High potential of Nanoimprint Lithography for LiDAR application

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ABSTRACT

In the European TINKER project, which pushes the development of LiDAR (Light Detection And Ranging) technology, NIL has been explored with the aim of improving manufacturing of the optical structures. More specifically, the main idea is to use NIL to manufacture the waveguide structures of the PIC chips for LiDAR. With this objective, the four partners closely involved in NIL: CEA-Leti, PROFACTOR, EV Group and Inkron, pooled their expertise and demonstrate the high potential of this technique.

This study led to the development of a new imprintable material with a high refractive index. Moreover, specific designs linked to the application and investigating the NIL physicals phenomenon were manufactured. The combination of both, material and design allowed to prove the capability to manufacture waveguide with NIL using the specified index material. The study was completed with optical functional tests. Furthermore, global manufacturing approach was studied and demonstrating the sustainability of NIL manufacturing and its ability to reduce manufacturing time and cost.

Keywords: Nano Imprint Lithography, NIL, LIDAR, Photonics

1. INTRODUCTION

LiDAR (Light Detection And Ranging) technology is becoming increasingly used in the automotive field[1], especially for autonomous driving. Multi-angle LiDAR is now necessary to obtain a complete environment map. However, the first concepts, installed on top of cars, occupied nearly one square meter[2]. The market is preparing to include LiDAR in front lighting[3], but devices still need to be produced. In this context, TINKER, a European project, serves as a bridge between automotive needs and semiconductor manufacturing systems. The automotive field includes specific constraints, whereas semiconductor manufacturing includes significant knowledge in integration, particularly for Photonic Integrated Circuits (PICs).

This study focuses on a specific part of the TINKER project called “additive manufacturing.” It proposes using different techniques to create devices, including cost reduction. NanoImprint Lithography (NIL) is one of the promising technologies to address this. NIL was discovered a few decades ago[4,5]; however, its wider utilization at an industrial level has occurred only recently[6,7]. The main idea is to use NIL to create optical systems such as waveguides on devices.

Since NIL replicates structures already present on an initial substrate called the “Master,” the first part of this study focuses on the manufacturing of the master. This includes various device tests but also takes into account NIL constraints. In the second part, the results obtained in terms of manufacturing as well as optical tests are discussed. Two main approaches are explored: firstly, the replacement of standard photolithography by NIL coupled with an etching step, and secondly, the use of NIL as additive manufacturing with functional resist.

2. MASTER MANUFACTURING

In this work a dedicated masters were manufactured, one of them is visible on Figure 1.a. These masters offer the possibility to use different kind of material for making the waveguide. Indeed, index of material used is essential for light coupling and propagation, as the material was not fully developed at the beginning of the study we chose to modulate the structure size to allow working with a specified couple of optical index. To performed this, two main parameters were taken into account. Firstly, the fact that test will be performed without cladding, thus the external optical index will be the air ones. Secondly, the IR laser used works with a wavelength of 1500 nm. Then three widths of waveguides have been set with five variations of coupler structure, as visible on Figure 1.b. An optical zoom of a set of structures is visible on Figure 1.c.

Moreover, we already know that structure resist filing is a challenge for the NIL thus we placed dummy structures in specific areas, as visible on Figure 1.d, to manage density without disturb light propagation. Four different case were set on design.

