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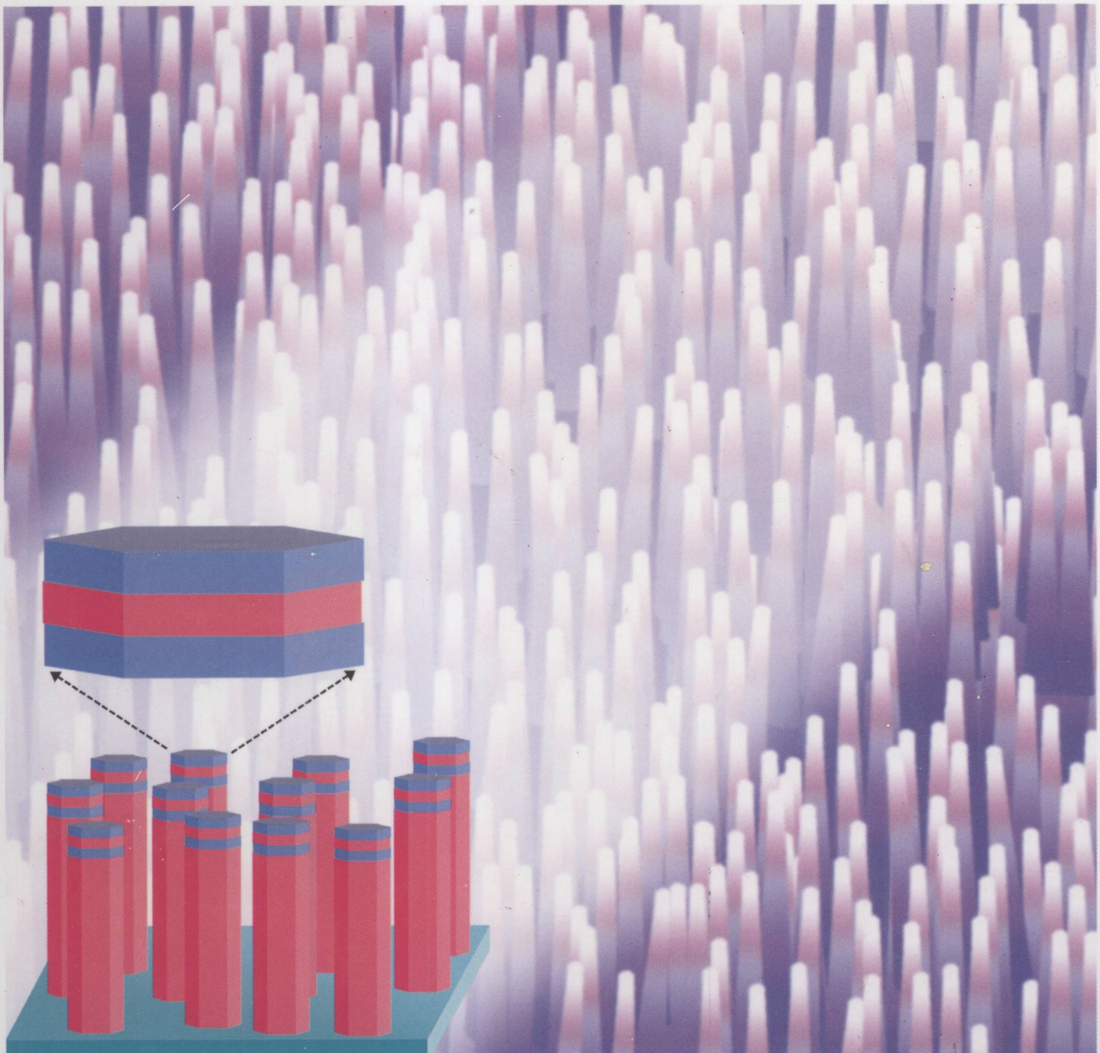
Nanophotonics and Nanofabrication



Nanophotonics and Nanofabrication

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Preface

This book outlines the principles and practices of nanofabrication based on the novel optical technology of *nanophotonics*, which utilizes the optical near-field, i.e. the nanometer-sized light that is localized on the surface of a nanometric material. In the early 1980s, the editor of this book (M. Ohtsu) started his pioneering research on optical near-fields because he judged that optical near-fields would be required to change the paradigm underlying optical science and technology. In the 1990s, conventional optical technology progressed very rapidly and the photonics industry developed, but further progress became difficult due to a fundamental limit of light known as the diffraction limit. However, there was a growing awareness among scientists and engineers that this limit could be overcome using optical near-fields. The key to utilizing optical near-fields is to realize novel nanometric fabrication and device operation by the control of an intrinsic interaction between nanometer-sized materials via optical near-fields. This has not been realized using conventional optical science and technology. This novel field of science and technology is nanophotonics.

One decade after the editor commenced his pioneering research into optical near-fields, a reliable technology was established for fabricating high-quality fiber probes. This led to the development of near-field optical microscopy and spectroscopy, with high resolution, beyond the diffraction limit of conventional optical microscopy. After establishing the fiber-probe technology, the nature of optical near-fields was studied by regarding the optical near-field as an electromagnetic field that mediates the interaction between nanometric materials. As a result, the physically intuitive concept of a *dressed photon* was established to describe optical near-fields, i.e. the interaction between nanometric materials is mediated by exchanging dressed photons.

