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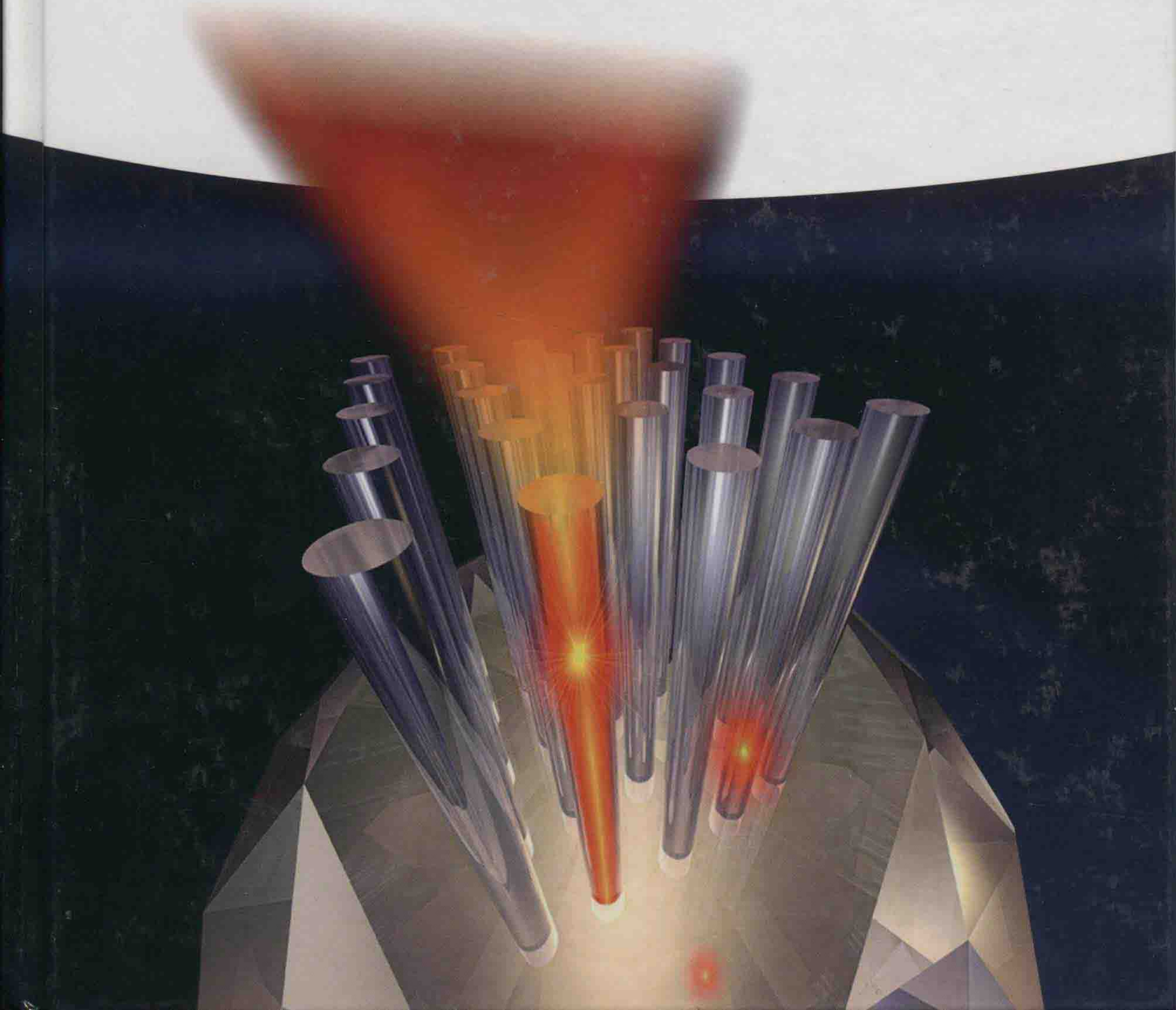
Optical Engineering of Diamond



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Optical Engineering of Diamond

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Cover Picture
Concept image of diamond photonic nanowire arrays with embedded nitrogen-vacancy color centers. By applying large-scale semiconductor manufacturing techniques to single-crystal diamond, we may utilize its unique and exceptional material properties in diverse areas of quantum science, optics and photonics, and nanotechnology. The work was performed by researchers at the Harvard University and Texas A&M. Created by Jay Penni, used with permission of Marko Loncar and Thomas Babinec.

