MICRO/NANO REPLICATION
MICRO/NANO REPLICATION
PROCESSES AND APPLICATIONS

Shinill Kang
To My Family
## CONTENTS

**Preface**  

1. **Introduction**  
   1.1 Introduction  
   1.2 Micro/Nano Replication  
   1.3 Application Fields of Micro/Nano Replicated Parts  
      1.3.1 Optical Data Storage Devices  
      1.3.2 Display Fields  
      1.3.3 Other Industries  
   1.4 Required Technologies for Micro/Nano Replication  

2. **Patterning Technology for Micro/Nanomold Fabrication**  
   2.1 Material Removal Process  
      2.1.1 Mechanical Machining  
      2.1.2 Laser Ablation  
      2.1.3 Silicon Etching Process  
      2.1.4 Focused Ion Beam Patterning  
   2.2 Lithography Process  
      2.2.1 Electron Beam Lithography  
      2.2.2 Photolithography  
      2.2.3 Reflow Method  
         2.2.3.1 Fabrication of a Mother Lens  
         2.2.3.2 Empirical Equation for the Volume Change Ratio of a Reflow Lens  
         2.2.3.3 Verification of the Model  
      2.2.4 Laser Interference Lithography  
         2.2.4.1 Theory of Laser Interference Lithography  
         2.2.4.2 Simulation of Laser Interference Lithography  
         2.2.4.3 Experimental Setup  

References 19
2.2.4.4 Fabrication of Nanostructures Using Laser Interference Lithography under Different Process Conditions 47

2.3 Electroforming Processes 50
  2.3.1 Theory of Electroforming Process 51
  2.3.2 Electroforming Results 51
    2.3.2.1 Metallic Mold for a Microlens Array 51
    2.3.2.2 Metallic Mold for Patterned Media 51

References 54

3. Modification of Mold Surface Properties 59
  3.1 Introduction 59
  3.2 Thiol-Based Self-Assembled Monolayer 61
    3.2.1 Thiol-Based Self-Assembled Monolayer and Deposition Process 61
    3.2.2 Experiment Results and Analysis 63
    3.2.3 The Changing Properties of SAM at Actual Replication Environment 64
    3.2.4 Analysis of Replicated Polymeric Patterns 70
  3.3 Silane-Based Self-Assembled Monolayer 73
    3.3.1 Silane-Based Self-Assembled Monolayer Deposition Process of Silane-Based Self-Assembled Monolayer 74
    3.3.3 Self-Assembled Monolayer on Polymer Mold 74
    3.3.4 Analysis of Replicated Polymeric Patterns 76
  3.4 Dimethyldichlorosilane Self-Assembled Monolayer 76

References 80

4. Micro/Nanoinjection Molding with an Intelligent Mold System 82
  4.1 Introduction 82
  4.2 Effects of the Mold Surface Temperature on Micro/Nanoinjection Molding 85
  4.3 Theoretical Analysis of Passive/Active Heating Methods for Controlling the Mold Surface Temperature 88
    4.3.1 Mathematical Modeling and Simulation 90
    4.3.2 Passive Heating 94
    4.3.3 Active Heating 98
4.4 Fabrication and Control of an Active Heating System Using an MEMS Heater and an RTD Sensor 102
4.4.1 Construction of an Intelligent Mold System 103
4.4.2 Control System for the Intelligent Mold System 108
4.4.2.1 Kalman Filter Observer of the Thermal Plant 111
4.4.2.2 LQGI Controller 113
4.4.2.3 Performance of the Constructed Control System 115
4.5 Replication of a High-Density Optical Disc Substrate Using the Intelligent Mold System 119
References 120

