INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF MICROMECHANICS AND MICROENGINEERING

J. Micromech. Microeng. 15 (2005) 1522–1526 doi:10.1088/0960-1317/15/8/021

SU-8 Ka-band filter and its microfabrication

K Jiang, M J Lancaster, I Llamas-Garro and P Jin

School of Engineering, The University of Birmingham, Edgbaston, Birmingham B13 8JY, UK

Received 5 October 2004, in final form 19 May 2005
Published 17 June 2005
Online at stacks.iop.org/JMM/15/1522

Abstract
This paper presents the design and microfabrication of a coaxial dual model filter for applications in LMDS systems. The coaxial structure is formed by five conductive layers, each of which is of 700 μm thickness. The filter uses an air filled coaxial transmission line. It is compact with low dispersion and low loss. The design has been extensively tested using a prototype filter micromachined using laser drilling on a copper sheet and the results show a good agreement with the theoretical calculations. The laser fabrication has exposed weakness in suitability to volume production, uneven edges and oxide residuals on the edges, which affects the filter performance. A process for fabrication of such a filter in SU-8 has been developed which is based on a UV lithographical process. In order to fabricate such thick SU-8 layers, the SU-8 process has been optimized in terms of UV radiation and post exposure baking. During the test fabrication, the optimized SU-8 process has produced microstructures with an aspect ratio of 40:1 and a sidewall of $90 \pm 0.1^{\circ}$. The high quality SU-8 structures can be then either coated with a conductive metal or used as moulds for producing copper structures using an electroforming process. The microfabrication process presented in this paper suits the proposed filter well. It also reveals a good potential for volume production of high quality RF devices.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Millimetre and microwave wave filters are traditionally open structures in either a coplanar or a microstrip form. Here the thin film metals are used to guide the microwaves and form passive signal processing functions such as filtering. The open thin film structures suffer from radiation and Ohmic losses. However, closed structures such as coaxial cables do not suffer the radiation and with the correct design have lower losses. Both coaxial and planar structures suit microfabrication well, where the design of the devices is largely limited in 2D. For this reason, MEMS filters have gained attention from researchers [1–3]. As the main material for MEMS devices, silicon has been used in constructing thin layer filters as proposed in [4, 5]. In recent years, the materials used in MEMS fabrication have expanded from silicon to various non-silicon materials, among which SU-8 photoresist is an obvious one [6]. Harris *et al* pointed out in [7] that as an alternative to silicon filters, the same structure can be made of SU-8 with a simpler fabrication process. SU-8 structures in a single layer can be made as thick as 1.5 mm using a UV lithography process [8], as opposed to the 0.5 mm thickness in the Si fabrication using the DRIE process. This gives more options in the filter design. Almost all microwave micromachined structures use suspended microstrip transmission lines. In this paper, a coaxial structure based Ka band dual mode filter is proposed. Compared with the structures mentioned in [4, 5, 7], the proposed transmission line structure is more compact and has an air propagation medium providing low loss. An SU-8 UV-lithographical process is discussed in this paper for the fabrication of the filter. The lithographical process has been optimized in soft bake time for the minimum UV absorption, resulting in quality patterns with very vertical sidewalls. The SU-8 patterns can be either coated by conductive metal, or used as the positive moulds for producing metallic components, such as copper, through an electroforming process. The low cost and high accuracy features of SU-8 structures show a promising future in building high performance Ka band

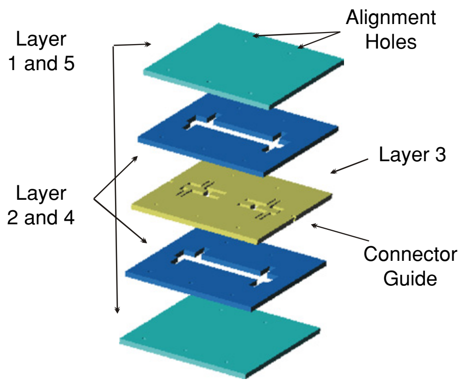

Figure 1. Coaxial assembly of the Ka-band dual mode filter.

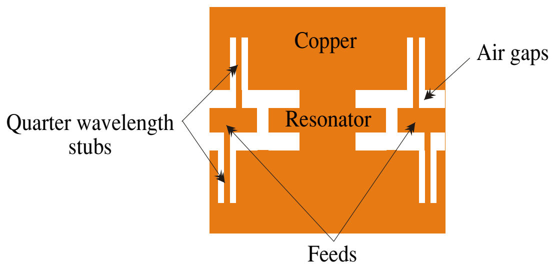

Figure 2. Centre conductor of the filter.

