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Fabrication of high aspect-ratio polymer microstructures for large-area electronic portal x-ray imagers

J.H. Daniel⁺, A. Sawant⁺⁺, M. Teepe⁺, C. Shih⁺, R.A. Street⁺, and L.E. Antonuk⁺⁺

⁺ Palo Alto Research Center, 3333 Coyote Hill Rd, Palo Alto, CA 94304

⁺⁺ Department of Radiation Oncology, University of Michigan, Ann Arbor, Michigan 48109

Abstract

Megavoltage x-ray imaging performed during radiotherapy is the method of choice for geometric verification of patient localization and dose delivery. Presently, such imaging is increasingly performed using electronic portal imaging devices (EPIDs) based on indirect detection active matrix flat panel imagers (AMFPIs). These devices use a scintillating phosphor screen in order to convert incident x-rays into optical photons, which are then detected by the underlying active matrix photodiode array. The use of a continuous phosphor introduces a trade-off between x-ray quantum efficiency and spatial resolution, which limits current devices to use only ~2% of the incident x-rays. This trade-off can be circumvented by “segmented phosphor screens”, comprising a two-dimensional matrix of optically-isolated cell structures filled with scintillating phosphor. In this work we describe the fabrication of millimeter-thick segmented phosphor screens using the MEMS (micro-electro-mechanical-system) polymer SU-8. This method is capable of being extended to large-area substrates.

Keywords

High aspect-ratio; SU-8; x-ray imaging; Large-Area MEMS; Polymer MEMS; Scintillator

1. Introduction

X-ray imaging is an important tool for medical diagnostics, materials evaluation and security imaging. Digital x-ray imaging is increasingly replacing conventional photographic x-ray film [1]. One of the most exciting developments in digital imaging is the recent development of active matrix flat panel imagers (AMFPIs), which consist of a two-dimensional addressable matrix of photodiode elements coupled to some form of x-ray converter. Depending on the type of x-ray converter used, AMFPIs may be classified as direct-detection type, which use a photoconductor such as amorphous Se, PbI₂, or HgI₂, and indirect-detection type, which use a scintillator material (such as Gd₂O₂S:Tb or CsI). The scintillator absorbs a fraction of the incident x-rays and emits visible light which, in turn, is detected by the photosensitive elements of the underlying active matrix array.

AMFPIs have found widespread use in a variety of medical x-ray imaging applications such as mammography, radiography, fluoroscopy and radiotherapy imaging. In particular, external-beam radiotherapy involves the delivery of high-energy x-rays (6 to 25 MV) to the site of the

tumor, typically, using a medical linear accelerator. Due to the fact that the radiation is delivered in daily fractions over a period of several weeks, it is essential to ensure that the treatment is repeatedly delivered exactly to the intended anatomical site (corresponding to the tumor) and that there is no significant variation in the treatment setup which may lead to geometric and dosimetric errors. Currently, such verification is usually performed using electronic portal imaging devices (EPIDs) based on AMFPIs, by acquiring images from the treatment portal [2]. (Hence, such imaging is also called *portal* imaging.) Presently-available AMFPI EPIDs use a relatively thin scintillating phosphor screen (typically, gadolinium oxysulphide) to convert x-rays into visible light photons, which are then detected by the underlying active matrix array. Since the x-ray energies encountered in radiotherapy are very high, relatively thick layers of x-ray converter are needed to detect a significant fraction of the incident x-rays. However, in the case of conventional phosphor screens of the type used in commercial AMFPI EPIDs, increases in the thickness of the phosphor layer are accompanied by corresponding reductions in the spatial resolution. Due to this tradeoff, current megavoltage imaging AMFPIs use converters that can detect only ~2% of the incident radiation. As a result, the imaging performance of these devices, as quantified by the spatial frequency-dependent detective quantum efficiency (DQE, a widely accepted metric of imaging performance) is only ~1% – compared to up to 70% DQE for diagnostic (i.e., kilovoltage) x-ray AMFPIs.

