Microfabrication of ultra-thick SU-8 photoresist for microengines

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ABSTRACT

A high quality UV-lithographic process for making high aspect ratio micro reciprocating engine parts on ultra-thick SU-8 photoresist CO_2 is described. The research work is part of an on-going microengine research project at the University of Birmingham. The project aims to develop a compact power plant for driving MEMS devices and replacing batteries. The novelty of engine design is that the engine is constructed in two layers only, and all parts are designed to suit the 2D microfabrication feature. Due to the strict requirements on the perpendicular geometry of the engine parts, the microfabrication research work has been concentrated in conducting a high quality UV-lithographic process on ultra-thick SU-8 for producing microengine parts. Based on the study of the optical property of ultra-thick SU-8 layer, optimized prebake time has been selected to obtain the minimum UV absorption by SU-8. The optimization principle has proved effective by a series of experiments of UV-lithography on different prebake times, and high aspect ratio structure (about 10) engine parts have been produced in 1000 μm ultra-thick SU-8 layers using the standard UV-lithography equipment. The sidewall angles are controlled between 85~90 degrees, which is a much better improvement than those reported so far.

Keywords: Microengine, Actuator, Ultra-thick SU-8 photoresist, Transmission spectra, High aspect ratio.

INTRODUCTION

Presented in this paper is the microfabrication of micro reciprocating engine parts using SU-8 and UV-lithographic process. The work is part of an on-going project at the University of Birmingham for the development of a micro internal combustion engine to provide power to general detached micro devices.

Currently, the most widely employed micro actuator is the electrostatic comb drives, which can be found in the digital mirror display systems developed by Texas Instruments[1], and also in Sandia's intricate safety lock for nuclear missiles[2]. Recently, micro rotary motors and indexing motors have been fabricated for demonstrated in Sandia's Microsystems laboratory. The rotary motor can provide variable speed and torque in very small steps. These achievements mark big advance in MEMS technology, and will inspire more inventions of micromachines. However, these actuators rely uniquely on electric power, which poses constraints to applications. For instance, electric powered micro unmanned air vehicles can hardly be developed due to their limited non-stop flying time. Microroborts and other detached devices will face the same problem. If electric motors are used only in microsystem, its future will be like our society where only electric vehicles are used. Clearly, an alternative should be sought, and the solution is likely to be micro combustion engines.

Since developed by IBM, SU-8, the negative epoxy-type near UV photoresist has long been considered as a low cost material for microfabrication, and its excellent mechanical property is particularly suitable in MEMS field for high aspect ratio structure applications [3-5]. For its excellent characteristics, ultra-thick SU-8 photoresist has been employed

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as the construction material in the research of micro power plant at Birmingham. Currently, the research work concentrates on developing a micro reciprocating engine powered by liquid CO_2.

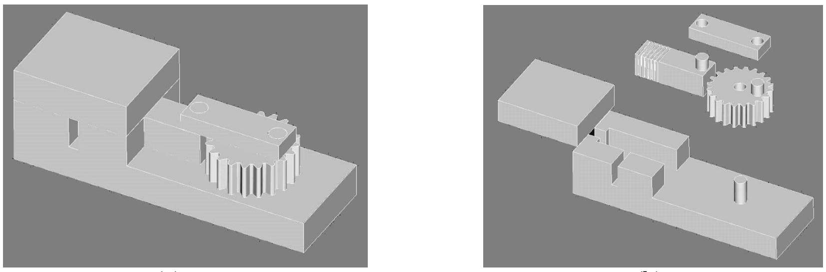
The design of the engine requires a strict vertical geometry and ultra-thickness on the piston and the cylinder for the prevention of the leakage. Conventional SU-8 processes often produce a trench with a wide top and narrow bottom profile, which is common for negative photoresist. The T-shape becomes more seriously when the thickness of SU-8 layer is approaching 500 μm or more [6]. Many factors contribute to this dimensional change, such as the volume change of the SU-8 resist during polymerization, chemical diffusion of crosslinking agents and several illuminations parameter. Therefore, the study of SU-8 optical properties in the near UV range is essential for optimizing the process of ultra-thick SU-8 layers.

