Efficiently writing circular contacts on production reticle

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ABSTRACT

As we prepare for 32nm-hp with 193nm immersion, complex and sometimes curvilinear shapes are going to be required on masks. Contacts and vias will be circular or oval in shape on the wafer, but are still drawn as over-sized squares or rectangles on masks and in CAD systems. Yet, for packing density of designs, particularly for DRAMs and SRAMs, in order to optimize for diagonal distances, a circular via shape on the mask is desirable. In addition, a circle has by definition the minimum perimeter for a given area, improving manufacturing tolerance. This paper demonstrates new techniques for writing circles of arbitrary diameters on masks efficiently and accurately using a production e-beam mask writer. Resist-exposed SEM images are shown, demonstrating the practicality of writing circles as mask shapes for production reticles.

Keywords: Photo mask, shaped-beam, shot count, mask writer.

1. INTRODUCTION

The state-of-the art in production mask writing today is based on the variable shaped beam (VSB) technique. Mask shapes are decomposed by fracturing to a set of non-overlapping rectangular shapes with certain size restrictions. The fractured shots tessellate the desired shape. In general, each of these shots are designed to be of uniform dose, though later steps adjust the dose to try to shoot as close to the original shape as possible after correcting for manufacturing effects such as proximity effects.

The presence of 45-degree triangular second aperture in the VSB machines allows 45 degree triangles to be shot in addition to the rectangles. An efficient use of 45 degree triangles in fracturing of SoC layouts is difficult, however.

The JEOL JBX-3200MV [1], a production mask writer, was modified to contain a differently configured second aperture in which a series of circular apertures replaced the triangular elements. As the change is contained to the second aperture and the system software and firmware, the change is field-upgradable. The production JBX-3200MV without modification is able to accept overlapping shots. Furthermore, each shot can be assigned one of 4095 distinct dose values, expressed as a percentage of the "nominal" base dose value.

We will first explain the motivation for the work. Then we will explain the hardware enhancement used and the model-based MDP technology. Finally, we will show some test printing results.

2. WHY CIRCLES?

2.1 Geometry Aspects of Circles

As we enter production volumes in 45-nm half pitch node, it is increasingly clear that on wafer, vias end up being circular when looked at from above. They are hoped to be cylindrical, but end up being somewhat conical. It is in fact desirable to fill in the corners to make them as close to a square as possible. This maximizes the contact area with the material above and below, minimizing the resistance and maximizing yield. There have been times where corner serifs were produced to minimize the corners from being rounded off, but today's state-of-the-art is to live with circles as the shapes on wafers as the effectiveness of serifs is diminished at low k1, but try to control Critical Dimension Uniformity

(CDU) particularly with respect to area uniformity, and to maximize depth of focus. This will be increasingly so for the 32nm half pitch node.

But yet, vias are drawn as squares on masks, and in CAD systems during the design stage. This compromises design flexibility and hurts manufacturability.

Design flexibility is an issue because circles can be packed more uniformly in all angles. Particularly in the 45 degree configuration (Figure 1), even though two circles on wafer should be allowed to be placed equidistant to the minimum design rule in the Y distance, because the vias are drawn as squares in CAD and in masks, the diagonally opposite vias have to be farther away to meet the design rules. To avoid this issue, it is possible to use 4X the shot count by using triangular apertures to shoot diamonds in diagonally opposite configurations. But this has the problem that another adjacent via may be to the right or just above it. It is clear that drawing circles allow the densest packing in all directions and provides maximum flexibility.

