

Method of Testing Microlenses for Image Sensors

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Abstract

Solid-state image sensors frequently use microlenses to improve their light sensitivity and many publications are available for designing, manufacturing, and optimizing their performance. Once the microlens has been fabricated, the final evaluation ultimately requires measuring their photo-electric performance in conjunction with an image sensor. However, the semiconductor wafers used to produce these sensors are costly and testing them can be complicated.

Improvements in image sensor sensitivity and microlens design can be implemented faster and at a much lower cost by superimposing a matrix of microlenses over another matrix of microscopic apertures on quartz wafers. In this physical model, each aperture simulates a pixel's photo-active area or region of maximum sensitivity. The matrix of apertures and microlenses is large enough to allow quick evaluation by conventional transmission densitometry. Also, critical parameters, such as: lens curvature, focal length and point spread function can be evaluated quickly using a single wafer. The wafers are much lower in cost and reusable.

Introduction

The light sensitivity of a solid-state image sensor is ultimately determined by its ability to gather photons, convert them into electrons and transport the electrons out of the device. The sensor's resolution is often described by the number of light-sensitive elements, or pixels, positioned in a line or in a rectangular array. These pixels are often heterogeneous in composition and may contain different regions within the pixel which are responsible for performing separate tasks, such as: light sensing, pixel isolation and signal readout.

Some pixel regions are sensitive to light but covered by polysilicon, which absorbs some of the light and reduces the sensor's sensitivity. Other pixel regions can be devoted to signal readout or isolation and are generally not sensitive to light at all. Therefore, each pixel region may have varying amounts of light sensitivity *and* spectral sensitivity; while the pixel's overall sensitivity is the integral of each pixel region and its contributing area. Sensitivity can be greatly improved by deflecting light away from the regions of poor or no sensitivity and onto the portion of the pixel with the highest sensitivity. This is the purpose of a microlens.

Figure 1 is a top-view scanning electron micrograph (SEM) of a pixel from a frame transfer charge coupled device (CCD). The raised portions are 5000 angstrom thick features of polysilicon, whose function is to help isolate and to transport photoelectrons. The polysilicon is not completely transparent but is actually orange-colored, which filters out blue and green light as shown in Figure 2. The non-active regions (channel stops) in between the polysilicon "fingers" are invisible in this micrograph. The effect of polysilicon filtering out blue and green light is shown in the spectral responsivity curve also in Figure 2. Even though the polysilicon covers only a portion of the active pixel region, the sensitivity is significantly reduced at shorter visible wavelengths. Deflecting the light away from the polysilicon region could result in improved blue and green sensitivity.

Figure 3 illustrates the spectral transmission of a blue-dyed positive photoresist used for producing color filter arrays on image sensors. Also shown in Figure 3 is the combined transmission of 5000 angstroms of polysilicon together with the blue filter. These films were deposited on quartz wafers. The total light transmission is found by integrating the area under the curve from 400-700nm. The result of this integral indicates that only 57% of the light passing through the blue filter actually penetrates the polysilicon. Furthermore, the peak transmission in the blue channel is shifted 40 nm into the green. Both the loss in signal and shift in sensitivity should produce significant losses in image quality.

Just like frame transfer CCDs, the pixels in interline transfer (IT) CCDs and CMOS image sensors are also heterogeneous and are comprised of different regions which perform different functions such as: photo-charge collection, isolation and transport. In CMOS image sensors, the ratio of the pixel region devoted to the sensing element compared to the entire pixel area is called the fill factor. Typically the sensing area, or photosite, comprises less than half of the pixel area *and* future designs of CMOS active pixel sensor (APS) pixels are not expected to exceed a fill factor of 63% by the year 2001.[1] Therefore, a dramatic improvement in IT CCD and CMOS image sensor sensitivity can be achieved by deflecting light away from the pixel circuitry so that it impinges directly on the photosite.

