Preface

The advances in micro and nanotechnologies nowadays are nothing less than spectacular. Materials, structures, devices, and systems never seen before are appearing at an accelerated pace, while new properties and novel phenomena are being discovered almost every day. The microelectromechanical system (MEMS) and microoptoelectromechanical (MOEMS) technologies have brought a multitude of devices with ultracompact dimensions and with vastly enhanced or even completely novel properties and characteristics. Nanotechnologies are continuously expanding and improving the toolbox of available materials and systems, smudging the limits between technological and natural, even biological, and the potentials for further expansion appear literally limitless. The quest toward ever smaller dimensions and ever-increasing control over structures and properties is continuing and is already having a profound influence on practically all fields of applied science, steadily permeating more and more facets of ordinary life.

What is valid generally, is also valid in optoelectronics and photonics, actually maybe even more so than in some other fields. Completely novel areas are being created, ensuring manipulation with light at an unprecedented level. Micro and nanofabrication of structures with a periodicity of refractive index that may extend to all three dimensions have resulted in photonic bandgap materials, also known as photonic crystals, ensuring manipulation with photons in a manner similar to that with electrons in semiconductors. Subwavelength structuring of metal-dielectric materials brought metamaterials, structures possessing electromagnetic properties not readily met in nature and often unexpected and sometimes even counterintuitive. These include materials with values of refractive index below zero or equal to zero. It also created the field of plasmonics, dedicated to manipulation with evanescent, surface-bound electromagnetic waves that build a link between electronics and optics, ensuring devices with compact dimensions of micro and nanoelectronic circuits that operate at the speed of optical signals. Structures and devices are being created which until recently were deemed impossible.

The advent of micro and nanophotonics has brought astounding enhancements to different passive and active devices. In the field of infrared technologies, MEMS and NEMS, it ensured the appearance of a new generation of thermal detectors,

with properties vastly surpassing traditional devices. Novel nanodevices are being produced where quantum structures are used to reach new levels of performance.

However, there is a glaring gap in the list of infrared devices enhanced by the micro and nanophotonic technologies. For decades, simple intrinsic photonic (semiconductor) detectors have been far superior to other devices for infrared detection. Even today they remain the optimum choice if one simultaneously requires sensitivity, selectivity, and speed at an acceptable cost. Yet relatively little has been done to improve their performance using the same technologies that brought the renaissance to so many other fields. There is no obvious reason why micro and nanophotonics should not bring about similar improvements to photonic devices that were superior to begin with. The results actually do exist, but are scattered throughout the literature and are sometimes quite underwhelming. The author is not aware of a systematic treatise dedicated to the application of novel approaches stemming from microphotonic and nanophotonic technologies to traditional semiconductor infrared detectors. The goal of this book is to fill this gap.

Nowadays, two large classes of optoelectronic devices are used for detection of mid- (MWIR) and long-wavelength (LWIR) infrared radiation in the atmospheric windows (3–5) and (8–14) μm: photonic (quantum) detector and thermal detectors. Photonic detectors have been ruling the market for several decades, mostly of intrinsic type, based on indium antimonide and mercury cadmium telluride. Besides having high values of specific detectivity and generally high performance, they are characterized by high response speeds. Even today they largely outperform the novel generation of thermal infrared detectors.

The largest drawback of photonic detectors of infrared radiation compared to thermal devices is their requirement for cooling. For this purpose one typically uses Dewar flasks with liquid nitrogen or various kinds of active coolers, including Joule–Thompson cryostats or multistage thermoelectric coolers. Such cooling systems obviously make the detector units overly complex, impractical for handling, and vastly increase their price.

It is no wonder that through the decades a large part of the research and development connected with semiconductor detector elements for mid- and long-wavelength infrared radiation was dedicated exactly to the question of how to fabricate devices with high specific detectivities and high speeds at elevated temperatures (the "HOT"—Higher Operating Temperature detectors). The seemingly simple task of fabricating uncooled infrared detectors with background-limited operation engaged armies of researchers and for some of them became the holy grail of photonic detector design.

This book is dedicated to the same task, observed however through the prism of modern microphotonic and nanophotonic technologies. We offer a systematic approach to different available methods for increase in the operating temperatures of photonic detectors up to room temperature, while simultaneously retaining the performance of cryogenically cooled devices. The avoidance of cooling requirements would reduce the detector price to a fraction of the previous one, but the main gain should be expended in improved performance, higher robustness and ease of use, and much more widespread utilization.

It is necessary to mention that this text is dedicated solely to intrinsic photonic infrared detectors. This means that we do not consider more complex structures of detector materials themselves, which include different nanocomposites like quantum wells, quantum wires, and quantum dots. The topic of this work is micro and nanophotonic technologies, and not advanced detector materials, although they also represent a huge field for potential improvements. However, practically all of the methods and techniques described here are also applicable to devices based on advanced detector materials.

An important motivation for this kind of book is obviously the wide and ever expanding applicability of infrared detectors, especially those for the long-wavelength range. Naturally, in today's society all kinds of sensors are in increasing demand, but infrared devices assume a special position.

The situation was quite different in the past. The majority of the MWIR and LWIR detectors were used for military applications, for implementations like night vision, heat seeking and guidance, etc. Materials used for these detectors were also specific and were mostly limited to narrow-bandgap semiconductors. These detectors were also used for lab work and generally scientific applications in physics, meteorology, geology, material science, astronomy, remote sensing, airspace research, etc. Mostly their users were highly demanding. This explains why cooled detectors became widespread—for such users the price was most often, albeit not always, second to performance.

