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Fabrication of multilayer microstructures using dry film resist and deep reactive ion etcher

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Abstract: In this Letter, the authors demonstrate fabrication of multilevel microstructures using inductively coupled plasma deep reactive ion etcher (ICP-DRIE) in conjunction with dry film photoresist (DFR) as etch mask. By limiting the usage of photoresist on the layers, both the chances of introducing contamination as well as wastage of photoresist are reduced. Thus, combining DFR with DRIE in microfabricating of multilevel microstructure has the potential to significantly reduce fabrication time, cost and contamination.

1 Introduction

Over the last two decades, the design and fabrication of multilayer micro-devices and systems for biological and medical applications have experienced extensive growth [1–3]. To date, many multilayer biomedical devices have been prepared by conventional lithography and microfabrication techniques with high reliability and ultra-fine resolution. However, fabrication of multilayer biological and medical devices demands the utmost cleanliness and even contamination in the range of few parts per million can cause problems. In using conventional fabrication methods, most of the patterning processes have been carried out using liquid photoresist. It is important to note that liquid photoresist is subject to remain inside the small (edge) multilayer microstructure. Therefore these devices should be contamination free from any remaining within the photoresist. In addition to fabricated multilayer devices, a fast, more reliable and low-cost fabrication method will provide an attractive enhancement to the manufacturing process.

Numerous methods are used to fabricate micro-devices with multilevel structures such as multilayer lithography [4], laser micromachining [5] stereolithography [6], solid-object printing [7] reaction-diffusion [8] and grey-tone masking [9]. Although all the aforementioned techniques are attractive, they either use grimy liquid resist processing or expensive masks. Recently, dry film photoresist (DFR) has been demonstrated for the purpose of multilayer lithography [10]. This process significantly reduces the processing time when compared to standard multilayer lithography. DFRs were originally developed 30 years ago for printed circuit board fabrication, but application for micro-electro-mechanical systems or microfluidic device fabrication started gaining interest only recently [11, 12]. DFRs have been also being reported to be useful for fabricating electroplating moulds [13–15], sealing of fluidic channels [16], as a mask for powderblasting of microchannels [17] and in dry etching [18].

DFR is applied using dry lamination, where photoresist is evenly rolled across the surface of a wafer under controlled temperature conditions. DFRs offer several advantages over liquid resists and these include good conformability, excellent adhesion on any substrate, no liquid handling, high process speed, excellent thickness uniformity over the entire wafer (no edge bead issues), simple handling, low exposure energy, short processing time, etc. However, mould or structures fabricated using DFRs often suffer with the presence of less vertical sidewalls. In addition, attempts to etch silicon substrates masked with DFR using RIE (using O_2, SF_6 and CHF_3) have shown little improvements in achieving perfect vertical sidewalls [18].

In this Letter, the importance of combining DFRs and inductively coupled plasma deep reactive ion etching (ICP-DRIE) to generate vertical wall multilayer structures is demonstrated. In this concept, photoresist was applied only onto the targeted areas to make the multilayer structure, unlike the use of wet photoresist, whereby the entire wafer is spin coated. In this manner, minimum photoresist enters the first layer, therefore lowering the probability of contamination during the fabrication of the subsequent layers. By using this technique, wastage of photoresist is reduced significantly, thus improving the cost effectiveness of the fabrication process.

2 Experiment

All photomasks were designed using L-edit software (Tanner EDA, CA). Masks were printed onto high precision photoplates (HY2, Konica-Minolta, Japan) with a Mivatec photoplotter (Mivatec, Germany), whereas the chrome mask used was obtained from Bandwidth Foundry (Sydney, Australia). Silicon wafers of 4′ (⟨111⟩, Silicon Quest, CA) were cleaned with acetone and isopropanol followed by blow drying with N_2.