In this paper, the design of the microengine is first introduced. Then the relationship between the prebake time and UV light absorption property is discussed in detail, which is followed by fabrication results. The results show that an optimum prebake time will improve the lithographical fabrication significantly, and the complete microengine has been produced using the proposed UV lithographic process of optimum prebake time.

THE DESIGN OF MICRO RECIPROCATING ENGINE

At this stage, a CO_2 cryogenic microengine is being test-fabricated. The performance of the engine will be investigated to identify potential problems such as tolerance control, leakage prevention, and efficiency of general microengines. A micro combustion engine will be developed based on the micro cryogenic engines.

The microengine is designed based on the mechanism of a two-stroke reciprocating engine, and its construction is shown Fig. 1, excluding the synchronization valve. With the consideration of MEMS fabrication features, the engine is designed in 2D shapes. The piston has a square cross section. Its contact surfaces with the cylinder are much larger than that of a conventional engine, and fine grooves are made on the surfaces for prevention of gas leakage. The cylinder is a large trench of square cross section, to be covered by a glass. The crank is made on a big gear with an eccentricity. The gear works as crankshaft, a flying wheel and a driving device to transmit the power to external devices. A synchronization valve is to be placed at the bottom of the cylinder, and will be triggered open to release liquid CO_2. The expansion ratio of the liquid CO_2 is 10, which is in the similar scale of that of combustive fuels. The outlet port of the engine is made on the wall of the cylinder as a groove.



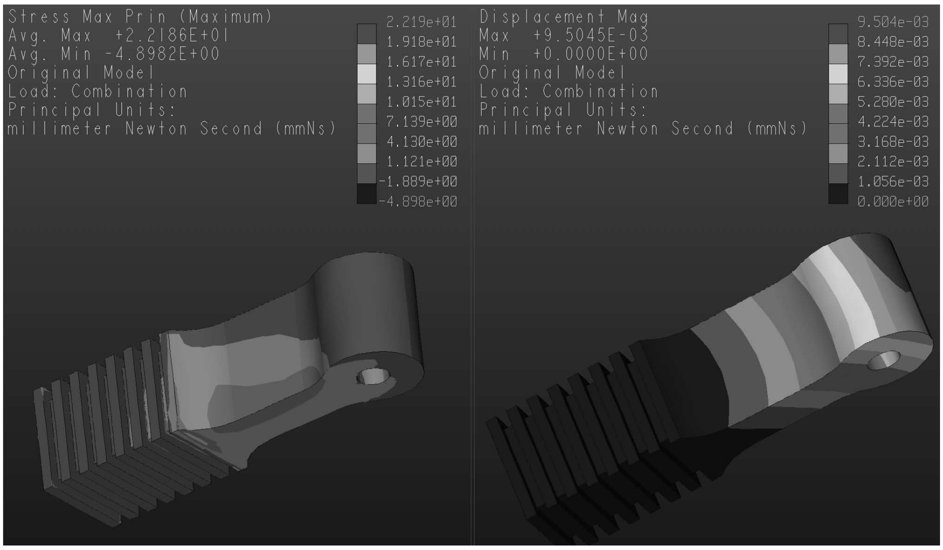
(a) (b)

Figure 1. Computer modelling of the micro reciprocating engine,
(a) an assembly of the engine, (b) an exploded view of the engine.

In one working cycle, liquid carbon oxygen is inducted when the piston reaches the bottom of the cylinder. CO_2 is then expanded to push the piston up until the exhaust port is reveal, through which most residual CO_2 will be let out. The gear and the driven external devices will provide a momentum to push the piston back to its bottom to trigger the CO_2 valve, and another cycle starts. The designed power output of the CO_2 engine is 2.56 mW, at a speed of 1000 rpm.

The construction material of the engine is SU-8 photoresist. The cross section of the piston is 1×1 mm. This is designed with the consideration of quenching distance for micro combustion engines to be developed in the next phase. The sidewalls of the cylinder are 1 mm thick.