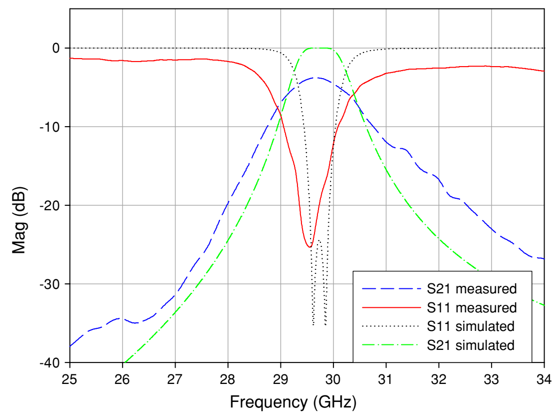

Figure 3. Response of the prototype filter.

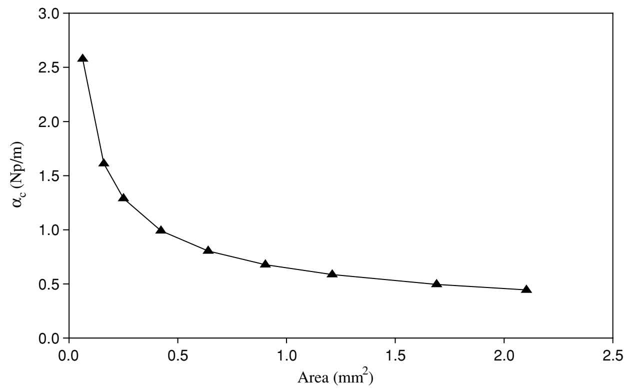

Figure 4. Attenuation constant for an air filled, 50 Ω square coaxial transmission lines versus the area of the cross-section used.

filters within a wide range of wavelengths. Therefore, the SU-8 technology demonstrates a good potential in producing micromachined microwave transmission lines.

2. The design of a coaxial ka-band dual mode filter

The structure of the coaxial Ka-band dual mode filter is illustrated in figure 1. The filter is formed by five conductive layers bonded together. The filter uses an air filled coaxial transmission line, which is compact with low dispersion and low losses. This design provides the low losses desired at millimetre waves. The tolerances for this coaxial structure become tighter as the frequency increases, and a smooth vertical component edge is required. These requirements can be met conveniently by the SU-8 microfabrication technology discussed in this paper.

Figure 2 shows the layer which is the centre conductor of the square coaxial line. A dual mode resonator is at the centre, with a feed on each side. The feed is supported by quarter wavelength stubs. The filter is designed for a 1% fractional bandwidth centred at 29.75 GHz with a 0.01 dB bandpass ripple. It measures 13.78 mm × 7.43 mm, with a height of 3.5 mm formed by five 700 μm layers.

To test the design a dual mode Ka-band prototype filter was made using a laser micro-machining process on a 700 μm thick copper sheet. The laser fabrication process is not suitable for volume production, but the prototype filter provides a valuable opportunity for microwave characterization and the testing of the design. Referring to figure 1, layers 2, 3 and 4 were produced by commercial laser micromachining for this test filter by laser cutting holes through the 700 μm copper sheet. The three layers were then clamped together using blocks of copper shown as layers 1 and 5 in figure 1. The package also contained microwave SMA connectors which provided input and output connections to the feed lines and the microwave test equipment. Extensive experiments have been carried out on the filter. The bandpass response of the dual mode Ka-band filter is shown in figure 3, where a good agreement between the theoretical and experimental results was obtained. The measured return loss degrades due to the laser fabrication error and layer misalignment, which also changes the coupling between the two microwave modes, this leads to an increase in the bandwidth of the filter. The transition from the connector to the circuit presents a small mismatch, which was mainly caused by fabrication tolerances at the time of mounting the connector to the layered circuit. The measured insertion loss of the filter is found to be 3.8 dB. The simulated response in figure 4 was achieved using Agilent HFSS v5.5 [9], and was done by simulating the complete electromagnetic signal distribution in the filter structure; it is based on perfect conductors to reduce computational time. In the simulation of the filter with conductor losses, only the pass-band frequencies of the filter were chosen. The losses in the simulation of the filter gave an estimated pass-band insertion loss of approximately −0.5 dB. The increased losses in the measured response are believed to be caused by the surface roughness and oxidation of the copper plates; this is due to the laser machining process. In the simulations, the effects of the connectors and the transitions were not taken into account.