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Foreword

Practically every publication on research involving diamond materials begins by touting the extreme and unique physical and chemical properties of diamond. It is for this reason that research and applications involving diamond materials has expanded tremendously during the past 25 years. This expansion has been driven by improvements in the synthesis of diamond materials, achieving purity, quality, uniformity, and morphologies that are unattainable in geologically mined diamonds, and thus enabling many new technological applications.

Today, engineered diamond materials are available in many forms, ranging from single-crystal gems and plates, through a range of polycrystalline plates and shapes with varying grain sizes and morphologies, to films and coatings with nano- to micro-crystalline grain sizes, and nanocrystalline powders. This diversity in diamond materials has attracted research and applications in many fields, including optics and lasers, quantum computing and communication, biology, high-energy and high-pressure physics, thermal management, tribology, electrochemistry, electronics, micro-electromechanical systems (MEMS), chemical sensing, and corrosion resistance.

The primary driver behind this blossoming of diamond materials is the rapid improvements and expansion in diamond synthesis achieved via by chemical vapor deposition (CVD). Improvements in diamond synthesis by high-pressure, high-temperature (HPHT) processes, and of nanopowders by detonation processes, have also contributed to the diverse research and applications of diamond.

Our expanding knowledge base on diamond materials, and their properties and processing, requires that we expand upon the existing array of books and reviews in the field. Given the intense interest in the applications of the many forms of diamond to optics and optical applications, this new book – *Optical Engineering of Diamond* – is a welcome and valuable addition to the field. The book will immediately assist many of the exciting and important developments employing diamond materials and their optical properties that are about to happen. Examples of the fields which will be impacted are quantum devices, lasers, infrared sensing, radiation detection, synchrotron and accelerator technologies, fusion research, biological research and drug delivery, jewelry and gems, and high-power and high-voltage electronics.

This book contains 13 chapters written by the leading experts in their subfields. The chapters compile and review a knowledge base that is not available anywhere else, and provide guidance for the processing, forming, shaping, and building of devices and structures from diamond materials. As such, *Optical Engineering of Diamond* will become a valuable reference work for researchers and technologists working with diamond materials.

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Preface

If one were to carry out a survey on the most important materials in optics that come to mind, the responses might include silica, yttrium aluminum garnet, and gallium arsenide. Over and above core optical properties such as transparency and luminescence, other important considerations come into play including durability, ease of manufacture, and thermal conductivity. But what if a material existed that displayed *all* of these properties on a vastly superior scale? A material of exceptional hardness, thermal conductivity, and transparency, that was also cheap, and easy to fabricate and modify? It is well known that diamond exhibits some of these properties and is indeed often touted as a being a "super material"; however, it also has a reputation for being expensive and difficult to synthesize, and still maintains the perception of being reserved for the wealthy. Nevertheless, the synthesis of diamond has advanced enormously in recent years, with diamonds of sizes spanning from several nanometers to multiple centimeters now routinely produced with qualities that often exceed that of natural diamond. This capability has come after innumerable failed attempts to make diamond, and we can now consider ourselves privileged to witness and participate in this "golden" age of diamond optics and photonics.

Today, considerable research efforts are underway in diverse areas such as diamond optics, photonics, lasers, quantum computing, and biomedicine. In quantum technologies for example, it is the room-temperature rigidity of the crystal lattice that is being harnessed to study quantum effects in an ideal isolated environment. The possibilities are multiplied with ground-breaking parallel developments in nanoscale imaging and manipulation, enabling the use of ultra-small diamonds in unique bioimaging technologies. Science magazines, general media, and blogs continuously report new developments, and some have already led to commercially available products. Just as the unique aesthetic properties of diamond have fascinated over millennia, so the fascination continues with renewed intensity for properties which have always resided just below the surface.