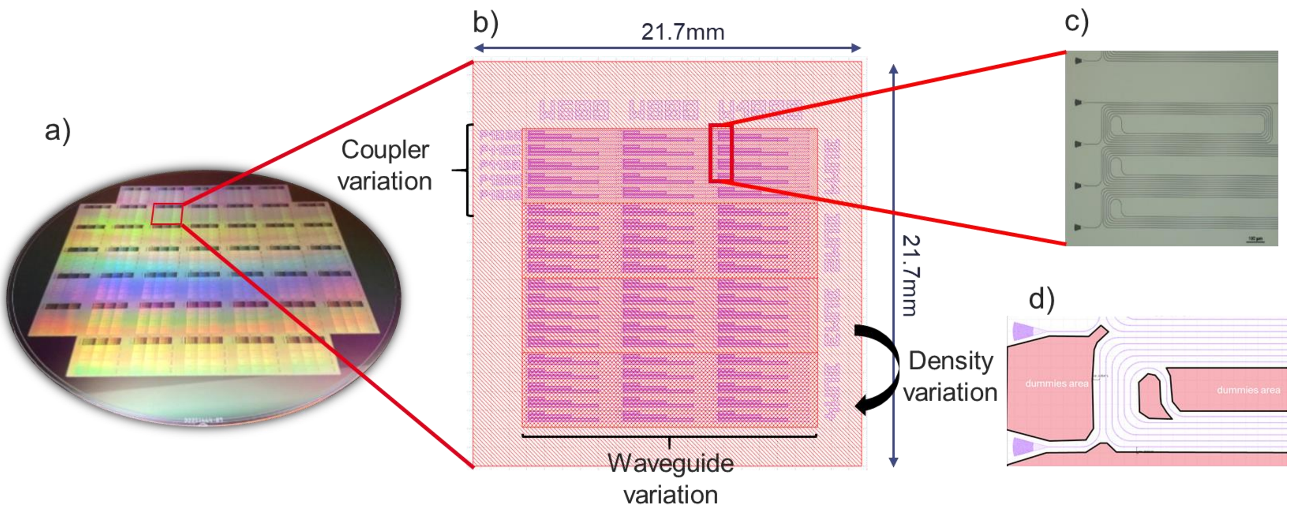

Figure 1 : Dedicated Master and associated design, a) master picture, b) design of one field, c) optical microscope picture on structure, d) part of design with dummies structure highlighted

3. NIL SETUP RESULTS AND DISCUSSION

In this study the different partners used their own developed processes and equipment, all of them are based on soft UV NIL technology. Some tests were performed at sample level but the final one and result presented correspond to wafer-scale imprinting.

Two approaches were tested, firstly the "Litho-etch" approach consist to replacing the standard lithography step by NIL while keeping all subsequent steps such as etching of substrate and stripping to obtain final structures. The second approach, which could be considered as additive manufacturing, consists of performing NIL on functional resist provide by INKRON, which will constitute the waveguide.

Litho-Etch approach

In this approach, the first replication was performed using our reference process. This process induces defects, more specifically a significant amount of resist along the waveguide, as shown in Figure 2.a. After different tests where we changed the contact speed between the stamp and the resist, as well as the orientation of the substrate, we obtained an optimized process that avoids this resist overage as visible in Figure 2.b.

One can see on Figure 3 that the different imprint structures are well defined. More especially, in Figure 3.a, we can see that all structures are filled without any bubbles or voids. In Figure 3.b the waveguide structure is correctly defined with, a flat part on top and a residual layer at bottom, which is maintained between 50 and 70 nm. The total structure height of 336 nm is consistent with master. Finally, the most critical structure, the coupler, is congruent to the master without any bridges inside the grating, as shown in Figure 3.c.

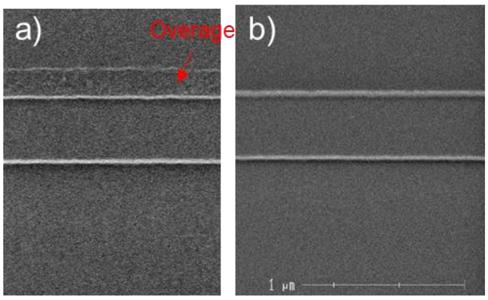

Figure 2 : Waveguide manufacture with NIL, a) without optimization overage resist is visible, b) after optimization waveguide is correctly defined

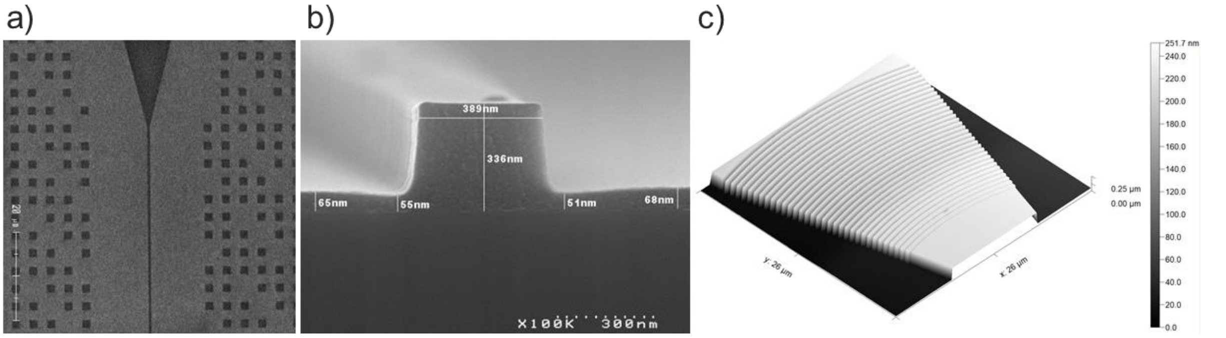

Figure 3 : Imprint result obtained on standard resist, a) SEM top view of waveguide with dummy structure, b) SEM cross-section view of one waveguide, and c) AFM measurement of coupler

