# 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

Micro/Nano Replication: Processes and Applications, First Edition. Shinill Kang.

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consumption. The Hitachi Research Institute in Japan anticipates that the development of nanotechnology will enable the commercialization of nextgeneration 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



FIGURE 1.1 Concept of micro/nano replication process.

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-areato-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,

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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/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 knowhow 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



[After the polymer injection process]



**FIGURE 1.2** (a) Schematic diagram of micro/nanoinjection molding process and (b) pictures of mold system and molded part of nanoinjection molding.

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 1.3 Schematic diagram of hot embossing process.

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 frication 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



**FIGURE 1.4** Schematic diagram of UV imprinting process for integrating micro/nanos-tructures on the electronic devices.

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 microand 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



FIGURE 1.5 Micro/nano replication technology and its applications.

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 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



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

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 1.7** 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 :  $1.6 \mu \text{m}$  for CD, pattern width : 150 nm and track pitch :  $0.32 \mu \text{m}$  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  $\sim 130$  nm. The main



**FIGURE 1.8** Schematic diagram of conventional fabrication process for metallic stamp for CD or DVD substrate.



**FIGURE 1.9** Images of fabricated metallic stamp for DVD substrate and injection-molded 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-tructured 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.



**FIGURE 1.10** (a) Schematic diagram of TFT-LCD structures, (b) SEM image of wire grid polarizer and (c) SEM image of prism sheet.

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.



**FIGURE 1.11** A schematic of UV roll nanoimprinting system to fabricate transparent conductive tracks and patterns for flexible TFT display.

Micro/nano replication technology can be applied to other types of display systems, too. Figure 1.11 shows a schematic drawing of UV roll nanoimprinting system to fabricate transparent conductive tracks and patterns on the flexible transparent substrate, which are essential for flexible TFT display. Conventionally, conductive tracks have been fabricated using metal lift-off or metal etching, where standard photolithography techniques are applied. However, since TFT should be formed on the flexible substrate for the case of flexible TFT display, roll nanoimprinting process can be an excellent candidate to realize such device. The details of the process will be explained in chapter 6.

#### 1.3.3 Other Industries

In addition to the information storage and display applications described above, micro/nano replication is regarded as an essential technology for the practical development of micro/nanobiodevices due to the disposable nature of such devices, and relevant research is underway. Required structures for a micro/nanochannel, a micro/nanomixer, and a micro/nanoreactor for lab-ona-chip technology have also been developed via micro/nano replication. In the optical communications field, micro/nano replication is employed to fabricate passive optical devices, such as optical waveguides, photonic crystals, microlens arrays, and optical ferrules, for the transfer, distribution, amplification, and filtering of optical signals, and the alignment of optical fibers. A series of active devices have recently been developed via the micro/ nano replication process, including a vertical cavity surface-emitting laser (VCSEL) diode and an active filter. In the semiconductor industry, nanoimprint lithography (which is based on the same principle as the nano replication process) is being applied as a next-generation patterning technology, which overcomes the limits of existing photolithography techniques. In the energy field, micro/nanoprocesses have been combined to fabricate a solar cell module coupled with a micro-Fresnel lens and a micro/nanolightcollecting device to improve the light efficiency of a solar cell, and a nanostructure electrode to enhance the reactivity of a fuel cell. In the imaging field, the technology is being applied to replicate SFF plastic/glass lenses with micro/nanoscale shape or precision, in response to the miniaturization of imaging systems. Technology based on the micro/nano replication process has been employed to fabricate a microlight-collecting device array for an image sensor, and a microlens array optical system. In particular, a waferscale image sensor module has been introduced, based on a concept to which the micro/nano replication and wafer-scale package processes are applied, and the development of related technologies is actively underway.

## 1.4 REQUIRED TECHNOLOGIES FOR MICRO/ NANO REPLICATION

Since there are various micro/nanofabrication technologies, each with its own pros and cons, a person with an overall insight into these technologies (including micro/nano replication) could play a very important role in the mass production of micro/nanocomponents. As interest in micro/nanotechnology has grown, there have been a variety of technical books and research papers concerning the principles and effects of processing parameters for specific micro/nanomachining or fabrication technologies. For the development of micro/nanodevices, it is important to have the designing skills to employ whichever manufacturing process is most appropriate, taking into account the advantages and limitations of each fabrication technique, as well as the function and geometrical characteristics, marketability, and working environment of the product. For the sake of commercialization, it is especially important that one's designing skills include micro/nanocomponents fabricated via micro/nano replication since this process is most suitable for the mass production of high-quality, low-cost micro/nanocomponents. The goal of this book is to present the fundamental principles of micro/nano replication, based on years of experience in the field, necessary for students and researchers to become involved in research or technological development in this area. The reader will obtain a detailed knowledge of the micro/ nanopatterning and replication processes, and the strengths and weaknesses of each process. An extensive knowledge of the micro/nanopatterning and



**FIGURE 1.12** Overview of the steps involved in the replication process for micro/ nanocomponents.

replication processes permits one to control the development of micro/ nanocomponents via micro/nano replication.