Usually, a large field of use for MWIR and LWIR detectors is overlooked—the free-space optical (FSO) telecommunications. This is certainly unusual when one bears in mind that communications themselves are one of the pillars of civilization itself, actually one could maintain that communications were those that created civilization in the first place.

In the field of free-space communication a special position belongs to microwave and optical wavelength ranges. In highly urbanized environments the so-called last-mile solutions are becoming increasingly important—instead of having to build transmission lines into the already existing infrastructure, which often requires astronomical expenses, it is much easier to utilize various wireless approaches. Since the majority of the existing FSO systems belong to the near infrared range, the available bands are becoming quite cramped. The long-wavelength IR range is thus mentioned as an alternative. This range is less sensitive to atmospheric disturbances like fog, smoke, rain, etc.; LWIR wavelengths are much less likely to accidentally damage eyes since vastly higher radiation thresholds are tolerated in this range. Last but not least, the LWIR range is not yet covered by strict regulations: it is literally a new territory waiting to be conquered. Low-cost uncooled detectors with high performance would be a significant step toward a more widespread use of such systems.

The applicability of the most of the methods presented in this book does not end with infrared detectors and is in reality much wider. An obvious and important field of use of different micro and nanophotonic methods for detection improvement elaborated in this book are solar cells, especially thin-film photovoltaics. Solar

energy harvesting represents a wide area of its own, but many of the approaches presented here may be applied to it with little or no modifications.

This book is organized into three chapters. The first chapter is introductory and considers various demands that may be posed to a general infrared detector, as well as which real types of detectors satisfy these demands best. General figures of merit of infrared detectors are analyzed and stress is given to the product of specific detectivity and bandwidth, which is taken to be one of the key factors of detector quality. The work then proceeds to present various particular mechanisms that define the mentioned figures of merit, especially the prevailing generation-recombination processes and the related noise mechanisms. The goal of this chapter is to estimate the most convenient choice among different infrared detectors and to consider which of its figures of merit could be optimized and how.

The second chapter of the book analyzes the possibility to enhance the detector performance utilizing photon management or light management. These methods may be denoted as equilibrium ones, since they do not generate excess charge carrier concentrations for their function and are related solely to handling of light flux outside the detector and within it. The equilibrium methods include various light trapping schemes both in the far field and in the near field with a goal to enhance the detector response. Since there are numerous approaches to this kind of enhancement, after a short literature review a possible classification of these approaches is proposed. Besides including all photon management methods known to the author, the use of the classification points out to some possible novel approaches, as well as to the use of certain methods that until now were utilized only in other fields of optical engineering.

Photon management methods are divided into two large groups. One group comprises structures that increase the incident optical flux. Among these, the text first considers optical concentrators, which include refractive and diffractive lenses, either separate or integrated with the detector, as well as some reflective nonimaging concentrators. The next subgroup is structures for decrease in reflection at the incident plane, which include interference antireflection films and diffractive subwavelength antireflection structures. An interesting new field in this domain is the use of plasmonics which brings optical concentration to the micro and nano levels—the enhancement occurs in the near field and utilizes evanescent waves.

The second equilibrium group encompasses structures for increase in the optical path of the beam which already entered the active area of the detector, the so-called light trapping structures. These structures simultaneously increase radiative lifetime through the mechanism of reabsorption—photon recycling. They include different surface relief structures for the increase in total internal reflection, from diffractive to macroscopic ones. Reflective detector surfaces also belong to this group, both the back-side ones and full resonant cavities (RCE—resonant cavity enhancement) with reflective surfaces both of the front and the back side of the detector. The most advanced structures for optical path and radiative time increase are radiative shields and photonic crystal enhancement structures, which represent a full cavity enhancement and may support the existence of multiple modes.

The third chapter of the book considers nonequilibrium methods for thermal noise management, which include manipulation with charge carrier concentration within the detectors utilizing external fields and which are implemented through the application of general micro and nanosystem techniques. These are very important, since they attack the very reason why photonic detectors are cooled. Since the operating wavelengths are long, i.e., the energies of incident photons are low, the bandgap of the utilized material must also be small. This means that thermal processes of carrier generation will start to compete with the detection process itself and thus cause excessive increase of generation-recombination noise. This is especially valid for noise caused by Auger processes that prevail in sufficiently pure semiconductors. The goal of nonequilibrium methods is to cause controlled perturbation of carrier distribution within the detector and thus locally decrease the carrier concentration below its equilibrium value, thereby directly decreasing the level of total generation-recombination noise. A systematic approach to these methods and a newly proposed classification stemming from it again show that in addition to the methods published in the literature one could utilize some new ones.

Special care is dedicated to the consideration of properties common to all types of nonequilibrium devices. Based on this a general model is defined to be utilized in simulation of any nonequilibrium detector, including the novel ones. The model is derived for isothermal processes, but can be extended to nonisothermal ones. When deriving the model, special care is dedicated to the limits of the model and the generality of the introduced approximations.

The third chapter considers the use of contact phenomena, i.e., structures utilizing a combination of a built-in dopant concentration gradient and the external electric field for suppression of Auger processes. Two main types are considered, exclusion-based photoconductors and extraction-based photodiodes. The text further considers the use of crossed electric and magnetic field and analyzes the use of galvanomagnetic phenomena, i.e., the magnetoconcentration effect for suppression of Auger processes. Finally, conclusions are drawn and assessment of possible future directions is given.



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