Characterization Methodology for Micro-Lens Performance in CMOS Image Sensors.

Vladimir Korobov, Christopher Cork, Hanan Wolf, Svetlana Fainleib
Tower Semiconductor Ltd, Israel

Introduction:

As the demand for cheaper and more powerful multi mega-pixel image sensors increases so does the need to decrease pixel size and add extra transistors to each pixel. This, however, will reduce the photoactive area and its sensitivity. This sensitivity loss can be overcome by using a microlens placed individually above each pixel. If the position and curvature of the lens is chosen correctly the lens will take light rays that would normally impinge on areas of the pixel that are not able to create photo current and concentrate it onto areas that can benefit, thereby increasing the electrical signal. This paper describes the techniques developed to enable the rapid optimization of microlenses for any given pixel. The techniques used were (1) ray tracing and resist melting computer models and (2) a generic microlens electrical test structure and (3) padded out arrays of actual customer pixels that allowed individual tuning of the microlens for these cases.

Simulation Methods:

As the positioning and curvature of the lens is critical and will differ with the layout and size of each pixel for each product it is essential to have a method of optimizing, characterizing and controlling the performance of these lenses. For this reason two techniques were developed in-house to predict the best microlens for any given customer's pixel. These are ray-tracing optical model and a generic electrical test structure to verify this simulation on wafer.

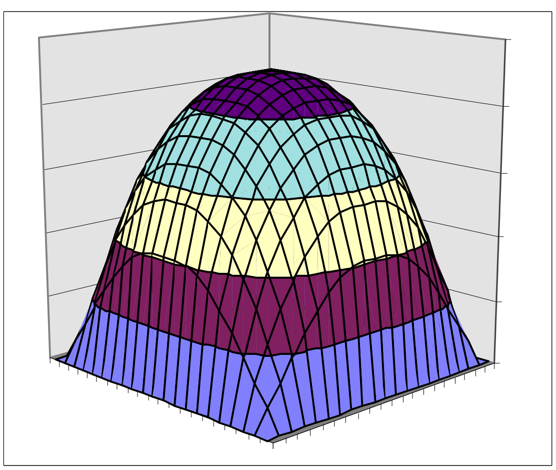

Fig.1 *Computer Modeled 3D Microlens Profile*

The modeling program generates the three-dimensional surface of a melted photoresist lens using an algorithm that minimizes the surface tension or area (Fig 1). Afterwards a ray-tracing program follows light rays in three dimensions through this lens and dielectric layers of defined thicknesses and refractive indices, to see how many impinge in a defined "photo active area" on the substrate (Fig. 2).

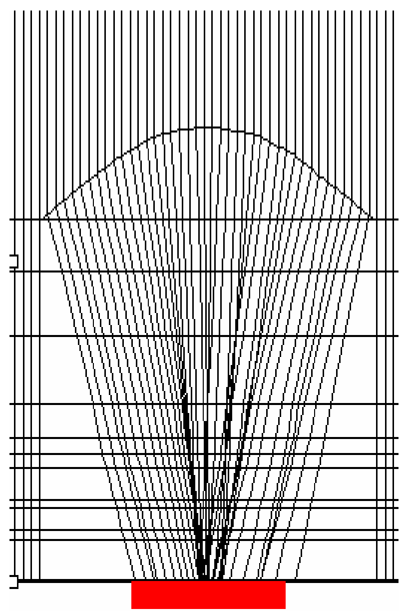

Fig. 2 *Ray- Tracing simulation from actual Microlens Cross-section, Highlighting photoactive area of the substrate.*

Generic Electrical Test Structure:

The electrical test structure (Fig. 3) was designed to produce a DC current reading suitable for electrical-test applications. A large area diode is defined approximately 300µm x 300µm in size. In this structure, an array of hundreds of openings in Metal 1 layer is defined. As aluminum is opaque to light, each opening approximates the light sensitive areas of each pixel. Above each hole, microlenses of the required dimensions can be formed so as to simulate the performance of a real microlens on a product pixel.

