Multiple-height microstructure fabricated by deep reactive ion etching and soft resist masks combined with UV curing

R Sato, T Sawada, S Kumagai, and M Sasaki
Department of Advanced Science and Technology, Toyota Technological Institute, 2-12-1 Hisakata, Tenpaku-ku, Nagoya, 468-8511, Japan
E-mail: mnr-sasaki@toyota-ti.ac.jp

Abstract. Multiple-height microstructures are realized by deep reactive ion etching and UV-cured photoresist used in the embedded mask process. Although the UV-cured photoresist is a soft mask, its material property becomes stable against resist thinner and UV exposure. A layered resist pattern can be realized by stacking normal photoresist on the UV-cured photoresist. The normal photoresist can be selectively removed by the flush exposure and developing after the first Si etching. This technique is applied to two MEMS devices.

1. Introduction

3D structures are frequently required in MEMS devices. In many cases, the shape in its depth direction is determined by the projection of a top single mask pattern (so called 2.5D). The mask pattern is on the top surface, since the photolithography patterning is only effective on the planer surface. The challenge towards 3D is changing the depth profile in a controlled manner. A grey scale mask can give 3D resist structure, which can be transferred to Si substrate [1]. Multiple-height structures having digital steps are realized by the embedded mask process. This process usually uses masks of resist and hard materials (e.g., SiO₂, SiN, Al). To prepare SiO₂ [2] or SiN [3] films, the process temperature must be high. A high temperature should be avoided to maintain already fabricated structures. As for the metal film [4, 5], there is a risk of contamination of the plasma chamber. Soft resist mask is preferred since the plasma cleaning can be applied. Recently, UV curing of the photoresist has been found to realize layered resist masks [6]. This previous method relies on the ashing rate difference (only 2-times) relating with the glass transition temperature for the selectivity. The process margin for the demonstrated micromirror is tight [7].

In this study, a new fabrication technique for improving the selectivity is described. Two devices are demonstrated.

2. UV curing

UV curing is the treatment realized by heating the photoresist under vacuum and UV irradiation. UV curing makes the resist molecules link together to form larger molecules. UV cured photoresist becomes stable against thinner and UV exposure. The over-coating of the additional resist layer does not change the underlying pattern. UV exposure only patterns the top layer of the normal photoresist [6]. During the process, the process plasma irradiates UV to the photoresist mask. For removing the photoresist after the plasma process, the positive type photoresist is useful since it can be removed by developing. The above things are basically valid for g-line photoresist. The photoresist used is
AZ1500 having thicknesses of about 3 µm. UV curing is at 100 °C, about 3 kPa for 40 min. The light (main wavelength 240-380 nm, ~1 W/cm²) of a high-pressure mercury lamp is irradiated.

3. Selective removal of normal resist against UV cured resist

Figure 1 shows one fabrication sequence. The 1st pattern is transferred to the photoresist and UV cured. Then the normal resist is coated and 2nd pattern is transferred. After the plasma processing (step 2), the top normal resist is removed by the flush exposure and the developing. The inset (b) in figure 1 shows the photo of the sample. The residue is observed and remains even at the over-dose condition (appropriate patterning condition is 70 mJ/cm²). This residue is considered to be the deposited film during the first Si etching using Bosch process. When ashing (corresponding to about 10 nm removal as for the photoresist) is introduced, the subsequent flush exposure and developing gives the result shown in inset (c). The residue is clearly removed and UV-cured photoresist remains stably. Then the 2nd Si etching can be applied.

