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Electrostatic Force-Assisted Nanoimprint Lithography (EFAN)

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ABSTRACT

We present and demonstrate a novel imprint method, electrostatic force-assisted nanoimprint lithography (EFAN), where a voltage applied between a mold and a substrate generates an electrostatic force that presses the mold into a resist on the substrate. We have successfully used EFAN to pattern nanostructures in a photocurable resist spin-coated on a wafer, with high fidelity and excellent uniformity over the entire substrate, in ambient atmosphere without using a vacuum chamber. In initial tests without any process optimization, 100 nm half-pitch gratings with a residual layer thickness of 22 ± 5 nm were imprinted across a 100 mm diameter wafer in about 2 s. Furthermore, numerical calculations show that the field magnitude experienced by the dielectric layers on the substrate is much less than their breakdown limit. Hence, EFAN is well suited for step-and-repeat nanoimprint lithography, and its simple operation can simplify and speed up multilayer alignment process.

Nanoimprint lithography (NIL) is a low cost, high throughput patterning technique with sub-10 nm resolution.[1,2] The method of pressing the mold into a resist is key to the performance and yield of NIL. Currently, the most commonly used technique is a solid parallel-plate press (SPP), which suffers the drawbacks of poor uniformity, shear and rotation stress, and large thermal mass, all leading to low yield, poor alignment, and damage to mold and substrate. An air cushion press (ACP), which uses a compressed fluid to press the mold and substrate together, can overcome these drawbacks,[3] yet it requires a pressure chamber, which adds complexity to NIL system design and operation for multilayer alignment and step-and-repeat operation. In this letter we present a novel imprint method, electrostatic force-assisted NIL (EFAN), where the force that presses the mold into a resist is an electrostatic force between the mold and the substrate.[4,5] EFAN can overcome the drawbacks of SPP, does not require a pressure chamber as in ACP, and is well suited for step-and-repeat NIL.

In EFAN, both the mold and the substrate have a conductive layer, and an applied voltage creates an electrostatic force between them, pressing the mold into the resist, as shown in Figure 1. In our particular experiments, our substrates are semiconducting Si wafers and our mold consists of a Pyrex glass body with a conducting layer of indium tin oxide (ITO) and a SiO_2 layer for molding patterns (Figure 1a). The relationship between this electrostatic pressure, P, and the required electric field, E, can be approximated by eq 1, in which ϵ_r is the average dielectric constant of resist layers between the mold and the Si wafer and approximately equal to 3 for our resists; V is the applied voltage; d is the distance between conductive layers (ITO

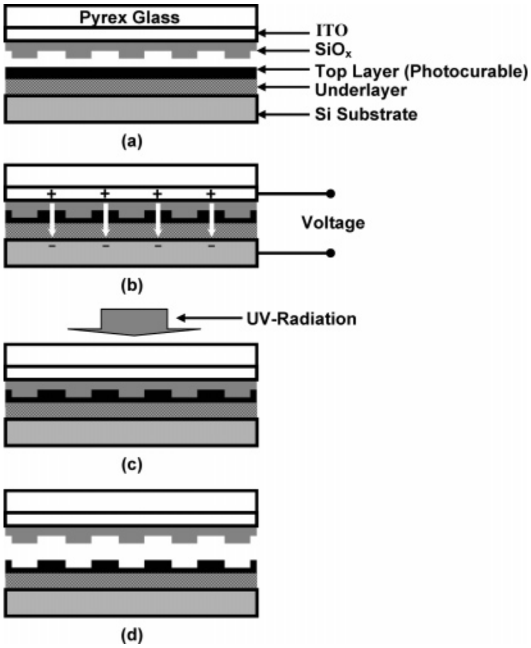

Figure 1. Schematic of electrostatic force assisted NIL (EFAN), where a voltage between the mold and the substrate generates an electrostatic pressure. (a) Implementation of EFAN; (b) imprinting by applying a voltage; (c) UV curing of the top-layer resist; (d) separation of the mold after resist curing.

