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Nanoimprint Lithography: A Processing Technique for Nanofabrication Advancement

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Abstract: Nanoimprint lithography (NIL) is an emerging micro/nano-patterning technique, which is a high-resolution, high-throughput and yet simple fabrication process. According to International Technology Roadmap for Semiconductor (ITRS), NIL has emerged as the next generation lithography candidate for the 22 nm and 16 nm technological nodes. In this paper, we present an overview of nanoimprint lithography. The classfication, research focus, critical issues, and the future of nanoimprint lithography are intensively elaborated. A pattern as small as 2.4 nm has been demonstrated. Full-wafer nanoimprint lithography has been completed on a 12-inch wafer. Recently, 12.5 nm pattern resolution through soft molecular scale nanoimprint lithography has been achieved by EV Group, a leading nanoimprint lithography technology supplier.
Keywords: Nanoimprint lithography; Soft molecular scale; Nanofabrication

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Introduction

Nanofabrication, as one of the key domains of nanotechnology, has received intensive attention in the scientific community. There are three approaches to nanofabrication: top-down, bottom-up and their hybrid approach. Top-down approach is referred to fabrication of smaller devices by using larger ones to direct their assembly, which has been developed based on the conventional IC fabrication process. Bottom-up process is to apply smaller components into more complex assemblies. More importantly, combined top-down with bottom-up is usually applied in nanofabrication.

Nanoimprint lithography (NIL), invented by Stephen Chou et al., has been regarded as a possible alternative to optical lithography due to its low cost, high throughput and high resolution [1-8]. Since its invention, lots of research has been conducted in order to further develop NIL as a technology. To date, thermal embossing, laser-assisted, step and flash and UV nanoimprint lithography have been incorporated into the field of NIL. Since 2003, nanoimprint lithography has been accepted by International Technology Roadmap for Semiconductor (ITRS) as the next generation lithography candidate, and now has been added to 22 nm and 16 nm nodes. The resolution of nanopattern by nanoimprint lithograophy could reach sub-5 nm [9].

In this paper, we will elucidate fundamental theory and discuss some critical issues in nanoimprint lithography. Important research achievements are also presented in this review paper.

Classification of nanoimprint lithography

A schematic of the process of nanoimprint lithography is shown in Fig. 1. First, the substrate is coated with the polymer layer or functional layer, and the mold is pressed onto the polymer layer. After curing the polymer, the imprint mold is released from the layer. As a result, micro/nano patterns are transferred onto the layer. Usually, the patterns on the layer are etched by reactive ion etching process.

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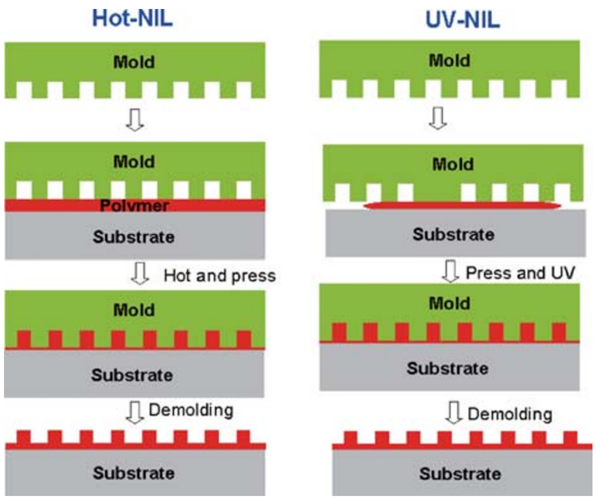

Fig. 1 Schematic illustrations for hot embossing and UV-nanoimprint lithography.

The main nanoimprint lithography technology is based on hot embossing lithography, UV-lithography and soft lithography. Depends on the kind of mold used, hard nanoimprint lithography and soft nanoimprint lithography are defined accordingly. SiO_2, Ni, Si, Si_3N_4, SiC molds are usually used for hard naonimprint lithography. Polymer materials, such as PDMS, PMMA, PUA, PVA, PVC, PTFE, ETFE, are main the components for the fabrication of soft molds. Depends on the curing approach to the spin-coated polymer, we have the differentiation into hot embossing lithography, UV nanoimprint lithography and hot-UV naoimprint lithography. Based on the imprinted area, the full-wafer nanoimprint lithography and step-and-repeat nanoimprint lithography are defined. Roll-to-roll nanoimprint lithography process is suitable for mass fabrication, and has application in the state-of-the-art flexible nanodevices. The classification of nanoimprint lithography is indicated in Fig. 2. The details of the process could be obtained from the relevant literature.

