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ELIMINATION OF MASK-INDUCED DEFECTS WITH VOTE-TAKING
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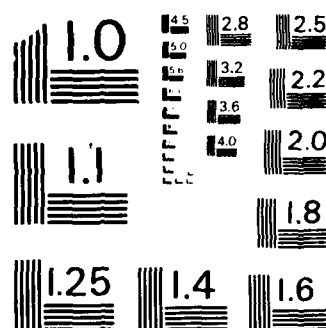
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Elimination of mask-induced defects with vote-taking lithography

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Abstract

The problem of ensuring adequately low density of defects in lithographic masks is becoming increasingly serious as circuit patterns become denser and more extensive. This paper discusses a radically alternative strategy to eliminate the effect of random defects on reticles. In this method, a number of reticle fields containing nominally identical patterns are aligned and exposed in sequence at the same site, each with an equal fraction of the nominal exposure dose. The optical intensity distribution impinging on the resist is the sum of the aerial images from these exposures. As a result, a random defect unique to a single reticle field affects only a minor part of the total exposure. The effect of this exposure deviation can then be minimized with an adequate resist contrast and a properly adjusted exposure dose. With the lithographic tools and resist process technology presently available, gross reticle defects can generally be reduced to minor distortions in the resultant features. A series of experiments have been performed with Shipley Microposit 1470 photoresist exposed with an Ultratech 900 1x wafer stepper, and demonstrated the feasibility of this technique. The effects of misalignment among fields, resist contrast, exposure dose, and defect size and type have been studied in particular. A novel etching process that permits the electrical detection of defects due to photolithography alone is being used to evaluate the effectiveness of this vote-taking scheme in VLSI patterning, and has demonstrated its capability of eliminating mask-induced defects, and no noticeable loss of lithographic yield when defect-free masks are used.

Introduction

Random photomask defects have been widely recognized as one of the major yield limiting factors in integrated circuit manufacture employing photolithography¹. These defects include particulate contamination, defects in mask material, and extraneous features arising from imperfect resist processing. State-of-the-art automatic mask inspection and repair systems are effective in substantially reducing the defect density, and the use of pellicles further helps preserve the mask quality². Such tasks, however, are rather demanding in time and resources and may not be justifiable in all fabrication environments. Moreover, exhaustive defect inspection is difficult due to limited detection sensitivity, and defects can still be generated after inspection. As greater emphasis is placed on stepper-based lithography and circuit patterns become denser and more extensive, the problem of ensuring adequately low density of mask defects is becoming increasingly critical. Therefore, alternative approaches to eliminating the impact of random mask defects are desirable. One such scheme based on the introduction of redundancy in resist exposure will be discussed.

Principle of vote-taking lithography

This exposure scheme derives its name from its analogy to the "vote-taking" strategy in fault tolerant logic designs³. It is also conceptually similar to the enhancement technique employed in image processing which averages multiple images to reduce the level of random noise with respect to the signal⁴. In this method, a number of mask fields containing nominally identical patterns are aligned and exposed in sequence at the same substrate site, each with an equal fraction of the nominal exposure dose. The resulting optical intensity that impinges on the resist is the sum of the aerial image from these exposures. Consequently, in a scheme using N fields, a random mask defect unique to a single participating field (*i.e.*, a nonrepeating defect) affects only $1/N$ of the total exposure. The effect of this exposure deviation can be minimized with a properly adjusted exposure dose and an adequate resist contrast. It is therefore possible to produce essentially defect-free resist patterns even though none of the mask fields are perfect, as exemplified in Figure 1. This method of recovering pattern integrity is especially valuable in situations where quick fabrication turnaround is the primary concern or the means for mask inspection and repair are not available.

From the above discussion, the key requirements for successfully implementing this technique are apparent:

(1) **Easy access to multiple mask fields.** A minimum of three fields are needed to correct both opaque and clear defects simultaneously without ambiguity. As will be clear in the discussions to follow, the choice of the number of fields to use is a tradeoff between the demand on resist contrast on one hand, and the required stepping time and risk of image quality degradation on the other. Most state-of-the-art photolithographic systems are now equipped with automated reticle handling mechanisms which can quickly and precisely change from one field to another, either on a different reticle or in a different part of the same reticle. As an example, the Ultratech 1x stepper currently uses 3 inch by 5 inch reticles which accommodate three or four independent fields in a row, and a field change on the same reticle can be completed in about 7 seconds⁵.