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and Si). To generate one atmosphere pressure, an electric field of 5 × 10^5 V/cm is needed. This pressure is sufficient for imprinting photocurable NIL resist, as well as deforming a standard 4″ Si wafer or the mold or both to make conformal contact over a large area. Later we will present a more accurate simulation of the electrostatic field obtained using a finite element analysis (FEA) method.

$$P = \frac{\epsilon_r{}^2\epsilon_0}{2}E^2 = \frac{\epsilon_r{}^2\epsilon_0}{2}\left(\frac{V}{d}\right) \tag{1}$$

For photocurable nanoimprint, double-layer resists were used with the top-layer imprinted and cured (Figure 1b, c, and d) and then transferred to the underlayer by reactive ion etching (RIE), thus increasing the aspect ratio of structures. The top and bottom layers use NXR-2000 and NRX-3000, respectively (Nanonex, Inc.). All resists were spin-coated on a 4-in. Si wafer. After a soft-bake at 80 °C for 20 min to drive out residual solvent, the underlayer had a final thickness of 150 nm. The top-layer (photocurable) was then spin-coated on the underlayer with a thickness of about 70 nm.

Our molds for EFAN have a trilayer structure, SiO_x/ITO/Pyrex glass, in which the ITO (50 nm) and SiO_x (140 nm) layers were coated by sputtering and plasma-enhanced chemical vapor deposition (PECVD), respectively. In making topographic patterns on the mold, 200 nm pitch gratings on a Si master mold were transferred to the PECVD SiO_x layer using traditional thermal-based NIL and RIE. As-fabricated 200 nm pitch gratings on PECVD SiO_x have 70/130 nm line/spacing, and the trench depth is 72 nm. Finally, the molds were treated with an anti-adhesion coating for better mold release after the imprint process.

Figure 2 shows the imprint process for a spin-on resist in atmosphere environment recorded by a digital camera at different times. Initially, the mold was put on the substrate without any external pressure. The Newton rings observed on the mold indicate that there is an air gap between the transparent mold and the substrate. After a voltage of 40 V was applied between the mold and the substrate, there were regions where the Newton rings vanished and the mold was pressed into the resist, making conformal contact (indicated by the darker area in Figure 2). The conformal contact area started at one location and grew (propagated) very quickly, and eventually covered the entire mold area in a time frame of about 2 s.

This propagation behavior of the imprinted area can be explained by the gradual deformation of the mold and the substrate driven by the electrostatic force. As indicated by eq 1, the electrostatic pressure is very sensitive to the distance between the mold and the substrate ($P \propto 1/d^2$). Since neither the mold nor the substrate is perfectly flat, initial contact occurs only for a few small regions; remaining regions still have a gap of several tens of microns. After applying the electric field, the electrostatic pressure within the soft contact regions is much larger than that of other regions (due to a shorter distance). If the electrostatic pressure within these initial contact regions is large enough, the deformation process will continue and the conformal contact area will propagate (grow) to imprint the entire mold area. In our further experiments, we found that this propagation behavior of conformal contact area can easily remove the air trapped in the gap, which is a critical problem for imprint in ambient atmosphere.[6]

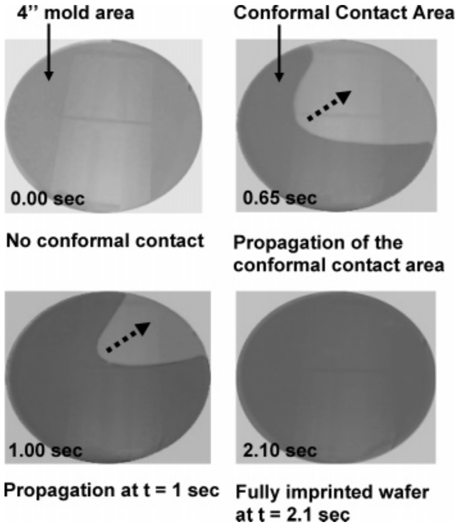

Figure 2. Dynamic EFAN process recorded by a digital camera. The darker (lighter) regions are the area that the mold and the substrate have a conformal (no conformal) contact. The dashed arrows show the propagation direction of the conformal contact area. At the beginning (0 s) without an applied voltage, there was no conformal contact, but a gap. Once the voltage is applied, contact at an initial local point propagates across the wafer. At 0.65 s, about half of the wafer is in conformal contact and is imprinted; at 1 s, about 3 quarters are in contact and imprinted, and at 2.1 s, the imprinting over entire the 4-in. wafer is completed.