5. Hot Embossing of Microstructured Surfaces and Thermal Nanoimprinting 123
5.1 Introduction 123
5.2 Development of Microcompression Molding Process 125
5.3 Temperature Dependence of Anti-Adhesion Between a Mold and the Polymer in Thermal Imprinting Processes 127
5.3.1 Defects in Replicated Micro-Optical Elements 128
5.3.2 Analysis of Polymer in Process Condition of Thermal Imprinting 128
5.3.3 Analysis of Replication Quality Fabricated in Different Peak Temperature 133
5.4 Fabrication of a Micro-Optics Using Microcompression Molding with a Silicon Mold Insert 138
5.4.1 Fabrication of Microlens Components Using Si Mold Insert 138
5.4.2 Analysis of Refractive Microlens 139
5.5 Fabrication of a Microlens Array Using Microcompression Molding with an Electroforming Mold Insert 140
5.5.1 Fabrication of Microlens Components Using Ni Mold Insert 140
5.5.2 Analysis of Replication Quality 143
5.6 Application of Microcompression Molding Process 147
5.6.1 Fabrication of a Microlens Array Using Microcompression Molding 147
5.6.2 Fabrication of Metallic Nanomold and Replication of Nanopatterned Substrate for Patterned Media

References

6. UV-Imprinting Process and Imprinted Micro/Nanostructures

6.1 Introduction
6.2 Photopolymerization
6.3 Design and Construction of UV-Imprinting System
6.4 UV-Transparent Mold
6.5 Effects of Processing Conditions on Replication Qualities
6.6 Controlling of Residual Layer Thickness Using Drop and Pressing Method
6.7 Elimination of Microair Bubbles
6.8 Applications
   6.8.1 Wafer Scale UV Imprinting
   6.8.2 Diffractive Optical Element
   6.8.3 Roll-to-Roll Imprint Lithography Process
6.9 Conclusion

References

7. High-Temperature Micro/Nano Replication Process

7.1 Fabrication of Metal Conductive Tracks Using Direct Imprinting of Metal Nanopowder
   7.1.1 Introduction
   7.1.2 Direct Patterning Method Using Imprinting and Sintering
   7.1.3 Imprinting and Sintering System
   7.1.4 Defect Analysis and Process Design
   7.1.5 Analysis of Imprinted Conductive Tracks
   7.1.6 Conclusions
7.2 Glass Molding of Microlens Array
   7.2.1 Introduction
   7.2.2 Fabrication of Master Patterns
   7.2.3 Fabrication of Tungsten Carbide Core for Microglass Molding
      7.2.3.1 Fabrication Process of Tungsten Carbide Core

References
7.2.3.2 Measurement of Shrinkage After Sintering Process 218
7.2.4 Surface Finishing and Coating Process of Tungsten Carbide Core 219
7.2.5 Comparison of Surface Roughness Before and After Finishing Process 221
7.2.6 Fabrication of Glass Microlens Array by Microthermal Forming Process 225
7.2.7 Measurement and Analysis of Optical Properties of Formed Glass Microlens Array 229

References 230

8. Micro/Nano-Optics for Light-Emitting Diodes 233

8.1 Designing an Initial Lens Shape 234
8.1.1 LED Illumination Design 234
8.1.2 Source Modeling 236
8.1.3 Modeling a Spherical Refractive Lens 236
8.1.4 Modeling a Micro-Fresnel Lens 238
8.1.5 Verifying the Micro-Fresnel Lens Performance 240

8.2 Fabrication Results and Discussion 245
8.2.1 Fabrication of the Micro-Fresnel Lens 245
8.2.2 Elimination of Air Bubbles 246
8.2.3 Optimization of the UV-Imprinting Process 247
8.2.4 Evaluation of the Micro-Fresnel Lens for LED Illumination 249

8.3 Conclusions 253
References 254

9. Micro-/Nano-Optics for Optical Communications 256

9.1 Fiber Coupling Theory 258
9.2 Separated Microlens Array 259
9.2.1 Design 259
9.2.2 Fabrication 260
9.2.3 Measurement Results 263
9.3 Integrated Microlens Array 266
9.3.1 Design 266
9.3.2 Fabrication 268
9.3.3 Measurement Results 269