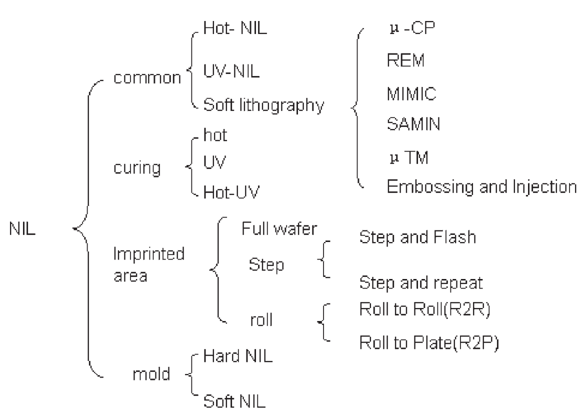

Fig. 2 Classification of nanoimprint lithography.

Research field of nanoimprint lithography

Nanoimprint lithography technology encompasses the integration of subject areas including electronic engineering, machine engineering, control engineering, materials, physics and chemistry. Research and development on novel methods, process controlling, fabrication of equipment, as well as devices and system is therefore becoming more and more important. The goal is to develop fabrication equipment and process, resulting in low cost, high efficiency and superior quality of the product. In the development of nanoimprint lithography, the basic processes and applications are highlighted. The basic processes include mold fabrication, the functional materials (imprint resists and transferred layer), controlling and optimization of imprint process and the development of imprint machine. The application fields of nanoimprint lithography are in electronic devices (high density memory), photoelectric devices (solar cells, light emitting diodes), optical components (polarizers, lasers, TFT-LCD, plasma sensors) and biological fields (biochips and microfluidic devices) [10-17]. The whole framework of nanoimprint lithography is outlined and shown in Fig. 3.

Critical issues in nanoimprint lithography

Nanoimprint lithography process can be divided into three steps: (1) mold fabrication and treatment, (2) imprint process, (3) subsequent etching (if required). The processes involved are mold fabrication, photoresist, process control and high-quality etching. To obtain small uniform nanopatterns, any process control in nanoimprint lithography is critical and become a series of related key technologies.

Mold

Mold is a functional unit for nanoimprint lithography. The fabrication of mold (hard or soft mold) and mold treatment are the key technologies are the prerequisite for the success of nanoimprint lithography.

Imprint mold (stamp, template) material used in hot nanoimprint lithography has high hardness, compression strength, tensile strength, low thermal expansion coefficient, good corrosion resistance and other properties, to ensure that the template can wear, deformation, maintain an accuracy and have longer life. Silicon, quartz, silicon nitride, and diamond can be selected as molds for nanoimprint lithography, and the soft polymer (e.g., PDMS) is suitable for large area imprint lithography.

