Microelectronic Engineering 86 (2009) 321–324

Contents lists available at ScienceDirect

Microelectronic Engineering

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

Applications of UV-nanoimprint soft stamps in fabrication of single-frequency diode lasers

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ARTICLE INFO

Article history:
Received 10 June 2008
Received in revised form 23 September 2008
Accepted 19 October 2008
Available online 1 November 2008

Keywords:
NIL
DFB-laser
UV-NIL
Nanoimprint lithography

ABSTRACT

We show how to use a modified poly-dimethyl-siloxane (PDMS) soft stamp to reduce pattern deformation and residual layer thickness in soft UV-nanoimprint lithography. A soft stamp thinned with toluene reduces the residual layer of a resist by as much as 50% compared to an unthinned stamp. We apply the soft UV-nanoimprint to prepare nanopatterned waveguides for a single-frequency diode laser. This laser operates with a side-mode suppression ratio of 50 dB, which indicates that the patterns are precise and uniform over the whole imprint field. To the best of our knowledge, this is the first single-frequency laser fabricated by soft UV-nanoimprint technology.

1. Introduction

Nanoimprint lithography (NIL), is a next-generation technology for patterning narrow linewidths on a substrate at low cost and high throughput [1]. Its resolution is not limited by the wavelength of light, and a single template can be used to accurately replicate a pattern from wafer to wafer. Soft, flexible stamps have many advantages over other types of NIL-stamps. For example, soft stamps conform to the shape of the substrates, enabling full-wafer imprints. Moreover, the wafer and the flexible stamp can be separated from each other with a minimal force. Soft UV-NIL also replicates patterns with an extremely high resolution (≈2 nm) [2].

A key characteristic in NIL is the formation of a residual layer on imprinted areas. This residual layer has to be removed after the imprint step. If this layer is too thick, a substantial loss of dimension may follow. We investigated modified soft stamps for reducing the thickness of the residual layer. The PDMS stamps are modified to make them effectively harder by thinning the PDMS with toluene, and backing the thin PDMS layer with glass. Earlier studies have shown that the PDMS–toluene mixture fills small cavities more easily than undiluted PDMS, due to the reduced viscosity of the modified PDMS [3,4]. We show how the effective hardness of the stamp and the viscosity of the resist affect the thickness of the imprinted layer.

In our stamp, a thin glass plate was sandwiched between a 2 mm thick (soft) PDMS carrier layer and a thin patterned PDMS layer. By diluting the patterned PDMS, different layer thicknesses are achieved. As the thin patterned layer is backed by an inelastic glass plate, we can modify the effective hardness (vertical spring constant) of the stamp. This leads to improved process results. When comparing NIL-resists with different viscosities, it was found that an effectively harder stamp can take advantage of the reduced viscosity of the resist, as the stamp is less prone to deformation. Importantly/critically, the glass layer also prevents lateral deformation of the structures, which is sometimes associated with soft stamps; any transverse bending or stretching of the patterns is harmful when fabricating precise photonic structures.

We applied soft UV-NIL to demonstrate a longitudinally single-mode distributed-feedback (DFB) laser with a high-aspect-ratio grating along the sidewalls of a narrow ridge (Fig. 1). A similar laterally coupled grating has been reported earlier using traditional lithography methods [5–8]. This approach needs no regrowth on the top of the grating layer, in contrast to present day DFB lasers. The process is easily scaled in wavelength as it requires only tuning of the grating period and tuning of the etching process. The external nano-scale grating and the micro-scale optical waveguide are printed simultaneously, which guarantees perfect alignment of these features.

2. Nanoimprint lithography and stamp fabrication

GaAs and InP substrates for optoelectronics applications are typically 2″ or 3″ in diameter. If a flexible stamp is used, the whole wafer can be patterned with a single imprint step [9]. Due to the

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doi:10.1016/j.mee.2008.10.010

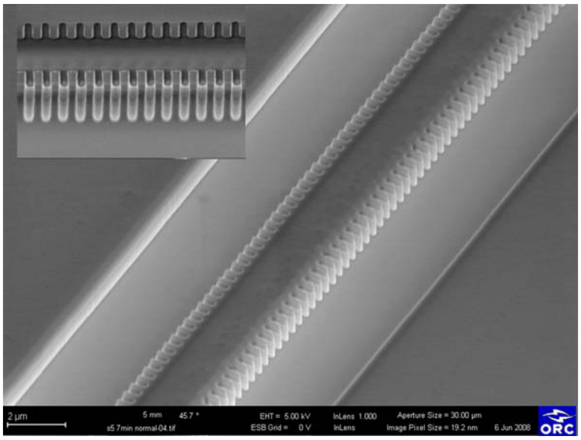

Fig. 1. SEM image from a corrugated waveguide etched into an epitaxial structure. The etch mask is still in place. Insert: waveguide imaged from side.

difference in lattice constants of the epitaxial layers, the wafers tend to curve, making large-area imprints with a non-flexible stamp almost impossible; the strain-induced curvature for 3″ epi-wafers may be several tens of micrometers.

GaAs and InP are fragile wafers, so the stamp must be gently detached from the wafer. A non-flexible stamp requires insertion of a sharp edge between the stamp and the substrate, while a flexible stamp can be gently peeled off the wafer. The pressure needed to make the imprint by soft UV-NIL is low, less than 0.5 bar. Softness of the stamp is an advantage, in particular, if the wafer is locally non-planar; for example if dust particles are present. With a too hard stamp, small particles prevent proper contact between the stamp and the substrate.