9.4 Conclusions 273
References 274
# Patterned Media

10.1 Introduction 276
10.2 Fabrication of a Metallic Nano Mold Using a UV-Imprinted Polymeric Master 278
10.3 Fabrication of Patterned Media Using the Nano Replication Process 290
10.4 Fabrication of Patterned Media Using Injection Molding 296
10.5 Measurement and Analysis of Magnetic Domains of Patterned Media by Magnetic Force Microscopy 302
10.6 Conclusions 307
References 307

# Optical Disk Drive (ODD)

11.1 Introduction 310
11.2 Improvements in the Optical and Geometrical Properties of HD-DVD Substrates 313
11.3 Effects of the Insulation Layer on the Optical and Geometrical Properties of the DVD Mold 318
11.4 Optimized Design of the Replication Process for Optical Disk Substrates 329
11.5 Conclusions 337
References 339

# Biomedical Applications

12.1 Introduction 341
12.2 GMR-Based Protein Sensors 342
12.2.1 Principle of GMR Protein Sensors 342
12.2.2 Principle of Guided-Mode Resonance Effect 343
12.2.3 Nano Replication Process of a GMR Protein Chip for Mass Production 346
12.2.4 Feasibility Test of GMR Protein Chip 359
12.3 Conclusions 362
References 362

Index 365
The increasing demands for micro/nanostructures or components in the field of digital display, digital imaging, data storage, optical communication, nanoenergy, and biomedicine would merit a priority in establishing the fabrication technologies for micro/nanostructures or components.

Among the various fabrication technologies for micro/nanostructures or components, the replication or molding process is regarded as one of the most suitable candidates for mass production, which may offer high quality at reasonably low cost. For this reason, researchers in both academic community and industrial sectors are beginning to actively engage themselves in pursuit of research and development in the respective field of interest.

The field of micro/nano replication or molding has recently come into existence, and thus an introductory textbook in micro/nano replication is sorely needed. A useful and desirable textbook should provide a basic (i.e., readily accessible to newcomers) interdisciplinary overview of the replicated micro/nanostructures or components, to wit: how they are designed, how the molds and stamps are designed and fabricated, how they are replicated, how the properties are predetermine d and evaluated, and what are the potential uses.

The fundamental problem for both students and researchers new to the field of micro/nano replication seems to be that micro/nanopatterning and replication are rarely introduced in undergraduate-level textbooks, consequently forcing students to turn to advanced review papers, edited collections of review papers, or more advanced and specialized textbooks to begin with a learning process. Unfortunately, this body of literature is relatively impene-trable for most of the undergraduates, new graduate students, and new researchers working in the field of micro/nano replication and molding. An introductory, comprehensive and self-contained textbook would be a welcome addition for students and researchers alike interested in their respective learning field.

This book will serve as an introductory textbook on the fundamentals of micro/nano replication or molding for micro/nanocomponents. It is based on lecture notes from an introductory micro/nanofabrication course I have been teaching at the graduate school of Yonsei University in Korea over the past
years. My goal is to see the textbook widely adopted and used internationally as a primary source for an introductory senior-level undergraduate or beginning graduate course covering micro/nano replication. The reader will be able to obtain a wider scope of knowledge about micro/nanomold making processes and micro/nano replication processes and the strength and weakness of each process from the book. The extensive knowledge on the micro/nanopatterning and replication processes will allow him/her to control the project on the development of micro/nanocomponents by micro/nano replication process.

However, this book is not limited to the audience in academia only, but will also be useful for the researchers and engineers in research institutes or industries. Especially in the area of micro/nano replication technology, new applications are introduced almost every day. Researchers and engineers in research institutes or industries can acquire basic and fundamental knowledge of micro/nano replication and molding.

I would like to acknowledge the financial support from the Korea National Research Foundation through the Center for Information Storage Device (CISD, an ERC directed by professor Young-Pil Park), the Center for Nanoscale Mechatronics and Manufacturing (CNMM, a 21C Frontier Program directed by Dr. Sang-Rok Lee), Nanoreplication and Micro-optics National Research Laboratory (an NRL Program), and Senior Researcher Supporting Program. Most of the research results of this book could not have been obtained without the financial and technical supports mainly from the Korea National Research Foundation for the past 10 years.

