Microelectronic Engineering 110 (2013) 132–140

Contents lists available at SciVerse ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

A method for in situ measurement of residual layer thickness in nano-imprint lithography

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ARTICLE INFO

Article history:
Available online 24 March 2013

Keywords:
Nanoimprint lithography (NIL)
Surface plasmon resonance (SPR)
Residual layer
Non-destructive measurement

ABSTRACT

Nanoimprint lithography has the advantages of high throughput, sub-10-nm fabrication process, and low cost. However, residual layer encountered in the imprinting process requires removal through reactive ion etching to maintain pattern fidelity. This study proposes a non-destructive method in situ to measure the thickness of residual layer, employing surface plasmon resonance in the imprinted feature during the imprinting stage. Variations in the thickness of the residual layer change the resonance patterns, including the reflectivity and resonance angle. Both experiment and simulation results demonstrate the effectiveness of this method in monitoring the thickness of residual layers.

1. Introduction

Nanoimprint lithography (NIL) [1,2], enabling the rapid replication of nanoscale patterns, is a promising technique for a wide variety of applications. To bring this technology to full industrial use, ensuring the quality of the imprinted pattern while increasing the throughput of the imprinting process is essential. High resolution [3] as well as reliable patterning over a large area [4,5] must be achieved.

The process of NIL is shown in Fig. 1. The mold with the required nano-scale pattern needs to be prepared. Typically, the pattern is fabricated on silicon or glass using e-beam lithography and etching. During the imprinting process, the mold is held in contact with a thermoplastic polymer to be imprinted at an elevated temperature and pressure to duplicate the profile of the pattern. This process can also be performed at room temperature, when the imprinted material of the thermoplastic polymer is replaced with a curable photo-resist. Whether a thermoplastic polymer or curable photo-resist is used as the imprinted material, a residual layer between the imprinted pattern and their supporting substrate must be removed through further processing (etching or lift-off process). Generally, reactive ion etching (RIE), an anisotropic etching process, is used to remove the residual layer. During the RIE process, the removal of the residual layer causes a slight lateral erosion and reduced aspect ratio in the imprinted pattern. To maintain the sharpness of the imprinted pattern, the thickness of the residual layer must be decreased. This problem is further exacerbated by a lack of uniformity in the thickness of the residual layer across the area of the imprinted pattern [6,7]. Non-uniformity in the thickness of the residual layer can lead to difficulties in the RIE process. The transferred pattern may be lost if the residual layer is not removed completely, while over-removal can reduce the aspect ratio of the features in the imprinted pattern. Despite the uniform contact between the mold and substrate, variations in the residual layer often exceed 50 nm [5]. As the scale of the pattern decreases, the problems associated with the residual layer need to be identified, analyzed and overcome. To better understand the problems associated with residual layers, an effective monitoring method must be developed.

Current techniques for the measurement of residual layer involve the use of scanning electron microscopy (SEM). This requires the substrate to be taken off-line and destroyed in the process of determining the residual layer thickness. The SEM process lowers productivity. To obtain an accurate estimate of RIE process, while enhancing the yield requires a reliable metrological method to determine the residual layer thickness. Two nondestructive methods have been proposed in the literature; one involves the use of X-ray [8–10], and the other uses scatterometry [11]. Despite the nondestructive nature of these methods, they are not necessarily suited for non-periodic structures. In addition, the measurement has to be performed after de-molding for both methods. These shortcomings significantly limit their use.

2. Method and numerical analysis

In recent years, surface plasmon resonance (SPR) has attracted intensive interest due to its important potential of high sensitivity

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http://dx.doi.org/10.1016/j.mee.2013.03.007

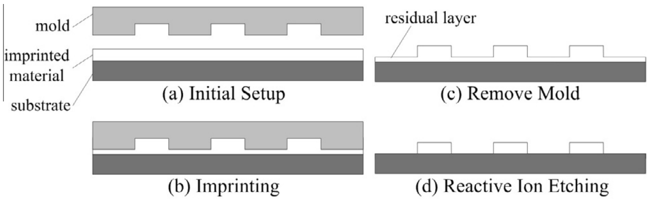

Fig. 1. Process of nano-imprint lithography.

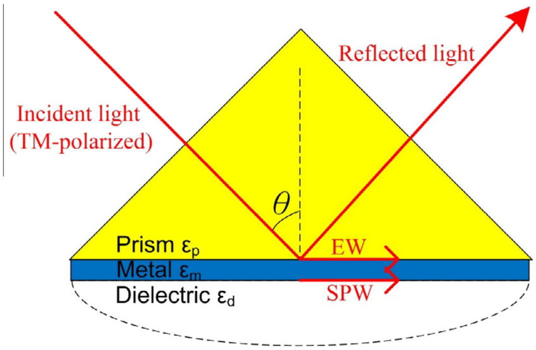

Fig. 2. Prism coupler-based SPR system (Kretschmann–Raether configuration).