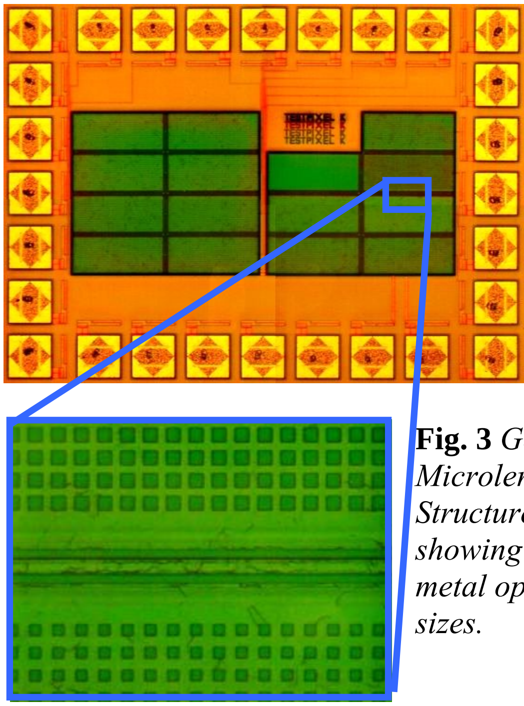

Fig. 3 *Generic Microlens Test Structure showing different metal opening sizes.*

The intensity of the light spot (Fig. 4) formed by the microlens at different distances from the center can be calculated by using several diodes each with successively larger window sizes while considering the difference in signal between them.

This method enables the optimization of the microlens curvature (1/focal length) for any given pixel.

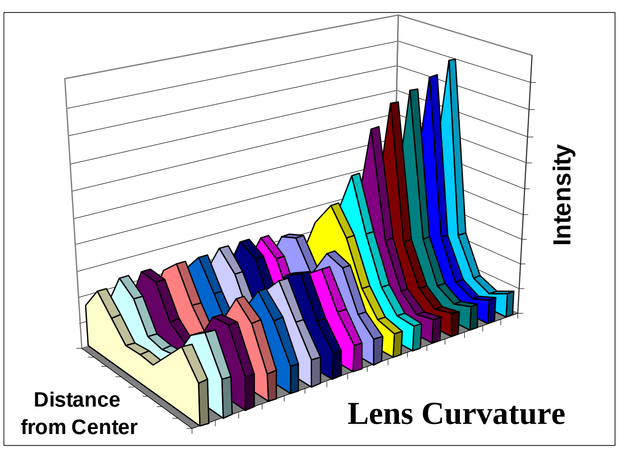

Fig. 4 *Intensity distribution of Spot Size as a function of lens curvature.*

Test Structure for Actual Pixels:

An electrical test structure using the customer's pixels can be incorporated into the customer's wafers to fine tune the optimization process on their actual pixels. The photocurrent of a single diode is a few pico-amps. To improve the signal an array of pixels is laid out appropriately. Thus, the individual pixel's response to microlens properties can be optimized directly on the customer's product as well as validating the usefulness of the generic electrical test structure and modeling software. In addition, it is not always clear where the true pixel's photoactive center is located. By exposing a wafer with multiple misalignments and analyzing photocurrent as a function of microlens misalignment, the photoactive center can be determined.

Verification of the optimization techniques:

A measure of the success of using a microlens can be defined as the ratio of photocurrent with and without microlens. This ratio or gain will now be called the Improvement Factor (Fig. 5). Clearly the smaller the photosensitive area in the pixel, the larger this number can be. This higher Improvement Factor can only be achieved over a narrow range of lens curvatures which require optimization, whereas for larger opening sizes the improvement is smaller but also much more stable.

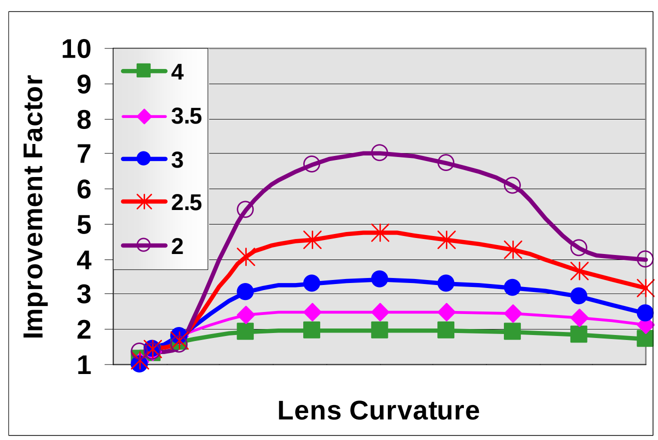

Fig. 5 *3D Simulation for 7µm Pixel. Improvement Factor vs. Lens Curvature for different photoactive areas.*