In this approach, etching was performed in two steps. Firstly, a sub-step to remove the residual layer, which led to a slight reduction in structure height, is applied. Secondly, the etching of silicon. One can see on Figure 4 that after this etching, structure obtained have two different edge slopes, which lead to a top width of 380 nm, a mid-width of 420 nm, and bottom width of 450 nm. Moreover an overetch of 19 nm is visible at the bottom of waveguide. Finally, the residual resist of 42 nm, on top of the pattern, will be removed with a stripping step. Figure 4 shows a control silicon wafer; the actual device was manufactured on SOI wafer with same etching and stripping recipes.

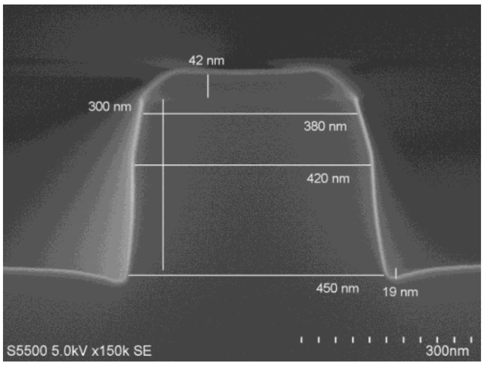

Figure 4: SEM cross-section of waveguide etch on silicon before the stripping step

Automated characterization of coupling/waveguide losses is performed at the wafer scale on a modified CASCADE probe station. Grating couplers are used so that light can be coupled from fibers placed almost vertically to the wafer surface, avoiding the need for optical access to the chip edge as visible in Figure 5.

The transmission spectrum of the test structure is compared with a parallel shunt to determine account for losses within the experimental setup, as visible in Figure 5. Different lengths of waveguides between the input and output couplers allow the waveguide propagation losses and the coupling losses to be separately evaluated.

Tests are repeated on a large number of optical dies over the wafer surface to obtain statistical information concerning fabrication variations. The different results are summarized in Table 1.

On can see in this same table that coupling loss is quite similar between standard sample made with photolithography and one made by NIL. The central wavelength obtained with NIL sample is shifted probably due to an overetching of the structure close to 20 nm. Finally, we can highlight that propagation loss is 17% less with NIL than photolithography. We assume that it could come from shape variation and also mitigation of high frequency roughness, as mentioned in another paper[8].

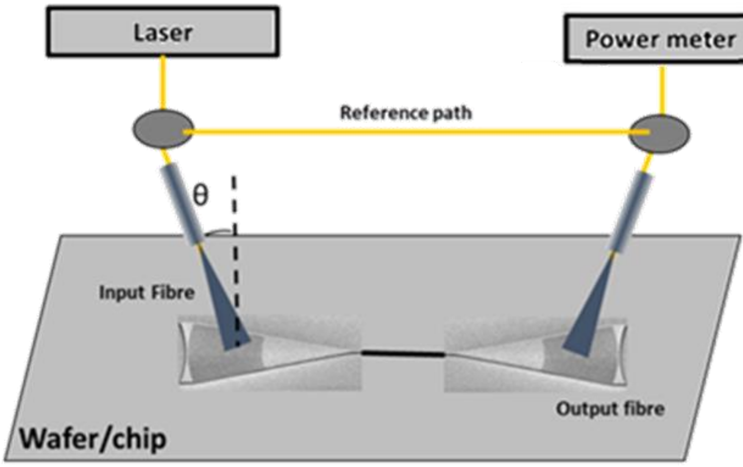

Figure 5 : Principle scheme of optical test setup

	Coupling Loss (dB)		Central Wavelenght (nm)		Propagation loss
Lithography	**Mean**	**3σ**	**Mean**	**3σ**	**(dB/cm)**
Optical	-2.4	0.2			1.2
Imprint	-2.2	0.1	1521	17.02	1