In order to circumvent this tradeoff between x-ray quantum efficiency and spatial resolution, and thereby achieve significant increases in the DQE performance, segmented or microstructured phosphor screens have been proposed [3,4]. Such segmented screens consist of a two-dimensional (2D) matrix of microfabricated, high-aspect-ratio cells that are filled with a suitable scintillating phosphor. The creation of such segmented detectors enables the use of a thicker layer of scintillating phosphor without the loss of spatial resolution due to spread of optical photons.

We have explored a detector design based on segmented phosphor screens, fabricated using a polymer MEMS (micro-electro-mechanical-system) approach. The screens were aligned to an underlying AMFPI (Fig. 1). The polymer walls are made opaque in order to achieve optical isolation between neighboring cells. Segmented screens based on photolithographically patterned polymer walls have been studied before for diagnostic imaging where thinner phosphor screens are sufficient, but where the resolution requirements are higher [5,6]. In this paper, we have focused on ultra-high polymer MEMS structures in the millimeter range.

A microfabrication method that is capable of high aspect-ratios (height to width ratio of a microstructure) and heights in the mm range was chosen. Previously, such structures were primarily fabricated using x-ray lithography or deep reactive ion etching [7,8]. Since the x-ray imagers target applications which require a sensor area comparable to part of the human body, the x-ray conversion screen has to be fabricated with methods that are large-area compatible (Large-Area-MEMS). Polymer microfabrication is a promising method because of the scalability to large substrate sizes.

The thick photopolymer SU-8 has been previously explored for several high aspect-ratio structures in the MEMS field [9,10]. Other thick photopolymers are emerging, but so far none has reached the aspect-ratio and thickness possible with SU-8. Because cross-linked SU-8 is difficult to remove, the polymer has its greatest value for applications in which it remains as a permanent microstructure. Here, we have chosen SU-8 for the fabrication of millimeter-high x-ray conversion screens using conventional UV photolithography.

2. Fabrication

The x-ray conversion screens were fabricated on 4 inch glass substrates with an SU-8 thickness of up to ~ 2.5 mm. Fig. 2 shows a photograph of a wafer with metal-coated SU-8 cells. The cell pitch in all samples was $508\text{ }\mu\text{m}$ and the width of the walls was designed on the mask layer to be $40\text{ }\mu\text{m}$. The following sections describe the fabrication of the conversion screens.

2.1. SU-8 processing

SU-8 processes have been described earlier for applications including microfluidics, microcantilevers or microgears [9,10]. However, when processing ultra-high photopolymer structures, the steps of resist-coating, exposure and development become rather challenging.

The thickness of the SU-8 layers was controlled by dispensing a calibrated amount of SU-8 polymer. The SU-8 reflows during the softbake and forms a layer with the desired thickness. This method was simpler than spin-coating of several layers. We used the high-viscosity SU-8-100 (Microchem Corp.) which has a $\sim 73\%$ polymer content. In order to evaporate the solvent, the softbake requires a well-leveled hotplate, otherwise the thickness of the layer will be non-uniform. For SU-8 layers with a thickness of about one millimeter, the softbake takes several hours at a temperature of $\sim 100^\circ\text{C}$. At the end of the softbake, the wafer has to be slowly cooled down to room temperature; otherwise excessive stress between the substrate and the thick SU-8 layer causes cracking and delamination of the SU-8.

On an exemplary SU-8 layer of good uniformity with an average thickness of 1.286 mm , we measured a thickness variation of $\pm \sim 15\text{ }\mu\text{m}$ over a 4 inch wafer. The measurement was done by cross-sectioning the wafer in the center and measuring the SU-8 thickness with a microscope at 17 equally spaced locations, neglecting the area close to the edges.