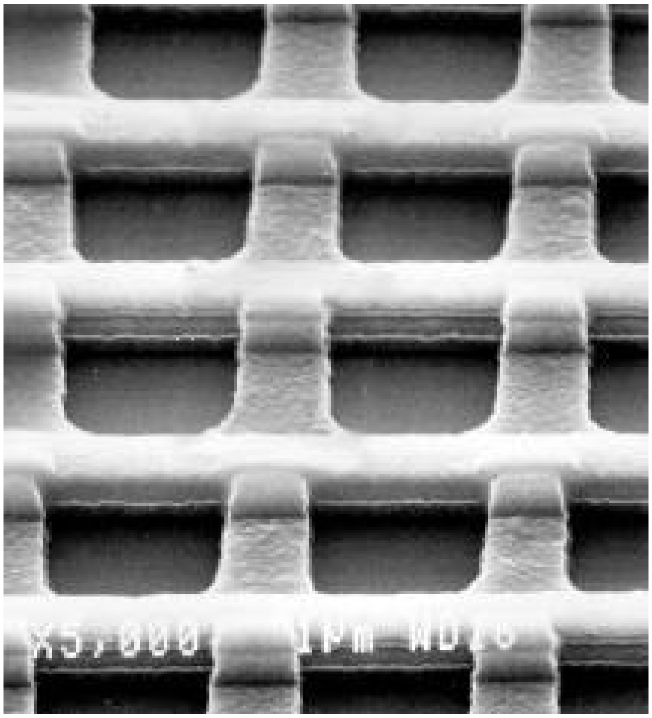

Figure 1. Scanning electron micrograph (SEM) of CCD polysilicon layers.

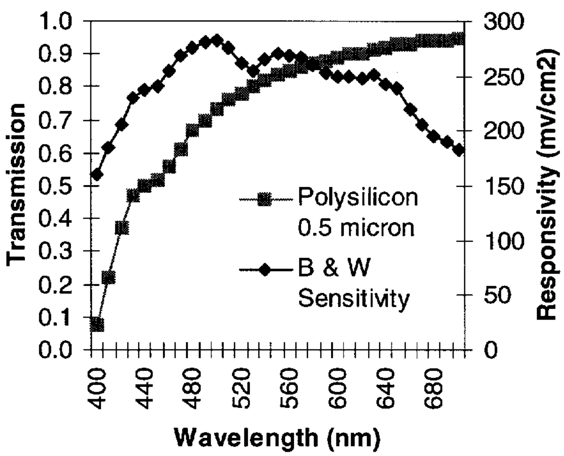

Figure 2. Spectral Transmission of 0.5 micron Polysilicon and B & W Sensitivity of CCD without microlenses.

Microlens Production

Microlenses can be manufactured by a variety of different methods[2,3,4,5,6] however one of the simplest methods is to use standard photolithographic techniques followed by melting or reflowing photoresist stripes into cylinders or squares into hemispheres.[7] This technique functions by exposing the resist to process temperatures in excess of the glass transition temperature (Tg). At the Tg, the cohesive forces which form the solid patterns are reduced and surface area is minimized to form a hemisphere (cylinder).

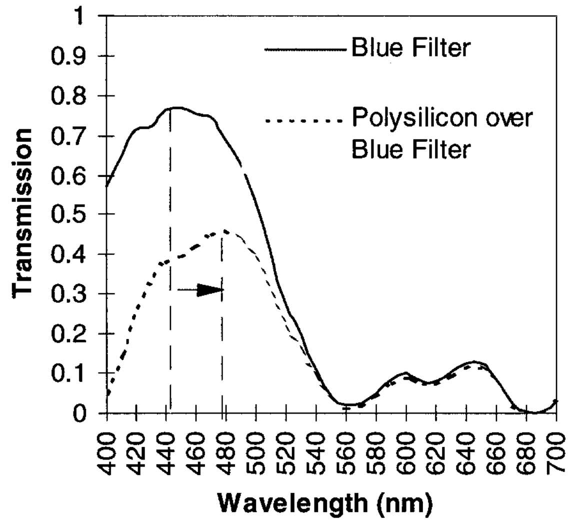

Figure 3. Blue light transmission through polysilicon.

In spite of the ease of manufacturing microlenses by reflowing novolac-based photoresists, several difficulties are frequently encountered, such as:

- Optical clarity of the photoresist
- Lateral spreading of the dimensions during reflow
- Glass transition temperature (Tg) of the color filters

These problems eventually complicate the procedure or reduce the performance.