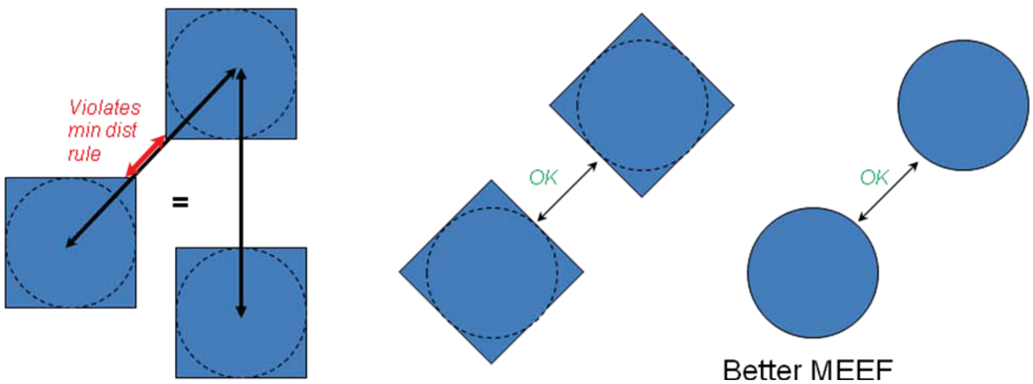
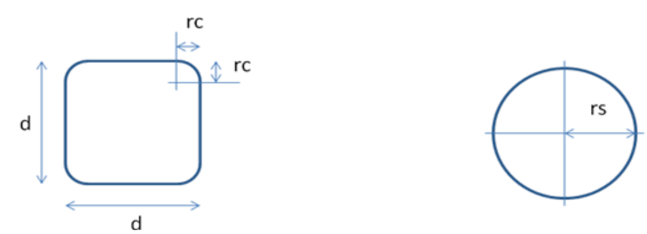


Figure 1. Vias and contacts on masks drawn as circles reduce the Mask Error Enhancement Factor (MEEF).

Manufacturing tolerance is also improved if circles are drawn on masks for vias. This is because Mask Error Enhancement Factor (MEEF) is better with circles than with a square with rounded corners of an equal area. Figure 2, 3, and 4 demonstrate the area calculations and the change in area from a given change in the edge amount. The area of a circle is affected 10% less than the area of the same sized rounded square when the edge is moved by 1nm. Since the area represents the energy being transmitted through the mask to the wafer surface, this represents more tolerance to manufacturing variation.



$$S_{RoundedSqaure} = d^2 + (\pi - 4)rc^2 \qquad S_{circle} = \pi . rs^2$$

$$rs = \sqrt{\frac{d^2 + (\pi - 4)rc^2}{\pi}}$$

rs = radius of a circle having the same area as the square with rounded corners

Example:
d=100nm, rc=5nm → rs=56.36nm

Figure 2. Calculating the areas of rounded squares vs. circles. The radius of the circle rs is calculated to match the area of the square with rounded corners. All dimensions are at 1X.

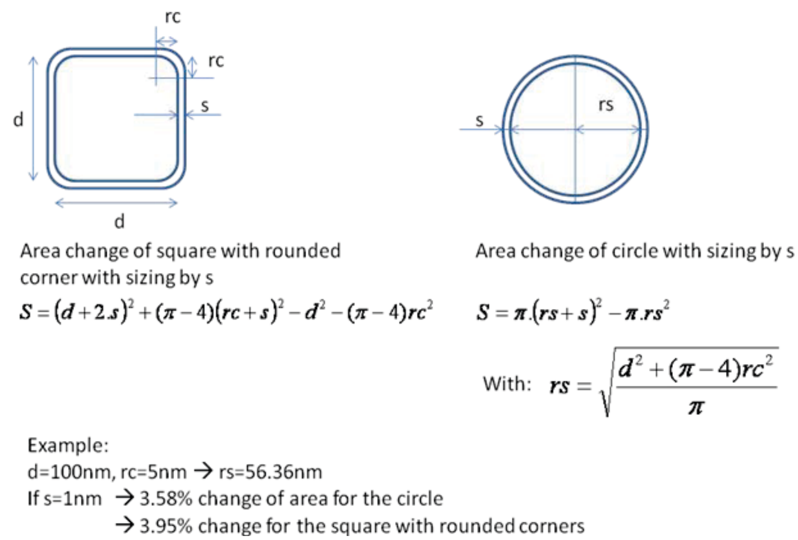


Figure 3. Calculating the area change from a given change in edge placement. The circle radius is chosen to match the area of the square with rounded circle as described in Figure 2. All dimensions are at 1X.