Usually, the nano-structure mold is fabricated by

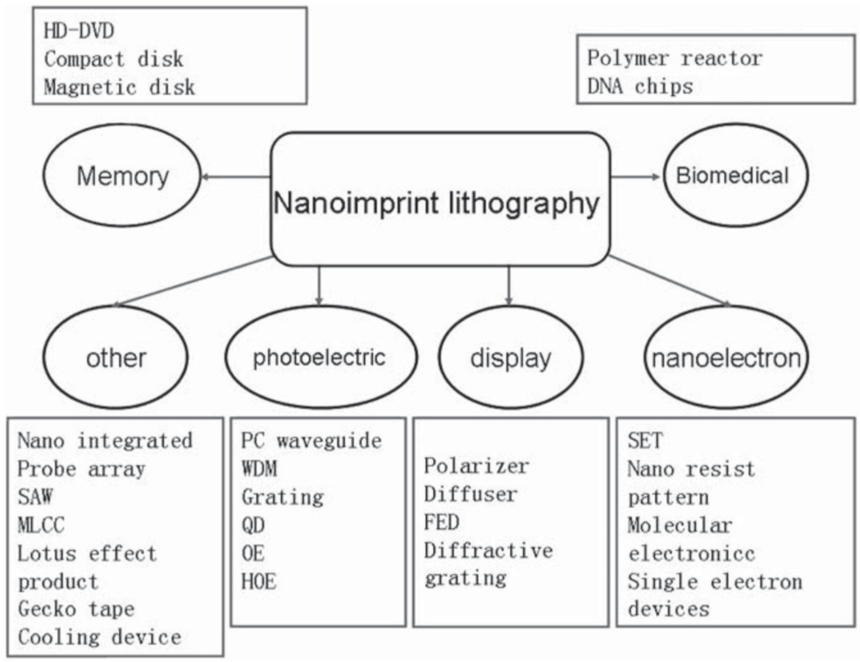

Fig. 3 Overview of nanoimprint lithography.

electron beam lithography. Before exposure, the substrate is spin-coated with a layer of electron sensitive resist, followed by exposure and development, resulting in the formation of nanostructures on the photoresist film. The patterns on the resist is transferred onto the substrate, and there are mainly two technical approaches, one is carried out by reactive ion etching, the other is the combination of lift off process and reactive ion etching, as shown in Fig. 4.

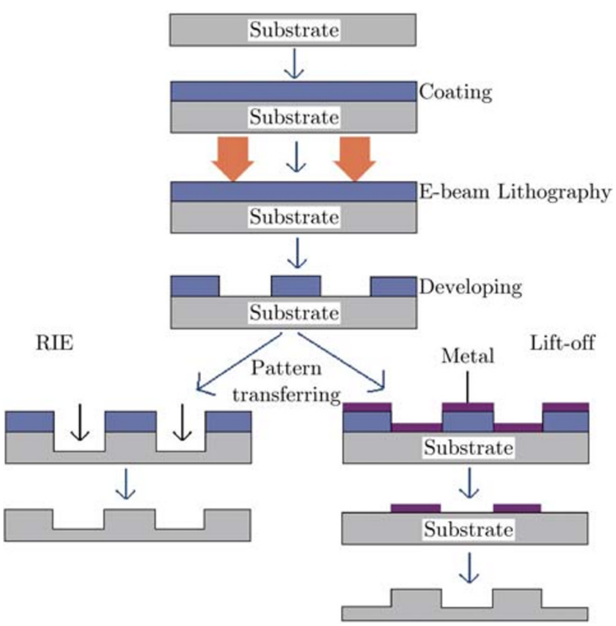

Fig. 4 Two main technical approaches of mold fabrication by electron beam lithography.

Figure 5 is SEM images of nanoimprint quartz mold by electron beam lithography and lift-off process. 100 nm diameter and 150 nm height of hexagonal photonic crystal are obtained. Figure 5(b) is tilted 30° SEM image.

However, the mold fabrication by electron beam lithography is time-consuming and tedious. The replication of soft mold based on the predefined mold is an alternative. In our research, the mother stamp is selected from porous alumina membranes (AAO) and the as-fabricated stamp is a composite mold. In the experiment, toluene diluted PDMS and h-PDMS layers were selected for the stamp material, respectively. The two materials can both act as soft material and applied to a large area imprint process [18-20].

Figure 6 shows a micrograph of the replicated soft mold. Its nanopillar arrays composed of h-PDMS were formed on the PDMS surface and the diameter is ~80 nm, which is consistent with the pitch of the AAO master (not shown here). The resulting patterns were shown in the SEM image of Fig. 6.

The replication based on AAO master offer a simple and an alternative to soft mold. The replication process and technology can also applied in other replication processes.