Precise leveling of wafers during the softbake is rather challenging. Therefore, we also investigated a polymer casting method with well-defined spacers [11]. At a temperature above T_g (glass transition temperature) of SU-8 a cover sheet with a flat surface (and anti-adhesion coating) is pressed onto the SU-8 and the spacers serve as a thickness gauge. This step occurs after most of the SU-8 solvent has evaporated. Upon cooling to room temperature, the SU-8 solidifies and subsequently the cover is peeled away.

Lamination techniques, such as described in Ref. [12], may also become promising once dry-film versions of SU-8 become available, particularly for large area processing.

The UV illumination of the SU-8 was done by backside exposure, similar to the method reported earlier for our high resolution x-ray conversion screens [5,6]. On the glass substrate, which served as the photomask, a layer of titanium was patterned to define the cells and peripheral alignment features. Backside exposure was chosen to ensure that the SU-8 walls had sufficient width and that the SU-8 was sufficiently cross-linked near the substrate. Narrow walls and poor crosslinking would otherwise result in delamination of the structures during the development step. Furthermore, by employing backside exposure, the SU-8 walls are automatically aligned with the alignment features which are needed for mounting the conversion screen onto the image sensor array. Fig. 3 shows an array of cells that was fabricated using backside exposure. We found that, even after long exposure times (a fluence of $\sim 10\text{ J/cm}^2$ @ 400 nm), the top section of the SU-8 walls in 1-2 mm thick resist was not well defined. This is due to the reduced light transmission of thick SU-8 layers. We measured a decrease of the transmission of 400 nm light from $\sim 86\%$ for a $\sim 350\text{ }\mu\text{m}$ layer to $\sim 62\%$ for a $\sim 1.2\text{ mm}$ thick layer. Moreover, photodarkening occurs during UV exposure. For a $\sim 1.2\text{ mm}$ thick layer of SU-8-100 the transmission decreased to $\sim 27\%$ after exposure to 2.4 J/cm^2 of 400 nm UV

light. The photodarkening is most likely caused by the photoinitiator, because it was not observed in photoinitiator-free SU-8.

Improved SU-8 structures were achieved by choosing double-sided UV exposure with front-to-backside alignment on a Karl-Suess MA8 exposure system. Fig. 4 shows SEM images of cell structures that were fabricated with this process. The walls are well defined along the height of the cells and it can be seen that the wall width is smallest near the center. Fig. 5 shows a detailed measurement of the SU-8 wall width. The fluence for the backside exposure was slightly higher than for the frontside exposure which explains why the minimum of the thickness curve is shifted away from the substrate. The distinct peak of the width near the substrate is likely due to diffraction of the 400 nm UV light at the $\sim 40\text{ }\mu\text{m}$ aperture in the photomask.

Due to the non-uniform width of the SU-8 walls, it is difficult to give an accurate value for the aspect-ratios achieved with this process. For the SU-8 cells in Fig. 4, the aspect-ratio for the walls is above $\sim 1:30$ ($1.6\text{ mm} : 50\text{ }\mu\text{m}$).

After UV illumination the samples underwent a post-exposure-bake in which they were gradually heated to 90°C and then slowly cooled down.

In the final development step the unexposed SU-8 was dissolved away by spray-development with a custom-built developing station.

2.2. Metallization

In order to prevent optical cross-talk between the cells, the cell walls have to be rendered opaque. A method that turns the SU-8 walls opaque, but not reflective, relies on the partial carbonization of the SU-8. When heating SU-8 structures in air to several hundred ($\sim 400^\circ\text{C}$) degrees, the SU-8 turns dark due to gradual carbonization. However, in this process we observed high stress between the substrate and the SU-8 and the walls tended to delaminate unless they were divided into small isolated segments. Furthermore, the walls still remained rather transparent because of their narrow width.