4. Applications

4.1. Microchannel with stepped sidewall for MEMS plasma source

Small plasma source is fabricated [8]. Figure 2 shows the fabrication sequence of the device. Steps (1)-(5) are the processing of Si wafer using the technique proposed. Stepped sidewall is introduced because the effect for decreasing the ignition power is observed in the model experiment. Although the physical mechanism is not clear at present, the gas flow condition seems to relate with this. The
stepped sidewall is fabricated by the embedded mask process. The first resist layer is patterned and
UV cured. The next resist is spin-coated on that (step 1). The 1st vertical Si etching by 100 µm is
conducted using the normal resist mask (step 2). Then, the normal resist is selectively removed (step
3). Additional Si etching is conducted by 100 µm (step 4). All resist mask is removed (step 5). Step 6
is attaching MgF2 glass with patterned Al electrode, which enhances the plasma ignition. Figure 3
shows the fabricated chip with the microchannel.

Figure 4 shows MEMS chip set in the coil connected to 100 MHz power supply. Microplasma is
generated at the apex of the triangle electrode. For the microplasma chip without stepped sidewall, the
input power of 124 W is necessary for the ignition. The stepped sidewall decreases the power to 102
W (-18%), which is the significant difference.

4.2. IR emitter with local texturing for enhancing the emission
The microheater is fabricated for the IR emitter as shown in figure 5. The wavelength selectivity is
realized since the almost IR is reflected back to the microheater and confined except the coupling with
the surface plasmon polariton on the grating.

Figure 6 shows the fabrication sequence. SOI (silicon on insulator) wafer is used (step 1). The
handle layer is Boron doped <0.02 Ω·cm and becomes the microheater. The first mask pattern is
transferred on the device layer defining the slit and cover (step 2). The device Si layer is etched (step
3). The second mask pattern is transferred on the backside handle layer defining a part of the spiral
heater (step 4). The center part is open. This mask is UV-cured. Then, the third mask pattern is
transferred on the second mask pattern. This resist is not UV-cured keeping as the normal resist. These
two patterns connect each other making the spiral heater structure (step 5). The handle Si layer is
etched (step 6). The normal resist layer is removed with the flush exposure and developing (step 7).
Using the underlying UV-cured resist mask remained, the additional Si etching is carried out. The
main aim is for roughening Si surface at the center area of 3.15x3.15mm². Since Si has the large
refractive index (about 3.45 for IR) compared to that of air (about 1), IR is reflected back at the
interface. Roughening surface (having the microstructure smaller than the wavelength) enhances the
emission. Figure 7 shows the photo of Si surface (a) before and (b) after etching controlling the
balance of the deposition gas and the etching gas. The surface roughness increases from 2 to 83 nm Ra.
Experimentally 1.3-times larger emissivity is observed compared to the original flat surface at the
wavelength of 650 nm. After removing the resist layer, the buried SiO2 layer is removed releasing the
heater structure (step 8). Figure 8 shows the fabricated microheater. The chip size is 6.5x6.5mm². The
center whitish region is the roughened area.
Figure 5. Schematic drawing of IR microemitter. (a) Assembled drawing. (b) Construction of elements.

Figure 6. Fabrication sequence of microheater.

Figure 7. Surface morphology (a) before and (a) after Si etching for roughening the surface.

Figure 8. One fabricated microheater. The side with roughened area for enhancing IR emission.

Figure 9. FT-IR spectra from the microemitter and the microheater reference (blackbody).

Figure 9 shows FT-IR (Thermo Scientific, Nicolet 6700) spectra. One curve is the emission from the output end. SPP related peak is at the wavelength of about 3.5 µm. Another blue curve is the reference directly observed at the microheater rough surface. The absorption at 4.2-4.3 µm can be attributed to CO$_2$ gas in the optical setup. The enhanced emissivity to the grating surface will contribute to the efficient transfer from the thermal energy to the IR wavelength designed.
5. Conclusion
Highly selective removal technique of normal resist against UV cured one is realized. The embedded mask process is combined using the normal resist stacked on UV-cured one. This demonstrates 2-step structures using only soft resist masks. The microchannel with stepped sidewall for MEMS plasma source and IR emitter with local texturing for CO$_2$ gas sensing are demonstrated showing the merit of the multiple-height structures.

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