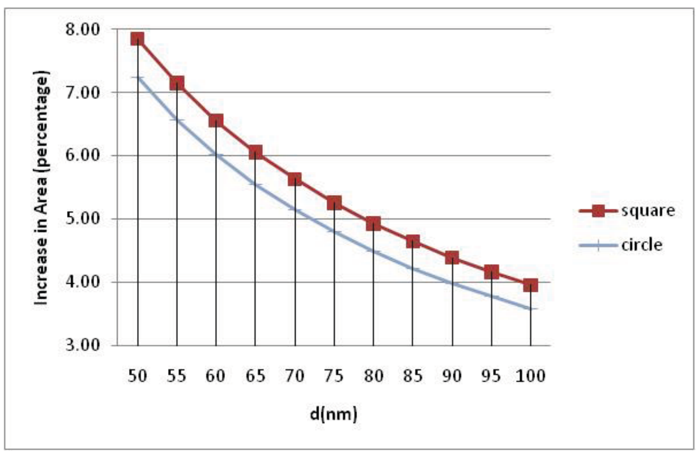


Figure 4. Increase in area for a rounded square and a circle of same area when the edge moves 1nm. All dimensions are at 1X.

With simple geometric calculation we can show that the area increase of the circle is less than that of a contact for the same sizing of 1nm as shown in Figure 4.

2.2 Lithography Aspects of Circles

The impact on this finding on lithography performance was evaluated using simulations. As shown below in Figure 5, the following test layouts were used.

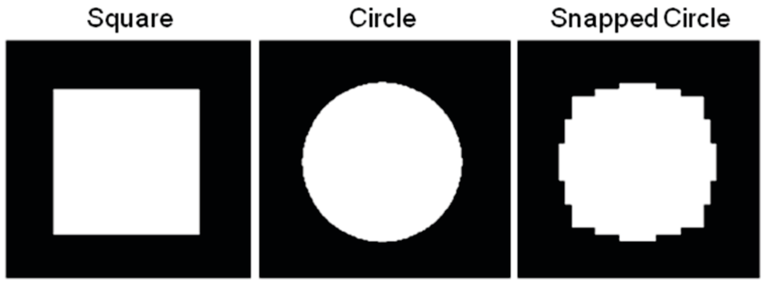


Figure 5. Layout used in the simulation. The contacts are all on a 200nm by 200nm pitch. The square pattern is 120nm by 120nm in size, the circle radius was set to 67nm and the shape of the snapped circle were adjusted in order to get approximately the same maximum intensity for all three contacts. Note that to match the area of the square, the circle diameter would need to be equal to 67.7nm which is quite close to the value used to match the maximum intensity.

The simulation conditions are the following: numerical aperture: 0.93, annular illumination (inner sigma: 0.55, outer sigma: 0.85), attenuated phase-shifting mask (6% transmission). The image is calculated at a depth of 75nm in a 150nm thick resist and the nominal focus was set up 50nm below the top of the resist. The MEEF was computed by sizing all edges by 1nm.

The calculated latent images shown in Figure 6 are very close to each other. Similarly, the slope versus distance along the pattern is very similar for all three contacts (Figure 7).

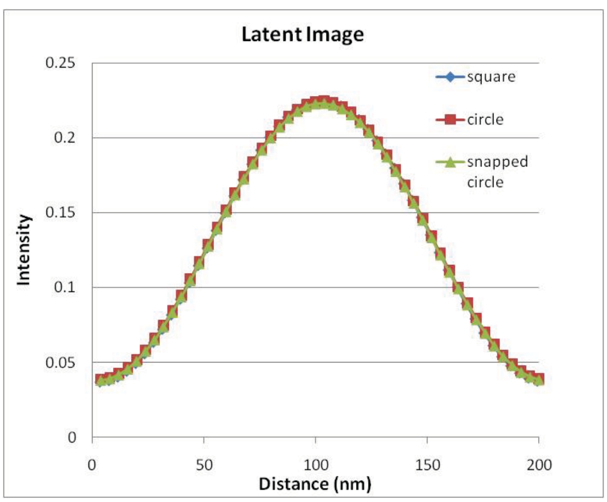


Figure 6. Latent image for the circle, square, and snapped circle.