Ideally, the walls should be reflective in order to reduce the loss of generated photons within a cell. Therefore, we investigated coating methods, such as metal sputtering, metal evaporation and silvering using nanoparticles. The bottom of the cells is already reflective due to the metal masking layer that was required for backside exposure.

Fig. 6 shows side-views of metallized walls ($1.3\text{--}1.4\text{ mm}$ tall) from cross-sectioned wafers with illumination from the back. The walls in Fig. 6a) were coated by sputtering a layer of titanium/aluminum and the walls in Fig. 6b) were coated by e-beam evaporation of aluminum at an oblique angle. For comparison, a section of the walls in Fig. 6b) was blocked off and remained uncoated. The sputter-coated samples showed low light transmission near the top of the walls, but increased transmission towards the substrate. The thickness of the sputtered aluminum was around $1\text{ }\mu\text{m}$ on a surface parallel to the substrate. The bright vertical gaps in the walls will be explained later with respect to Fig. 9.

By using oblique evaporation at an angle that was optimized with regard to width and height of the SU-8 cells, we achieved better coating of the walls towards the bottom. This can be seen in Fig. 6b) and also in the SEM image in Fig. 9. The $\sim 1.4\text{ mm}$ tall SU-8 cells were coated with e-beam evaporated aluminum at an angle of $\sim 15^\circ$ to the normal of the substrate. As can be seen in Fig. 6b), there seems to be a greater problem with pinholes in the evaporated aluminum layer. However, in this sample the walls were only coated on one side and the evaporated layer of aluminum was only $\sim 0.5\text{ }\mu\text{m}$ thin on a surface parallel to the substrate. In order to block

light in all directions, the sample would have to be coated from at least two perpendicularly oriented oblique angles. For coating all the wall surfaces, the sample should be mounted on an oblique rotating stage during evaporation.

In Fig. 6c), SU-8 walls are shown that were coated with a layer of silver from an aqueous solution of silver nanoparticles. In this case, the solution was vacuum-filled into the cells to reduce coating defects from trapped air. Subsequently, the sample was heated to evaporate the solvent and to fuse the nanoparticles. The resulting layer blocks the light well and it has a good reflectivity. This coating method is also promising for taller cells for which vapor deposition may be difficult. However, a drawback is the high cost of silver nanoparticle solutions.

For the screens that were characterized, we employed the sputtering method because it was the easiest to implement in our process and because it appears to be most suitable as a large-area fabrication process. Different sputter processes such as biased directional sputtering may give improved coatings, but the process was not available to us. Oblique evaporation is a very promising coating method for achieving good coverage in deep cells, but the requirement for special mounting of the substrate poses a problem, particularly for large area substrates.

2.3. Phosphor filling

After metallization, the SU-8 cells are filled with a scintillating phosphor. Typically, this is a powder consisting of a material such as terbium-doped gadolinium oxysulfide, $\text{Gd}_2\text{O}_2\text{S:Tb}$ (GOS), which emits visible light upon excitation by the x-rays. GOS emits in the green wavelength range, which is where the amorphous silicon p-i-n photodiodes of the image sensor array have their highest sensitivity.

The introduction of the phosphor into the cells has to be optimized in order to obtain a uniform light output from the screen. We prepared a slurry by mixing the GOS with a low surface-tension liquid and a dispersant. The cells were then filled with this slurry, as described in more detail in Ref. [13]. A low-viscosity UV curable polymer or a low-viscosity cyanoacrylate was used to permanently bind the phosphor powder in the cells.

Fig. 7 shows a cross-section of ~ 1.2 mm high SU-8 cells that were filled with GOS phosphor. The image shows that dense filling can be achieved, but occasional voids in the phosphor due to trapped air require careful process optimization. Fig. 8 shows a structured phosphor screen in which the phosphor was mixed with glass spheres. This method might increase the light output from upper phosphor regions [13].