and real-time property. Surface plasmon resonance has been applied to bio-sensing [12–14], measure the refractive index [15,16], estimate filling rate for NIL [17], etc. Fig. 2 shows a typical structure for exciting surface plasmon. The prism-coupled SPR structure is called the Kretschmann–Raether configuration [18]. The most obvious feature is the base surface of the prism coated with a thin metal film. When TM-polarized light beam incidents through the prism on the prism-metal interface at an angle equal to or greater than the total reflection angle, a part of incidence light is reflected back into the prism while a part propagates along the prism-metal interface in the form of an evanescent wave (EW). The propagation constant of the EW can be given by the following expression:

$$\beta^{EW} = \frac{\omega}{c}\sqrt{\varepsilon_p}\sin\theta \tag{1}$$

where β^{EW} is the propagation constant of the EW, ε_p represents the dielectric constants of the prism, c denotes the speed of light in vacuum, ω and θ represent the frequency and incidence angle of light, respectively.

If the metal layer is sufficiently thin, the EW can penetrate through the metal layer and couple with a surface plasmon at the outer boundary of metal layer. The surface plasmon wave (SPW) propagates along the metal-dielectric interface and penetrates into the dielectric layer. The propagation constant of the SPW can be described by following expression:

$$\beta^{SPW} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m+\varepsilon_d}} \tag{2}$$

where β^{SPW} is the propagation constant of the SPW, ε_d and ε_m represent the dielectric constants of the dielectric and metal medium, respectively.

Surface plasmon resonance means that the propagation constant of the EW exactly matches with the SPW at similar frequency, which can be described by Eq. (3). Most energy of the incident light will propagate along the prism-metal interface and the reflectivity of the incident light will decrease obviously.

$$\beta^{SPW} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m+\varepsilon_d}} = \frac{\omega}{c}\sqrt{\varepsilon_p}\sin\theta = \beta^{EW} \tag{3}$$

In prism coupler-based SPR system, the dielectric medium is referred to as a sensing field. A change in the refractive index of the dielectric medium produces a change in the propagation constant of the SPW, thereby affecting the coupling condition between the light wave and the surface plasmon. Therefore, the change in SPR characteristics can be understood by the characteristics of reflected light, which include the change of coupling angle, wavelength, phase, intensity and polarization. In the developed system, a monochromatic light is used to excite surface plasmon, and the reflectivity spectrum is used to estimate the change of coupling angle for information in the dielectric medium. According to Eq. (3), the strength of coupling will occur in a specific incidence angle (θ). The strongest coupling results a minimum intensity of reflected light in reflectivity spectrum, and the incident angle of the minimum reflectivity is denoted as the resonance angle θ_{SP}.

According to the principle of SPR and the Kretschmann–Raether configuration, one can propose a non-destructive method to measure the thickness of the residual layer prior to the de-molding process. Fig. 3 shows the proposed mold feature and monitoring method. The mold contains a layer of glass with high refractive index, a metal thin film, a low refractive index dielectric layer, and a dielectric pattern layer, as shown in Fig. 3(a). In order to obtain a more accurate SPR reflectivity spectrum, two approaches are

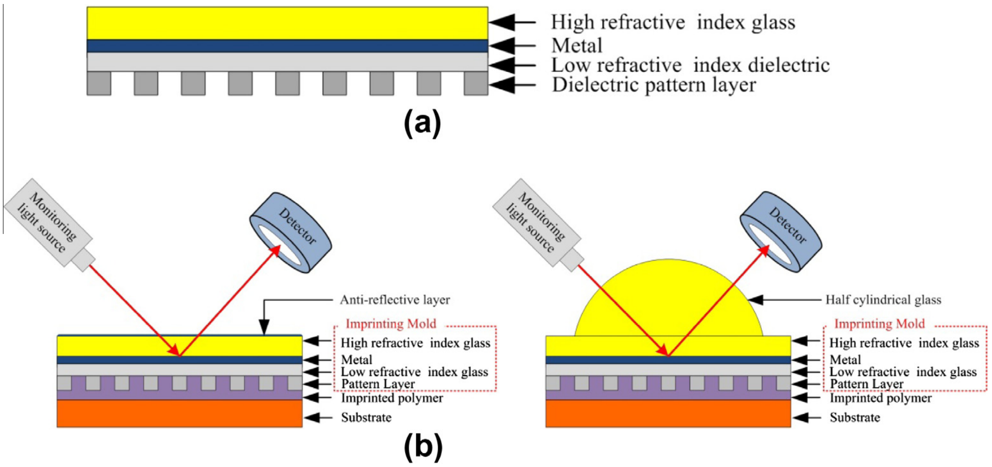

Fig. 3. Proposed mold feature and monitoring method. (a) Schematic of the proposed mold. The mold contains a layer of glass with high refractive index, a metal thin film, a low refractive index dielectric layer, and a dielectric pattern layer. (b) Monitoring setup for measuring residual layer thickness. A half cylindrical glass or anti-reflective layer is used to obtain a more accurate SPR reflectivity spectrum.