During nanoimprint lithography process, the template is contacted on the surface of the photoresist. Therefore, the adhesion between the template and the photoresist is a critical element. If adhesion is too strong, the pattern will result in defects, and also contaminates the mold and decrease the lifetime. The strength of adhesion between the photoresist and the nano-imprint template can be determined by their surface: low surface energy will determine the ease for

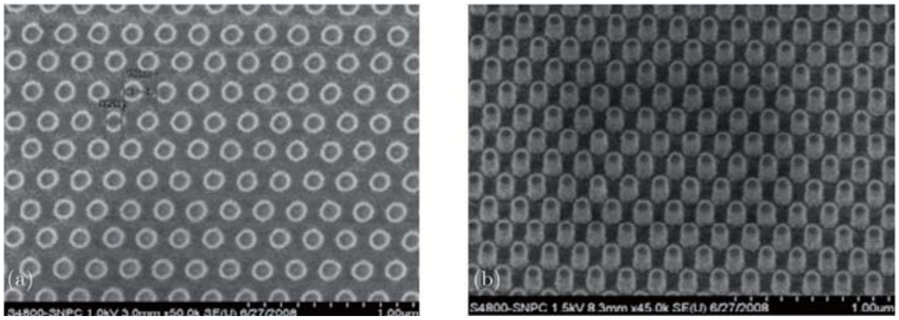

Fig. 5 Nano-structured mold fabricated by electron beam lithography: (a) Top view; (b) Titled 30°.

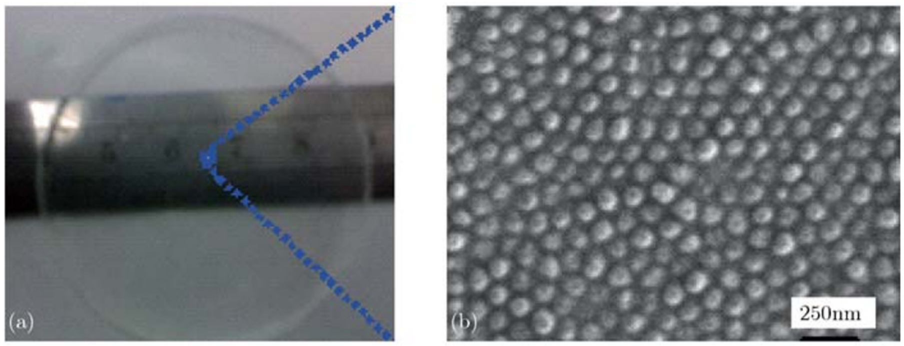

Fig. 6 (a) Photograph of a 2-inch replicated mold made from h-PDMS; (b) A representative SEM image of h-PDMS mold.

for separation. Anti-adhesive treatment is necessary to decrease the risk of defect. In our research [21], a self-assembled monolayer (SAM) of 1H, 1H, 2H, 2H-perfluorodecyltrichlorosilane (FDTS) is formed by vapor phase instead of liquid phase to decrease the surface energy. Our developed method of anti-adhesive mold is simple and can obtain nanopatterns over large area.

Resist

Photoresist used in nanoimprint lithography is different from the conventional optical lithography of the photoresist. The resist has the following properties: inherent properties of the resist (with a good substrate adhesion, low shrinkage, low viscosity), coating properties (controllable thickness in the 50∼500 nm, smooth surface, surface roughness is less than 5 nm) and good resistance to etching (at least 1:3 etch selectivity, relative to Si or SiO_2) [22-25].

Defect

In nano-imprint process, due to the environment, materials, or processes, for example, air bubbles, the mold deformation, uneven coating, unparallel between the substrate and the mold, and so on, will produce a variety of defects [26-27]. How to control and avoid the emergence of various defects in imprint lithography and improve the quality of imprint pattern is therefore key issues.

Overlayer

As the performance of electronic devices increases, the use of integrated chips becomes mandatory. If nanoimprint lithography is adopted in the IC product line, the use of the overlayer technology must be resolved. Currently, the overlay process is aimed at the field of nano-imprint, which is the most difficult and important issue. The application of Moiré fringe alignment method can obtain higher alignment accuracy, which can reach a precision of 20 nm [28].

3D pattern

Three-dimensional (3D) structure in the micro-system field has a very important prospect. Small structure, light weight, high sensitivity, low cost and superior performance of the device can be fabricated by 3D fabrication technology. It has greatly promoted the development of the product miniaturization and portability, increasing the device and the function of the system density, information density and interconnection density, and more importantly, it can greatly save materials and energy.

A unique benefit of nanoimprint lithography is the ability to pattern 3D structures. Multi-layer interconnect structure fabricated by nanoimprint lithography, its unique physical transfer process can not only reduce costs, with high resolution, but significantly reduce the number of processing steps in the formation of complex three-dimensional structures [29].