For optimum light output, the light scattering within the phosphor should be kept small. Ideally a binder polymer which is optically matched to the phosphor would be desirable. Since the refractive index of GOS lies around a value of 2.2, while most polymer resins range between 1.3 and 1.7, perfect optical matching cannot presently be achieved. In the future, nanoparticle-polymer composites with increased refractive index may provide better optical index matching [14].

2.4. Assembly

As illustrated Fig. 1, the phosphor screen is laid directly onto the image sensor. The cells of the conversion screen must be aligned to the pixels of the image sensor array. Presently, this alignment is done visually using cross-hair alignment features on the periphery of the conversion screen (Fig. 2). Alternatively, passive alignment methods have been proposed which employ microstructures to guide both substrates into place [15].

The surface of the phosphor screen has to be smooth and flat to guarantee close contact between the screen and the surface of the image sensor array, otherwise light can leak between

neighboring cells. To achieve this, the surface of the phosphor screens was slightly polished using glycol-based diamond polishing slurry ($\sim 0.1 \mu\text{m}$ particles) and polishing pads from 14 to $5 \mu\text{m}$ grade.

Ideally, the SU-8 cells would be patterned directly onto the image sensor array, but this is problematic with respect to the metallization of the walls and with regard to the fabrication yield. In our experiments to evaluate the phosphor screens, they were only temporarily laid onto the flat panel imager because only a single image sensor panel was available. This may have caused non-ideal light coupling between the phosphor screen and the image sensor. We suggest that, in a more robust setup, a thin layer of transparent polymer be applied between the conversion screen and the image sensor array and the phosphor screen be permanently attached to the image sensor around the edge with an adhesive. If the optical properties of this polymer are chosen carefully, the light coupling between the phosphor cells and the sensor will be improved.

3. Design variations

Due to the considerable thickness of the SU-8 layer, the structure in Fig. 4 with continuous SU-8 walls may develop stress and cause wafer bow or delamination. Therefore, we investigated cell designs with stress-relieving gaps in the walls (Figs. 9, 10). Gaps are also advantageous during the fabrication process. For example, the development of the thick SU-8 structures is improved because developer liquid can circulate more easily compared to the situation in closed cells where the convection of the developer liquid is restricted. Gaps also improve the introduction of phosphor slurry into the cells because trapped air can escape more easily. The SU-8 structure behaves like a sieve in which the fluid drains away leaving behind the particles. However, the inclusion of such gaps raises the concern of light-leakage between the cells. Therefore, we designed the cells with gaps that are laterally offset which avoids a continuous light path over several rows of cells. The walls in Figs. 6 and 9 also show that, in an optimized fabrication process with double-sided exposure, the gap is much narrower (or even closed) near the top of the cells which reduces light leakage in the region where the phosphor screen will be closest to the image sensor array. As shown in Fig. 10, alternative designs with overlapping wall sections were considered. Such a design provides a gap while minimizing transmitted light, but it also occupies more area and therefore reduces the fill factor of the phosphor screen. We therefore did not pursue these designs in greater depth but focused on the structures shown in Figs. 6 and 9.

4. Discussion

With the approach described above, prototype segmented screens were fabricated on substrates up to 4 inches in diameter. The performance of these prototypes was evaluated under radiotherapy irradiation conditions using an array with a pixel pitch matched to that of the cells of the screens and the results have been reported in Refs. [13] and [16].

From these studies, it is apparent that the x-ray sensitivity of the segmented phosphor screen is affected by a combination of quantum efficiency and optical transport characteristics of the phosphor. Our experiments demonstrated that, with the segmented phosphor approach, a significantly increased quantum efficiency for a phosphor-based detector can be achieved, while maintaining adequate spatial resolution. However, although light spreading was reduced, the effect was in some cases lower than theoretically expected. This is likely due to a small, but non-negligible amount of optical cross-talk between adjacent cells as well as non-ideal optical coupling between the phosphor screen and the image sensor array. Since our SU-8 screens were metallized by sputter-coating, a small amount of light coupling in the area near the substrate may have occurred. Other metallization processes, as discussed in Section 2.2.,

may provide improved opacity. Also, cell designs with overlapping cell walls, as discussed with respect to Fig. 10, may reduce light leakage through the gaps in the cell walls. The interface between the phosphor screen and the image sensor is also likely to have contributed to reduced light coupling. This issue can be addressed by improving the planarity of the phosphor screen surface and by using an optical polymer for index matching between the phosphor screen and the image sensor.