The majority of components in the micro reciprocating engine, such as the piston, the cylinder, the connecting-rod and the gear, are subject to loading. Deformation of cylinder walls may increase leakage dramatically, and excessive stress on a part will break it. Finite element analysis has been used for predicting the dynamic stress and deformation of the piston, cylinder and linking rod. Fig.2 shows the maximum stress and deformation occurring in the piston for a working cycle. The maximum stress is 22.19 MPa, which is well far below the SU-8's fracture stress of 34MPa[9]. The amount of deformation on the cylinder is 1.56×10^{-6} mm, which can be ignored. The maximum deformation occurs on the piston, and the value is 9.50×10^{-3}. Such a deformation on the piston will not affect the performance of the piston.



(a) Stress analysis (b) Deformation analysis.

Figure. 2. FE analysis on the piston of the engine with

PREBAKE TIME AND UV LIGHT ABSORPTION PROPERTY

SU-8 photoresist has been employed in the fabrication of the microengine. SU-8 is known as suitable for high aspect ratio structures. The fine grooves on the piston surfaces have an aspect ratio of 10, and the sidewalls of the cylinder and piston surfaces require strict vertical geometry. The fabrication tolerances for the fitting the piston into the cylinder are the minimum for reducing the leakage. Besides, all parts of the engine will be 1000 μm thick. These requirements of the engine design have posed major challenges for the microfabrication of the engine.

One of the properties of SU-8 is its low UV absorption. This property enables a uniformed exposure of the photoresist up to much bigger range compared with other thick photoresists. The ideal vertical sidewall profile is obtained based on the low UV absorption property. However, the transparency of SU-8 deteriorates as the layer gets thicker. It becomes more evident when the thickness is over 500 μm.

Only a few references can be traced on ultra-thick SU-8 UV transmission spectrum [6]. Most of the references found so far provide only the transmission data of an SU-8 layer of a certain thickness, prepared with a constant prebake time and measured at a given wavelength [7, 8].

A proper prebake time is one of the most important control factors for the photoresist process [10]. Most investigations on the effect of the prebake time are focused on reducing the remaining solvent in SU-8 to improve the fabrication quality [11]. Such study has identified the minimum prebake time for vaporizing all solvent in SU-8. Cui, et al [11] recommended that a prebake time of about 30 h is necessary to vaporize the solvent for an SU-8 layer of 1000 μm. In this paper, the effects of longer the prebake times are discussed in terms of absorption property.

In the microengine project, the UV light absorption property of SU-8 photoresist has been investigated. The transmission measurements have been performed by using a HITACHI UV-3100 Spectrophotometer in the range of 360 nm to 460 nm with a 1 nm increment. The specimens are prepared by using commercial SU-8 (SU-8-50) from MicroChem Corp. with Corning glass as the substrates. The thickness of the SU-8 specimens is of 1 mm, and a bare glass substrate is used as reference in the measurements. The specimens are prebaked at 95°C for a time varies from 10 to 40 hours.

The transmission spectra shown in Fig. 3 illustrate that when the prebake time is long, the transparency property deteriorates, which indicates that more UV light will be absorbed if the prebake time is longer. It is understood that the prebake process will enhance the polymerization of SU-8. The enhancement of the polymerization decreases the transparency property in the UV range, thus decreases penetration length through the SU-8 layer. Penetration length is used to describe the absorption depth. The intensity of light passed through the distance L_p (Penetration Length) in the medium will decay to 1/e of its incident intensity, which is about 37%. For an SU-8 film of a penetration length thickness, the layer can be exposed uniformly at the given wavelength [6]. A high transparent SU-8 layer effectively extends the penetration length, and leads to achieve a high aspect ration feature. In comparison with the transmission spectra in Fig. 3, short prebake time is an effective method for obtaining a low UV light absorption layer, and achieving a high quality ultra-thick SU-8 structures.

