UV Enhanced Substrate Conformal Imprint Lithography (UV-SCIL) Technique for Photonic Crystals Patterning in LED Manufacturing

Ran Ji[a1], Michael Hornung[a],
Marc Verschuuren[b], Robert van de Laar[b], Jan van Eekelen[b],
Ulrich Plachetka[c], Michael Moeller[c], Christian Moormann[c]

[a] SUSS MicroTec Lithography GmbH, Garching, 85748, Germany
[b] Philips Research, Eindhoven, 5656AE, The Netherlands
[c] AMO GmbH, Aachen, 52074, Germany

[1] e-mail: ran.ji@suss.com

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[§] e-mail: ran.ji@suss.com

Introduction

The global LED (light emitting diode) market reached 5.5 billion dollars in 2008 and is dominated by portable device backlighting applications e.g. mobil phones, PDAs, GPS, Laptop, …… Emerging applications including general lighting will drive the market towards 9 billion dollars by 2011, according to Yole development report. However, the luminous efficiency needs to be improved significantly in order to open the market for LEDs to replace traditional light bulbs [1]. Photonic crystal (PhC) structures in LEDs have been demonstrated to enhance light emission efficiency by diffractive waveguide structures. It is still a great challenge to fabricate PhC structures on LED wafers cost-effectively [2], [3].
Nanoimprint lithography (NIL) [4] is a simple method to fabricate nanostructures and it has attracted considerable attentions in many applications due to its high resolution, high throughput and low cost of ownership (CoO). There are several NIL candidates for mass productions in the market: hot-embossing lithography (HEL), UV-NIL [5] with rigid quartz stamps and UV-NIL with flexible stamps [6]. HEL has been discarded from PhC LEDs application due to its thermal cycles and therefore low throughput. UV-NIL with rigid stamps provides excellent resolution down to sub-20 nm. However, the process relies strongly on the substrate flatness and production environment. It is not suitable for patterning of most of the LED wafers, which have roughness of more than 10 μm. In addition, most of the existing LED factories are designed as class 1,000 or above, which will limit the yield of the process and increase the CoO of imprint stamps dramatically. UV-NIL with soft stamps, e.g. PDMS stamps, allows the large-area imprint in a single step with less sensitivity to substrate flatness and particles. However, the resolution is normally limited to several hundred nanometers due to the stamp distortion caused by imprint pressure.
Substrate Conformal Imprint Lithography (SCIL) [7], a novel NIL technique developed by Philips Research and SUSS MicroTec, bridges the gap between UV-NIL using rigid stamps for best resolution and soft stamps for large-area patterning. Based on a cost-effective upgrade on SUSS Mask Aligner, the aligner capability can be enhanced to nanoimprint with sub-50 nm resolution up to 6 inch dimater area without affecting any established conventional optical lithographic processes on the machine. In this paper, the process details of SCIL technology and the imprint tooling are briefly described. Additionally, the introduction of SCIL into high volume manufacturing of high brightness LED (HB LED) is discussed.

SCIL principle

In order to reduce the CoO (cost of ownership) of large-area imprint stamps, SCIL process uses composite working stamps consisting of a glass carrier with patterned rubber [8] which are replicated from the original master pattern. Philips Research developed SCIL master replication tooling (MRT) and automatic separation tooling, which allow the end-users to produce high quality SCIL stamps themselves from their own masters and this tooling is available from SUSS MicroTec Lithography GmbH. Before stamp replication, the silicon master surface needs to be modified with 1H,1H,2H,2H-Perfluorodecyltrichlorosilane chemistry as anti-adhesive layer [9] in order to protect the master against contaminations of PDMS residuals. The PDMS working stamp is then replicated from the master and simultaneously adhered onto a thin glass carrier in MRT. Figure 1 shows a finished composite SCIL stamp. One hand, the in-plane rigidness of the glass carrier avoids lateral stamp deformation caused by vacuum fixing on the stamp holder; on the other hand, the flexibility in the out-of-plane direction of the thin glass and PDMS allows conformal imprint over large areas.