I owe a great debt of gratitude to Professor Emeritus K. K. Wang at Connell University, who was instrumental in shaping my research goal in the field of "replication."

I would like to express my warmest thanks to the professors of College of Engineering at Yonsei University for their friendship and encouragement throughout the journey of writing this book. I would also gratefully acknowledge the dedicated supports from the colleagues of CISD, CNMM, Nano Manufacturing Research Center (under the direction of professor Sang Jo Lee), The Korean Society for Technology of Plasticity (KSTP), the Korean Society for Precision Engineering (KSPE), The Korean Society of Manufacturing Technology Engineering (KSMTE) and the Korea–Japan Joint Polymer Processing Committee of KSTP and The Japan Society for Technology of Plasticity (JSTP).

Special thanks go to the former and present graduate students of the Nanoreplication and Micro-optics National Research Laboratory at Yonsei University for their invaluable assistance in preparing this book.

And last but not the least, I am very grateful to the publisher’s staff, and especially Mr. Jonathan T. Rose, Editor, for their support, encouragement,
and willingness to offer generous assistance during the entire book publishing project. As I cannot guarantee that this book is free of unintended errors, any corrections and suggestions from the readers are highly appreciated.

Shinill Kang
CHAPTER 1

Introduction

1.1 INTRODUCTION

Nanotechnology is receiving more attention as an innovative technology that will lead the way to the future, along with information technology (IT) and biotechnology (BT) [1,2]. Nanotechnology permits the structure, shape, and other characteristics of a material to be controlled on a nanometer scale ($10^{-9}$: 1/1,000,000,000 m). Since the size of an atom or a molecule is generally on the order of 1/10 of a nanometer, nanotechnology actually provides control of the structure of a material at the atomic or molecular level (i.e., a minimal quantity of the material). While existing microtechnology is limited to product miniaturization [3–9], nanotechnology enables not only the miniaturization of components but also the creation of completely new devices based on innovative concepts since materials can be freely manipulated at the molecular level. Accordingly, nanotechnology is expected to usher in innovative changes in all industrial areas, including electronics [10–12], biology [13–15], chemistry [16,17], and energy-related fields [18,19]. Nanotechnology is regarded as being in the embryonic stage, intermediate between science and technology. However, considering the current speed of technological development and the widespread ripple effects across related industries, there is no question that a substantial market for nanotechnology will eventually be created. The National Science Foundation (NSF) of the United States predicts that the size of the nanotechnology market will exceed US$ 1 trillion in 10–15 years [20]. A market worth US$ 300 billion or more will be created in both the materials and the semiconductor industries, and active practical use of nanotechnology is expected in a variety of industries, including medicine, chemistry, energy, transportation, environmental science, and agriculture. For example, in the electronics industry, it is expected that new components will be developed, surpassing the limits of existing electronic devices with respect to miniaturization, speed, and power.
consumption. The Hitachi Research Institute in Japan anticipates that the development of nanotechnology will enable the commercialization of next-generation semiconductors, in which the processing rate will be increased by a factor of 100 while power consumption is reduced by a factor of 50, together with terabyte data storage technology, in which the storage capacity will be increased by a factor of 50. Present nanotechnology market predictions pertain only to the early nanotechnology market. It is difficult to predict how nanotechnology will evolve, and what ripple effects it will create. However, considering its innovative characteristics, it is clear that nanotechnology has a tremendous capacity to create sweeping changes in the present technology paradigm.

The potential of nanotechnology has been foreseen for a long time. In 1959, the prominent American physicist Richard Feynman predicted the possibility of manipulating materials at the atomic level [21]. He anticipated that new material properties, which could not be achieved at that time, would be realized if materials could be manipulated at the atomic and molecular levels. So why has nanotechnology (which is capable of creating such an enormous ripple effect) only so recently emerged into the spotlight? The answer is, experimental results to support the theories and the development of fundamental technologies, such as the fabrication, observation, and measurement of nanoscale features, were first necessary. Furthermore, inexpensive technologies for fabricating nanostructures, which are essential to the commercialization of nanotechnology, have only recently been developed, based on existing macro- and microfabrication technologies. Among the various types of nanostructure fabrication technologies, replication-based techniques are widely used in the mass production of nanostructures due to their high repeatability, high reliability, and low cost. A replication process that can be applied to nanostructures has recently been developed, and is expected to facilitate the practical use of nanotechnology products.

