Gridded Design Rules (GDR) in combination with lines/cuts double patterning allow imaging of 16nm designs with 193nm immersion lithography. Highly regular lines/cut patterns result in the existence of a well-defined optimal set of lithographic conditions. Since cuts are all of identical shape and relatively sparse, good image quality can be obtained with minimal or simplified pattern correction (OPC equivalent) to compensate for proximity effects. The use of local interconnect (LI) is shown to offer further reduction of the required number of cuts and improves pattern uniformity and image quality.

Critical cut patterns of poly and M1 layers in selected worst case standard GDR cells were considered. Simultaneous co-optimization of cut geometry as well as lithographic conditions such as scanner entrance pupil illumination was used to bring all cuts within ~1nm of target CDs at best focus. Optimized conditions significantly reduced the sensitivity of printed patterns to proximity effects. Manufacturability was verified using DOF and NILS metrics before and after co-optimization. Experimental lens entrance pupil illumination and lens aberrations including polarization effects were included in the analysis.

1D Gridded Design Rules

Achieving 16nm designs with 193nm lithography is difficult even with immersion technology. In this work we extend on our earlier 22nm results [1],[2] to show simulation-based simultaneous optimization of layout and lithography which produces a viable approach to 16nm. This is consistent with the emerging industry consensus that restricted design rules and multiple exposure techniques will extend 193nm immersion as far down as 7nm [3].

The approach relies on 1D Gridded Design Rules with Lines/Cuts (1D GDR LC) selective double patterning. Due to the highly regular patterns of 1D GDR LC we are able to determine a sharp lithographic optimum as a result of numerical co-optimization of key layout parameters and lithography settings such as scanner illumination, etc. In comparison, conventional two-dimensional designs include multiple pattern types and densities, which makes it difficult to find a set of well-defined optimal lithography conditions which balance good image quality for isolated/dense lines, 2D corners, etc. as illustrated in Fig. 1. 1D GDR LC designs use double patterning to superimpose cuts onto a regular lines pattern as shown in Fig. 2 [4],[5] and an SEM image shown in Fig. 3.
Critical layers (cuts in 1D GDR LC) consist of a number of identical cut patterns with varying density. We use larger size cells considered the worst case from a standard cell library and show that after co-optimization CD error can be brought to 1-2nm at best focus conditions. We further consider manufacturability of the cell and show Depth of Focus (DOF) and Normalized Illumination Log Slope (NILS) metrics before and after co-optimization. Co-optimization relies on efficient parametrization of the layout with a small number of independent parameters. This is clearly well possible in particularly for cuts in the lines/cuts approach 1D GDR LC Fig. 4.

We find that traditional OPC (iterative local correction of layout patterns driven by deviation between simulated patterns and specified targets) is typically no longer able to converge at 16nm rules. This is due to the low contrast and non-local dependence of printed patterns on the layout. Attempts to optimize litho conditions and OPC iteratively typically do not converge. However, we were able to obtain a solution using simultaneous co-optimization of litho and layout as discussed in this work. It seems likely that this type of approach may therefore replace OPC for sub-22nm designs.

### Neighborhood Effects

Lithographic environment of the cell may be of substantial importance due to relatively small cell size in comparison to wavelength and the range of litho effects. Therefore we carried out our analysis including cell neighbors as shown in Fig. 5. Given the low contrast and narrow process windows it is likely that such optimization will be necessary in production situations, which means that some final layout pattern correction may be needed after the cell is placed.

### Realistic Scanner Properties

Thanks to a partnership with a leading scanner manufacturer we were able to consider realistic lens distortions using experimentally obtained Jones-Zernike expansions as well as realistic entrance pupil illumination. Imaging properties of idealized scanner lens and illumination are compared to a realistic scanner lens model at 16nm as
shown in Fig. 6. In our comparisons so far it appears that scanner imaging quality is high and only small image degradation due to scanner aberration is expected even at 16nm imaging conditions.

**CO-OPTIMIZATION APPROACH**

Simultaneous optimization of layout patterns and lithography settings is made possible by the uniformity and repeatability of the lines/cuts patterns, in particular for the critical cuts layer (Fig. 2). We use direct optimization and experimentally validated lithography simulation to find optimal conditions to create the patterns. Our basic optimization variables are (Fig. 7):

1. cut geometry (width, height, hammer heads Fig. 4)
2. illumination of the scanner lens entrance pupil. Other parameters such as polarization, mask transmittance, etc. are included as an option (phi1,phi2,sigma,siso) Fig. 15, Fig. 16.
3. bias for each individual cut (over/undersize) to account for proximity effects (C0,...,CN)

The optimization cost function was the RMS CD error across all cuts. Minimizing this cost function also reduces variation among cuts by getting all CDs close to the same target value. Of course, some differences between shapes printed for each cut as well as their process margins cannot be avoided and are seen in Fig. 8, Fig. 9 and Fig. 10.