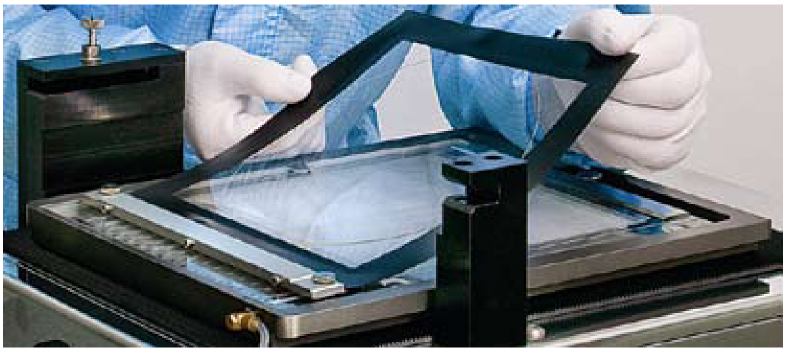

Figure 1: Photograph of loading a flexible SCIL stamp onto a SCIL stamp holder.

Although the PDMS stamp can compensate the waviness of the substrate, directly contacting a large-area stamp during replication can lead to non-conformal imprint or “bubbles” in case of using perpendicular imprint process. To achieve a substrate conformal contact between working stamp and substrate, SCIL process relies on a sequential imprinting process. In addition, capillary forces help pulling the stamp into the liquid imprint resist. The approaching of the flexible stamp starts from one side and spreads to the whole stamp subsequently by releasing the vacuum in the grooves step by step and applying an small over pressure of 20 mBar on the stamp. (Figure 2 (a) to (c)). This sequent contact mechanism prevents the flexible stamp from trapping air and therefore ensures that the stamp follows exactly the undulating topography over whole substrate surface. The imprint resist’s that are used are wetting on the PDMS and the resulting capillary forces fill up features with resist. The capillary forces are leading which minimize the structure deformation and lateral stamp distortion during the imprint process. In this way sub-50 nm resolution patterns have already been demonstrated. After conformal contact over the entire substrate is carried out, the imprint resist layer is cured by UV exposure or in case of using imprint sol-gel based resists diffusion of the sol-gel solvent into the PDMS stamp (see ref. 7). The automatic separation of the stamp from the substrate is performed by switching on the vacuum in the grooves consequently, which is opposite to the imprint process (Figure 2 (d) to (f)). This results in a low force peeling action which removes the stamp from the patterned resist layer and avoids damage to stamp or patterns.

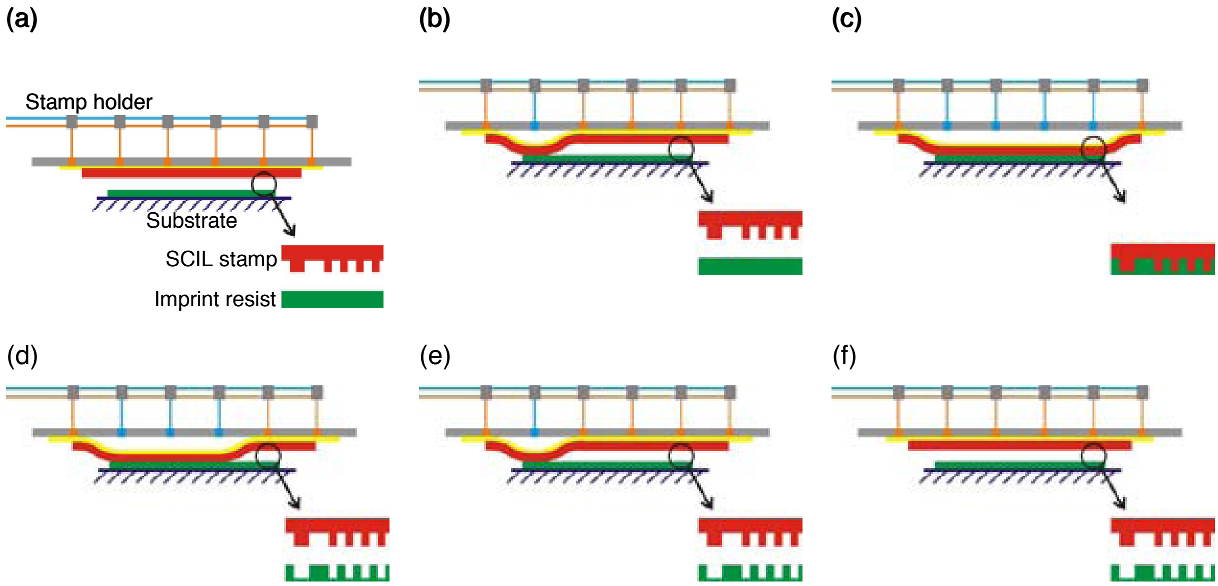

Figure 2: Schematic illustration of the SCIL imprint and separation sequences. (a) The SCIL stamp is fixed on the stamp holder by vacuum; (b) the imprint process starts from one side of the stamp; (c) the imprint is completed by releasing the stamp holder vacuum grooves one by one; (d) after curing of the resist, the separation process starts from the other side of the stamp; (e) and (f) the separation process is completed by switching on the vacuum in the grooves one by one.