Replication processes are carried out by transferring the geometry of a mold that has the negative shape of the desired product [22]. The mold is filled with material, as shown in Figure 1.1. The process generally includes heating a thermoplastic material to increase its fluidity, filling the inner geometry of the mold with pressurized molten plastic, solidifying the plastic by cooling it, and removing the resulting structure from the mold. Among the diverse materials available, thermoplastics are commonly used to fabricate replicated parts in a variety of fields because of their advantageous thermal, mechanical, optical, and electrical characteristics. However, replication processes employing thermoplastics have limited applicability to micro/nanostructured products due to material- and process-related limitations such as high processing temperature and the pressure required to fill cavities with small feature sizes. Therefore, an alternative replication process for
micro/nanoscale structures has been developed using thermocurable polymers or ultraviolet (UV)-curable polymers, which exist in liquid phase at room temperature and present no difficulties in filling cavities with small feature sizes. Recently, replication processes using glass or metals have also been developed, in order to overcome the limitations of polymers.

Although conventional replication processes and equipment are well established for macroscale products, specialized techniques are required for fabricating components with small feature sizes (especially nanoscale structures), such as the construction of molds with nanoscale cavities and the elimination of defects in replicated parts attributable to the large surface-area-to-volume ratios of nanoscale structures. These issues have also arisen in the replication of microstructured patterns, and a variety of modifications to conventional replication processes and equipment have already been introduced to improve the quality of the resulting microstructures. Some of the ideas employed in microreplication can be extended to nano replication technologies. However, new concepts in mold fabrication and replication methodology are also being developed to realize a greater variety of micro/nanoscale products because the modification of conventional technologies is limited to specific types of products. Since each of the various techniques for fabricating micro/nanomolds and replicating micro/nanostructures has its own pros and cons, it is necessary to select a mold fabrication method and a replication process suitable for the characteristics of the desired products.

The purpose of this book is to present the techniques and principles governing specific types of micro/nano replication, as well as the characteristics of processes for fabricating micro/nanomolds, for the benefit of developers, researchers, and students interested in micro- and nanoscale products. The reader can obtain a fundamental knowledge of micro/nano replication, including the design of micro- and nanoscale components, the selection of an appropriate mold fabrication technique and replication process, the control of processing parameters, and technologies for evaluating the characteristics of micro- and nanoscale components, with application examples drawn from a variety of industries related to information storage devices.
optoelectronic elements, optical communication, biosensors, and the like. Throughout this book, practical technologies will be presented for developing micro/nanoproducts via a replication process.

1.2 MICRO/NANO REPLICATION

Micro- and nanoscale products can be defined as (1) having a weight of several milligrams or less, (2) having a micro/nanoscale pattern, or (3) requiring micro/nanoscale precision [23]. Among the various techniques of fabricating micro- and nanoscale products, micro/nano replication processes are in wide commercial use because they provide high productivity and reproducibility. These procedures replicate a micro/nanoscale product or pattern, using material with appropriate optical, thermal, and/or mechanical properties, and a mold with the negative geometry of the desired product. Thermoplastic polymers are widely employed as replication materials, but thermosetting polymers, glass, metallic inks, and the like can also be used, depending on the requirements of the final products. Micro/nano replication is one of the most promising methods for fabricating nonelectronic micro/nanodevices. However, these processes recently have also been applied in fields related to the fabrication of electronic micro/nanodevices, such as integrated micro/nanooptoelectronic devices and the nanopatterning of electronic devices (nanoimprinting).