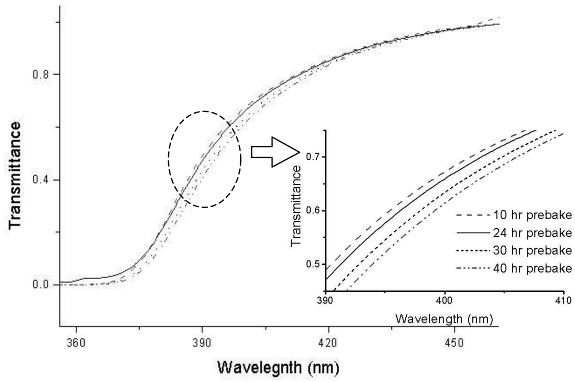


Figure 3. UV Transmission spectra of unexposed ultra thick SU-8 layers coated on micro slide

Keeping high transparency of SU-8 after prebake process is a principle in the microengine fabrication, where all the parts are 1000 μm in thickness. While short prebake time results in good transparency, insufficient prebake will make SU-8 solidification incomplete, and cause irresolvable residuals in the development.

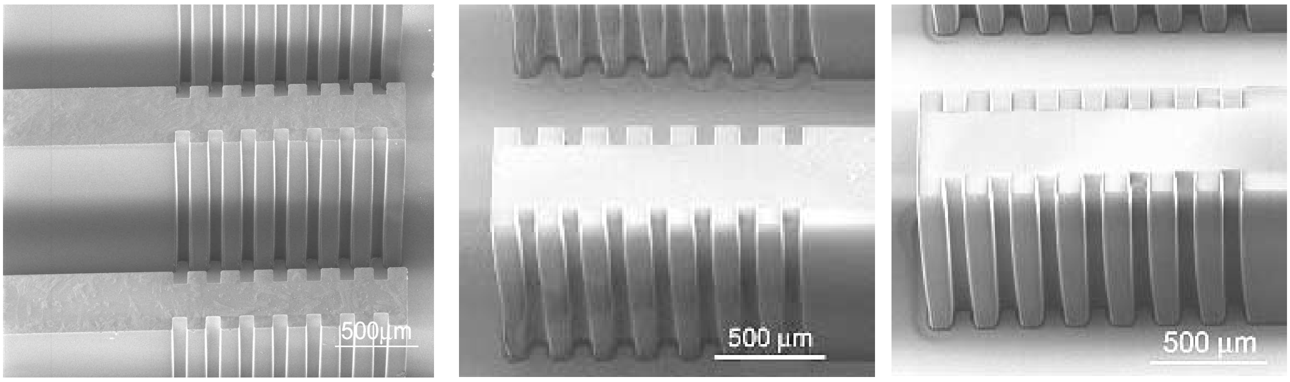
EXPERIMENTAL FABRICATION

During the fabrication of the microengine, a series of UV lithography experiments were carried out using commercial SU-8-50 supplied by MicroChem. SU-8 layers of 1000 μm thick were prepared on 4 in silicon wafers. CANON PLA-501-FA aligner was used for UV light exposure. The wavelength band of the aligner is set in the range of 365-436 nm.

Three types of UV lithographic processes are selected to show the effects of the prebake time on the results. Group 1 specimens were firstly prebaked at 65°C for 2 hours, and then the temperature was increased to 95°C and kept for 24 hours. The exposure dose was set at 17.5 units, followed by a postbake at 65°C for 15 min, and then 95°C for 25 min. The development was processed using EC-Solvent for 3 hours. An SEM image of the engine piston fabricated using this process is illustrated in Fig. 4a.

Group 2 specimens were similarly prebaked at 65°C for 2 hours, and then the temperature was increased to 95°C and kept for 30 hours. The exposure dose was set at 18 units, followed by the same postbake times and development. An SEM image is shown in Fig. 4b. Group 3 specimens were also prebaked at 65°C for 2 hours, and then the temperature was increased to 95°C and kept for 40 hours. The exposure dose was set at 19 units, followed by the same postbake times and development. An SEM image is shown in Fig. 4c.