(2) **Precise feature placement and good feature size uniformity on the reticle.** These factors are important to the resist image quality resulting from multiple-field exposures. Excessive placement errors or feature size variations can cause skewness or loss of acuity in the resist profile. With the placement accuracy on the order of $0.1 \mu\text{m}$ available on the advanced electron beam pattern generation systems⁶, excellent registration among fields can be obtained. We have also been able to maintain a critical dimension (CD)

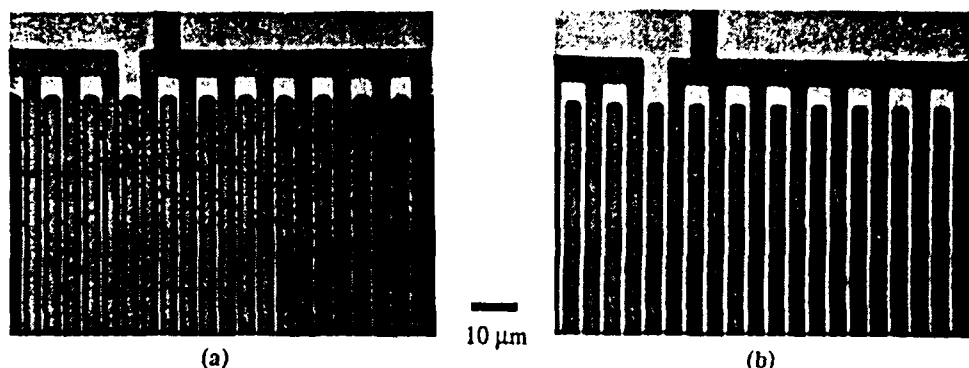


Figure 1. Elimination of mask-induced pattern defects by vote-taking lithographic technique. (a) shows the wafer resist pattern resulting from exposure with one of three reticle fields which contains random defects, and (b) shows an equivalent pattern resulting from the exposure with all three reticle fields.

control better than $\pm 0.1 \mu\text{m}$ over a 5 inch chromium plate using conventional positive photoresists, such as Shipley Microposit® 2400, exposed on a MEBES system. It should be noted that, in general, the control of these factors is easier when fields on the same reticle are used.

(3) *Absence of repeating defects.* The density of random defects should be sufficiently low to assure that similar defects are not present at corresponding sites in more than one field. This condition is necessary in a three-field voting scheme, and can normally be satisfied by the electron beam reticle generation process where each pixel is patterned independently.

(4) *Accurate alignment on stepper/aligner.* Similar to item (2) discussed above, this is an important factor that contributes to well defined resist images. Advances in photolithographic equipment have improved the alignment capability significantly, with overlay performance consistent with submicrometer geometries now available⁷. We have consistently obtained overlay accuracy better than $0.15 \mu\text{m}$ using the Ultratech stepper and electron-beam generated reticles. In the vote-taking exposure process, overlay of the image fields is achieved by aligning them sequentially to the *same* target on the substrate. Without the field-to-field target feature variations adding to the alignment variations here, even higher precision can be obtained.

(5) *Adequate resist contrast.* The desired resist response should be such that the exposure due to a clear mask defect does not cause thickness loss, while the exposure deficiency caused by an opaque defect still does not affect resist dissolution in the developer. The required resist/developer contrast can be determined with reference to Figure 2, where the characteristic of a typical positive photoresist is depicted schematically with resist thickness remaining after development plotted against the exposure dose. Here D_i is the extrapolated dose below which the resist is essentially insoluble, D_c is the extrapolated dose above which no resist remains after development, N is the number of reticle fields used in the vote-taking scheme, and D_0 is the exposure dose received by each field. With the resist contrast defined as $\gamma = [\log_{10}(D_c/D_i)]^{-1}$, the minimum contrast, $\gamma_{\min}$, needed for completely removing the effect of defects in an idealized situation (as represented by the dashed line in Figure 2) can be shown to be