To fabricate micro/nanocomponents via a replication process, it is necessary to prepare an appropriate mold with micro/nanocavities. Figure 1.12 illustrates the steps involved in the replication process for micro/nanocomponents [34]. The first stage in the fabrication of micro/nanocomponents is the design process, which consists of component design, tolerance design, and process design. In the process design step, mold fabrication, surface treatment, and micro/nano replication methods are selected to satisfy the specifications of the final component. After the mold fabrication and replication processes have been carried out, the device technology must be confirmed. This typically includes the measurement of geometrical and functional characteristics, and a reliability test.

In the design stage for micro/nanoreplicated components, component design, tolerance design, and process design should be considered. In the component design, the shape of the device is optimized via simulation or performance analysis to meet the required specifications. The component design must be conducted in conjunction with the tolerance design to control the various errors that may result from the fabrication or working conditions of the component. In the tolerance design, it is also necessary to determine a fabrication process that satisfies the tolerance requirements of the product while ensuring optimum economic efficiency and marketability. In particular, in micro/nanotechnology, it is often necessary to combine different fabrication methods to develop a new type of component, which may be difficult to accomplish with existing fabrication technologies alone. Therefore, a designer of micro/nanoreplicated components should understand not only the physical performance of a structure but also the fabrication process, working conditions, and marketing environment. It is essential to have a general understanding of the characteristics of the specific technologies used in the micro/nano replication process, as well as the characteristics of its fields of application. The first half of this book contains a brief introduction to the characteristics of each technology used in the fabrication of micro/ nanoreplicated components, while the second half discusses the design, fabrication, and testing of micro/nanocomponents, including practical examples. These examples will provide an understanding of how this technology is applied in actual industrial sites, and will assist researchers in designing processes and configurations for developing micro/nanoproducts.

Since micro/nano replication requires a mold with the negative configuration of the final product, it is essential to understand the mold fabrication technologies that can achieve the configuration and tolerance of the design. Micro/nanopatterning is widely used for fabricating micro/nanocavities, and the procedures can generally be classified as point-by-point machining techniques or lithography techniques. Mechanical machining, laser machining, focused ion beam machining, and E-beam lithography are included among the point-by-point techniques, in which a designed structure can be obtained via a combination of machining technologies, carried out to a specific point and a precise stage using tool-path data. Projection lithography, interference lithography, and the like are included among lithography techniques, in which large-area micro/nanopatterns, especially those larger than  $1 \text{ mm} \times 1 \text{ mm}$ , can be obtained via a single-exposure process using a photoresist. Although structures prepared via a patterning process can be used directly as molds in the micro/nano replication process, silicon, polymer, or metal molds (fabricated by silicon etching, polymer replication, or metal electroforming) are more commonly used, to ensure their durability against chemical and mechanical damage and/or releasing properties. Chapter 2 discusses the principles and characteristics of the various micro/nanofabrication processes that can be used to fabricate micro/nanomolds. In addition to the usual micro/nanofabrication technologies, the reflow process, which is widely used to fabricate microlenses for digital imaging and displays, and holographic lithography, a patterning method for creating periodic nanostructures over a large area at low cost, are discussed in detail. The electroforming process for the realization of highly durable metallic micro/nanomolds is also discussed in detail.

In conventional replication, the technique of coating a mold with a siliconbased releasing agent is widely employed to overcome the releasing problem caused by the adhesive force between a mold and a replicated product. The releasing problem is more critical in micro/nano replication because of the low rigidity and high surface-area-to-volume ratio of a micro/ nanostructure. However, it is impossible to apply existing releasing agents to micro/nanomolds since the releasing layer that is formed on the surface of the mold is thick enough to influence the micro/nanopattern. As a method for improving the releasing characteristics of a mold without influencing the micro/nanopattern, surface treatment using a self-assembled monolayer (SAM) is essential to micro/nanotechnology. Various types of materials and processes can be used to apply an SAM antiadhesion layer, depending on the type of mold and micro/nanostructures in question. Chapter 3 discusses the materials and processes for applying a SAM antiadhesion layer to a silicon/glass or metallic mold. The reliability of the SAM antiadhesion layer in micro/nano replication is also examined by analyzing the influence of an SAM on the micro/nano replication conditions.

