Circles: One Key to Successful Lithography at Advanced Nodes

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It is no secret that optical lithography is approaching its useful limits as process technologies push to 32-nanometer half-pitch (32nm-hp, or the 22-nm logic node). Advanced optical proximity correction (OPC), including inverse lithography technologies (ILT), is being explored to preserve resolution to extend the use of current 193-nm immersion (193i) lithography. But these and other techniques to improve the resolution of optical lithography contribute negatively to the other limiting issue facing the mask-making world: write time.

As we approach the resolution limits of optical lithography, printing simple shapes on the wafers requires a co-optimization of the illumination source and of the mask design in order to achieve a sufficient manufacturing margin. Such optimization yields curvilinear mask shapes including both printing shapes and sub-resolution shapes. For example, in the case of annular illumination, the best shape for a sub-resolution assist feature around an isolated contact or via is a circular ring. All points along such curvilinear assist features are equidistant from the main contact or via feature that they are trying to assist, resulting in fundamentally better-printing wafers than rectilinear assist features. With the feature density increase at 32nm-hp, the shot-count required to produce all of the curvilinear assist features necessary to maintain acceptable depth-of-focus (DOF) may render masks unmanufacturable in terms of both write-time and cost.

Recently, eBeam Initiative members have introduced a new approach that leverages the rounding nature of e-beam technology to break the current deadlock between the need for curvilinear assist features to extend the viability of optical lithography and the practical considerations of write-time and cost.

Rectangles: When “Good Enough” No Longer Is

The fundamental, radiating nature of light is circular. Historically, however, both computer-aided design (CAD) systems and variable-shaped beam (VSB) lithography systems have used rectangles as the basis for mask geometries because they are easier and faster to process than circles or curves. As a result, today’s mask rules are rectilinear and essentially at odds with the nature of light.

Until recently, using rectangles was a viable engineering solution. However, for 32nm-hp and below, the ability to use circles for mask lithography becomes critical, both for design and for manufacturing.

Round Pegs from Square Holes

Vias, or contacts, are a simple illustration of the design issues that arise from using squares where circles are more desirable. Conventionally, vias are drawn on masks as squares. However, the rounding nature of the light projected through the square mask feature results in cylinders on the wafer. These rounded vias function perfectly well on the finished wafer, so the fact that square vias on the mask result in round vias on the wafer has been an accepted, established fact of semiconductor design and manufacturing.

Given that the industry accepts that vias and contacts are circular on the wafer, it is now time to draw vias and contacts as circles on masks, and perhaps also in the CAD systems as well. This transition will naturally take time, as the inertia of the existing infrastructure is strong. However, for both design density and manufacturing yield, it is better to draw circles on masks.

For design density, circular vias on the mask are more effective than square vias because circles can be packed more uniformly at all angles. As shown in Figure 1, this is especially apparent with two or more vias placed in a 45-degree configuration. In this case, when the vias are drawn as squares by the CAD system and on the masks, diagonally opposite vias have to be more widely spaced to meet design rules (far left). It is possible to use four triangular shots to create diamonds in diagonally opposite configurations. But this has the problem that another adjacent via may be to the right or just above it (center). It is clear that circles enable the densest packing in all directions and provide maximum flexibility.