$$\gamma_{\min} = \frac{1}{\log_{10}(N-1)}$$

Table 1 lists the values of $\gamma_{\min}$ for selected values of N , and indicates that the contrast requirement becomes less stringent as N increases. This reduction in the required contrast, however, is significant only when N is small, and therefore may be offset by the additional stepping time and higher risk of resist image degradation as $N > 4$. Contrast levels consistent with the values in Table 1, obtained with

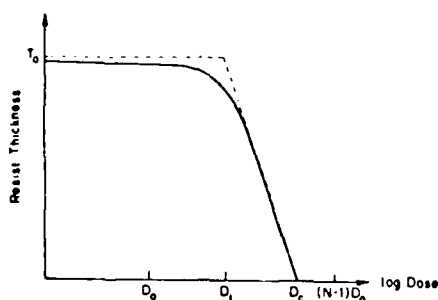


Figure 2. Schematic plot of remaining resist thickness vs. exposure dose for a typical positive photoresist process, illustrating the contrast requirement for vote-taking lithography.

Table 1. Resist contrast requirement

N	$\gamma_{\min}$
3	3.3
4	2.1
5	1.7
6	1.4

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commonly used photoresist, have been reported in the literature⁸. It should be noted that complete defect correction is difficult to achieve in practice due to the deviation of resist characteristics from the ideal even if γ meets the above requirement. Such deviation, coupled with limited exposure latitude, usually results in residual variations in the feature geometry.

In summary, the capabilities of currently available lithographic equipment and processes have provided a good opportunity for exploring the vote-taking lithography scheme.

Experimental procedures and results

All the experiments described here were performed in the Stanford Integrated Circuits Laboratory using the standard fabrication processes and existing equipment without modification. A 1 $\times$ test reticle for the Ultratech 900 stepper was written on a MEBES I electron beam pattern generator. Three of the four available fields on this reticle contain nominally identical patterns, but with "defects" intentionally introduced in one field; the fourth field contains only alignment target features needed to facilitate the vote-taking exposure. The simulated defects include both opaque and clear features embedded in 6 μm pitch gratings, ranging from 0.5 to 3 μm in size. Shipley 2400 photoresist was used as electron-beam resist, resulting in a CD variation within 0.1 μm over the plate. Wafers with a 0.5 μm polysilicon film deposited on 0.1 μm SiO₂ were coated with a 1.1 μm single layer Shipley 1470 positive photoresist. Alignment targets were first patterned and subsequently etched into the polysilicon layer. Photoresist was then coated again for a three-field vote-taking exposure using these targets. Shipley MF312 developer was used in a puddle development process, of which the γ value was estimated to be 1.9. Referring to Table 1, this resist contrast would be suitable for $N \geq 4$, but still falls substantially short of the level required for the best performance in a three-field voting scheme. Better results can be expected if more fields were used, and this was indeed demonstrated in a work reported earlier⁹.

Resist profile and overlay

To study how the resist features may be affected by the use of multiple exposures, results from single exposure and three-field vote-taking exposure (with equal total dose) were compared on an SEM, and are shown in Figure 3. Here no noticeable degradation of the resist profile acuity is present. A somewhat surprising difference observed in this experiment, although not seen clearly in Figure 3, is the consistently much smoother surface on resist features obtained by the vote-taking exposure scheme. For instance, while standing-wave induced patterns on resist sidewalls are apparent with single exposure, they have virtually vanished in the case of multiple-field exposure. This is likely a result of spatial averaging among the contributing aerial images, and a progressive modification of the optical properties of the resist following each exposure.