After starting to develop a novel theory to describe this interaction, it was found that optical near-fields, i.e. dressed photons, could be used to realize novel photonic devices, fabrication techniques, and systems. Therefore, in 1993, the idea of nanophotonics was proposed. This is a novel technology that utilizes the optical near-field to realize novel devices, fabrications, and systems. Following elaboration of the idea

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of nanophotonics, much theoretical and experimental work has been carried out, and several novel functions and phenomena have been discovered in device operation and fabrication techniques. The objective of this book is to review the innovations of nanofabrication using nanophotonics.

In conventional optical science and technology, light and matter are discussed separately, and the flow of optical energy in a photonic system is considered unidirectional, from a light source to a photodetector. By contrast, in nanophotonics, light and matter have to be regarded as being coupled to each other and the energy flow between nanometric particles is bidirectional. This means that nanophotonics should be regarded as a *technology fusing optical fields and matter*. The term nanophotonics is occasionally used for photonic crystals, plasmonics, metamaterials, silicon photonics, and quantum-dot lasers using conventional propagating light, although they are not based on optical near-field interactions. The development of nanophotonics requires far-reaching physical insights into the local electromagnetic interaction in the nanometric subsystem composed of electrons and photons.

Chapter 1 of this book reviews the history, background, and present status of research and development in nanophotonics, including its application to nanofabrication; it also comments on future perspectives. Chapter 2 presents the principles of nanofabrication based on dressed-photon models, describes adiabatic and nonadiabatic processes in nanofabrication, and demonstrates their application to chemical vapor deposition and lithography.

Chapters 3–12 review practices of nanofabrication: Chapter 3 deals with nanofabrication using self-organization and related technology in order to control the size and position of the fabricated nanometric materials. Chapter 4 describes a method of fabricating semiconductor quantum dots, which is an important fundamental technology for realizing nanophotonic devices. Chapter 5 describes the optical properties of a ZnO nanorod heterostructure, which is also a key material for nanophotonic device applications. Chapter 6 discusses lithography based on nanophotonics, which was developed by industry. The details of a lithography system are reviewed and various fabricated patterns are presented. Chapter 7 deals with the fabrication of FePt nanopatterned media for high-density magnetic storage. It also reviews the technology of block-copolymer lithography to be used for this fabrication. Chapter 8 reviews a nanophotonics recording device for a high-density storage system that increases the storage data density to 1 Tbit/inch^2. Chapter 9 reviews the performances of X-ray devices that were fabricated using nanophotonic lithography; their high-quality performance is demonstrated and, thus, the potential of nanophotonic lithography as a novel nanofabrication tool may be recognized. Chapter 10 is devoted to describing periodic nanostructure formation on hard thin films using femtosecond laser ablation. Chapter 11 reviews a novel nanophotonic waveguide composed of quantum dots with low-loss optical energy transmission and low crosstalk. It describes the principle of operation, modeling, fabrication process, and performance of the waveguide. The final chapter concerns the intrinsic characteristics of hierarchy in optical near-fields and its application to nanofabrication, such as generating smaller-scale structures from larger-scale ones via optical near-field interactions. Each chapter is written by leading scientists in the relevant field. Consequently, I hope that high-quality scientific and technical information is provided to scientists, engineers, and students who are, and will be engaged in, nanofabrication and its applications.

Tokyo, September 2008 *Motoichi Ohtsu*

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Contents

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1
Introduction

Motoichi Ohtsu

1.1
History

Nanophotonics is a novel technology that utilizes the optical near-field, which is the electromagnetic field that mediates the interaction between nanometric particles located in close proximity to each other. The true nature of nanophotonics is to realize 'qualitative innovation' in photonic devices, fabrication techniques, and systems by utilizing novel functions and phenomena caused by optical near-field interactions, which are impossible as long as conventional propagating light is used. The author first proposed nanophotonics in 1993 as a way to transcend the diffraction limit, which impedes reducing the size of photonic devices, to improve the resolution of optical fabrication techniques, and increasing the storage density of optical disk memories [1]. Based on his proposal, the Optical Industry Technology Development Association (OITDA) of Japan organized the nanophotonics technical group, and intensive discussions on the future direction of nanophotonics started in April 1994, in collaboration with academia and industry. Although photonic crystals, plasmonics, metamaterials, silicon photonics, and quantum dot lasers have been popular subjects of study in recent years, they are all based on diffraction-limited wave optics. Even if novel or nanometer-sized materials are used for these subjects, the size of a photonic device cannot be reduced beyond the diffraction limit as long as propagating light is used for its operation.

This chapter describes the history and present activities of nanophotonics. Before nanophotonics was founded, the study of optical near-fields started in Japan in the early 1980s, separate from European and American research [2]. Few attended when the author was invited to the first international workshop on near-field optics in 1992 [3], but the numbers have increased very rapidly in subsequent conferences, and near-field optics has become very popular worldwide.

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