The main drawback of the SU-8-based phosphor screen is the significant amount of optical absorption along the depth of each segmented element. Consequently, the overall optical gain (i.e., number of light photons *escaping* the scintillator per absorbed x-ray photon) is highly dependent on the depth of x-ray interaction within the segmented detector. Such a depth dependent optical gain gives rise to a form of noise known as optical Swank noise, which causes significant reduction in the DQE performance [13,17]. Reducing this depth-dependent noise may be possible by incorporating light guides into the phosphor or by gradually varying the phosphor density and/or phosphor brightness with depth so as to compensate for the lower light gain near the x-ray side of the phosphor compared to the array side. Fig. 8 shows an example of how the phosphor density can be adjusted by adding glass beads and the fabrication techniques mentioned below in section 4.1. are a possibility for screens with gradually varying phosphor density. Moreover, novel binder materials may reduce light scattering by providing better matching of the refractive indices.

Further improvements in the DQE may also be achieved by fabricating even taller cell structures and the suggested alternative fabrication techniques mentioned in the following section may be promising in this regard, particularly for large area devices.

4.1. Alternative microfabrication techniques

Due to the challenges encountered in processing ultra-thick layers of photopolymer, other fabrication processes which build on the described SU-8 process have been explored. These may be particularly promising for fabricating even taller structures or for lowering the cost of the fabrication process. While fabricated structures based on these alternative processes have not yet been tested as x-ray conversion screens, such fabrication methods are briefly described here to serve as inspiration for future microfabrication directions.

In one approach, relatively thin layers of SU-8 cells are filled with a phosphor-polymer compound. Thin layers are less difficult to fabricate compared to millimeter-thick ones. The layers are released from their substrate employing, for example, a sacrificial layer and, after being aligned, several layers are bonded or laminated together. This concept also allows varying the phosphor density from layer to layer which may be beneficial with regard to the above mentioned optical Swank noise of the conversion screen [13]. In Fig. 11, such a structure consisting of four layers is shown. In this lamination method, the SU-8 might be replaced by electroplated walls which can also be fabricated in a large-area-compatible process.

A molding technique would be a desirable alternative to lithographic patterning, particularly with respect to large-area processing at a reduced cost. However, direct molding of millimeter high structures is difficult, especially on large areas. We therefore developed a method in which the phosphor screen can be molded by stacking thinner layers. Fig. 12 shows an image of a polymer structure that was formed from seven layers of a UV curable polymer using an SU-8 mold. Each layer is only about 100 μm tall and, at this height, the molding process is relatively simple. For the x-ray conversion screen, we mixed the cross-linkable polymer with the GOS phosphor powder to form a molding paste which was solidified using UV light. The spaces that define the opaque wall structures were filled with an opaque material such as a reflective silver paste. Similar to the previous method, the phosphor density may be varied from layer to layer.

Except for potential alignment errors, there is, in principal, no height limit for structures which are fabricated with the described methods. By varying the cell pitch from bottom to top these approaches are also promising for structured screens with oblique walls. With cell walls gradually becoming more oblique from the center of the screen towards the edge of the array, a 'focused' conversion screen would be possible. Such a structure is desirable for very thick phosphor screens where the parallax of x-rays due to their origin from a point source may otherwise cause imager noise [16].