![Fig. 6 Impact of considering realistic scanner aberrations described by Jones-Zernike expansions: idealized pattern shown in blue, pattern including aberrations shown in red. Minimum CD vs defocus shows modest change from the behavior predicted for idealized scanner properties (no aberrations).](image)

![Fig. 7 Successive iterations of nonlinear co-optimization. CF is the cost function (RMS CD error), w,h,a are global cut shape parameters, phi1,phi2,sigma,siso are illumination parameters, C0,C1 are individual cut biases (C2,...,CN not shown in the above figure). Total simulation time is on the order of 5-10 minutes depending on cell and chosen settings.](image)

![Fig. 8 Exposure-defocus (smiley) plot for two selected cuts: worst case (diamonds) has 35nm depth of focus, best case (triangles) shows around 60nm. Different optical environments of each cut lead to differences in process margins.](image)
Optional use of local interconnect (LI) to manufacture 1D GDR LC designs can help reduce the necessary number of cut patterns. As a result, it is possible to reduce variation in local cut density and proximity. Better pattern uniformity and process windows can therefore be obtained.

Fig. 11 shows a zoom-in of a cell without LI. Two dense clusters of cuts are clearly seen, which are difficult to resolve due to low contrast. This leads to a narrow process window and potential problems with insufficient overlap between lines and cuts even after oversizing the cut patterns as shown in Fig. 9.

In comparison, when the same cell is implemented using LI, the overall number of cuts is smaller and tight cut clusters are avoided as shown in Fig. 12 and Fig. 13. This results in better pattern separation (contrast) and wider process windows indicated by tighter spacing (i.e. less sensitivity) of patterns obtained for various defocus values. Fig. 14 shows the effects of 10nm oversize to assure good overlap of cuts over lines and avoid potential yield issues. In comparison to the non-LI case Fig. 9 we can see that while isolated cuts print similarly, but problematic clusters of cuts are avoided.

**Fig. 9** Post-optimization cut patterns for the M1 layer. Oversized patterns to simulate etch by 10nm and improve coverage of lines by cuts are also shown.

Insert: CD histograms for cuts before optimization (red, sigma =15nm) and after optimization (green, sigma=1nm).

**Fig. 10** Image quality loss with increasing defocus, contours are for defocus increment 2.5nm

**Fig. 11** Without the use of Local Interconnect a relatively large number of cuts with varied environments must be printed in the cell. Two problem areas are highlighted, where high cut density leads to difficulty in separating the patterns from each other. The insert shows how one of the problem areas degrades rapidly with increasing defocus, contours are for defocus increment 2.5nm.

**Fig. 12** and **Fig. 13** show the effects of implementing the same cell using LI, which results in better pattern separation and wider process windows.

**Fig. 14** shows the effects of 10nm oversize to assure good overlap of cuts over lines and avoid potential yield issues.
A data base capturing the measured lens entrance pupil illumination was built in collaboration with an industry leading scanner manufacturer. As a result, we were able to carry out optimization directly in equipment variables such as lens zoom settings, apertures, etc. This ensures practical relevance of results and provides an interesting comparison between idealized and realistic illumination patterns. In addition, measured lens polarization effects and distortions are included using Jones-Zernike expansions, providing scanner-specific manufacturability predictions (Fig. 6).

**Fig. 12** Use of Local Interconnect (LI) to avoid problem areas cause by dense cut clusters and low contrast. The figure shows no problem areas for the same cell with LI as the one shown in Fig. 11 without LI. In comparison to Fig. 11 the insert shows much improved robustness of the image with respect to defocus, contours are for defocus increment 2.5nm.

**Fig. 13** Use of Local Interconnect (LI) to avoid problem areas caused by dense cut clusters and low contrast (larger view of patterns shown in Fig. 12). Aerial image shows mostly well-separated cuts which result in improved process margins.

**Fig. 14** Oversized cut patterns to improve overlap of cuts over lines in the LI case. Better uniformity in comparison to the non-LI cell Fig. 9 is seen.

**Fig. 15** Idealized “tophat” illumination

**LINK TO SCANNER ILLUMINATION DATA**

A data base capturing the measured lens entrance pupil illumination was built in collaboration with an industry leading scanner manufacturer. As a result, we were able to carry out optimization directly in equipment variables such as lens zoom settings, apertures, etc. This ensures practical relevance of results and provides an interesting comparison between idealized and realistic illumination patterns. In addition, measured lens polarization effects and distortions are included using Jones-Zernike expansions, providing scanner-specific manufacturability predictions (Fig. 6).
CONCLUSIONS

Design-process co-optimization for 1D GDR standard cells was used to reduce CD variation and improve manufacturability of the critical cut layer. This reduction of variation substantially alleviates the need for proximity correction and produces manufacturable designs at 16nm using 193nm immersion lithography. Optional local interconnect is shown to improve image quality by reducing the number of necessary cuts and improving their uniformity.

REFERENCES