The schematic of the multilayer fabrication process opted in this work is shown in Fig. 1. The cleaned Si wafer was first heated on a hot plate to 90°C, and then the negative tone DFR (PERMX 3014, thickness 14 μm, DuPont, Singapore) was laminated over the wafer and baked for another 10 min at 120°C. After exposure, the wafer was baked for 30 min at 150°C and then developed using PGMEA for 6 min (Fig. 1*a*). This first resist layer was then used as a mask for first silicon etch step using ICP-DRIE implementing Bosch process (Fig. 1*b*). It is important to note that any traces of PGMEA will be evaporated during the etching process under high vacuum and dense plasma, making the process completely contamination free.

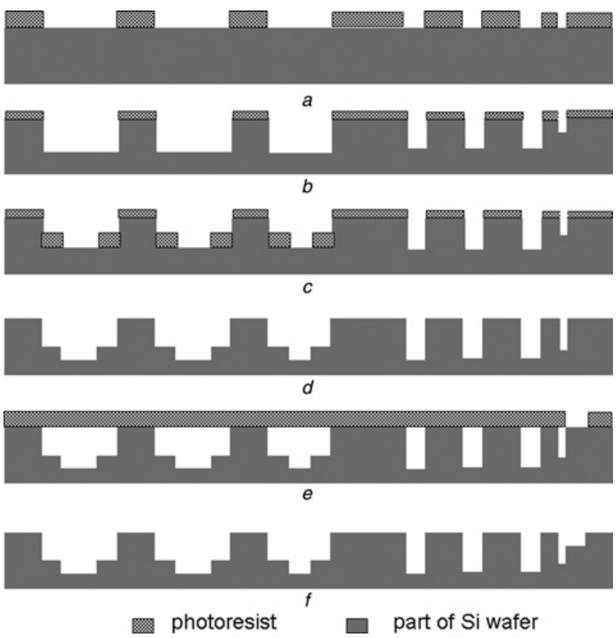

Figure 1 *Schematic of multilayer multidimensional fabrication process*

a First resist
b Si-surface after first etching step
c Second resist layer on targeted Si area
d Si-surface after second etching step
e Third resist layer
f Final multilayer multidimensional microstructure

Before the photoresist of the first layer was completely consumed during the first etching process, small pieces of dry photoresist were hand crafted and laminated on the ‘freshly etched’ targeted areas of the Si surface, under the microscope. It is important to note that to achieve faster process and high accuracy, for small area lamination, commercially available two-axis motorised stages with less than 100 nm resolution can be utilised. Similar to the process before, exposure and development were carried out to prepare another resist mask for the second etching step as shown in Fig. 1*c*. Fig. 1*d* illustrates the triple-layer pattern formed after etching. To add an additional dimension, another resist mask was created followed by another dry etching step as shown in Figs. 1*e* and *f* by using the same process as mentioned above.

3 Results and discussion

As mentioned previously, DFRs offer several advantages over liquid resists apart from significant reduction in the processing time when compared to standard multilayer lithography. In this work, DFR was applied using dry lamination, where film is evenly rolled across the surface of the wafer under controlled temperature conditions, followed by dry etching using the Bosch process. Another advantage of using DFR is that even the smallest piece of film can be laminated on small target areas (Fig. 1*c*). Furthermore, DFR showed excellent stability during the whole dry etching process. In addition to uniform thickness, DFR provides more reliable and uniform etching mask and increases both reliability and reproducibility of the process when compared to spin coating of photoresist. Spin coating of resist often depends on temperature in the processing place and density of resist.

The Bosch process is a time-multiplexed etching process, consisting of alternating passivation and etching steps by using C_4F_8 and SF_6 gases. The C_4F_8 polymerisation step deposits a uniform layer of polymer on the wafer and the SF_6 gas uses fluorine atoms to etch the Si surface. By controlling the degree of sidewall passivation, nearly perfect anisotropic etches (with 90° sidewalls) have been achieved.