By capturing the state of the art in diamond optical engineering, this book aims to provide a resource in a convenient and accessible form to support further research and development. Written by 39 experts from 12 leading research groups, the book includes chapters on detailed optical properties, fabrication, and engineering techniques of diamond, and reviews several of its topical optical applications. By way of introduction, Chapter 1 provides an in-depth review of the linear and nonlinear optical properties intrinsic to diamond. Six subsequent chapters deal with growth and shaping methods, and with engineering the content of diamond. In Chapter 2, *I. Friel* reviews diamond growth by chemical vapor deposition, and includes descriptions of the growth principles and of properties and applications of high-optical-quality material. In Chapter 3, *J.R. Hird* describes the fascinating history of diamond polishing, and reviews in detail modern polishing techniques and the associated wear mechanisms and surface properties. This chapter also includes a description of techniques used to achieve surface roughnesses approaching atomic dimensions. In Chapter 4, written by *F. Nikolajeff* and *M. Karlsson*, techniques used to create refractive elements such as domes, diffractive optics, and lens arrays are reviewed. Recipes for plasma based-techniques for producing micro-structures are a valuable feature of this chapter. In Chapter 5, *C. Bradac, T. Gaebel,* and *J.R. Rabeau*, review the properties, synthesis, and applications of nitrogen-vacancy color centers in diamond, a vitally important topic that underpins a large focus of present-day diamond optical research. The possibility of creating diamond light-emitting diodes and laser diodes was one of the early drivers for diamond synthesis, and progress in this challenging task is reviewed in Chapter 6 by *S. Koizumi* and *T. Makino*, who also discuss in detail the electro-optical properties of n-doped diamond. Surface optics is a topic of growing importance; hence, in Chapter 7, *V. Petrakova, M. Ledvina,* and *M. Nesladek* report experimental and modeling results on the effects of the surface proximity and the lattice termination on the properties of color centers. The applications for this phenomenon in areas such as biosensing are also discussed in this chapter.

The chapters in the final section of the book provide a comprehensive review of the major and topical optical applications. In Chapter 8, *R.P. Mildren, A. Sabella, O. Kitzler, D.J. Spence,* and *A.M. McKay* review the recent progress of diamond Raman lasers, and discuss the highly promising outlook for creating high-power devices of broad wavelength reach. In Chapter 9, *P. Neumann* and *J. Wrachtrup* provide a detailed description of the optical and spin properties of the nitrogen vacancy center and discuss the important application area in quantum information processing. Subsequently, in Chapter 10, *S. Tomljenovic-Hanic, T.J. Karle, A.D. Greentree, B.C. Gibson, B.A. Fairchild, A. Stacey,* and *S. Prawer* describe applications for fluorescent diamond in quantum key distribution and metrology, and comprehensively review the methods used to create the enabling photonic structures such as waveguides and optical cavities. The use of diamond as heat-spreaders in optical systems such as high-average-power lasers and light-emitting diodes is reviewed in Chapter 11 by *A.J. Kemp, J.-M. Hopkins, J.E. Hastie, S. Calvez, Y. Zhang, E. Gu, M.D. Dawson,* and *D. Burns.* This chapter includes model results that highlight design considerations and optical applications in which diamond provides striking advantages. Direct write laser fabrication is a highly practical method for manipulating the surface and bulk of diamond, and in Chapter 12, *V.I. Konov, T.V. Kononenko,* and *V.V. Kononenko* report extensively on the principles of laser processing; these authors also discuss in detail a large range of applications such as laser polishing, the fabrication of diffractive optics, and direct-write of conductive structures in the bulk. Finally, in Chapter 13, *N. Mohan* and *H.-C. Chang* review the applications of fluorescent nanodiamond in biomedicine. This chapter describes the properties of nanoprobes, the challenges involved in their mass production, and the numerous ways that they are being used *in vivo* and *in vitro* for particle tracking and bioimaging.

This book constitutes important milestones in the fields of optical device engineering and diamond science. We are very grateful to the contributing authors, who all responded enthusiastically to our invitation and produced extremely valuable chapters. We also acknowledge the contributions of numerous colleagues who have shared our enthusiasm for this project, and the editorial staff at Wiley for their assistance, in particular Valerie Moliere and Anja Tschörtner. Many thanks to Andy Edmonds, Stefania Castelletto, and Torston Gaebel for their assistance in proofing manuscripts. We are grateful to Jim Butler for supporting the book concept from the outset, providing expert advice along the way, and for contributing the Foreword. The future of diamond optics is bright, and we look forward to the exciting developments ahead.

Sydney, August 2012 *Richard P. Mildren and James R. Rabeau*

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