The future of nanoimprint lithography

Since the publication of the first imprint article in 1995 by Stephen Chou, the number of research papers published has grown tremendously, as shown in Fig. 7. From a few papers per year in the late nineties, it is now increased to about 400 per year.

In Fig. 8, we list the distribution of published NIL papers on various countries, including the United States, Japan and South Korea, the top three ranked nations for published literature. It is noted that the United States has published more than 660 articles in the subject area of NIL.

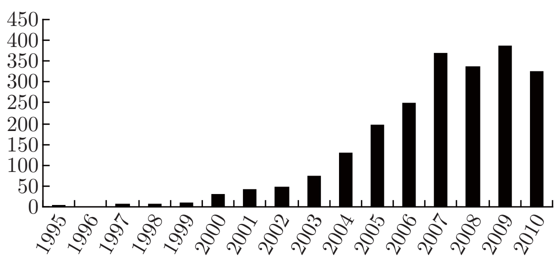

Fig. 7 Number of published articles indexed in SCI-E from 1995 to 2010, as a function of year.

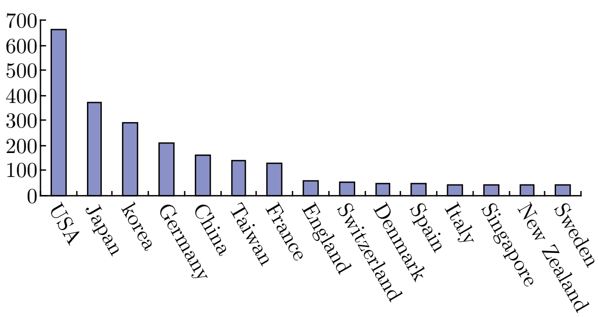

Fig. 8 National distribution of the research papers indexed in SCI-E from 1995 to 2010.

NIL is a simple, low-cost nanofabrication technique. It has been widely used in biomedical devices, high-density storage, photonic crystals, polymer electronics, solar cells, sensors and high-precision printed circuit board production. For NIL to be used effectively for industrial applications, the issue of efficiency, cost, and quality must be addressed. For example, the fabrication of nanoimprint molds is largely dependent on other lithography techniques, which makes it a lingering barrier for nano-patterning. In some sense, nanoimprint lithography is still an infant. A lot more work has to be done in order to make NIL fully blossom in wider industrial application.

Conclusion

Nanoimprint lithography involves the mechanical replicas of patterns, which is neither limited by diffraction, scattering effects nor secondary electrons. It is a very promising technology for the production of micro/nano structures on the wafer level. This paper reviews the current state and development of nanoimprint lithography and highlights some critical issues in this nanofabrication technique.

Acknowledgment

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References

[1] S. Y. Chou, P. R. Krauss and P. J. Renstrom, Appl. Phys. Lett. 67, 3114 (1995). http://dx.doi.org/10.1063/1.114851

[2] S. Y. Chou, P. R. Krauss and P. J. Renstrom, Science 272, 85 (1996). http://dx.doi.org/10.1126/science.272.5258.85

[3] S. Y. Chou, P. R. Krauss and P. J. Renstrom, J. Vac. Sci. technol. B 14, 4129 (1996). http://dx.doi.org/10.1116/1.588605

[4] W. Wu, Appl. Phys. A 80, 1173 (2005). http://dx.doi.org/10.1007/s00339-004-3176-y

[5] H. Lee, S. H. Hong, K. Y. Yang and G. Y. Jung, Microelectro. Eng. 84, 573 (2007). http://dx.doi.org/10.1016/j.mee.2006.11.009

[6] S. H. Kim, K. D. Lee, M. K. Kwon and S. J. Park, Nanotechnology 18, 055306 (2007). http://dx.doi.org/10.1088/0957-4484/18/5/055306

[7] H. Lee, S. H. Hong, K. Y. Yang and G. Y. Jung, Microelectron. Eng. 84, 573 (2007). http://dx.doi.org/10.1016/j.mee.2006.11.009

[8] M. Colburn, S. Johnson and M. Stewart, Proc. SPIE 379, 36 (1999).