The thickness of the layers in the filter has an important effect on the filter performance. A large cross-sectional area of the coaxial line has the advantage of having a low attenuation constant, as shown in figure 4, where the losses of 50 Ω transmission lines are compared at 50 GHz [10]. It is desired to propagate a TEM mode, which is the lowest order mode in a coaxial line. Higher order (TE and TM) modes can also exist at higher frequencies for a given coaxial cross-section, as discussed in [11]. The line here is designed in such a way that the cut-off frequencies of the higher order modes are above the operating frequency, which limits the size of the cross-section. The appropriate layer thickness of a specific design becomes a trade-off between having a low attenuation constant for the transmission line, and deciding at what frequency the higher modes will start to propagate.

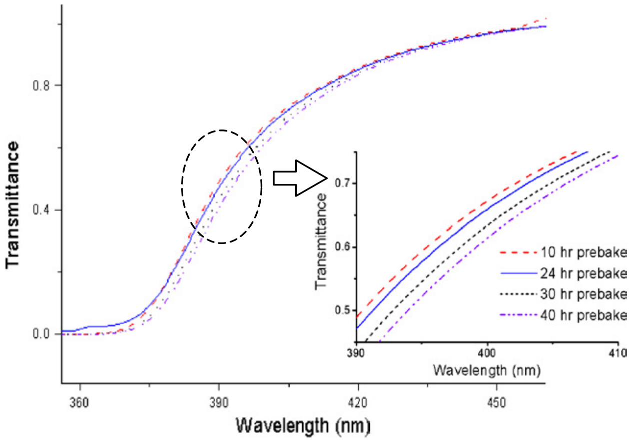

Figure 5. UV transmission spectra of unexposed ultra-thick SU-8 layers coated on glass.

3. SU-8 microfabrication process

SU-8 is a near UV photoresist. It has advantages over other photoresists in its good mechanical properties, suitability of building very thick layers, low costs in volume fabrication and good potential for forming high aspect ratio structures. Because of these properties, the applications of SU-8 are gradually widened beyond the applications of the traditional photoresists as a new microstructure material. In this project, the design of the filter requires 700 μm thick layers and a smooth vertical sidewall for the best filtering performance. SU-8 is chosen to build the filter.

The maximum thickness listed in the SU-8 data sheet [12] is 40 μm, for which a detailed fabrication process is provided. In order to fabricate 700 μm thick structures, it is necessary to develop a new SU-8 process. The general fabrication process of SU-8 recommended by [12] includes coating, soft bake, exposure, post exposure bake, development and hard bake. In the initial ultrathick structure fabrication experiments, the time for soft bake, exposure and post exposure bake was increased from 20 mins up to 30 mins, but the fabrication results were disappointing. The typical problem is the sloppy sidewall of the structure. A further study on SU-8 optical properties helps improve the fabrication quality.

SU-8 is transparent in colour and has a low UV absorption property. This property enables a uniformed exposure of the photoresist to a much larger depth than other thick photoresists. In theory, an ideal vertical sidewall profile could be obtained if the UV light went through the entire layer without losses, but in reality, the transparency of the SU-8 deteriorates as the layer gets thicker and the intensity of the UV light reduces. This becomes more evident when the thickness is over 500 μm. It is, therefore, important to maintain the best transparency of the SU-8 coating before UV exposure. Only a few references can be traced on an ultrathick SU-8 UV transmission spectrum [13]. 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 soft bake time and measured at a given wavelength, referring to [14] and [15]. A useful reference is the work by Zhang *et al* [16] which states that a proper soft bake time is one of the most important control factors for a thick photoresist process. However, most investigations on the effect of the soft bake time are focused on reducing the remaining solvent in SU-8 to improve the fabrication quality [17]. Such study has identified the minimum soft bake time for vaporizing all solvent in SU-8. Cui *et al* [17] recommended that a soft bake time of about 30 h is necessary to vaporize the solvent in an SU-8 layer of 1000 μm. In this paper, the effect of long soft bake time is discussed with regard to the absorption property of SU-8.