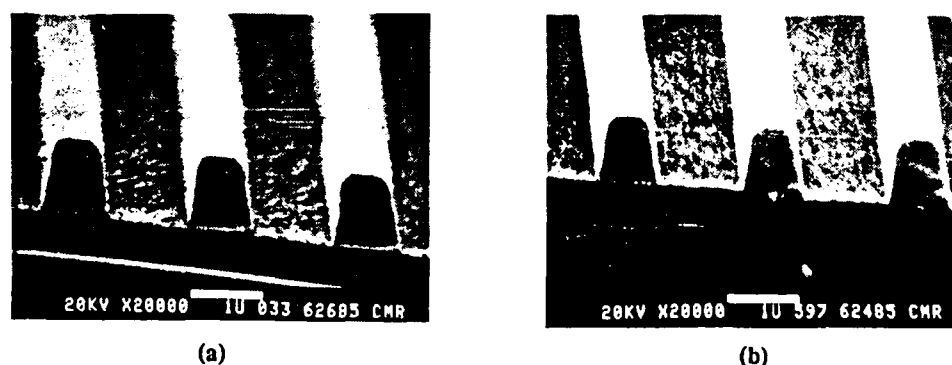


Figure 3. Comparison of resist profiles resulting from (a) a single exposure, and (b) a three-field vote-taking exposure, respectively, with equal total dose.

The effects of misalignment among the superposing images have also been studied carefully. The Ultratech stepper was programmed to perform vote-taking exposures, with a variety of offsets introduced among the three fields. Figure 4 compares resist profiles resulting from an exposure without image offsets and those from exposures including image shifts of 0.1 μm and 0.25 μm , respectively, in both directions. With this particular resist process, only insignificant profile changes are observed even with 0.25 and -0.25 μm shifts (Figure 4c). Such misalignment tolerance could be attributed to the convolution with the lens transfer function and a nonlinear transformation in the resist/developer system. It should be noted here that the effect of misalignment on the resist profile is expected to be more pronounced when the resist contrast improves because of the increased discrimination between different dose levels; this is a disadvantage of using higher-contrast resists.

The alignment accuracy offered by the present generation of lithographic tools is generally much superior to the situation simulated above. The Ultratech stepper being used can scan a resist target with a consistency better than 0.03 μm at one σ . As mentioned in the previous section, the shifts among images in the vote-taking exposure are expected to be relatively small because all the fields register to a common target. Figure 5 illustrates an example where the amount of misalignment, as read from optical verniers, is plotted for each field in one three-field voting exposure experiment over 32 sites on a wafer. An error range of at least $\pm 0.05 \mu\text{m}$ should be associated with each data point due to limited resolution of the verniers and the intrinsic placement tolerance of the MEBES. Taking this into account, the relative registration among three fields is quite satisfactory even at certain sites where anomalous target features have caused excessive alignment errors.