5. Conclusion

We have presented a polymer microfabrication approach for thick, high aspect-ratio segmented x-ray conversion screens based on UV lithography. The performance of the screens shows that the approach has promise and the patterned walls are efficient in decreasing light spreading, but improvements are still needed. Other fabrication processes employing lamination and molding were explored as they may be potentially simpler and offer additional functional advantages, but at the present stage no conclusive answer has been found as to which method will be the most promising for a manufacturing process.

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Figure 1.

Portal x-ray imaging during radiotherapy (a). In order to minimize the irradiation of healthy tissue, the high-energy x-rays are used to treat the tumor and to image its location. In b) an exploded view of the x-ray imager is shown. When assembled, the structured x-ray conversion screen is laid onto the active-matrix flat-panel imager with precise alignment of the cells to the pixels of the sensor array.

Figure 2.

Photograph of 2.5 mm high SU-8 cell structures (508 μm pitch) on a 4 inch diameter glass wafer. The SU-8 cells are sputter-coated with aluminum. Alignment features on the periphery assist in the alignment of the conversion screen to the image sensor array. The inset shows a close-up view of the cells.

Figure 3. SEM image of SU-8 cells (~1.7–2 mm high) which were fabricated by single-sided UV exposure through the glass substrate (backside exposure).

Figure 4. SEM images of ~1.6 mm high SU-8 cells fabricated with double-sided UV exposure (a, b). The side-view in b) shows the thickness variation of the walls.

Figure 5.

Wall thickness as a function of cell depth for the cell structures in Fig. 4. The aperture in the photomask for defining the SU-8 wall structures was $\sim 42 \mu\text{m}$ wide. The peak near the substrate is probably due to diffraction of the 400 nm UV light. This peak is slightly higher for the front-side exposure because of the likely presence of a small gap between the mask and the SU-8 surface. The dotted lines indicate the trend of the wall thickness for front and backside exposure, respectively.

Figure 6.

Side-view of SU-8 walls from cross-sectioned cell arrays (~ 1.2 - 1.3 mm high) after metallization. The walls were illuminated from behind. Sample a) was coated with sputtered aluminum and the image reveals that the upper part of the cells blocks the light quite well while the lower part still lets some light through. The coating in b) was obliquely evaporated

aluminum which resulted in an opaque coating from the top to the bottom of the cell walls (except for pinholes). In c), the cells were coated with a layer of silver nanoparticles. The dashed line indicates the boundary between the substrate and the SU-8 walls. The long vertical gaps in the walls are introduced for processing reasons and they are also shown in Fig. 9.

Figure 7. SEM image of ~1.2 mm high SU-8 cells filled with a GOS phosphor compound. A dense phosphor packing is achieved, but voids due to trapped air can pose a problem.

Figure 8.

Photograph of SU-8 cells which are filled with a phosphor compound that was mixed with glass spheres ($\sim 55\ \mu\text{m}$ diameter). The height of the SU-8 cells is around 1.3 m and the walls in this sample were not coated with a metal.

Figure 9.

SEM image of SU-8 cells (~1.3 mm high) with narrow gaps in the cell walls. The gaps are beneficial during the development process of the SU-8 because they improve the circulation of the developer liquid and they facilitate the introduction of the phosphor slurry. This sample was coated with aluminum by oblique evaporation.

Figure 10. SEM images of alternative designs a) and b) for cell walls with gaps. The geometry with oblique gaps reduces optical cross-talk between the cells. The cell height of the shown structures is only around 170 µm.

Figure 11.

Four-layer stack of phosphor filled SU-8 cells. A ~130 micron thick layer of SU-8 cells was filled with a phosphor-polymer compound and four such sheets were aligned and laminated together. The SU-8 walls are uncoated in this sample.

Figure 12.

SEM image of a layered polymer structure. Seven polymer layers were molded on top of each other using a $\sim 100\ \mu\text{m}$ deep mold made from SU-8. Passive alignment was used and, after molding of each layer, the gaps were partially filled with an opaque material.