The shape and values of the curves generated by the modeling software (Fig. 5) are similar to those from the generic microlens electrical test structure as shown in Fig. 6. For each lens curvature a different wafer needed to be produced. Now, instead of showing the data in terms of spot size (as in Fig. 4) it is shown in terms of improvement factor. The range of thicknesses used in this experiment did not reach the optimum value but clearly shows the need for optimization for small size openings. Results from the generic test structure can be used to calibrate the simulation model.

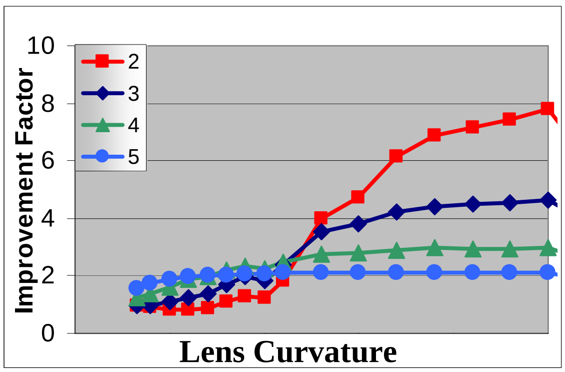

Fig. 6 *Electrical Results 7µm pixels. Improvement Factor vs. lens curvature for different image-sensor pixels.*

Similar graphs can be generated for improvement factor vs. lens curvature for different actual pixels (Fig. 7). Pixel A in this case was a large 20µm by 20µm pixel, which could not benefit from the resist thicknesses used. The other pixels were all around 7µm by 7µm and showed similar curves. Using these curves in combination with the simulation or generic microlens results allows an estimation of the photosensitive area of these actual pixels.

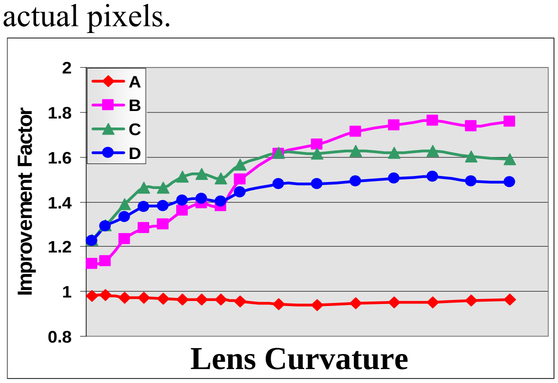

Fig. 7 *Electrical Results 7µm+ pixels. Improvement Factor vs. lens curvature for different image-sensor pixels.*

Smaller Pixels

As the pixel size decreases and with it the photoactive area, the benefit of using microlenses increases. The simulation for a 4µm pixel shown in Fig. 8 shows that the need for precise lens curvature optimization becomes increasingly important at this technologically important pixel size.

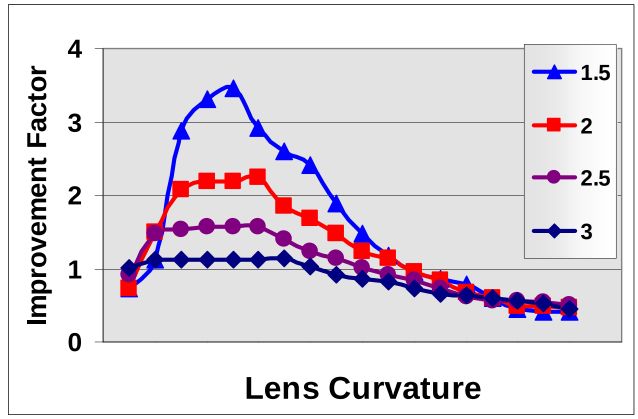

Fig. 8 *Modeled Improvement Factor vs. Lens Curvature for a 4µm pixel.*

Comparing this result to the 7µm pixel case in Fig. 5 where the X Axis covers the twice the range, it is clear that much lower lens curvatures are required and that the need for precise set-up become even more critical.