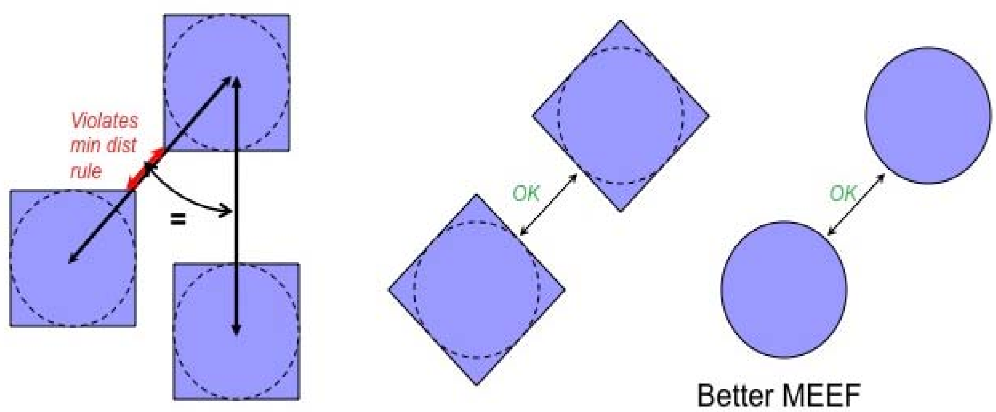

Figure 1. Using circles on the mask for vias and contacts benefits both design density and manufacturing tolerances.

Manufacturing tolerance is also improved if circles are drawn on masks for vias. Mask error enhancement factor (MEEF) is better with circles than with a square with rounded corners of an equal area. The most important parameter in manufacturing tolerance for vias on wafers is the uniformity of the area. Even though today's manufacturing tolerance is mostly measured one-dimensionally using critical dimension (CD) uniformity, it is actually the area of the exposed “circle” that is the determining factor for manufacturing uniformity and tolerance to error. This is because the exposed area on the wafer is directly proportional to the amount of energy that the light projects to expose the resist on the wafer for that via. For any given error in printing an edge of the feature (for example, if the edge is 1nm inwards because of the resist condition), a circular via on the mask would have 10% less variation in area and the energy of exposure on the wafer than a square via of equal area[1].

The Unmanufacturable Mask

At 32-nm-hp, a large number of curvilinear assist features are needed to produce vias with acceptable DOF. Figure 2 shows the results of a study performed by Samsung, testing various means of producing vias with achievable DOF, along with the number of e-beam shots required to produce the mask features.

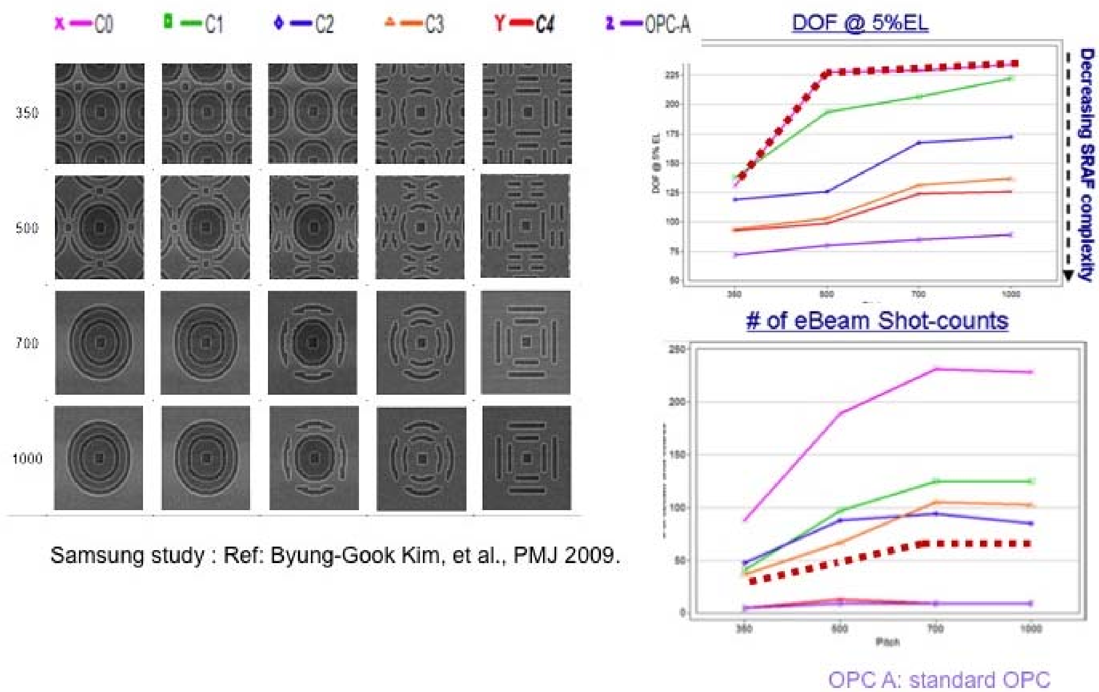

Figure 2. Curvilinear assist features are critical to achieving acceptable DOF at advanced process nodes, but traditional approaches to creating these features can be too costly in terms of write-time.