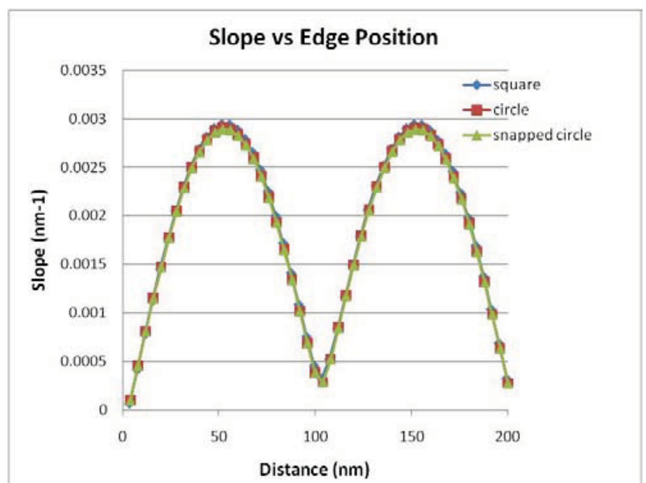


Figure 7. Slope versus edge position for the square, circle, and snapped circle.

The process latitude for the three contacts was also simulated. As shown in Figure 8, the process latitude is virtually identical for all three contacts.

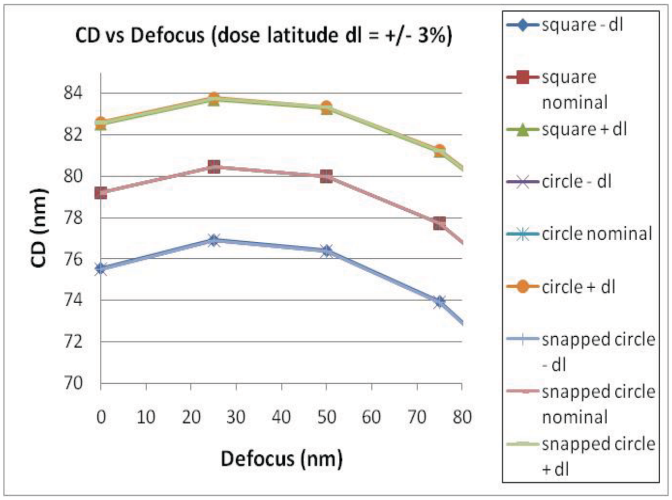


Figure 8. CD versus defocus for nominal dose, nominal dose – dl (dose latitude), nominal dose + dl for all three contact types. The dose latitude dl was set to 3% of nominal dose. Very small adjustments of the threshold to get the same CD of 80nm for all three contacts made the curves perfectly overlay.

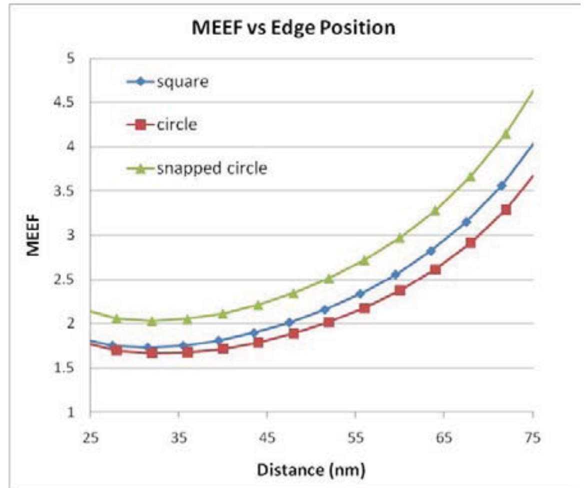


Figure 9. MEEF versus edge position for square, circle, snapped circle.

