Microfabrication Using Silicon Mold Inserts and Hot Embossing

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Abstract— We have successfully demonstrated the feasibility of fabricating three-dimensional microstructures by using a combined silicon mold insert and micro hot embossing process (SMIHE). Anisotropic silicon wet etching process has been used to define microstructures on top of a four inch silicon wafer. The whole wafer is then used as the mold insert in a micro hot pressing machine to duplicate plastic microstructures repeatedly. Fine micro pyramid shape microstructures with base width of 30 μm and height of about 21 μm have been fabricated by this method as a demonstration. They have very smooth surfaces and may be suitable for optical applications. This new process shows promise for achieving high yield, reliable fine micro structures on plastic films.

I. INTRODUCTION

The modern microfabrication process started when the integrated circuit (IC) technology was first introduced in the early 1960s. Batch fabrication is the key factor for the success of IC process. Nowadays, IC devices have been batch fabricated and sold with prices that other technologies can not compete with. Mechanical engineers, on the other hand, have developed technologies like injection molding and hot embossing process to duplicate plastic structures which have been used in our daily life, from drinking cups to frames of computers. Both of the IC technology and injection molding or hot embossing processes have a similar function — to reproduce products quickly and massively.

Recent development of MEMS (Micro Electro Mechanical Systems) has basically followed the success of IC technology and injection molding/hot embossing processes. Silicon micromachining uses silicon as a mechanical material [1] and IC compatible processes have been used or modified to make fine microstructures for applications in different areas. LIGA process [2], which uses X-ray lithography, electroplating and molding process to fabricate microstructures is one of the applications among many others to use injection molding or hot embossing process for

fabricating micro parts. One of the possibility is to use silicon micromachining process and combine it with molding process to fabricate microstructures.

Previously, diamond precision machining has been used for making micro cars [3], micro channels or micro pyramids [4]. However, it is difficult to maintain the surface roughness of microstructures made by these mechanical machining methods. A DEEMO (Dry Etching, Electroplating and MOolding) process which uses dry silicon etching process, electroplating process and moulding process to make deep three-dimensional structures has also been developed [5]. In this paper, anisotropic silicon etching process is used to make fine microstructures on silicon wafer which is then used as mould inserts in the hot embossing process to make plastic microstructures. In case of isotropic silicon etching, this combination has recently been applied for the fabrication of microlenses [6, 7].

II. DESIGN AND FABRICATION

A. The SMIHE Process

The SMIHE (Silicon Mold Insert Hot Embossing) process consists of two major steps: the silicon mold insert and hot embossing as shown in the left hand side and right hand side of Fig. 1, respectively. First, silicon wafer is gone through the lithography process by using the standard UV light exposure as seen in Fig. 1 (a). The patterns on the mask are then transferred onto the photoresist on top of the silicon wafer. Silicon micromachining process is then followed by either dry etching or wet etching processes to make three-dimensional microstructures into the silicon wafer. Fig. 1(b) applies after these steps. The masking material is then removed and the wafer has patterned microstructures on top now as shown in Fig. 1(c). The whole silicon wafer is then used as the mold insert in a hot embossing machine as illustrated in Fig. 1(d). Plastic material which generally has transition point at medium temperature is then used for the hot embossing process. The fine micro patterns are transferred onto the plastic material and this hot embossing process can be re-

Figure 3: An optical photo showing a portion of silicon mold insert.

small bubbles and incompletely filled pyramid tips. Step-wise increasing temperature and force up to 200°C and 10 kN yields better results. Finally we realized nearly perfect micropyramids by varying also the molding time under optimum temperature and pressure conditions. The high molding forces we introduced arose a new problem in the demolding process : for small forces demolding takes place automatically upon cooling to room temperature. In the case of high molding force, this was no longer sufficient. We had to apply temperatures around 0°C and introduce a water film between mold and polymer making use of the additional capillary forces exerted in this way. With a small number of tests, we achieved a parameter definition which was sufficient for the experiments described here. On the other hand, fine tuning of the process conditions will be necessary to obtain perfect molding results.

III. FABRICATION RESULTS AND DISCUSSIONS

Showing in Figure 3 is an optical micrograph with pyramid structures made on the surface of a silicon wafer. This micro photo is focused on top of the silicon wafer and pyramid shapes inside the silicon can be barely observed. The size of these pyramids is $30\text{ }\mu\text{m}$ on each side and about $21\text{ }\mu\text{m}$ in height into the silicon. The correspondent angle at the top of the pyramid is about 70° due to the silicon anisotropic etching process. The space from one pyramid to another is about $2\text{ }\mu\text{m}$, although better width control can be achieved if the lithography step can be improved.

Figure 4 is a SEM microphoto showing a portion of the silicon mold insert. On this particular portion, there are defects due to improper lithography and the later sil-

Figure 4: A SEM microphoto showing the silicon mold insert with defects.

Figure 5: Reflected microstructure made of PMMA material by the SMIHE process.

Figure 1: The schematic diagram of the SMIHE process.

peated to duplicate fine plastic microstructures as shown in Fig. 1(e).