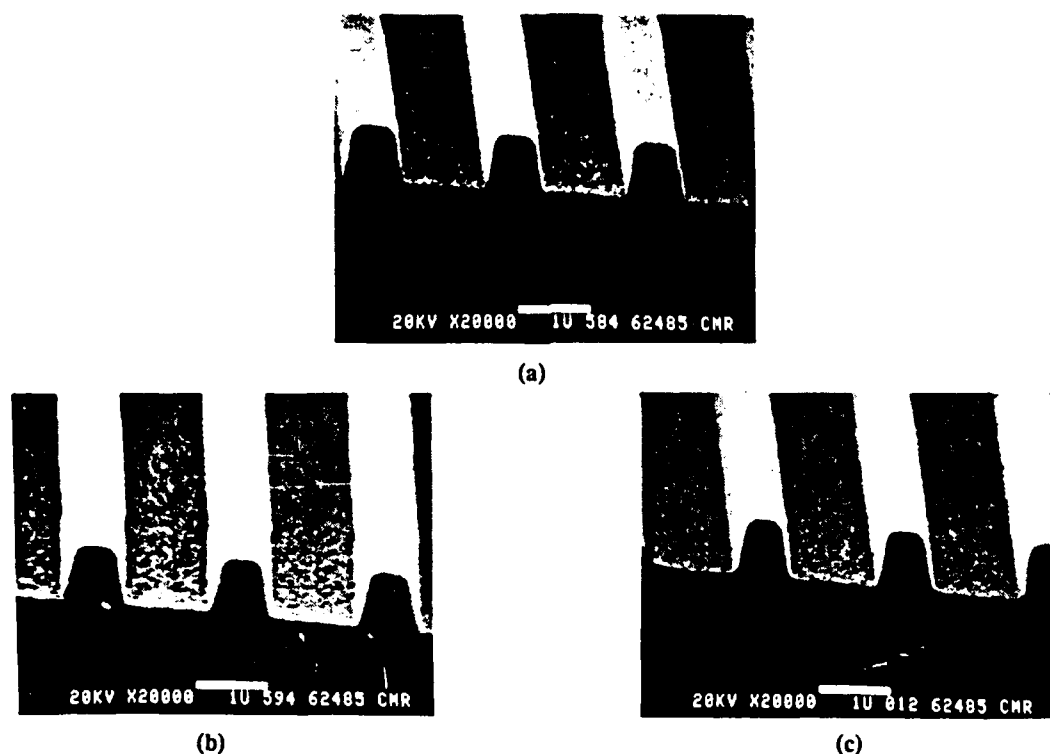


Figure 4. Resist profiles resulting from three-field vote-taking exposures with (a) no image offset, (b) image offsets of 0.1 and $-0.1 \mu\text{m}$, and (c) image offsets of 0.25 and $-0.25 \mu\text{m}$.

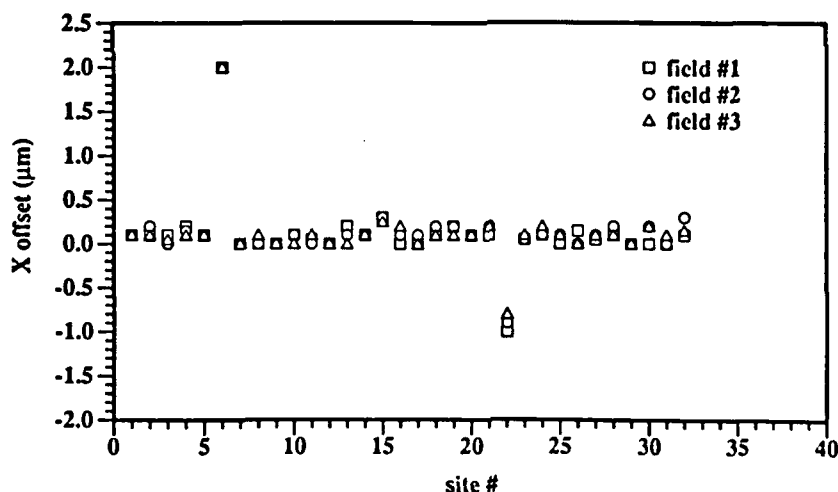


Figure 5. Estimated alignment errors, over a wafer, of all individual exposures in a three-field vote-taking scheme using an Ultratech 900 stepper.

Effect of exposure dose

Three-field vote-taking exposures were performed with various exposure doses on the same wafer. A Nanometrics CWIKSCAN IIIIE SEM inspection system was used to nondestructively measure the resulting linewidth variations at defect sites. The resist patterns were then transferred into the underlying polysilicon layer by plasma etching, followed by another linewidth measurement on the CWIKSCAN. Figure 6 shows the photographs of polysilicon lines obtained with selected doses, and that of the reticle field containing introduced defects. Both clear and opaque defects have resulted in residual linewidth changes which are functions of the exposure dose. Particularly notable is Figure 6c, which represents an extreme case where a gross over-exposure resulted in loss of integrity of the resist

and hence the underlying substrate features in areas affected by clear defects. In the other extreme, the opposite failure mode occurred in the clear-defect region when a dose considerably below nominal was used.