An optically transparent photoresist is one important design feature for manufacturing microlenses. Most photoresists become quite transparent after exposure and are suitable as long as their Tg can be reached without significant yellowing. A small (0.5 µm), lateral spreading of the photoresist also occurs during reflow and must be taken into account. Therefore, stabilizing the color filters against both yellowing and distortion while reflowing the microlenses, is a difficult challenge.

Microlenses are not usually patterned directly onto the surface of the image sensor, but are separated by another layer to adjust the proper focal length. This is frequently accomplished with monochrome sensors by coating a planarizing layer of “spin on glass” (SOG) followed by the microlens photoresist coating. However, very high temperatures (200^{o}C) are required to stabilize the SOG coatings which can distort or yellow the color filters. Therefore, SOG coatings are not usually compatible with color filters. The pixel topography can be sufficiently planarized and the microlens focal length set with the color filters as long as the filter patterns do not overlap.

A chemical stabilization process for both color filters and microlenses can also replace or reduce the oven bakes normally used to stabilize the photoresist by incorporating hexamethylcyclotrisilazane (HMCTS) into the photoresist. This stabilizes the filter/focus layer before applying the microlenses without yellowing.[8]

Chrome/Quartz Apertures

Model

Our objective was to accelerate the lengthy, expensive and iterative process of designing, fabricating and testing microlenses on image sensors. This method of simulating the CCD pixel layout of polysilicon and channel stops, with patterns of chrome metal on quartz wafers, eliminates the need for fabricating image sensors except for final design verification. The chrome apertures shown in Figure 4 simulate the most sensitive region of the pixel, which in this case are the “windows” between the CCD’s polysilicon features and the channel stops. The patterned array is large enough (25mm^2) such that the increase in light transmission through the apertures can be measured directly with conventional transmission densitometry.

Semiconductor wafer fabrication is not perfect and frequently less than 100% of the image sensors on a single wafer pass all of the stringent tests. In order to find the fully functional sensors, complicated and very expensive opto-electrical wafer testing is required to probe the wafer and to map out the yielding sensors. Since it is almost impossible to determine in advance which sensors will pass, it can be difficult to introduce additional process variables for micro-lenses on a single wafer, called “wafer splits”. This forces the microlens designer to consume an entire wafer for each factor. This problem is eliminated with chrome on quartz wafers since the number of steps to produce them is small and the yields are extremely high.

Testing Procedure

A clean quartz wafer was vapor treated with HMCTS and spin-coated with positive photoresist to produce a 1.2 micron thick coating. Alignment marks in the photoresist were exposed by an ASM 2500/10 Stepper and developed in tetramethylamonium hydroxide (TMAH). The alignment marks were etched into the quartz through the cleared area of the photoresist to a depth of 1200 angstrom using a buffered oxide etch (NH_4F& HF 10:1). The photoresist was then removed from the wafer and cleaned. Chrome metal was vacuum evaporated onto the side of the wafer with the alignment marks to produce an optical density of approximately 3.0 (1800-3000 angstrom). The chrome side of the quartz wafer was spin-coated again with 1.2 microns of photoresist and exposed to the aperture reticle in the stepper and developed. The chrome apertures were etched using a solution of ceric ammonium nitrate and nitric acid followed by a rinse. The photoresist was removed and the wafers were cleaned. The wafers were now ready for the filter/focus layers and microlenses.