Table 1 : Result obtained on structure manufacture with standard photolithography "Optical" and NIL "Imprint"

Full additive manufacturing

The second approach, named in this case "full additive manufacturing", starts with flow inspection. Indeed, we manufactured in the previous part the "coupler structure" and the "rib waveguide"; nevertheless, global device includes, for optical operation, two other patterns: the "strip waveguide and the "free space coupler", which are both at different depths but also in core material as visible in Figure 6 with the real light management level of LiDAR application. Thus, the main idea was to establish that we can, thanks to additive manufacturing and more especially NIL, manufacture these four kinds of patterns at the same time.

On one hand, standard approach needs 15 steps to manufacture the global structure. This includes different: deposition (used as hard mask), photolithography, etching and stripping steps. On the other hand, NIL can replicate these structures in one step on functional resist, i.e. material which will be used as core material, and residual layer obtained could be removed if necessary with a quick dry etching step. Therefore, this approach could create the optical part of the device with only 2 steps, which represent an 80% decrease. This factor could be applied at the same time to cost, manufacturing time and ecological footprint.

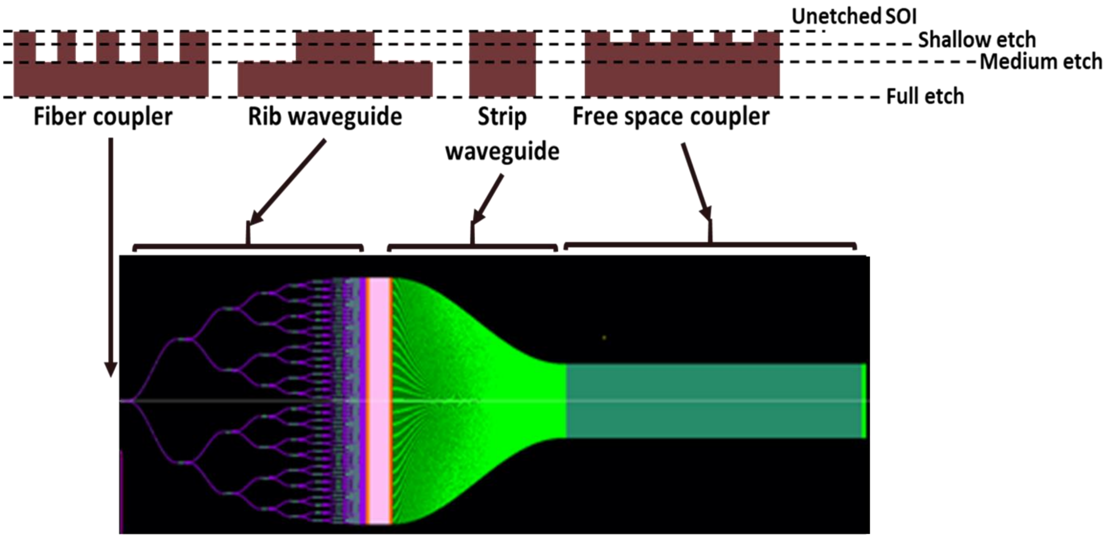

Figure 6 : Global scheme of light management level of LiDAR application,
with the different subsystem in cross view, all this element are made of same material

To be valuable, this approach must be coupled with the used of a specified material index. Indeed, the standard resist index is close to 1.4 which is not enough to be used as waveguides core material. In this study, INKRON developed a UV-curable and imprintable material with an index close to 1.9 at wavelength used as visible in Figure 7.C. This material also has good transmittance, as visible in Figure 7.C, which is essential for LiDAR applications. Moreover, the thickness coated can be easily adjusted, as mentioned in Figure 7.A.

Nevertheless, the first imprint of this new material showed difficulty in correctly filling the structures, i.e., voids were present in the structure. This led to the use of a large amount of resist, which then induced a higher Residual Layer Thickness (RLT). Although dummy structure areas were foreseen the RLT obtained with a significant amount of resist was too variable, as visible in Figure 8.a. To improve this, the design could be modified, which would require manufacturing a new master, or the resist deposition process could be changed. This last solution explained in Figure 8.b is compatible with this new material, as demonstrated by the partner with different droplet tests visible in Figure 7.b. However, using inkjet resist with NIL remains a challenge in terms of tooling. Managing both the resist amount and pattern density must be performed on the same equipment or on tools that can align the wafer precisely to guarantee local concordance between structures and resist amount.