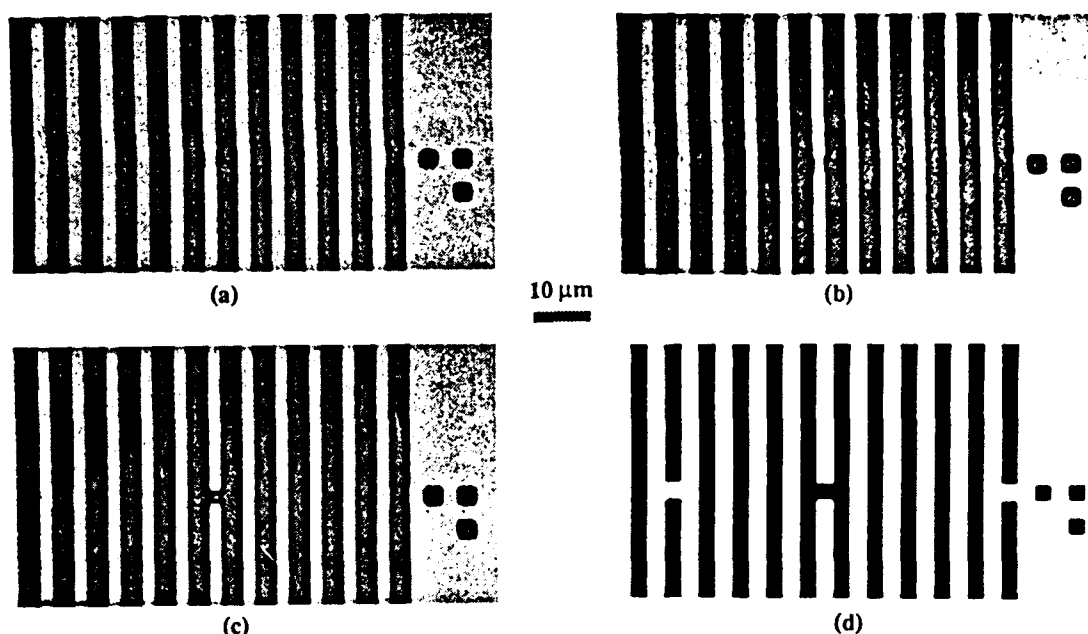


Figure 6. Photographs of patterns transferred into polysilicon following three-field vote-taking exposures with total doses of (a) 90 mJ/cm², (b) 110 mJ/cm² and (c) 120 mJ/cm², respectively; and (d) reflected-light photograph of the defect-bearing pattern in one reticle field. The three-square reference mark is common to all reticle fields.

Plotted in Figure 7 are measured deviations from the nominal 3 µm feature size arising from 3 µm × 3 µm defects, both before and after the polysilicon etching. The defect-induced deviation in the line/space width was aggravated by the pattern transfer process, SF₆/C₂ClF₅ plasma etching in this particular case. It is also seen to vary with the exposure dose in opposite ways for the two different types of defects, as also indicated in Figure 6, and a balance is reached around the nominal exposure. This balance of feature-size change between defect types, however, should not be an invariable criterion for determining the exposure dose. Depending on the pattern context and the subsequent pattern transfer process, it may be desirable to bias the dose in favor of either type of defect in order to yield a better overall result. As an example, for a grating in which spaces are wider than lines, space-width changes resulting from opaque defects are more tolerable; this would allow the use of a relatively low dose which emphasizes the correction of clear defects.