A variety of replication materials and processes can be employed to fabricate micro/nanostructures. The developers of micro/nanoreplicated products are expected to cultivate the ability to select the most suitable replication materials and processes for the target product, based on an understanding of the characteristics of the various replication methods. Generally speaking, micro/nano replication techniques can be classified as injection molding, hot embossing, UV imprinting, or high-temperature replication. In injection molding, a molten polymer is injected into the mold cavities under high pressure, and then cooled until it solidifies. In hot embossing, both the mold and the replication material are heated to the glass transition temperature of the material, and then pressed to replicate the pattern from the mold to the material. In UV imprinting, micro/nanostructures are fabricated using a liquid-state, UV-curable resin at room temperature and relatively low pressure, and the liquid state of the initial material eliminates the fluidity problems that interfere with the filling of the micro/nanocavities. High-temperature replication is particularly applicable to the replication of metallic or ceramic materials.

Chapter 4 is intended to help readers understand the basic injection molding process, and presents a technique of efficiently heating the mold surface to improve the transcribability of the molded micro/nanostructures. A theoretical basis for the generation of the solidification layer is discussed, as well as methods of preventing this layer from forming in optical data storage media, by using an intelligent mold system. Chapter 5 is concerned with the hot embossing (or thermal imprinting) process. A process optimization technique is introduced for minimizing various defects occurring during the hot embossing process, together with an analysis of the adhesion force between the polymer material and the mold surface. Methods for measuring the geometrical and optical characteristics of micro/nanoreplicated components are also presented via a variety of examples. A design, fabrication, and evaluation technique is introduced for the optical pickup components of an SFF optical data storage system and patterned media, as a practical application of hot-embossed micro/nanostructures. Chapter 6 discusses the UV imprinting process and its applications. The photopolymerization mechanism and a method of analyzing the degree of photopolymerization using the Fourier transform infrared (FTIR) transmission spectrum are briefly described. The design and construction of a UV imprinting system and process control are also considered. The effects of processing conditions on the elimination of microair bubbles, replication quality, and residual layer thickness are examined. Finally, some practical applications are presented, such as wafer-scale integration of micro/nanocomponents in an optoelectronic circuit, eight-stepped diffractive optical elements, and roll-to-roll conductive tracks fabricated by nanoimprint lithography. In addition to the polymer-based micro/nano replication technologies discussed in the previous chapters, Chapter 7 introduces high-temperature micro/nano replication technology for metallic and glass materials. The micro/nano replication of a metal is accomplished by the sintering of metallic nanoparticles. Chapter 7 presents the technologies used for mold fabrication, surface treatment, process control, and characteristic analysis for the realization of microconductive tracks over a large area via high-temperature replication. Besides these, the chapter describes a replication process that can be applied to fabricate micro- and nanoscale components made of glass, which provides better optical characteristics and environmental resistance than plastic materials. In particular, a technology for fabricating a tungsten carbide (WC) mold with a micro/nanopattern for the glass molding process is concurrently discussed.

To evaluate the characteristics of micro/nanoreplicated components, both geometrical and functional characteristics should be measured and analyzed. Since the performance of micro- and nanoscale components depends on shape, it is very important to ensure their geometric accuracy. To analyze the geometrical characteristics of micro- and nanoscale components, a surface profiler, an optical microscope, a white-light interferometer, an AFM, a scanning electron microscope (SEM), and other such instruments can be used, depending on the characteristics of the materials and the shapes to be measured. However, since there is no common technique for analyzing the functional characteristics of micro/nanocomponents, specialized equipment or a specialized setup is required to measure these characteristics for any given component. Miniaturization of existing measurement systems for macroscale products has been widely employed in the measurement of micro/nanoscale components, and specialized equipment that can accurately analyze the characteristics of particular components is constantly being pursued (e.g., the near-field scanning optical microscope, or NSOM). Since the working performance of a micro/nanostructured device is just as

important as the shape and characteristics of a single micro/nanopattern, a method for characterizing device performance should be developed for each application.

The latter half of this book is focused on the design, fabrication, and evaluation of micro/nanocomponents for specific applications. Chapter 8 describes the design and evaluation techniques used for UV-imprinted micro-Fresnel lenses for LED illumination systems, which are expected to occupy a large part of the market in the illumination industry. Chapter 9 describes the design and evaluation techniques used for both hot-embossed separate microlens arrays and UV-imprinted integrated microlens arrays for optical fiber coupling. Chapter 10 describes a fabrication technique for discrete track media and patterned media for next-generation hard disk systems, as well as a method for evaluating the magnetic properties. Chapter 11 describes a process optimization technique for optical data storage media. Chapter 12 describes the design and fabrication processes for nanoreplicated photonic-crystal, label-free biosensors, together with an evaluation of their biomolecule detection capabilities.

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