are used to fabricate the most important devices of optical communications systems. This comprises III–V semiconductors for lasers, LEDs, and photodetectors, organic materials for active and passive devices, silica materials for standard SMFs, dielectric multilayer systems for filter applications, and silica-based materials for PLCs (see Table I). The articles in this issue review materials properties and fabrication technologies and try to link basic materials characteristics to device performance.

We have tried to avoid overlap with aspects of the topic that have already been covered in previous issues. We have therefore left out any aspects linked to doping with rare-earth elements [see *MRS Bulletin* 24 (9) (1999) pp. 16–56]. Optical fibers made of microstructured silica have also been treated earlier [*MRS Bulletin* 26 (2001) pp. 608–646], as have vertical-cavity surface-emitting lasers (VCSELs) [*MRS Bulletin* 27 (2002) pp. 497–537]. Optical devices based on microelectromechanical systems (MEMS) were reviewed in *MRS Bulletin* 26 (2001) pp. 282–340.

In this issue, the contribution from Tu and Yu covers element semiconductors and arsenide-based, phosphide-based, and dilute nitride-based III–V semiconductors for photonic applications roughly between 600 nm and 2000 nm wavelengths. A strong emphasis is placed on advanced light sources and photodetectors. Current trends are aimed toward achieving GaAs-substrate-based VCSELs at 1.3 μm and potentially also at 1.55 μm.

The article by Hangleiter reviews the success story and some mysteries of Group III nitride semiconductors for LED

and laser applications, mainly in the wavelength range between 350 nm and 500 nm, which have created an immense market. For these materials, it is important to counteract enormous dislocations produced by heteroepitaxial growth and enforce improvements in *p*-doping. Physical details, materials properties, and device potential are emphasized.

Fuhrmann and Salbeck describe the new world of organic materials for photonic applications. Materials aspects and the wide range of options for tailoring the desired optical and mechanical properties are highlighted. Organic light-emitting diodes are given special emphasis, and other applications in optical communications such as organic solid-state lasers, optical switching, and data storage are covered as well.

Guenot's article on glass fibers for optical transport gives a short overview of fibers based on different materials systems and concentrates mainly on standard SMFs made of doped silica for long-haul telecommunications application in the 1550 nm wavelength window. Guenot shows in detail how different intrinsic and

Table I: Material Systems Used for Optoelectronic Device Applications.

	Element Semiconductors	III–V Semiconductors	II–VI Semiconductors	Dielectric Materials	Inorganic Glasses	LiNbO ₃	Organic Materials	Metals	Ceramics	Garnet
Lasers	(★)	★★★	★	★★	★	★	★	★	★	★
Light-emitting diodes	★	★★★	★	★	★	★	★★★	★		
Photodiodes	★★	★★		★			★	★		
Modulators	★	★★★		★	★	★★★	★★	★	★	
Optical isolators	★						★	★		★★
Multiplexers/demultiplexers	★	★		★★	★★		★	★		
Power-splitters/combiners	★	★		★★	★★	★	★	★		
Amplifiers		★★★			★★★		★	★		
Filters and add/drop devices	★★	★		★★	★★	★	★	★		
Space switches and circulators	★	★		★	★	★	(★)	★		
Gain equalizers, variable attenuators	★	★		★★	★	★	(★)	★		★
Dispersion compensators		★		★	★	★	(★)			
Fibers					★★★		★★			
Waveguides	★★	★		★★	★★	★	★★		(★)	

Note: The relative importance of a material system for a certain device application is indicated by the number of stars, from (★) = less important to ★★★ = very important, and represents the authors' view of the current status. Pure electronic devices are not included.

extrinsic loss contributions influence the fabrication of fibers with ultralow optical propagation losses.