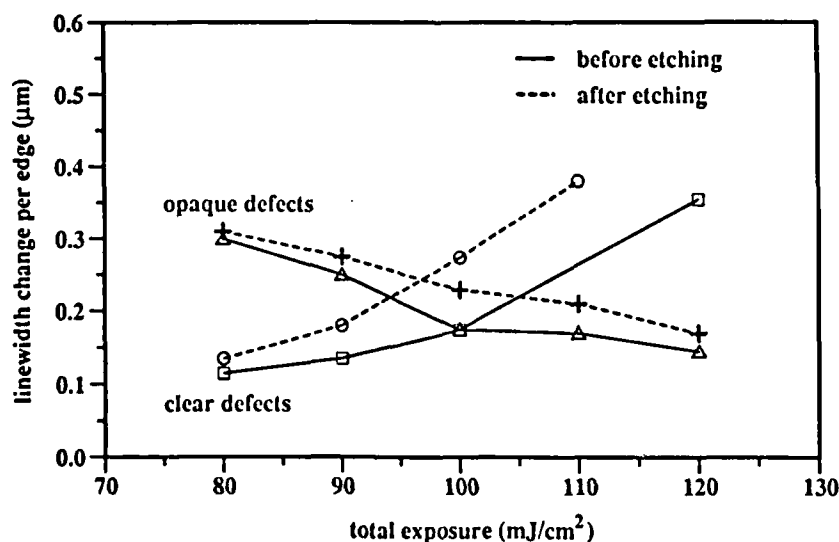


Figure 7. Measured change in line/space width caused in a 3 µm grating by 3 µm × 3 µm defects as a function of the total dose used in a vote-taking exposure.

Effect of defect size

Figure 8 shows the residual line/space width changes caused by defects of various sizes and both polarities, measured in polysilicon features obtained with a three-field voting exposure at the nominal dose. As these data indicate, the feature-dimension change arising from a very small yet printable defect is approximately proportional to the defect size, up to a certain critical size corresponding to the resolution limit of the projection optics. For defects larger than this critical size, the feature-dimension change becomes essentially independent of the defect size.

A related observation here is that, for the same size and polarity, isolated defects tend to be easier to correct than those attached to features. This phenomenon is especially pronounced with small defects, and is believed to be a result of the *proximity effect* in projection lithography¹⁰.

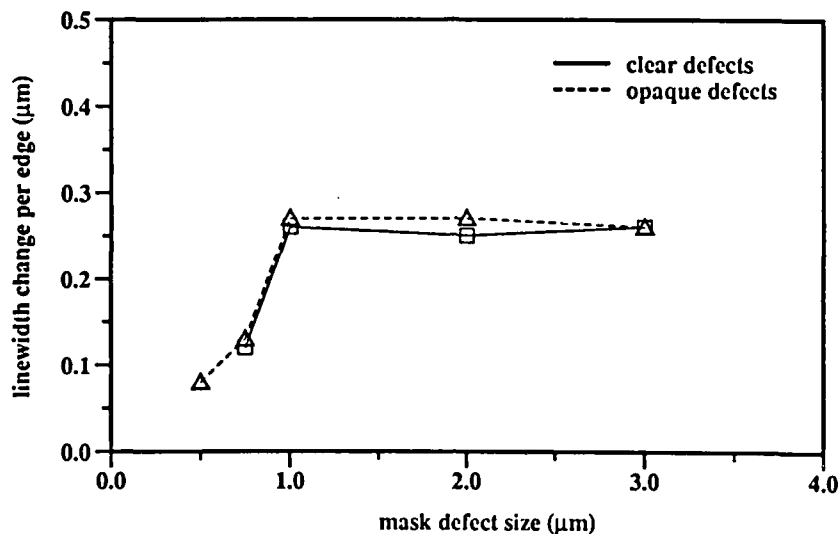


Figure 8. Residual feature-size change, obtained at the nominal dose, as a function of the defect size.

Evaluation of effectiveness in VLSI patterning

A reticle for the Ultratech stepper was generated using MEBES, and contained specially designed electrical defect test structures to verify that the voting scheme can eliminate random mask defects in large-area high-density fineline patterning applications. In one of the three fields used for this experiments, deliberate defects of various sizes were introduced into half of the patterns (see Figure 9) by inserting extra rectangles in the original graphics file; this field will be referred to as field C. Both opaque and clear defects were introduced (in module types 1 through 4 shown in Figure 9), with dimensions ranging from $2 \times 1 \mu\text{m}$ up to $20 \times 20 \mu\text{m}$. The test structure consisted of interdigitated combs with interleaving serpentes to detect defects as shorts and opens, and has a $2 \mu\text{m}$ nominal line/space width and an area of 2.4 mm^2 . The other half of this field had perfect patterns (module type 5) to serve as the control structures. The other two fields, to be termed fields A and B, had only perfect patterns. Again a fourth field provided appropriate alignment targets to facilitate the experiment.