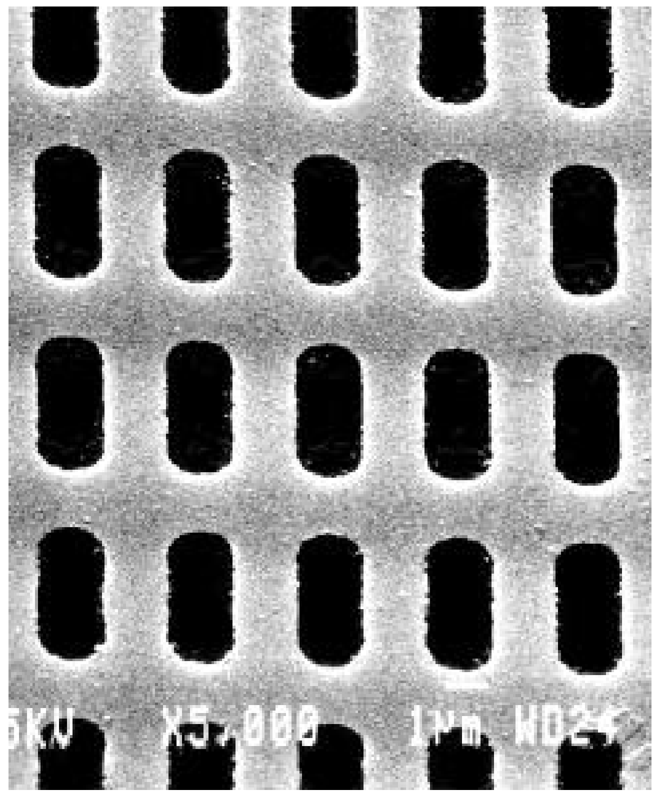

Figure 4. A top-view SEM of a 1500 angstrom thick pattern of apertures(shown in black) in chrome on quartz wafers. The color filters, focusing layers, conforming layers and microlenses are applied and patterned on these apertures for evaluation.

A 2 micron coating of positive photoresist was spin-coated, HMCTS stabilized and baked. A 2.2 micron coating of a transparent, positive microlens photoresist was spin-coated and patterned in the stepper. After development in TMAH, the clear resist patterns were reflowed on a hot plate. The wafers were then cooled and measured on a transmission densitometer.

Experimental Results

A quartz wafer was patterned with an array of chrome apertures, coated with a uniform focus layer and then patterned with a second array of microlenses. Transmission density measurements were made using a 3mm diameter aperture and the microlenses surface facing the light source.

Table 1. Density Measurements of Chrome/Quartz Wafers.

		Apertures	Apertures+ Microlenses	Optical Gain
Transmission	Calculated	28%	65%	66%
Density	Calculated	0.56	0.19	
Transmission	Actual	37%	51%	33%
Density	Actual	0.43	0.29	

Discussion

The array of chrome apertures is basically an 8,000 line per inch half-tone screen. Based on the design layout, the apertures should have transmitted 28% of the light. Not taking into account the transmission of the quartz wafer, the optical density of the chrome aperture array should have been 0.56 (-logT). The actual measured density, including the quartz, was 0.43. The density was lower than expected because of the sidewall angle of the photoresist and the wet etch process.

The light-gathering power of the microlenses is theoretically limited by the surface area that they cover. Assuming 100% lens efficiency and no absorption due to the photoresist, the maximum increase in transmission for this microlens design is 66%. This should have reduced the optical density from 0.56 to 0.19. Instead the optical density was actually reduced from 0.43 to 0.29. The actual optical gain measured was actually 33%. This is probably due to lateral spreading of the microlens pattern which was not compensated for.

Conclusion

It is clear that superimposing microlenses over chrome apertures on quartz wafers is a rapid and effective tool for designing microlenses. The chrome/quartz wafers are much less expensive than wafers with fully functional image sensors and are reusable. Analysis takes only a few seconds with an inexpensive densitometer and no setup is required. Spectral analysis can also be approximated, again without additional setup. A single chrome/quartz wafer can be used to measure the line or point spread function of the microlens by misaligning the lenses and apertures at 0.1 micron increments.