Multiple curvilinear assist features clearly provide the best DOF. Not surprisingly, these also require the highest shot count. The study and its follow-up show promising results for getting acceptable DOF with acceptable write-times for DRAM volumes. However, for system-on-chip (SOC) designs where the trade off of mask cost vs. wafer yield is not as clear, mask write times need to reduce even more to be viable. With traditional approaches, only acceptable mask cost and mask yield *or* acceptable wafer yield can be achieved. Both are needed for viable manufacturing of SOCs.

[1] A mathematical study will be available from PMJ-2010

Circles Break the Quality/Manufacturability Stalemate

Clearly, this stalemate between mask quality and manufacturability must be addressed before 32nm-hp can be adopted widely, particularly for SOCs. Circles are an intuitive answer, as they work with – not against – the rounding nature of light. However, the use of rectangles has been the engineering solution of choice for a reason: circles are much more difficult to process, both in terms of design and manufacturing.

Two main technologies are needed to enable the use of circles in lithography: CAD fracturing technology that can produce circles, and e-beam technology that can write circles. Further, both technologies need to be able to create circular shapes with practical processing times.

On the CAD side, eBeam Initiative member company D2S, Inc. has created design-for-e-beam (DFEB) mask technology that leverages the rounding nature of e-beams and can fracture design features into circular mask features with reduced shot count.

On the manufacturing side, using a circular aperture for e-beam CP provides a simple path for drawing the circles created by the D2S mask technology. Circles can share stencil space with commonly used rectangles, replacing less widely applicable triangles on some stencils.

Overlapping Circles

The ability to use circles to create main features such as vias is important for both mask quality and throughput. At 32-nm-hp, however, the curvilinear assist features required to get acceptable DOF dominate e-beam shot-count for via and contact masks. The high shot-count required for these features is partly due to the conventional approach of using rectangular shapes to create the curves. It is also due to the fact that conventional CAD fracturing systems fracture design features into *non-overlapping* shapes. As with the limitation to rectilinear shapes, this “rule” is a historic engineering solution designed to streamline processing.

However, the ability to overlap e-beam shots can have a dramatic impact on overall shot count. Figure 3 shows several approaches to creating curvilinear assist features. The target shape on the mask is shown in the upper left. Using conventional, non-overlapping, rectangular VSB shots to achieve this shape, as shown in the upper right, requires 40 VSB shots. By using overlapping rectangular shapes, the shot-count can be improved to 15. However, by using overlapping circular shots, the shot-count is further reduced to just 13 – an almost 70% reduction in shot count over the conventional approach using non-overlapping rectangles.

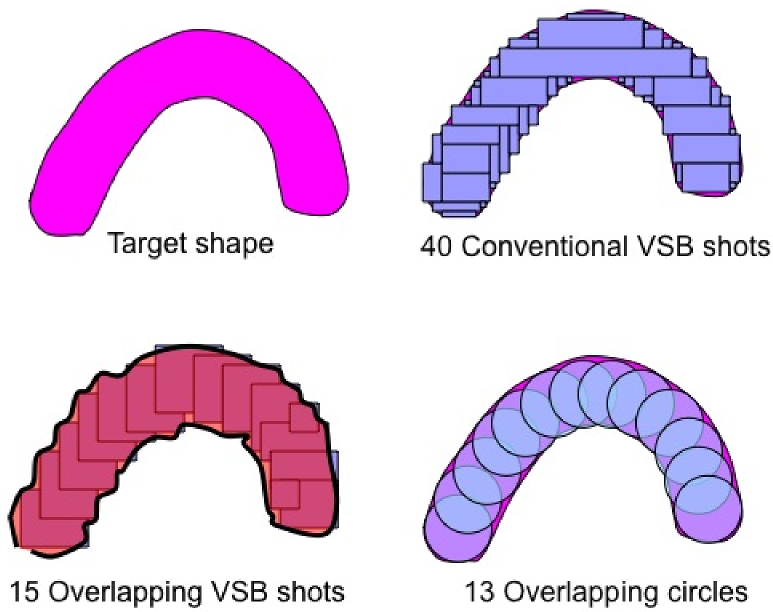

Figure 3. By overlapping circular VSB shots, smooth curves are achievable with far fewer shots