According to the type of replication material and the processing conditions, micro/nano replication techniques can be categorized into (1) micro/nanoinjection molding, (2) hot embossing (thermal imprinting), (3) UV imprinting, and (4) high-temperature micro/nano replication.

Micro/nanoinjection molding uses established injection-molding equipment to fabricate polymer micro/nanoproducts [23]. The accumulated know-how and machining technology of conventional injection molding can be applied to micro/nanoinjection molding. This type of process is especially suitable for industrialization of micro- and nanoscale components since it has the shortest cycle time among existing micro/nano replication processes. Figure 1.2 shows (a) a schematic of the micro/nanoinjection molding process and (b) pictures of mold system and molded part of nanoinjection molding. In an injection molding process, hot molten polymer is fed into a micro/nanomold cavity along a sprue, runner, and gate, as illustrated in Figure 1.2a. Since the viscosity of a thermoplastic polymer increases as it cools, and since it is difficult to fill micro/nanostructured cavities with a high-viscosity polymer, a critical issue in micro/nanoinjection molding is to overcome problems related to fluidity characteristics during the filling stage [24–26].

To overcome the fluidity problems encountered during the filling stage of micro/nanoinjection molding, a method of heating the mold and material
above the glass transition temperature ($T_g$) of the material was developed, known as hot embossing (thermal imprinting) [27–28]. Figure 1.3 shows a schematic diagram of the hot embossing process. A thermoplastic material is placed on a mold with micro/nanocavities, heated (together with the mold) above its glass transition temperature, and gradually pressed into the mold. Once the micro/nanocavities are filled with the material, the mold and material are slowly cooled, and the replicated part is extracted from the

FIGURE 1.2 (a) Schematic diagram of micro/nanoinjection molding process and (b) pictures of mold system and molded part of nanoinjection molding.
mold. Since the hot embossing process does not require the melting and injection of the thermoplastic material, a system for hot embossing is much simpler and cheaper than an injection molding system. However, the cycle time of a hot embossing process is much longer due to the heating and cooling time of the system. Therefore, batch processing is commonly applied to mass production of hot-embossed micro/nanostructures. Hot embossing is also suitable for the fabrication of micro/nanocomponents with high aspect ratio, which are difficult to fabricate by micro/nanoinjection molding, due to the high friction and thick solidified layer in a cavity with a high aspect ratio. Furthermore, products fabricated by hot embossing are subjected to only a small amount of residual stress since the flow is restricted to the short length within the micro/nanocavity. The characteristic of low residual stress makes hot embossing a suitable procedure for fabricating a wide range of optical components because the performance of an optical component can be degraded by birefringence, which is caused by residual stress. However, precise process control is still required to increase the size of the embossed area, which is necessary in digital display fields and other industries requiring high productivity.

Unlike the micro/nanoinjection molding and hot embossing processes, in which thermoplastic materials are melted or softened by heating in order to fill the cavities, UV imprinting uses a UV-curable resin, which exists in a liquid state at room temperature, and is polymerized by UV irradiation [29–30]. Because of the initial liquid nature of a UV-curable material, a variety of defects caused by low fluidity during micro/nano replication with a thermoplastic material can be eliminated. Therefore, UV imprinting can provide replicated parts with high-aspect-ratio micro/nanostructures and low birefringence. Moreover, the refractive index of a UV-curable resin is easily tuned, which is advantageous to the design of aberration-free imaging optics. UV-curable resins also exhibit high thermal and chemical resistance, which is important for developing highly durable products used in harsh working environments. In addition, UV imprinting can be applied to the integrating of micro/nanostructures on electronic devices, as depicted in Figure 1.4, since
the process can be conducted at room temperature and low pressure. Optical alignment is also possible when a transparent mold is used.