Figure 3a shows SEM images of 200 nm pitch gratings imprinted in the top resist layer by EFAN. A zoom-in image shows the as-imprinted structures having 130/70 nm line/spacing and a trench depth of 72 nm, which are identical to those in the mold. The thickness of the residual layer is about 22 nm.

The as-imprinted pattern in the top-layer was faithfully transferred into the underlayer by RIE in order to increase the aspect ratio of the resist structures (Figure 3b). In this pattern transfer, a CHF_3/O_2-based RIE recipe was first used to remove the residual layer of the top-layer resist, opening the etching windows, and then another O_2-based RIE process etched the underlayer down to the Si surface. As shown in Figure 3b, the aspect ratio of gratings was enhanced for three to four times by RIE.

We carefully studied the imprint uniformity within a 4-in. wafer by capturing cross-sectional SEM pictures at different locations (Figure 3c). It is found that the variation of the trench depth or the residual layer thickness over the entire wafer is ±5 nm or ±7% to the initial thickness of the resist layer, which is within the tolerance range for post-imprint processes such as the RIE transfer.

One important question is whether the electric field between conductive layers causes any electrical damage to the structures on the substrate. Our experimental results did not show any visible damage. This is not surprising since the breakdown field of gate silicon dioxide is 10^7 V/cm,

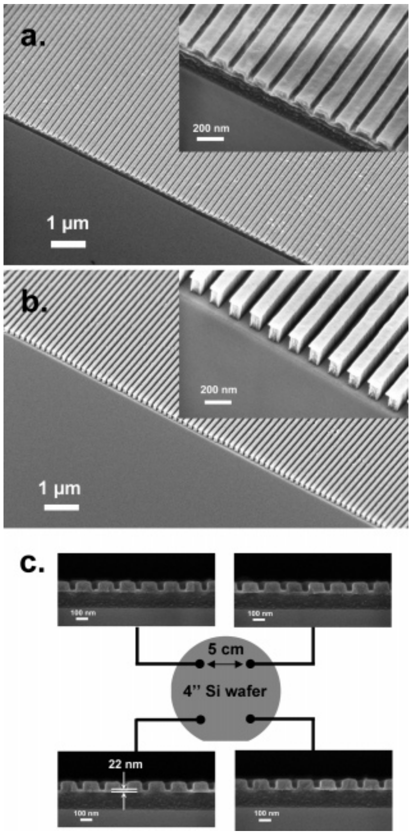

Figure 3. SEM images of (a) as-imprinted 200 nm period gratings in the top-layer (photocurable) of double-layer resist by EFAN (inset is a high-magnification image), and (b) 200 nm period gratings in the underlayer transferred from the top layer by RIE. (c) Cross-sectional SEM pictures captured from different locations on a 4-in. Si wafer showing the imprint uniformity in as-imprinted photocurable top-layer resist.

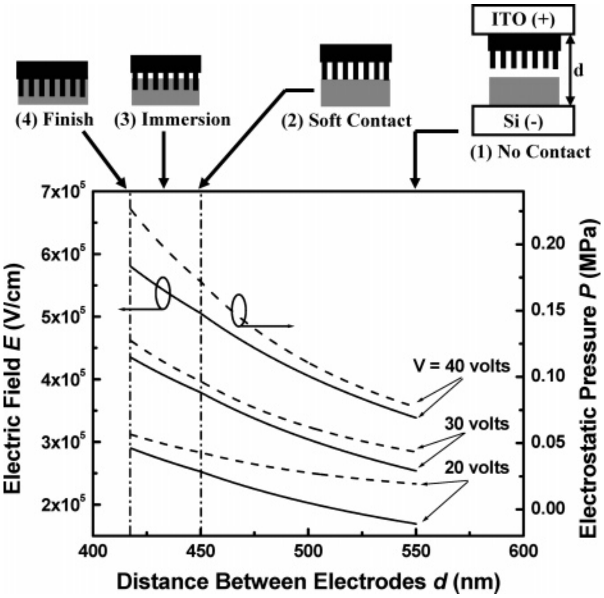

Figure 4. Simulation of the electric field during EFAN: The field magnitude experienced by a SiO_2 layer on the Si wafer as a function of the distance between the ITO layer in the mold and the semiconducting Si wafer (solid curves). The electrostatic pressure as a function of the distance between conductive layers (dashed curves).