The SCIL imprint tooling is retrofitable on SUSS MA6 or MA8 Gen3 mask aligners. This upgrade can be installed on-site with very limited efforts. The SCIL process therefore benefits from standard mask aligner features, such as precise alignment, automatic WEC (Wedge Error Compensation) and uniform UV exposure. The upgrade kit consists of a stamp holder, a frame adaptor for stamp holder, a substrate chuck, pneumatic controller and software. Substrates up to 150mm in diameter or in special forms can be handled by the tooling. The software allows a quick switch between conventional lithography process and SCIL process. All relevant process parameters, e.g. WEC type, process gap, sequence step time, exposure time, etc. can be predefined in the software and the SCIL process can be carried out full- or semi-automatically.

Figure 3: Photograph of MA6 mask aligner with SCIL upgrade tooling.

Experimental results

In this paper, a 6 inch silicon master (Figure 4) from AMO GmbH (Aachen, Germany) with 2D hole array fabricated by laser interference lithography and etching processes has been used for stamp replication. A 6 inch multilayer SCIL imprint stamp was replicated from this master using the MRT tooling. Full field imprint with the replicated SCIL stamp has been carried out into a 120 nm thick imprint sol-gel layer on a 6 inch substrate. After removal of the residual layer (ca. 20 nm) by CF_4 RIE, the structures were transferred into silicon substrate to a depth of 300 nm. Finally, the imprinted sol-gel layer was stripped by HF dipping. Figure 5 shows the imprinted wafer after structure transfer and resist stripping and demonstrates imprint uniformity and structure fidelity of the SCIL process.

(a) (b)

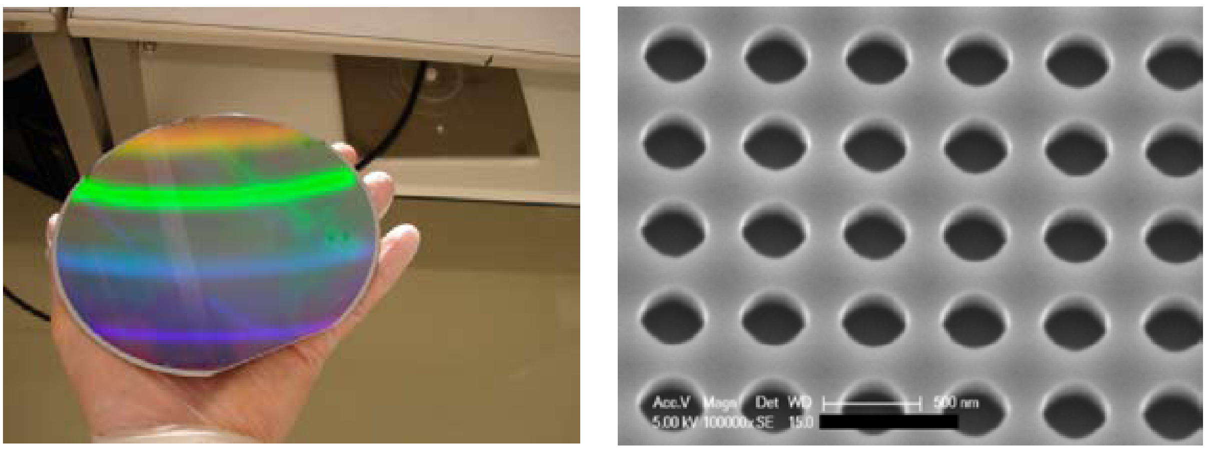

Figure 4: (a) Photograph and (b) SEM image of the silicon master with 2D holes array made by laser interference lithography and etching processes; the pitch is 513 nm; the diameter and the depth of the holes are 340 nm (±5% over 6 inch area) and 200 nm, respectively.