The UV light absorption property of SU-8 photoresist has been investigated by measuring the transmission using a HITACHI UV-3100 spectrophotometer in the range of 360 nm to 460 nm with a 1 nm increment. The specimens are prepared using commercial SU-8-50 from MicroChem Corp on Corning glass substrates. The thickness of the SU-8 specimens is 1 mm, and a bare glass substrate is used as a reference in the measurement. The specimens are baked at 95 °C for a time varying from 10 to 40 h.

The transmission spectra shown in figure 5 indicate that when the soft bake time is long, the transparency property deteriorates and more UV light will be absorbed during the exposure time. Penetration depth is usually used to describe the absorption depth. The penetration depth is defined as the depth in which the incident light is decayed to a value that corresponds to a fraction of 1/e of the incident light. For an SU-8 film of a penetration depth thickness, the layer can be exposed uniformly at the given wavelength [13]. A highly transparent SU-8 layer effectively extends the penetration depth, and leads to producing a high aspect ratio feature. In reference to the transmission spectrum plot in figure 5, it can be observed that an SU-8 layer with a short soft bake time has higher transmittance than those with a long soft bake time. Therefore, a short soft bake time is identified as a method to reduce the UV light absorption. Keeping high transparency of the SU-8 after soft bake is important for the fabrication of the thick square coaxial transmission line.

Cracking is commonly observed in SU-8 structure fabrication, and has also been studied in this project. Cracking is considered to be caused by the internal tensile stress in an SU-8 structure. Factors for such a problem include sudden temperature increase in a hot plate, high stress concentration as a result of improper mask and structure design, and big temperature difference during a complete SU-8 process. Cracking due to the first two causes can be greatly improved by ramping temperatures up and down each time, placing component patterns evenly throughout the wafer in the mask design, and using arcs instead of sharp corners in the device design. The third cause of cracking may be more significant than the first two and much attention should be paid to it. In fact, the coefficient of thermal expansion of SU-8 is $50 \times 10^{-6}\,K^{-1}$, about 12 times as much as that of Si, which is $4.2 \times 10^{-6}\,K^{-1}$. The higher the temperature is during the soft bake time, the more internal stress will exist in the SU-8 once the temperature drops down. In addition to the internal stress caused by the temperature change, the shrinkage of the SU-8 due to liquid evaporation usually adds more internal stress to the SU-8 layer. This is because with liquid evaporation, the volume of the SU-8 is reduced, but this reduction in volume is resisted by the rigid wafer, causing internal stress across the SU-8 layer. In most cases, the stress will not cause cracks immediately. However, when the exposed wafer is immersed in the developer, the mechanical property of the SU-8 begins to compromise considerably and the cracking problem begins to surface. Therefore, keeping a low temperature during the soft bake step will help reduce the internal stress and reduce cracking.

A series of experiments have been carried out and the optimized SU-8 structure fabrication processes have been identified for different thicknesses of SU-8 layers. The UV light source is a combination of g-line (436 nm), h-line (405) and i-line (365 nm). The optimized process for producing a 700 μm thick SU-8 layer consists of the following steps. (a) A Si wafer is cleaned with acetone and DI water, and then baked at 200 °C for 20 min. (b) SU-8-50 is deposited onto the wafer by direct casting and a scraper is used to spread it over. The deposited SU-8 on the wafer is then left for 20 min to get flat. (c) The wafer is baked first at 65 °C for 2 h, and then at 95 °C for 15 h. Afterwards, the temperature is ramped down to room temperature at a rate of 3 °C per minute and the coated wafer is left there for another 15 min. (d) A 1.5 mm thick quartz mask coated with bright chrome is used for high resolution fabrication. (e) The coated wafer is exposed with energy density 1712 mJ cm^{-2}. (f) The post exposure bake is carried out first at 65 °C for 15 min and then at 90 °C for 25 min. Then the temperature is ramped down to room temperature at a rate of 3 °C per minute. (g) The exposed wafer is immersed in EC solvent, supplied by Chestech, for 1.5 h at room temperature and agitated gently using a magnetic stirrer. (h) The wafer is rinsed with IPA to remove the residual developer. (g) The SU-8 structures are released in KOH solution at 40 °C in 1 h.