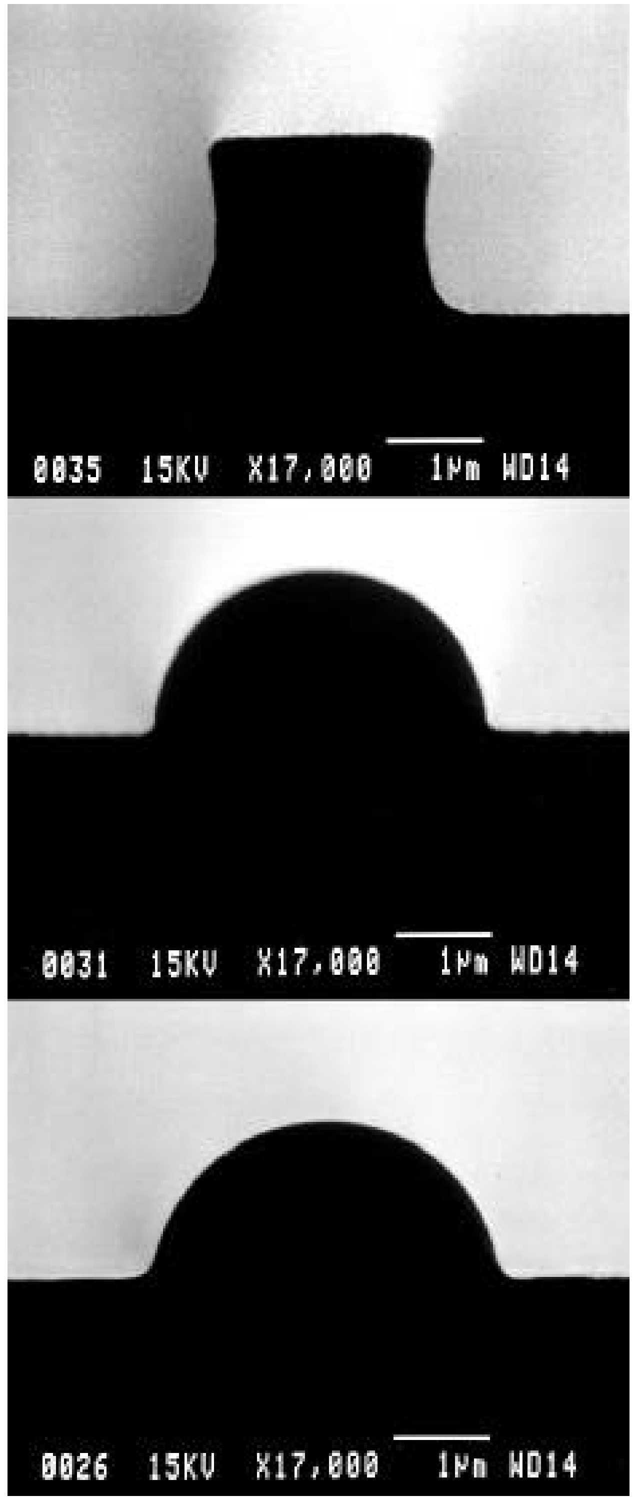

Figure 5 Cross-sectional SEM of a 6 micron wide stripe of positive resist and the same stripe after 2 minutes and 4 minutes of exposure to a hot plate at 125C. Both photoresist patterns are supported by a 2 micron filter/focus layer of dyed photoresist.

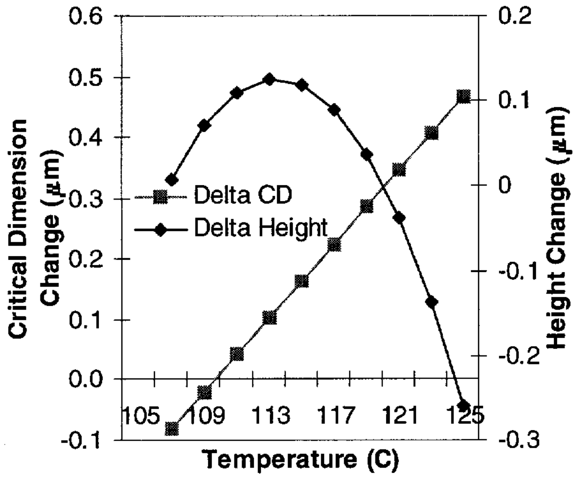

Figure 6 Changes in critical dimension and height for microlenses after a 2 minute hot plate reflow.

The CCD designer has two principle tradeoffs to consider when designing the polysilicon dimensions in a pixel: blue sensitivity and well capacity. Well capacity is a measurement of the number of electrons the pixel is capable of collecting. As the polysilicon dimensions shrink and the “windows” open up, the well capacity decreases with increasing blue sensitivity. In this application the microlenses increase the blue (and some green) sensitivity which can be be accurately measured with this model. However, a previous understanding of the effect on well capacity is required to complete the entire pixel design.

Acknowledgments

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