(a) (b)

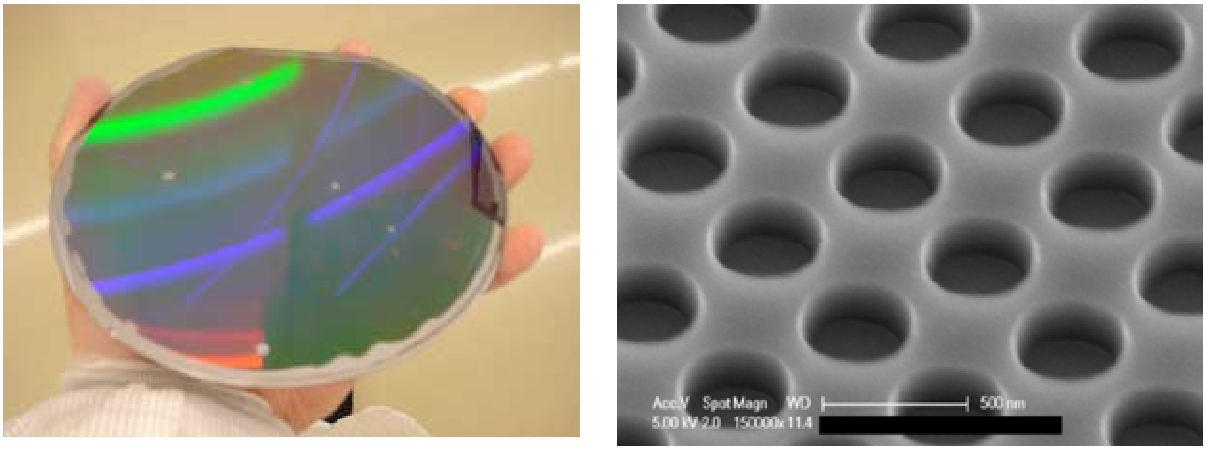

Figure 5: (a) Photograph and (b) SEM image of the imprinted wafer after structure transfer and stripping of the imprint sol-gel.

As mentioned before, the curing of sol-gel relies on the diffusion of solvents into the PDMS stamp, which is time-limiting. Depending on the operation and preparation conditions, the curing time varies from 5 to 15 minutes. In order to improve throughput and repeatability of the process, a UV enhanced SCIL process is developed and demonstrated. AMONIL (AMO GmbH, Germany) resist has been used as imprint resist for SCIL process. The needed exposure dose is 2J/cm^2 at a wavelength of 365 nm and by using a standard 1000 W lamp on Süss mask aligners the curing time is less than 3 minutes. Figure 6 shows SEM images of imprinted structures in AMONIL resist layer and the transferred structure in silicon substrate. The structure depth and the residual layer thickness were 170 nm and 36 nm, respectively. The residual layer was removed by RIE with HBr gas and the structures were transferred into silicon substrate to a depth of 125 nm by RIE. The remaining resist layer was still 65 nm. In order to investigate the imprint uniformity, over 6 inch area of the imprinted wafer, the structure depth, residual layer thickness and the pitch of 5 positions (south, north, center, west and east) were measured by SEM. The results are listed in Table 1. The pitch of the periodic structures varies from 513 nm to 515 nm. The structure depth and residual layer thickness have variation of ± 3.5 nm and ± 2.5 nm, respectively. If we consider the measure tolerance of the SEM and the variation of the initial resist thickness caused by spin-coating, the SCIL process in AMONIL resist shows excellent imprint uniformity and therefore guarantees the fidelity of structures transfer. The same imprint process was also carried out on quartz, sapphire and GaN substrates. The resist exhibited excellent adhesion on these substrates and the stamp separated without problems from the cured resist. An important benefit from UV-curing is the significant increase in throughput compared to sol-gel processes.