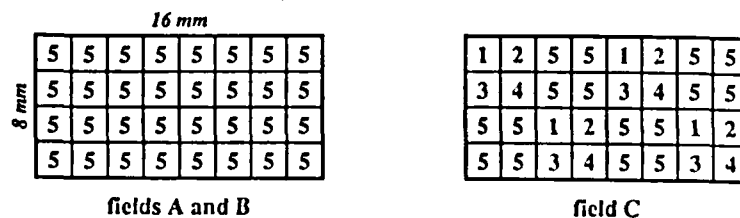


Figure 9. Strategy of reticle layout for evaluating the effectiveness of the vote-taking scheme. Modules of type 5 contain defect-free test structures, and deliberate defects were introduced in modules of the other types.

Three sets of experiments were performed as described in the following. Except for the exposure method, all wafers underwent an identical process sequence. Three wafers were used in each group:

1. Each wafer was exposed with a single exposure of field C. This was the control experiment to determine the baseline yield under normal process conditions.
2. Each wafer was exposed with three exposures of field C. This was to determine the effect of the triplicated exposure scheme on the yield in areas free of defects, through yield statistics for modules of type 5.
3. Each wafer was exposed in a full voting scheme using all three fields. This was to determine the impact of vote-taking exposure on the yield in areas affected by defects, through yield statistics for the defect-bearing modules.

The wafers had a 100 nm aluminum film deposited uniformly on a polysilicon substrate prior to the coating of a 1.1 μm Shipley 1470 resist layer.

Two special processing techniques were employed in these defect studies to minimize the process complexity and hence the number of variable involved, with an aim to obtain the best estimate of *lithographic defect* density. One is the use of latent images in resist for alignment rather than fabricating targets into the substrate. The wafers were exposed first with the field containing target features with a rather high dose which produced the latent target image that can be detected by the automatic alignment mechanism of the Ultratech stepper. The wafers could then be fed back directly into the stepper to be exposed with the pattern fields and, as a result, only one development step was needed. The other technique consisted in the use of alkaline developer (for conventional novolac-based photoresists) as an agent for consecutive developing and etching. Once development is complete the active mode of the developer is switched to electrolytic etching of the underlying metal patterns. Details of this technique will be described in a later publication. Due to the continuity between developing and etching it can be claimed that the resulting defects are *solely lithographic defects*.

Without displaying detailed data, a short summary of results is presented in Table 2. Here the *normalized yield* is defined as the yield of a group of structures relative to the yield of patterns without introduced defects within the same experiment group. 176 and 352 points per wafer were measured for each defect structure and each non-defect structure, respectively, to determine the yield. Because no dependence of the results on the defect size was apparent, in agreement with the observation noted in the previous section, all data points associated with the same defect polarity were combined in the calculation.

Table 2. Normalized yields illustrating the effects of vote-taking lithography scheme.

Experiment		Normalized yield (%)	
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Group 1 (1 field, single exposure)	defect structures	0	0
	non-defect structures	100	100
Group 2 (1 field, triple exposure)	defect structures	0	0
	non-defect structures	100	100
Group 3 (3 field, voting exposure)	defect structures	99	97
	non-defect structures	100	100

As expected, zero yield was obtained in defect structures in both groups 1 and 2 which used only field C. The third experiment, however, showed almost perfect normalized yields in the same structures, indicating nearly complete elimination of the mask-induced defects by the vote-taking scheme. In addition, the yield in the non-defect structures in group 2 was found to be essentially the same as that obtained in group 1, suggesting that the increase in process complexity due to the triplicated exposure has not created any adverse effects.

Conclusion

The feasibility of the vote-taking photolithography scheme has been verified through extensive experiments in various equipment and process parameters that affect its performance. A lithographic yield study using novel defect monitoring techniques has further demonstrated its effectiveness in eliminating mask-induced defects in actual VLSI patterning with linewidth, area and density comparable with state-of-the-art circuitry. Presently available equipment and conventional resist technology are adequate for implementing this scheme in a wide range of applications, and future advances in these areas should further extend the capability of the vote-taking lithography to meet the next generation lithographic needs.

Acknowledgment

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