In comparison with the ultrathick SU-8 process proposed in [8], the optimized process differs in several aspects. First, the soft bake temperature is kept at a maximum 95 °C rather than 120–130 °C. The relatively low soft bake time helps reduce the internal stress of the SU-8 structures, and reduce and eliminate cracks of the structures. Second, a metal mask is used to increase the edge quality of the structures. Third, a Si wafer, rather than a glass substrate in [8], is used as the substrate in the process. The optimized process has led to obviously improved fabrication results. Figure 6 shows an SU-8 layer with a smooth and vertical finish on the edge, which is important to the quality of filtering. The highest aspect ratio presented in [8] is 15:1. The aspect ratio achieved by using the optimized process, however, has been much increased.

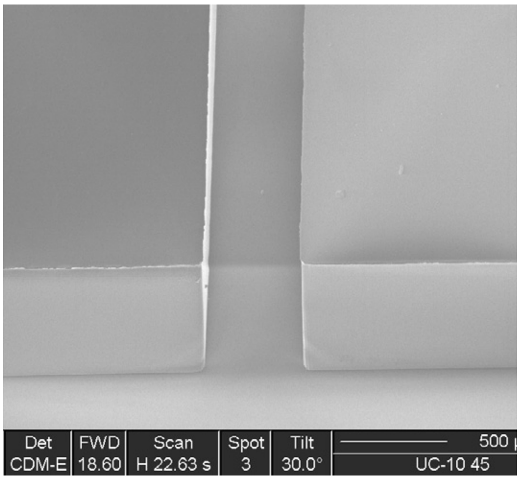

Figure 6. An SU-8 layer of 700 mm thickness, fabricated for the filter.

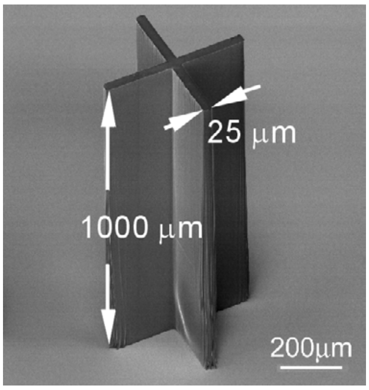

Figure 7. An SEM image of a high aspect ratio cross.

Figure 7 shows one of the experimental results produced by using the optimized process. The structure is a cross of 25 μm in thickness and 1000 μm in height, which is an aspect ratio of 40:1. The thickness of 1000 μm is sufficient for the filter applications. The sidewall angle in these experiments is controlled within 90 ± 0.1°, which is a significant improvement compared with those reported so far [8, 17]. This high quality fabrication result is an important characteristic for a quality coaxial transmission line.

The optimized SU-8 fabrication process has been used to produce the filter components. Figure 8 shows the five SU-8 layers of the Ka-band filter made using the fabrication process described above. The filter components are crack free, but a slight bend has been observed once they are released from a Si substrate, due to the internal stress. The bend will not pose significant problems in bonding and filter performance, as the five components will be aligned using the alignment holes before an adhesive bonding takes place. The SU-8 components will be coated with Au for good conductivity, and then bonded before being put into a brass housing, as shown in figure 9. The characterization of the SU-8 filter will follow. Filter component moulds have also been produced using SU-8 and work is going on to produce copper filter components using the electroforming process. The results are expected to come out shortly.

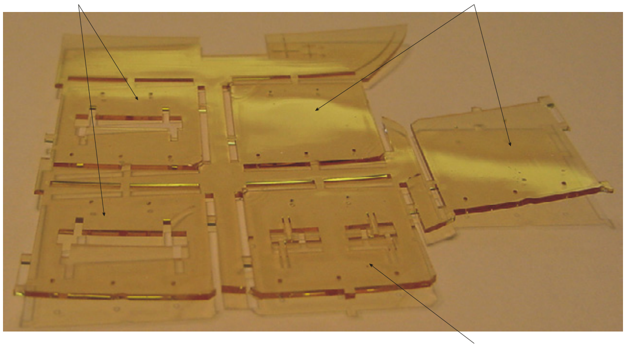

Figure 8. 700 μm thick layers of the Ka-band filter made of SU-8.

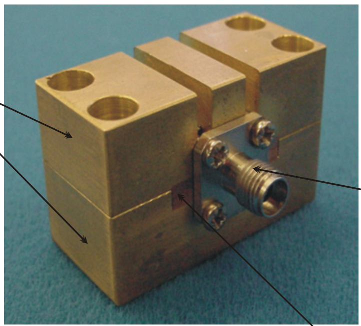

Figure 9. Photograph of a complete layered coaxial device.