nearly 20 times higher than the average electric field needed for generating 1 atm pressure estimated by the simple 1D capacitor model. However, the simple 1D capacitor model is not sufficient for accurate prediction of the electrical damage threshold and electrostatic pressure, because both the distribution of field magnitude and effective electromechanical force are 3D in nature and are strongly affected by the spatial distribution of dielectric structures between electrodes. For example, a sharp variation of dielectric constant in space can generate a very large field magnitude locally. Our simulation based on finite element analysis (FEA) adds complete details of dielectric structures (oxide mold, air, double-layer resists, and dielectric on the wafer) into the calculation of electric field. We calculated the field experienced by a gate oxide layer (10 nm), the most important dielectric layer in MOSFET fabrication, during the EFAN process. Other simulation parameters are based on our experiments described above.

The solid curves in Figure 4 show the magnitude of the electric field in the oxide layer as a function of the distance between two conductive layers (ITO in the mold and the Si substrate; the distance is indicated by *d* in the schematic figure). The different curves correspond to different applied voltages (20−40 V), and schematic figures above the graph indicate the various stages of the imprint process. When the imprint is completed, i.e., the topographic pattern on the mold is completely filled with the liquid resist, the field magnitude reaches a maximum, which is around $3-6 \times 10^5$ V/cm. This magnitude is much smaller than the breakdown field of the typical silicon oxide layer ($\sim 10^7$ V/cm). However, it should be pointed out that for certain electrostatic sensitive devices with delicate dielectric structures, the electric field used in EFAN may degrade or damage the structures. One can alleviate the damages by using proper resist and mask materials and reducing the sharp corners.

When the insulating layer on the EFAN mask leaks, there can be an electric current flowing through the resists, causing heating or electrochemical reaction, all of which are detrimental to NIL. Besides depositing a high-quality insulating layer, one can use a current limiting voltage source to control the leakage current.

Our simulation also provided more accurate values for the electrostatic pressure between conductive layers as a function of their separation *d* (dashed curves in Figure 4). In the soft-contact regime, which corresponds to the region around the vertical dashed line at $d = 450$ nm, the pressure is about 0.92−1.7 atm (0.09−0.17 MPa) with the typical applied voltages (30−40 V). This pressure is large enough to deform the photocurable liquid resist and bend the Si wafer to conform the mold, hence extending the conformal contact area.

Finally, in comparison with other pressing methods, the throughput of EFAN should be at least the same if not better. An electrostatic force can be applied between a mold and a wafer faster than a mechanical force or fluidic force. Yet, the throughput of an imprintor is not limited by how fast that an imprinting force can be applied, but by the times for removing air and aligning the layers between a mold and a wafer. The simplicity and flexibility of EFAN can simplify these processes, and hence offer a higher throughput.

In summary, we have presented a novel imprint method in which an electrostatic force presses the mold into a resist spin-coated on a 4-in. substrate. Due to the distance-dependent property of the electrostatic force, the conformal contact usually starts at a small particular soft-contact region and then extends to cover the entire mold area. In our further observation, we found that this propagation behavior could significantly reduce the chance of trapping air bubbles. Using EFAN we patterned 200 nm pitch gratings in a photocurable top-layer, which was faithfully transferred into an underlayer by RIE, increasing the aspect ratio of the imprint pattern. We studied the imprint uniformity over a 4-in. wafer and found the variation of the trench depth or residual layer thickness was ±5 nm, or ±7% of the initial thickness of the resist layer. Simulation of the electric field during EFAN confirms that sufficient electrostatic pressure for imprint can be achieved without electrical damage to the dielectric layers.

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