The SEM images of corresponding triple-layer structure, made using the step shown in Fig. 1 are shown in Figs. 2*a*–*c*. To demonstrate fabrication of microstructures of different etch depth in a single dry etch process, etching mask of different dimensions were employed. The result shown in Fig. 2*a* clearly indicates the effect of mask dimension on etching rate. The etching rate of structures with small width is lower than that of wider structures; hence multilayer structures can be achieved. The picture in

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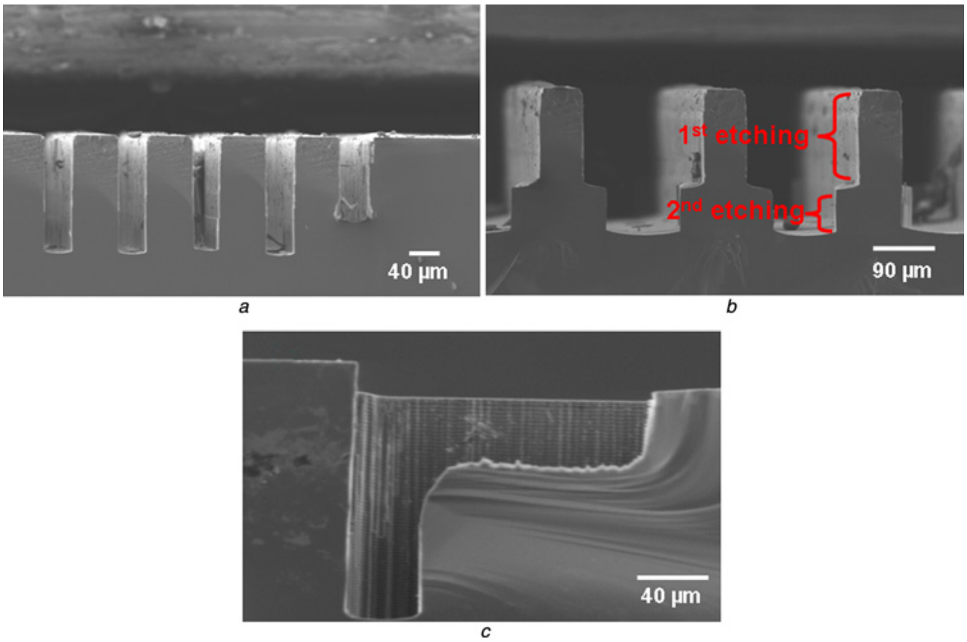

Figure 2 *SEM images of multilayer structures*
a Second etching
b and *c* Second etching but deeper structure

Fig. 2*c* shows a three-dimensional microchannel structure fabricated using the process described above. The single structure on right side in the SEM picture (Fig. 2*a*) was etched through a small dimension etch mask of DFR, whereas the remaining four structures were etched through etch masks of relatively large dimensions.

To demonstrate the simplicity of DFR in creating an etch mask at the micron level, a small piece of DFR was laminated onto the target area of 30 µm. The result of the etch product is shown in Fig. 2*b*, which corresponds to steps represented in Figs. 1*c* and *d*. In addition, to demonstrate flexibility and accuracy of DFR lamination on the target area and to add another dimension of etch depth, another round of etching was performed through a new etch mask, followed by etching. The result of the last step of etching is shown in Fig. 2*c*. As any other technique this process has some limitations, such as (i) it is difficult to achieve DFR thinner than 10 µm, hence limit its applications and (ii) laminating small areas is limited by the available alignment tools and the accuracy of the automatic stage, therefore laminating areas smaller than 30 µm, manually is challenging.

4 Conclusion

In this Letter, fabrication of multilayer microstructures by using DRIE in conjunction with DFR has been demonstrated. The process was found to significantly reduce overall cost, fabrication time and contamination because of resist. It is hoped that this combination approach will attract significant interest in the area of microdevice preparation for biological and medical applications.

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