The contribution from Hibino covers planar lightwave circuits based on doped silica glass. He describes fabrication technology and the arrayed waveguide grating multiplexer as a device example. The author also discusses ways to overcome polarization dependence, which is a key issue for planar optical devices. Special emphasis is placed on the description of a route toward higher integration densities. This is possible through increasing the doping level of the germanium-doped silica core layer, which leads to a higher refractive-index contrast between the core and cladding layers and thus to a smaller minimum bending radius of the waveguides. An alternative approach that leads to even smaller bending radii and higher integration densities is to use silicon oxynitride (SiON) as the material for the core layer.^{1,2}

Sargent and O'Brien describe thin-film-based optical filter technology based on multilayer stacks of refractory oxides, which are important materials for passive optical devices and for reflectivity modification of optical surfaces in general. The authors review materials systems and the fabrication technology used in the production of thin-film-based optical filters for applications in wavelength-division multiplexing.

In nearly all cases, material qualities such as purity, homogeneity, and crystalline perfection have been found to be crucial for powerful device components and systems. Examples are extremely low-light-absorbing optical fibers, the emission efficiencies of organic LEDs and lasers, and the high quantum efficiencies of arsenide- and phosphide-based conventional semiconductor LEDs and lasers. However, astonishing exceptions also exist, such as the poor crystalline quality of Group III nitride semiconductors, re-

vealing extremely high dislocation and defect densities but nevertheless an unexpectedly high optical-light output.

On the other hand, many materials classes allow researchers and device developers tremendous freedom to combine different materials in complicated geometric constructions, thus enabling hetero-interfaces in nearly arbitrary orientations in three-dimensional space by involving epitaxy, deposition, etching, and other processes.

In the past few years, there has been intense activity in the field of Group III nitride semiconductors and organic materials. Enormous impetus for full-color LED displays and high-density optical storage has been provided by the implementation of blue LEDs and blue semiconductor lasers. Another breakthrough was the development of a new generation of white LEDs and organic LEDs. Further cost reductions will take place, opening up a revolution in illumination technology in the public and private sectors. Major advances have also been made in the field of modern optical-fiber technology. Materials such as polymers, silica glass, and fluoride glass now cover a tremendous spectral range, enabling short-distance as well as long-haul fiber communications. With significant advances in ultrafast semiconductor lasers and the development of VCSELs, attractive compact ultrabright coherent light sources are available for high-data-capacity communications systems.

However, considering these successes in photonics, it is important to mention that directly generated green laser light is not commercially available. II-VI semiconductors and Group III nitrides did not succeed in opening up this spectral range without restrictions. It is worth noting that efficient green nitride LEDs are available by the help of the quantum-confined Stark effect, shifting the emission from the blue-green to longer wavelengths. Unfortunately, this support does not hold for

lasers being characterized by almost flat-band conditions above threshold. Once again, this underlines the importance of understanding the relevant physics in materials science.

In optoelectronics, the band discontinuities (band lineups) and bandgaps of inorganic and organic semiconductor heterostructures play a crucial role. However, in most cases, lineup engineering and bandgap engineering are not independent from each other. This often causes serious restrictions in device design. However, interesting and attractive exceptions exist: adding N to GaInAs reduces the energy of the conduction-band edge, and introducing Sb into GaInAs energetically increases the valence-band edge. Concerning the importance of band discontinuities³ in optimizing device performance, interesting parallels are observed in inorganic and organic semiconductor devices.

Finally, micromachining is of increasing importance in current and emerging optoelectronic systems⁴ and will likely bring further interesting and new materials aspects into photonics. Also, photonic crystals are a welcome addition to photonic device applications, since they bring the promise of tremendous gains in functionality. Thus, we are convinced that photonics will have an opalescent future and most probably will become one of the technological highlights of the 21st century.

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with AlGaInP-based visible materials and nanostructures following in the mid-1990s. Since 1994, his work on III-nitrides has been at the center of his interest. Hangleiter received his diploma degree in physics in 1982 and his PhD degree in physics in 1985, both from the University of Stuttgart, Germany. From 1986 to 1987, he was a visiting researcher at IBM Research in Yorktown Heights, N.Y., returning to the University of Stuttgart as an assistant professor. From 1994 to 1998, he was a Heisenberg fellow of the Deutsche Forschungsgemeinschaft.

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