As expected from our simple geometrical calculations, the MEEF is substantially better for the circle compared to the square and the snapped circle which is the worst performer. This implies that the well accepted idea of Manhattanizing the curvilinear layout to reduce fracturing complexity makes the MEEF larger and is therefore not as desirable as keeping the original curvilinear shapes.

Combined together, circles are the better shape for vias and contacts than rounded squares on masks, and better on the CAD system than squares. In addition, the nature of both light and e-beam are rounded. We try very hard to make both light and e-beam good at X-axis and Y-axis preferred instruments. But at the end of the day, they are both naturally circular instruments. Even with e-beams, and even with masks typically being 4X the dimensions of the wafer, at 32nm half pitch, features in the 50-60nm range will need to be written for sub-resolution assist features on masks. With the short-range blur of 20-40nm range for production e-beam machines, even e-beam mask writing is going to be significantly subject to the circular nature of e-beams.

However, writing circles with the conventional methodology using rectangular (or even triangular) VSB shots is not practical. Regardless how "sufficiently round" is defined, the stair stepping required when tessellating the shape will require too many shots to be practical.

3. CHARACTER PROJECTION OF CIRCLES

Character Projection has been successful in direct writing of wafers. This technique takes advantage of the accuracy of e-beam in which OPC is entirely avoided. Therefore every time a certain flip flop standard cell is used in a design, a character designed for a layer of that flip flop can be used to shoot that entire cell with all its constituent shapes at once. The pattern is stamped exactly the same way every time it appears on the wafer. Plus, the avoidance of the 4X factor allows a much larger pattern (like a flip flop cell at 45nm logic node) to be shot at once, making the technique more effective.

In mask writing, however, other than in certain highly repetitive structures where post-OPC, the patterns still repeat or in the case where a large number of dies are repeated on the mask (like for DRAM for example in order to maximize the scanner throughput), such large scale use of character projection is not practical.

For drawing circles, however, character projection is ideal. They are small structures that potentially use up many even smaller VSB shots. In addition, unlike with VSB shots (whether rectangular or triangular), we do not try to cut the second aperture shape with the first aperture. As such the accuracy of the shots will be higher for these character projection shots. The only challenge is to control accurately the size.

With VSB, the overlapping of the first aperture with the second aperture is what produces various different sizes. For a circle, the only extension of the same technique would require a camera-like annular diaphragm consisting of multiple planes to approximate a circle. But such a mechanism is not practical for an e-beam machine.

An alternative method was devised to provide a continuous range of diameters of circles. The production JBX-3200MV system was altered to use a new second aperture that contains a series of discrete sized circles (Figure 10).

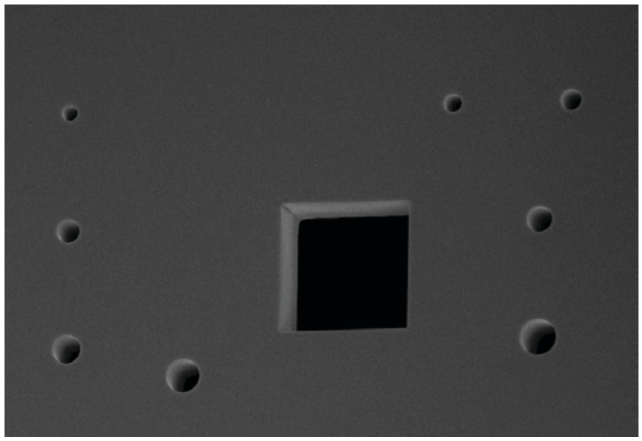


Figure 10. Photograph of the second aperture manufactured for the JBX-3200MV.

Applying the model-based mask data preparation capability, dose modulation capability of the JBX-3200MV is used to oversize and undersize each circle. Circle is a unique shape. It is the only shape for which overdosing and under-dosing preserves the shape. So taking advantage of the nature of e-beam, we can shoot a continuous range of sizes of circles by using a discrete set of circular apertures. Dose variation and the size variation achieved are shown in Figure 11 and Figure 12.