Lens Alignment

Just as lens thickness or curvature set-up is important for pixels requiring a high Improvement Factor, so is the alignment set-up and tolerances to maintain this in production.

The sensitivity of improvement factor to misalignment can be determined to decide on the class of lithography tool and overlay specification to run the microlens.

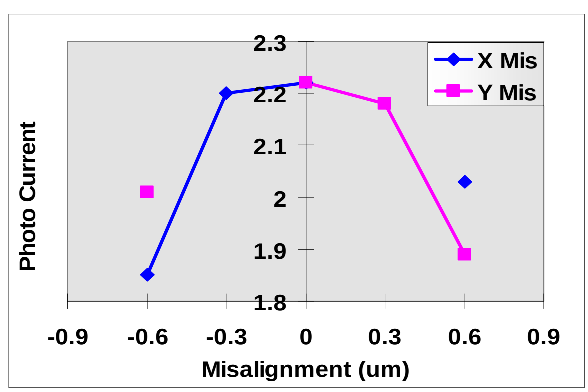

Fig. 9 *Photocurrent vs. Misalignment for a 3x3µm opening in a 7x7µm pixel using the generic microlens structure.*

Fig. 9 shows the Improvement Factor vs. programmed misalignment of Microlens mask to Metal 1 using the generic microlens structure. This shows that Microlens to Photoactive overlay specification should be no greater than 0.3µm for a 7µm square pixel with a 3µm square photosensitive area.

Microlens definition is the last photolithography stage in fabricating image sensors and is usually aligned to the last metal layer. The Active Area Mask typically defines the photoactive area, which is one of the first steps. Due to manufacturing tolerances there will be a consistent offset between the Microlens and the Active Area of a few tenths of a micron, which cannot be measured directly in-line due to the significant vertical distance between these layers. In addition, it is not always clear where the photoactive center of the pixel is. For instance, the center of the diode may have a contact with an opaque metal pad on top. Either way, for high Improvement Factor microlens applications, it is important to find the optical center experimentally on the actual pixel itself.

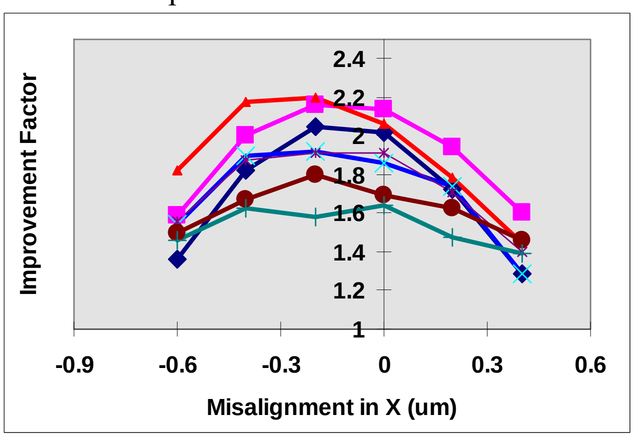

Fig. 10 *An example of Improvement Factor vs. Misalignment for different lens curvatures for a 5.5µm pixel.*

Fig. 10 shows the results of programmed misalignment vs. improvement factor for various lens curvatures on a real pixel. The optimum position is at about –0.2µm misalignment. The rapid decrease in Improvement Factor with positive misalignment when running at 0µm misalignment shows the importance of centering the microlens if repeatable results are required.

Conclusion:

Ray tracing simulation and using generic microlens electrical test structures are powerful methods to predict the optimum lens curvature for microlenses over a wide range of sizes and types. Electrical and computer modeling results have shown the increasing importance of having these tools to optimize microlens shape as pixel sizes and photosensitive areas decrease. This can be measured in terms of Microlens Improvement Factor, which is the ratio of photo-current generated with and without microlens.

These techniques also provide a key for understanding the importance of overlay for good repeatability. The determination of the overlay specification and finding the true photoactive centre of the pixel are key to achieving a robust process control in terms of improvement factor. The latter requires using a dedicated electrical test structure containing that particular pixel. These techniques can be extended to also consider off-axis illumination and diffraction effects.

With the development of these techniques it is possible to provide a fast turnaround to determine the optimal microlens processing conditions for a wide variety of pixel types and sizes. This procedure will allow them to be manufactured with consistently good performance.

Acknowledgments:

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