While a typical micro/nano replication process serves to fabricate micro- and nanoscale components from a polymer material, glass or metal nanoparticle materials with a high melting point can also be used, depending on the field of application. Generally speaking, replication processes have not been applicable to glass materials, which have better optical characteristics and environmental resistance than plastic materials. However, it has recently become possible to fabricate glass products by replication due to the development of glass materials with low melting points, precisely machined mold materials with high-temperature hardness, economical high-temperature heating methods, and so on [31,32]. The glass molding method was first applied to fabricating aspherical glass lenses for a small optical imaging system. (Aspherical glass lenses possess superior optical characteristics, but cannot be economically fabricated by conventional abrasive machining techniques.) The field of application for glass molded optical parts has recently been expanded to include micro- and nanoscale components made of glass. High-temperature micro/nano replication technology combined with the use of metallic inks, which contain metallic nanoparticles, has made it possible to realize micro- and nanoscale components via a powder metallurgy process [33]. The micro/nano replication of metallic nanopowders provides a simple means of creating metallic conductive patterns, compared to the assortment of available semiconductor processes.

1.3 APPLICATION FIELDS OF MICRO/NANO REPLICATED PARTS

The development of micro/nanotechnology has been achieved through top-down fabrication methods such as E-beam lithography and other
lithography-based techniques, and bottom-up methods such as self-assembly. Recently, micro/nanotechnology has found practical applications in a variety of fields, in combination with micro/nano replication technology. Figure 1.5 shows the areas in which micro/nano replication technology has been adopted.

### 1.3.1 Optical Data Storage Devices

Generally speaking, information storage devices can be classified as either magnetic information storage devices (which write and read information through changes in magnetic signals) or optical information storage devices (which write and read information through changes in optical signals). Optical information storage devices, including compact discs (CDs), digital video discs (DVDs), and Blu-ray discs (BDs), employ a variety of components fabricated via micro/nano replication processes. Figure 1.6 illustrates the application of micro/nanoreplicated components to optical information storage devices. With the increasing demands of small form factor (SFF) information storage devices for portable data storage, the miniaturization of optical data storage systems (including optical pickup units and data storage discs) is underway. Micro/nano replication has been adopted for fabricating wafer-scale optical components, in order to solve various problems that occur in the alignment of single-piece optical components.

Among the various components, the optical disc, which is the key component of an optical data storage system, is fabricated via inexpensive injection molding. This is the primary driving force behind the development
of optical discs as a distributable medium. In compact disc read-only memory (CD-ROM) format, which was the first optical data storage format, information is recorded as nanopatterns on an injection-molded substrate, with a pattern width of 600 nm. The CD medium is created by forming nanopatterns on an injection-molded substrate that has been coated with any of a variety of materials. Figure 1.7 shows a schematic diagram of the cross-sectional structure of CD and BD substrates, together with atomic force microscope (AFM) measurement images of nanopatterns on an injection-molded CD substrate.

A ROM optical disc is fabricated by designing an initial nanopattern on the substrate (depending on the type of data to be stored), and the information is

FIGURE 1.6 Application fields of components of optical information storage devices fabricated by micro/nano replication process.

FIGURE 1.7 Schematic diagram of cross sectional structure of optical disk media and AFM measurement results of nanopatterns on injection-molded CD/BD substrate (pattern width : 600 nm and track pitch : 1.6 μm for CD, pattern width : 150 nm and track pitch : 0.32 μm for BD).
analyzed in terms of changes in the reflectivity of laser light according to the presence/absence of the pattern. In the case of a random access memory (RAM) disc, the nanopattern takes the form of tracks, which provide information about the position of data. Information is written to a RAM disc by changing the characteristics of a recording material that coats the substrate, using the heat energy of a laser, and information is read by analyzing changes in the reflectivity of laser light according to changes in these characteristics. To fabricate optical data storage medium with designated nanostructures, a series of micro/nanotechnologies are applied, including laser lithography to fabricate a master pattern, electroforming to fabricate a mold, and the final injection molding process. Figure 1.8 shows a conventional process for fabricating a metallic stamp for the injection molding of a CD or DVD substrate. A cleaned glass substrate is coated with a photoresist (PR), and laser lithography is conducted after the coated PR layer has been soft-baked. Following the development process, a seed layer for electroforming is deposited via electroless metal plating, and electroforming is carried out. The backside of the electroformed plate is polished, the metallic mold is separated from the master pattern, and a hole is punched to obtain the final metallic stamp. The metallic stamp is then installed in an injection molding machine, and an inexpensive micro/nanoinjection molding process is applied to fabricate an optical data storage disc from a substrate with a diameter of 120 mm and a thickness of 1.2 mm. Figure 1.9 shows an image of a fabricated metallic stamp for a DVD substrate, together with a fabricated DVD substrate.