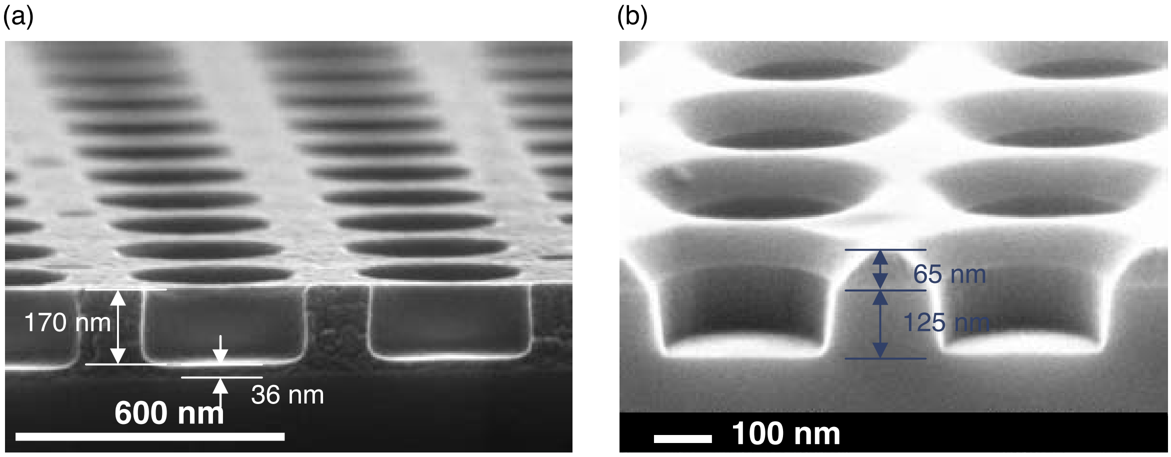

Figure 6: SEM images of (a) imprinted structures into AMONIL resist, the structure depth is 170 nm and the residual layer is 36 nm; (b) bird-view after removal of residual and structure transfer into Si substrate for 125 nm by RIE, the remaining resist thickness is 65 nm.

Table 1: Imprint uniformity

	south	north	center	east	west	variation
Pitch (nm)	515	513	515	513	513	± 1
Structure depth (nm)	167	169	170	165	172	± 3.5
Residual layer (nm)	35	40	36	38	35	± 2.5

Considerations for the introduction of SCIL into LED fabrication

Two key parameters have to been fulfilled in order to successfully introduce a NIL process into high volume LED manufacturing: CoO and repeatability.

The multilayer stamps used in SCIL process are replications from an original master, which is fabricated by advanced lithography and etching techniques. From such a master, countless working stamps can be replicated and there is no lifetime limitation of the working stamp observed. In this way millions of wafers can be imprinted from a single master template and the CoO of stamps is therefore minimized for mass production.

The 2D PhC structures for the HB LED wafers are desired to be hole arrays, which requires an array of protruding structures on the working stamp and therefore hole arrays on the master template. This makes the master fabrication with Electron-Beam-Lithography or Laser-Interference-Lithography quite comfortable since complicated lift-off processes can be avoided, which can lower the fabrication cost as well. In addition, the 2D protrusions array on the working stamp is very process-friendly during mastering due to its uniform structure density distribution.

Repeatability is another key parameter for successful process industrialization. By using rigid stamps on UV-NIL steppers or full-field UV-NIL machines, particles in the atmosphere or III-V growth defects are unavoidable, will lead to permanent stamp damaging and additionally wedge errors and/or areas where no contact is made. The composite stamp design used with SCIL is insensitive to these particles and defects. The soft PDMS layer can locally deform around particles on the substrate or stamp surface and therefore minimize the defect areas (Figure 7). This contact of the particles with the structures on the stamp will not lead to stamp damages since the flexible stamp can deform elastically.

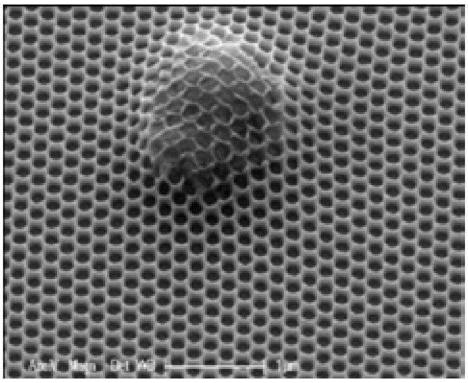

Figure 7: SCIL imprint over a particle. Even the particle has been patterned.

Conclusions

In this paper, a revolutionary NIL technique, SCIL, and the corresponding tooling solution on SUSS mask aligners has been introduced. The imprints of 2D holes array over 6 inch area in sol-gel and AMONIL resist with soft PDMS stamp have been demonstrated. The structure depth and residual layer uniformity have been evaluated by measurements on the imprinted wafer. The capability of the UV enhanced SCIL process in AMONIL resist on different substrates has also been demonstrated. The unique consequently imprint principle and the composite stamp guarantee the conformal imprint and the compatibility for production atmosphere. This technique shows therefore great potential in high volume production of HB LED due to its excellent reliability.

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