[9] F. Hua, Y. G. Sun, A. Gaur and M. A. Meitl, Nano Lett. 4, 2467 (2004). http://dx.doi.org/10.1021/nl048355u

[10] W. M. Zhou, G. Q. Min, Z. T. Song, et al. Nanotechnology 21, 205304 (2010). http://dx.doi.org/10.1088/0957-4484/21/20/205304

[11] Y. B. Liu, T. Zhang, G. X. Zhang, et al, Nanotechnology 20, 315304 (2009). http://dx.doi.org/10.1088/0957-4484/20/31/315304

[12] L. Jay. Guo, Adv. Mater.19, 495 (2007).

[13] S. H. Ahn and L. J. Guo, ACS Nano 3, 2304 (2009). http://dx.doi.org/10.1021/nn9003633

[14] V. D. Mihailetchi, H. Xie, B. Boer, L. J. Anton Koster and P. W. M. Blom, Adv. Funct. Mater. 16, 699 (2006). http://dx.doi.org/10.1002/adfm.200500420

[15] T. Erb, U. Zhokhavets, G. Gobsch, S. Raleva, B. Stuhn, P. Schilinsky, C. Waldauf and C. J. Brabec, Adv. Funct. Mater. 15, 1193 (2005). http://dx.doi.org/10.1002/adfm.200400521

[16] S. K. Park, Y. H. Kim, J. I. Han, D. G. Moon, W. K. Kim and M. G. Kwak, Synthetic Metals 139, 377 (2003). http://dx.doi.org/10.1016/S0379-6779(03)00195-4

[17] J. F. Chang, B. Sun, D. W. Breiby, M. M. Nielsen, T. I. Solling, M. Giles, I. McCulloch and H. Sirringhaus, Chem. Mater. 16, 4772 (2006). http://dx.doi.org/10.1021/cm049617w

[18] X. L. Li, Q. K. Wang, J. Zhang, et al, Microelectron. Eng. 86, 2015 (2008). http://dx.doi.org/10.1016/j.mee.2008.12.090

[19] W. M. Zhou, X. M. Niu, G. Q. Min and Z. T. Song, Microelectron. Eng. 86, 2375 (2009). http://dx.doi.org/10.1016/j.mee.2009.04.024

[20] W. M. Zhou, J. Zhang, X. L. Li and Y. B. Liu, Appl. Surf. Sci. 255, 8019 (2008). http://dx.doi.org/10.1016/j.apsusc.2009.05.006

[21] W. M. Zhou, J. Zhang, Y. B. Liu, X. L. Li, X. M. Niu, et al. Appl. Surf. Sci. 255, 2885 (2008). http://dx.doi.org/10.1016/j.apsusc.2008.08.045

[22] Y. Hirai and Y. Tanaka, J. Photopolym. Sci. Technol. 15, 475 (2002). http://dx.doi.org/10.2494/photopolymer.15.475

[23] E. K. Kim, N. A. Stacey, B. J. Smith, M. D. Dickey, S. C. Johnson and B. C. Trinque, J. Vac. Sci. Technol. B 22,131 (2004). http://dx.doi.org/10.1116/1.1635849

[24] X. Cheng, L. J. Guo and P. F. Fu, Adv. Mater. 17, 1419 (2005). http://dx.doi.org/10.1002/adma.200401192

[25] B. K. Long, B. Keith Keitz and C. Grant Willson, J. Mater. Chem. 17, 3575 (2007). http://dx.doi.org/10.1039/b705388f

[26] L. Chen, X. G. Deng, J. Wang, et al, J. Vac. Sci. Technol. B 23, 2933 (2005). http://dx.doi.org/10.1116/1.2130352

[27] H. S. Park, H. H. Shin and M. Y. Man, IEEE Trans. Semicond. Manu. 20, 13 (2007). http://dx.doi.org/10.1109/TSM.2006.890315

[28] N. H. Li, W. Wu and S. Y. Stephon, Nano Lett. 6, 2626 (2006). http://dx.doi.org/10.1021/nl0603395

[29] P. Maury, M. Péter, X. Y. Ling and N. David, Nanotechnology 18, 044007 (2007). http://dx.doi.org/10.1088/0957-4484/18/4/044007