The technologies for fabricating metallic stamps and optical data storage discs with nanopatterns are still commercially used for fabricating Blu-ray media, which is the most recent optical data storage format, with a storage capacity of 47 gigabytes and a data pit width of ~130 nm. The main

**FIGURE 1.8** Schematic diagram of conventional fabrication process for metallic stamp for CD or DVD substrate.
difference between the fabrication technologies for CD and BD is the mastering source: a laser for CD and an electron beam (E-beam) for BD.

The CD system is considered to be the first commercial application of nano replication technology, in which data is read from the changes in reflectance caused by nanopatterns (pattern width: 600 nm for CD) on an injection-molded substrate. The series of technologies used to fabricate micro/nanos-structured devices (master patterning, mold fabrication, and replication) have also been applied in various other areas, thereby affecting the present state of micro/nano replication.

1.3.2 Display Fields

As the quality of life and visual information continue to be enhanced, the technologies related to flat-panel digital displays are rapidly developing. There are already a variety of flat-panel display systems and technologies, including organic light-emitting diodes (OLEDs), projection displays, liquid-crystal displays (LCD), plasma display panels (PDPs), and three-dimensional (3D) display technologies. Throughout the flat-panel display industry, enlargement of the display area, improvement of the image quality, and reduction of the fabrication cost are the important issues, and various micro/nanoreplicated components are playing an important role in resolving them.

LCD systems account for the greatest portion of flat display systems. Figure 1.10 shows a schematic diagram of a thin-film transistor liquid-crystal display (TFT-LCD). A TFT-LCD requires a backlight unit (BLU) to provide a surface light source for the rear side of the display since an LCD does not emit light on its own. The BLU includes a lamp, a lamp reflector, a light-guide plate, a diffuser sheet, a prism sheet, and a protector sheet. The light-guide plate is a device that creates a uniform light source by receiving incident light from the lamp, and scattering it according to a pattern formed on its surface.
In a typical design, the density of the scattering pattern is low on the section of the plate adjacent to the light source since a greater amount of light propagates in this section. The density of the scattering pattern is higher on sections of the plate farther from the light source, where a smaller amount of light propagates. In general, there are three methods for producing the scattering pattern. In the first method, the surface of a plastic substrate is coated with a reflective ink. In the second method, the pattern is formed via chemical or mechanical machining of a plastic substrate. In the third method, micro/nano replication is used to form appropriate micro/nanostructures on the surface of the light-guide plate, so that light is diffusely reflected by these structures. Initially, light-guide plates were fabricated via silk screening and corrosion processes, in which an organic pigment pattern was printed on a plastic substrate machined according to the intended outline, and a corrosion process was carried out using the printed pattern as a barrier. However, this process has a number of disadvantages, including increased processing time, increased costs, and degraded quality since it is divided into initial machining, printing, and material corrosion processes. Nowadays, patterned light-guide plates with controlled micro/nanostructures fabricated by micro/nano replication are widely used. Light-guide plates produced by micro/nano replication offer the advantages of reduced fabrication cost, improved productivity, and high quality. To fabricate a patterned light-guide plate, a variety of mold fabrication techniques can be employed, including superprecision machining, reflowing, etching, laser interference lithography, conventional photolithography, and electroforming, depending on the desired pattern configuration (e.g., lens, prism, or dot). Micro/nanoinjection molding is widely used for fabricating patterned light-guide plates due to its highly industry-friendly characteristics. However, hot embossing and UV imprinting processes are sometimes employed to obtain large-area, ultra-thin, or high-quality components.