Perhaps more importantly, the 13 overlapping circular shots produce far smoother curves than 15 overlapping rectangles. The previously cited Samsung study provides some evidence that a truly curvilinear shape is better at assisting the DOF of vias than a more “jagged” one.

Today’s advanced e-beam systems are able to overlap shots. The D2S DFEB mask technology enables the CAD side of the equation by fracturing design elements into overlapping shapes where such overlaps will save e-beam shots, without undue impact on overall processing time.

Even if an e-beam system cannot accommodate circles on the same stencil with rectangular shapes, if the system is capable of creating overlapping shots, the D2S DFEB mask technology can enable near-curvilinear shapes to be shot effectively. Overlapping the right combination of rectangles can create shapes on the mask that will write as circles on the wafer (see Figure 4). These rectangles become, in essence, a “character” that is produced by multiple e-beam shots. Using this “multi-shot” character-projection (CP) approach enables a “library” of commonly occurring features, such as vias to speed processing both during fracturing and during mask writing.

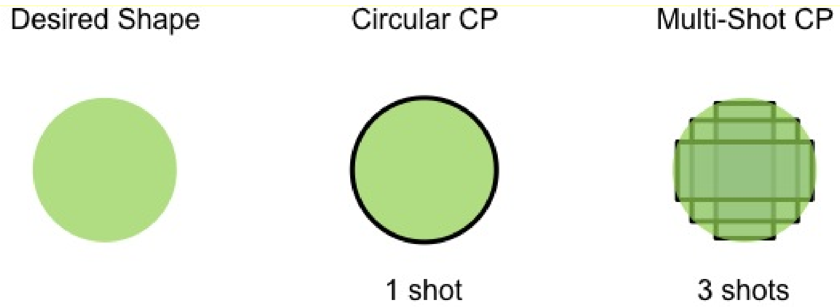

Figure 4. Overlapping several rectilinear shots to create one "multi-shot" CP enables circular CP for machines without the ability to include circles on stencils.

Closing the Circle
Optical lithography is reaching its practical limits. The curvilinear assist features required to achieve acceptable DOF are pushing mask-writing times out of the realm of feasibility for 32nm-hp. The basic engineering assumption to use only non-overlapping rectangles built into today's CAD and lithographic systems is at the heart of the problem.

Using circles as a basic lithographic shape addresses both DOF quality and throughput time for processing ubiquitous elements such as vias. Using overlapping circles to create the numerous curvilinear assist features required to maintain acceptable DOF reduces shot-count dramatically for the elements that contribute most to the problem. And if overlaps are allowed, a set of overlapping rectangles is able to produce circles and near-curvilinear shapes with far reduced shot count than conventional MDP and mask-writing techniques allow.

Some of today's advanced e-beam systems are capable of adding circles to existing stencils by substituting existing triangles, which have less general application, with circles. Those systems without this capability can use multi-shot CP techniques with overlapping rectangles to create a circular shape.

The key to using circles lies in the CAD system that fractures design data into mask shapes. The exclusive use of non-overlapping rectangles to create all shapes on a mask simplifies the fracturing process, but creates possibly insurmountable throughput issues at advanced nodes. New DFEB mask technology from eBeam Initiative member D2S, Inc. enables fracturing into circles as well as rectangles and allows overlapping shapes to create curvilinear features with far fewer e-beam shots.

The collaborative work of eBeam Initiative members enables circles to be used in lithography for today's most advanced nodes, and extends the useful life of optical lithography for another generation of masks.