There are also economic reasons favoring the use of soft stamps in diode laser fabrication. The main method for micro-patterning lasers is contact UV-lithography. Many modern UV-contact aligners (such as *EV Group EVG620* and *Suss Microtech MA6*) support full-wafer NIL with soft stamps. Additional investment in NIL tooling is a low-cost solution compared to the purchase of a stand-alone NIL system. Moreover, UV-lithography is in any case preferred in other lithography steps in the manufacturing process. A template made by electron beam lithography (EBL) is replicated on the soft stamp which, in turn, is used to replicate the pattern on the substrate wafer. Throughput of full-wafer NIL is 10–20 wafers an hour. This is considerably higher than with direct EBL.

Our NIL templates were processed on silicon-on-insulator (SOI) wafers by EBL (at *XLith GmbH*). These wafers allow for accurate depth control of silicon etching. This application had a 225 nm linewidth, and to keep the aspect ratio around 0.7 we chose a silicon layer thickness of 175 nm. The insulating layer of the SOI stops etching at precisely the same thickness over the whole area. An anti-adhesion layer on the template can be formed, e.g., using 1H-, 1H-, 2H-, 2H-perfluorodecyl-trichlorosilane (FTDS) in vapor phase, as we did [10].

A flexible UV-transparent stamp was replicated from the master template in a three-layer process. First, a 2 mm thick cushion layer was cast from PDMS (*Sylgard 184 – Dow Corning*). Second, a thin flexible plate was attached on the PDMS cushion using a plasma-activation method [11] which resulted in an irreversible strong bond between the glass and the PDMS. Third, a thin layer of hard-PDMS (or h-PDMS) mixed according to the recipe of Ref. [12], was spin-coated onto the template. The cushion with the thin glass was then brought into contact with the master template, and the h-PDMS-layer was cured. We thinned the h-PDMS with toluene, as we expected that as the thickness of the h-PDMS is decreased, the effective hardness of the stamp is increased. By varying the relative proportion of toluene and the spin speed, different thicknesses (and effective hardnesses) were obtained. We compared two layers; first undiluted h-PDMS spin coated at 1000 rpm, and second a modified layer (toluene 33 mass%) coated at 4500 rpm. The achieved layer thicknesses were 30 μm for undiluted h-PDMS and 5.5 μm for diluted h-PDMS.

The waveguide and the grating were defined by etching a narrow corrugated pool on both sides of the waveguide, as illustrated in Fig. 1. A polarity-reversing process (lift-off) was used to define the etch mask for the pool. The centre-to-centre spacing between the ridges was 300 μm and the width of the pools was 4 μm. We note in passing that imprinting with an unthinned stamp was non-trivial. Deformation of the h-PDMS layer and limited resist flow caused imperfections in the imprint result. Our imprint tests were carried out with an EVG620 mask aligner equipped with a 3″ NIL tool. The stamp area was 25×25 mm^2, the imprint pressure was 0.3 bar, and pressure was applied 10 min before curing. An exposure dose of 2 J/cm^2 was used in all experiments.

We compared two stamps having different h-PDMS layer thicknesses (a 30 μm layer and a toluene-diluted 5.5 μm layer) and two resists of different viscosities *AMONIL* and *mr-UVCur 06. AMONIL* (from *AMO GmbH*) has been extensively employed with PDMS stamps because it does not suffer from oxygen-inhibited curing. However, *AMONIL* has a relatively high viscosity of 50 mPa·s compared to *mr-UVCur 06*, which has a viscosity of 14 mPa·s (supplied by *Micro Resist Technology GmbH*). In our preliminary tests *mr-UV-Cur06* exhibited no adverse effects due to formation of an oxygen-inhibition layer.

The cross-section of the imprint was inspected by atomic force microscope (AFM) and then compared with the template. The imprint quality was verified by an optical microscope and a scanning electron microscope (SEM). An ellipsometer was also used to measure the thickness of the spin-coated layer and the imprinted resist layer between the waveguide structures. AFM inspected imprint profiles were identical across the imprint field.

We chose two parameters from AFM graphs to quantify imprint quality. Parameter "etch margin" describes the difference in height between the lowest non-imprinted area and the highest imprinted area. Stamp bending quantifies the degree to which the stamp bends near the waveguide compared to the flat, nondeformed, area between waveguides. Fig. 2 illustrates how the parameters "etch margin" and "stamp bending" are defined. The surface level at both edges of the micrograph was the same as the level of the virgin spin-coated and cured layers. The thickness of the residual layer of the imprint was always equal to the thickness of the spin-coated and cured layer due to the low density of patterns. It was important to minimize the thickness of the residual layer, as etching of this layer could otherwise lead to a loss of accuracy in lateral dimensions. A high etch margin increases the process latitude in the subsequent etch steps. Figs. 3 and 4 illustrate how these two figures of merit behave as a function of residual layer thickness.

The stamp bending is minimal when the resist layer is thick, since a deep channel between the stamp and the wafer promotes a lateral flow of resist and, therefore, distributes the pressure evenly. Under these conditions an ideal imprint is achieved. A cross-section of such an ideal case is shown in Fig. 2, line 1a. When the channel depth decreases, the stamp bending increases, as the resist is only collected from the vicinity of the pattern. The flow of resist creates an area which is partially depleted of resist. In this case the stamp is pressed too deeply, and stamp bending becomes significant. An example of an imprint profile suffering from large bending is illustrated in Fig. 2, line 1b.

Beyond a certain limit, reduction in resist thickness starts to reduce the bending of the stamp. In this case the lateral flow of the resist is so limited that it does not consume resist near the pattern; the resist can only flow within the pattern. This is, however, a poor