Figure 4b is regarded as a typical T-shaped structure, which appears frequently in the fabrication of ultra-thick SU-8 devices, especially when the thickness is above 500 μm. A little over-exposure has been observed on the top part of the piston grooves. The same image also reveals a typical under-exposure condition along the lower part of the grooves.



a b c

Figure. 4. The microengine pistons fabricated using different prebake and exposure conditions

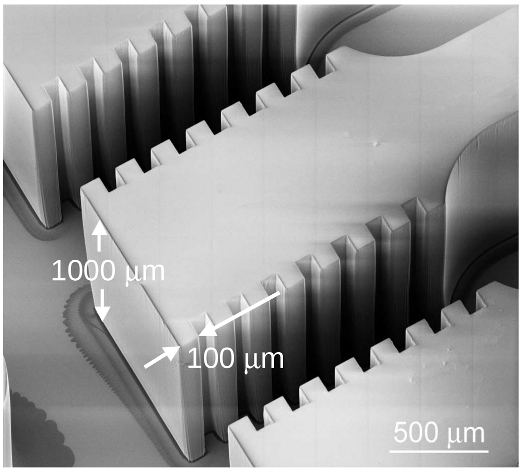


Figure 5. The Piston array fabricated with the optimized parameter.

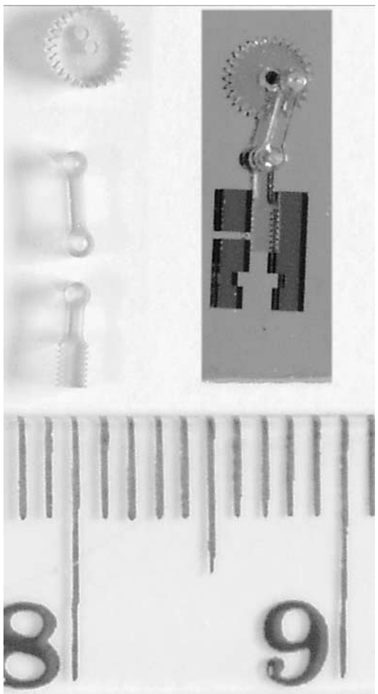


Figure. 6. The micro CO_2 reciprocating engine and its detached parts, fabricated using SU-8 photoresist.

Due to the limit of the penetration length of the UV source used, there is no improvement by only increasing the exposure dose amount, the result of which is shown in Fig. 4c. Figure 4a is the fabrication result of a less prebake time under smaller exposure dose amount. A uniformed exposure has been achieved throughout the layer and a longer penetration length was obtained. The lithographic process used in Group 1 yields the optimal results.

Figure 5 shows another SEM image of a piston array, which was fabricated using the UV lithographic process based on the optimized parameters. The width of the vertical bar on pistons is 100 μm, and the height of the bar is 1000 μm. The sidewall angle is controlled between 85~90 degrees, which is a significant improvement compared with those reported so far [11].

The complete reciprocating engine has been fabricated using the UV lithographic process discussed above. Figure 6 is the assembly of the micro CO_2 engine. The synchronization valve will be fabricated separately.

CONCLUSION

This paper presents the research work on the development of a micro cryogenic reciprocating engine, using SU-8 and UV lithographic process. The microengine was designed based on a two strokes reciprocating engine, and significant modifications have been made to accommodate the 2D feature of MEMS fabrication. All engine parts, except pins, are design to be fabricated on a 1000 μm thick SU-8 layer. The design has been verified using FEA, and the analysis results shows that the strength and deformation of the SU-8 engine parts are strong and rigid enough. During the fabrication, the UV lithographic process for SU-8 was studied, and the prebake time was identified as crucial for the ultra-thick SU-8 layer. The prebake time was then optimized. With the improved UV lithographic process, the aspect ratio of 10 has been achieved, and the strict requirement of the vertical sides of the piston and cylinder has been met. The improved UV lithographic process proves to be a success in the microengine fabrication. The assembly of the microengine is illustrated in the paper.

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