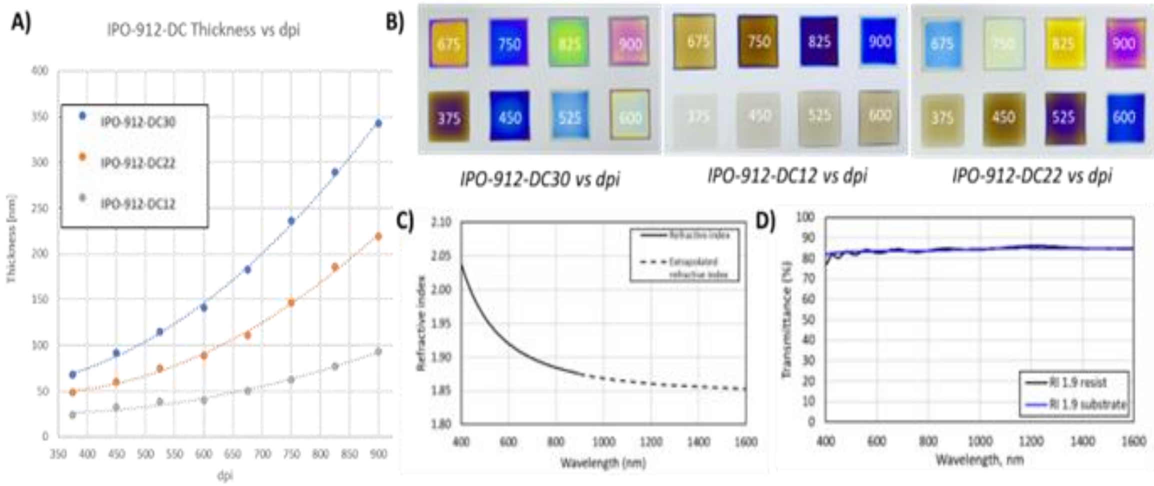

Figure 7 : Resist developed by Inkron wish a) thickness information,
b) optical imaging, c) refractive index and d) transmittance results

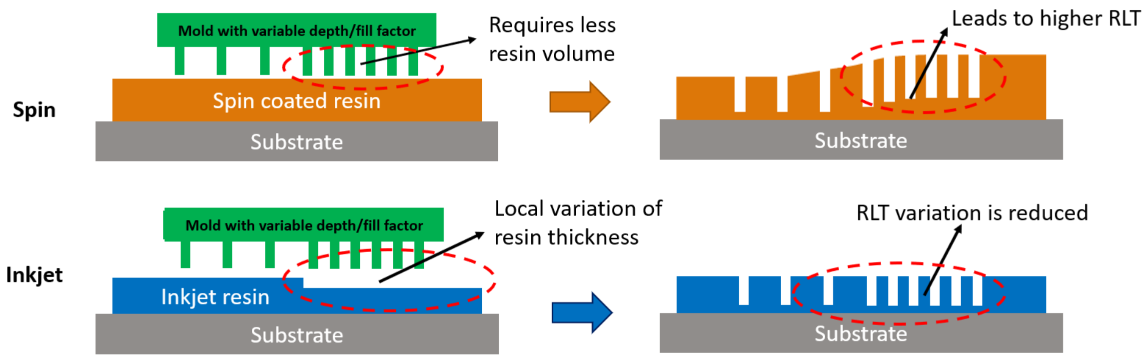

Figure 8 : Resist layer illustration with on top spincoating technology and on bottom inkjet technology.

4. CONCLUSION AND PERSPECTIVES

In this work, we obtained quantitative results, which show the high potential of NIL for optical applications. Indeed, the results obtained are better than those obtained with standard lithography, especially in terms of light propagation loss. We also developed a demonstrator which proof that light could be coupled into waveguides made by NIL, travel through these waveguides, and be decoupled on demand.

A specific resist was developed to push this approach further with full additive manufacturing. We demonstrated that the use of this kind of approach could have a significant ecological impact and could also lead to time and cost savings.

Some challenges remain, such as the correct filling of structures. Although specific structures were placed in the design, it was not sufficient. A specific way inkjet technology was therefore opened; the resist developed in this project could be used with this technique.

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