4. Conclusions

An air filled Ka band dual mode filter has been designed, and the characterization results show a good agreement with the theoretical prediction. The filter is designed in five planar layers and bonded together to suit microfabrication. A new SU-8 fabrication process has been developed to produce the 700 μm thick filter components. Through analysis of the transmittance spectra of SU-8 layers prepared in different soft bake times, the optimum soft bake time is identified which enables the SU-8 layer to absorb the minimum UV light in order to maintain a uniformed UV exposure throughout the layer. The optimized process has produced microstructures with an aspect ratio of 40:1 and very vertical sidewalls in 1000 μm thick layers, sufficient for producing a range of quality filters. 700 μm thick SU-8 filter components have been produced using the presented SU-8 process. The conductivity of the filter can be resolved either by depositing a metal coating on the surface of the filter components using a sputtering process, or by using the SU-8 structures as the moulds to produce metallic components using electroforming. In either of the processes, high quality geometry of the SU-8 components will be maintained for a good filtering performance. The microfabrication process presented in this paper suits the proposed filter well. It also reveals a good potential for volume production of high quality RF devices.

References

[1] Bircumshaw B *et al* 2003 The radial bulk annular resonator: towards a 50 Ω RF MEMS filter Boston *Transducers'03: Digest of Technical Papers* vols 1 and 2 pp 875–78
[2] Shen S H, Young S T and Fang W L 2001 High-performance MEMS bandpass filters for acoustic signal processing applications *Proc. SPIE* **4591** 292–301
[3] Diamantis S *et al* 2000 A programmable MEMS bandpass filter *Proc. 43rd IEEE Midwest Symp. on Circuits and Systems* vols I–III pp 522–5
[4] Blondy P, Brown A R, Cros D and Rebeiz G M 1998 Low loss micromachined filters for millimetre wave communication systems *IEEE Trans. Microw. Theory Tech.* **46** 2283–8
[5] Brown A R and Rebeiz G M 1999 A high performance integrated K-band diplexer *IEEE Trans. Microw. Theory Tech.* **47** 1477–81
[6] Llamas-Garro I, Jiang K, Jin P and Lancaster M J 2003 SU-8 microfabrication for a Ka-Band filter *4th Workshop on MEMS for Millimetrewave Communications (Toulous, France, 2–4 July)*
[7] Harris J E, Pearson L W, Wang X, Barron C H and Pham A V 2000 Membrane-supported Ka band resonator employing organic micromachined packaging *IEEE MTT-S Digest* pp 1225–8
[8] Lin C-H, Lee G B, Chang B W and Chang G L 2002 A new fabrication process for ultra-thick microfluidic microstructures utilizing SU-8 photoresist *J. Micromech. Microeng.* **12** 590–7
[9] Ansoft H FSS. http://www.ansoft.com
[10] Lau K C H 1988 Loss calculations for rectangular lines *IEE Proc.* H **135** 207–9
[11] Gruner L 1983 Higher order modes in square coaxial lines *IEEE Trans. Microw. Theory Tech.* **31** 638–41
[12] Microchem 2002 NANO^{TM} SU-8, negative tone photoresist formulations 2-25 http://www.microchem.com/products/pdf/SU8_2-25.pdf
[13] Ling Z G, Lian K and Jian L K 2000 Improved patterning quality of SU-8 microstructures by optimizing the exposure parameters *Proc. SPIE* **3999** 1019–27
[14] LaBianca N and Gelorme J D 1995 High aspect ratio resist for thick film applications *Proc. SPIE* **2438** 846–52
[15] Lee K Y, LaBianca N, Rishton S A, Zolgharnain S, Gelorme J D, Shaw J and Chang T H P 1995 Micromachining applications of a high resolution ultrathick photoresist *J. Vac. Sci. Technol.* B **13** 3012–6
[16] Zhang J, Tan K L, Hong G D, Yang L J and Gong H Q 2001 Polymerization optimization of SU-8 photoresist and its applications in microfluidic systems and MEMS *J. Micromech. Microeng.* **11** 20–6
[17] Cui Z, Jenkins D W K, Schneider A and Mcbride G 2001 Profile control of SU-8 photoresist using different radiation sources *Proc. SPIE* **4407** 119–25