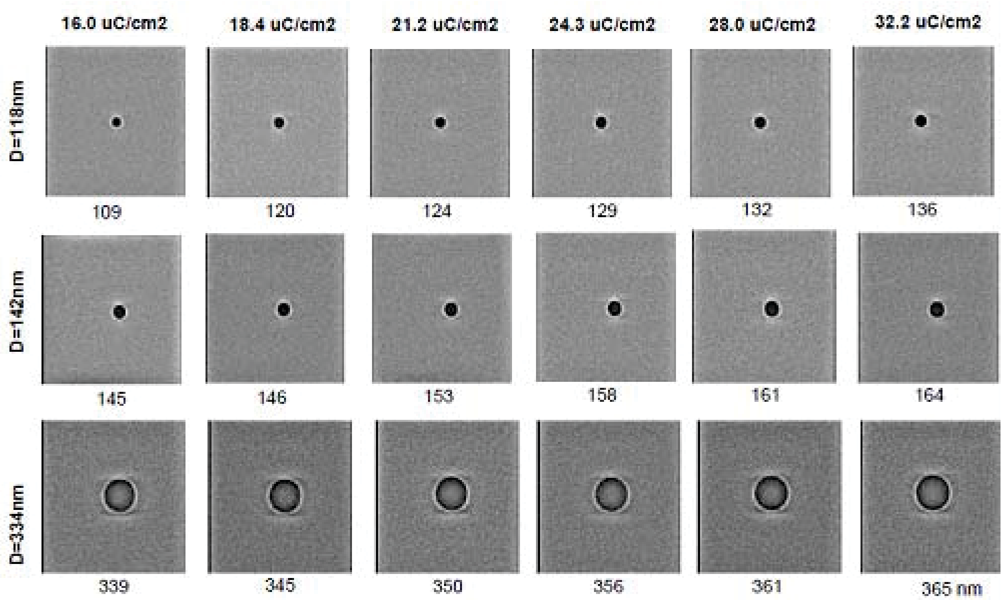


Figure 11. Resist-exposed images of the circles with various doses.

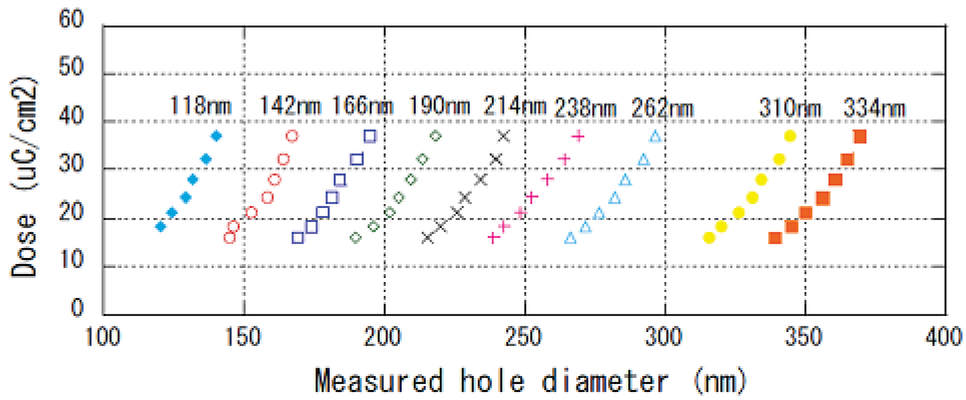


Figure 12. Measured diameters for each circular character as dose is varied.

The results show that an approximately 24nm stepping in between each aperture size can produce a continuous range of diameters of circles on the mask. Each contact still costs exactly one shot in the mask write time.

4. SUMMARY

A new approach to mask writing was introduced that combines hardware and software innovations. The hardware innovation is to use character projection of circles to draw circles with one shot. The software innovation is Model-Based Mask Data Preparation where e-beam simulation is the basis of calculation for the shot list. By using MB-MDP, the ability to overlap shots on the JBX-3200MV are fully exploited, and particularly when combined with the ability to use circular apertures, demonstrates significant advantage in writing circles and curvilinear assist features.

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