B. Silicon Mold Inserts (SMI)

The silicon mold insert described here was designed and manufactured in the laboratory of Institute of Applied Mechanics, National Taiwan University, Taiwan. In our try out process, only one mask has been used to make 3-dimensional microstructures on top of silicon wafers for mold inserts. Anisotropic silicon etching technique [8] is used to make these microstructures including V-groove microchannels and micro pyramid structures. The minimum width used in the mask is $2\mu\text{m}$ and the whole four-inch wafer is divided into several areas with size of one centimeter square. Each area has same pyramid arrays with base width of either $100\mu\text{m}$ or $30\mu\text{m}$.

Figure 2 shows cross sectional view at the conclusion of key process steps. In the first step of the process, a (100)-oriented lightly doped silicon wafer is put on a masking layer which is thermally grown SiO_2 as shown in Fig. 2(b). The single mask is then used to define the pattern by using a $1\mu\text{m}$ thick resist. The unwanted silicon dioxide layer is then removed by using HF solution as seen in Fig. 2(c). The wafer is then put into 80°C KOH liquid for anisotropically etching silicon until the pyramids are formed into the silicon wafer. After these steps, Fig. 2(d) applies. The final step is to use HF solution to remove all the SiO_2 layer and the final structure is shown in Fig. 2(e).

Figure 2: The process sequences for the silicon mold insert.

C. Hot Embossing (HE)

The silicon mold described previously has been used for hot embossing experiments which were performed together with and within the plastic molding group of the institute for Microstructure Technology of the Research Center Karlsruhe, Germany. The mold insert with pyramid microstructures to be duplicated has been mounted into a hot embossing machine which is normally used for molding LIGA-microstructures. We applied a $300\mu\text{m}$ thick PMMA sheet which was placed on top of the silicon mold. Hot embossing takes place under vacuum ($\sim 0.1\text{ mbar}$) to realize complete filling of the mold with PMMA. After evacuation the mold is heated up to the molding temperature which lies above the glass transition temperature of the polymer. Higher temperatures are favourable because the lower viscosity of the PMMA facilitates the molding process. After molding, the polymer is cooled down to below the glass transition temperature. Molding force will be maintained during cooling in order to preserve the PMMA microstructures from shrinking. As soon as the predetermined temperature has been reached, the microstructures can be demolded from the mold insert. For every mold insert with different microstructures, the adequate hot embossing parameters like force, temperature and time have to be determined. To avoid thermal and mechanical damage of the sensible silicon mold, we started at low temperature and minimal forces. Observation of the result under an optical microscope revealed

icon wet etching process. We have taken microphotos of this area on both the silicon mold insert and the hot embossed PMMA structure intentionally to examine the SMIHE process. Shown in Fig. 5 is the SEM microphoto of the PMMA microstructure fabricated by the SMIHE process. Figure 5 looks like the reflected image of Fig. 4 and these two figures demonstrate the excellent reproduction capability of our process. Several individual pyramids on both the silicon mold and the PMMA final product have been examined as marked 1 to 5 in both figures. This examination has further shown exact one to one match between the silicon mold and the plastic products.

The oblique view of an SEM micrograph shown in Fig. 6 is the array of plastic micro pyramid structures made by the SMIHE process. The quality and repeatability of the process can be demonstrated by this figure. Figure 7 shows the close view of a plastic pyramid structure seen in a SEM micrograph. The small white bar on the right hand side corner represents the scale of only $5\ \mu\text{m}$. It is clearly observed in this photo that the surfaces of these micro pyramids are extremely smooth and no defects can be identified. The excellent quality of the surface is important for optical applications and this fine result comes from both the fabrication of the silicon mold insert and the hot embossing process. Despite the optimization of the hot embossing process with respect to temperature, force and molding time, in some cases, minor problems occurred during demolding, as can be seen from the slightly deformed pyramid tips in Fig. 8. The pyramid tip is completely filled with PMMA, but deformation can be recognized in the tip region. Deformation may also be in the origin of the particle which can be seen on the left pyramids face (cf. Fig. 8). This particle of only $1\ \mu\text{m}$ thickness demonstrated the very good quality which are characteristic for the surfaces of the mold as well as of the PMMA microstructure.

Shown in Fig. 9 is a whole silicon mold inserts (right hand side) and a hot embossed plastic duplicate (left hand side), respectively. The silicon wafer has size of four inches in diameter and the plastic duplicate is a little smaller than four inches due to the limitation of our lithography machine. This photo demonstrates the feasibility of making large area hot embossing process to increase the production speed.

IV. CONCLUSIONS

The SMIHE (Silicon Mold Insert Hot Embossing) process has been established in cooperation between IAM, National Taiwan University and IMT, Forschungszentrum Karlsruhe, Germany, and the capability of using a whole four-inch wafer as the mold insert has been successfully

Figure 6: An SEM microphoto showing arrays of micro pyramid structures fabricated by the SMIHE process.

Figure 7: A close view of a micro pyramid.

Figure 8: A close view SEM microphoto showing the tip of a micro pyramid is deflected.

Figure 9: A whole four-inch silicon mold insert (right) and fabricated PMMA microstructure (left).

demonstrated. In our first try out process, micro pyramids with base width of $30\text{ }\mu\text{m}$, height of $21\text{ }\mu\text{m}$ have been fabricated. The pyramids are the reflected images of the silicon mold insert which is made by using an anisotropic silicon etching process. No material shrinkage is found during the hot embossing process and the tips of the pyramids remain the original wet etching angle of 70 degrees. The surfaces of the plastic products are very smooth and may be suitable for optical applications.

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