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Modeling the edge-placement yield of a cut process for self-aligned multiple patterning

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ABSTRACT

Overlay errors and cut-hole critical dimension variations are serious concerns in complementary lithography that can drive the scaling of IC technology down to (half-pitch) 7 nm. Their combined effect on the edge-placement accuracy of cut holes over the 1-D grating structures is critical to the yield of spacer based self-aligned multiple patterning processes. In this paper, an edge-placement yield model for such a cut process is presented. The yield-related features are identified and a probability-of-failure function is introduced to construct the yield formula. Both overlay errors and cut-hole critical dimension variations are taken into account and the key parameters that impact the process yield are investigated. Our calculation results show that an optimal cut-hole overhang must be identified first in order to achieve the maximum yield. The scaling trend of the edge-placement yield is also studied and a non-trivial challenge is found when the half pitch of IC patterns reaches sub-10 nm.

1. Introduction

One practical patterning solution to continue semiconductor scaling down to (half pitch) sub-10 nm is to use 193-nm immersion (193i) lithography and self-aligned quadruple/sextuple patterning process [1–3]. For example, the "complementary" lithography [1] was proposed for logic fin and gate patterning. It starts with a spacer based self-aligned multiple patterning (SAMP) process to fabricate the 1-D grating structures while several 193i (or one EUV) cut steps help to form the desired fin/gate structures. The capability to predict the cut-hole placement yield of such a cut process is therefore critical for a continuous scaling of IC technology. Although the basic yield theory and models for semiconductor fabrication were already developed [4–6], significant effort is still needed to build a specific yield model for SAMP cut processes.

In the next section, a geometric model of cut-process edge-placement yield will be developed based on the concept of probability-of-failure (POF) function. A physical and statistical analysis to correlate the process yield with the overlay errors and cut-hole critical dimension (CD) variations will be presented. A general formula to calculate the cut-process edge-placement yield is then derived by taking various failure mechanisms into account. The key process parameters including the cut-hole overhang and statistical indices of the overlay-error and cut-hole CD distributions are identified and their impacts on the cut-process yield are discussed. We show that the optimal overhang must be identified first in order to achieve the maximum yield. Moreover, we study the scaling trend of the cut-process edge-placement yield as technology evolves.

2. Cut-process edge-placement yield model

A schematic description of the cut-process overlay errors and cut-hole CD variations, both of which affect the edge-placement accuracy of cut holes, is shown in Fig. 1. In a lithography process, the shape of cut patterns is often designed as a rectangle on the mask, but its diffraction-limited image printed on the wafer is close to an ellipse. A perfect placement of two cut holes with the exact feature sizes we desire is shown on the left side of Fig. 1. However, the actual result of a cut process is always disturbed by both its random overlay errors and cut-hole CD variations, as shown on the right side of Fig. 1. Here we reasonably assume overlay errors and cut-hole CD variations can be tightly controlled such that only two edge lines are affected. In other words, the cut-process yield is only impacted by the edge line to be cut and the other (affected) edge line right next to the cut hole, as shown in Fig. 1. We also assume the cut holes are designed to be symmetrically placed over the lines (i.e., symmetric placement) and the shape of the hole is symmetric such that its two edges have the same statistical characteristics. As a result, although an actual overlay errors and cut-hole CD variations can be either up or down, only

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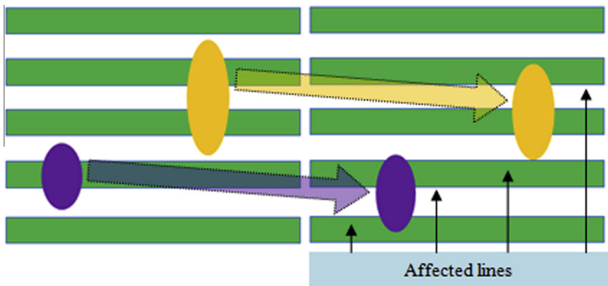

Fig. 1. A schematic description of the cut-process overlay errors and cut-hole CD variations. Left: cut holes with perfect placement and desired CD. Right: cut holes with misalignment and CD variations. The two affected lines for each hole are indicated by the thin arrows.

one direction needs to be considered when calculating the induced yield loss (e.g., downward direction as indicated in Fig. 1).

We assume the probability density function of overlay errors (one direction only as the 1-D grating structure can always be designed in certain direction) can be described by the Gaussian distribution:

$$f(x) = \frac{1}{\sigma_1\sqrt{2\pi}}\exp\left[-\frac{(x-\mu)^2}{2\sigma_1^2}\right] \tag{1}$$

In this paper, we shall follow the standard rule in the statistics literature to specify the random variables and sample values differently by using capital or lower-case symbols. For instance, X stands for the random variable of one type of overlay errors while x is the sample value of an overlay error. On the other hand, the variables in the probability density function are always lower case. Here, μ is the mean value of overlay errors, σ_1 is the standard deviation (overlay-error index: $|\mu| + 3\sigma_1$). We also assume the probability density function of cut-hole CD variations Y (defined to be the deviation from the mean CD in the affected direction) obeys the Gaussian distribution:

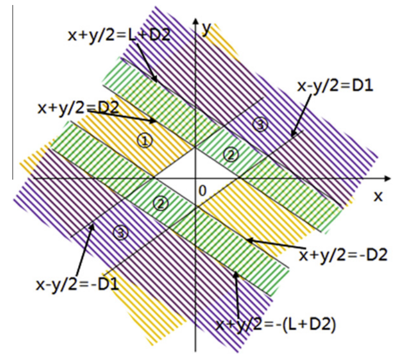

Fig. 4. The integration regions to calculate the yield.

$$g(y) = \frac{1}{\sigma_2\sqrt{2\pi}}\exp\left[-\frac{y^2}{2\sigma_2^2}\right] \tag{2}$$

where σ_2 is the standard deviation of cut-hole CD variations. This distribution equivalently specifies the mean value of cut-hole CD variations is zero. Since we only consider the effect of CD variation from one edge of a cut hole, a new variable, Z can be defined as the random variable of cut-hole CD variation due to one single edge. Apparently, a simple relation $Z = Y/2$ exists and the probability density function of Z can be described as: $(\sqrt{2\pi}\sigma_2)\cdot\exp\left[-2z^2/\sigma_2^2\right]$. Naturally, we assume that hole CD variations and overlay errors are independent such that their joint probability density function can be written as:

$$h(x,z) = \frac{1}{\pi\sigma_1\sigma_2}\cdot\exp\left[-\frac{(x-\mu)^2}{2\sigma_1^2} - \frac{2z^2}{\sigma_2^2}\right] \tag{3}$$

Consequently, the yield can be calculated as:

$$Y = 1 - \iint_D \mathrm{POF}(x,y)\cdot\frac{1}{2\pi\sigma_1\sigma_2}\cdot\exp\left\{-\frac{1}{2}\left[\frac{(x-\mu)^2}{\sigma_1^2} + \frac{y^2}{\sigma_2^2}\right]\right\}dxdy \tag{4}$$

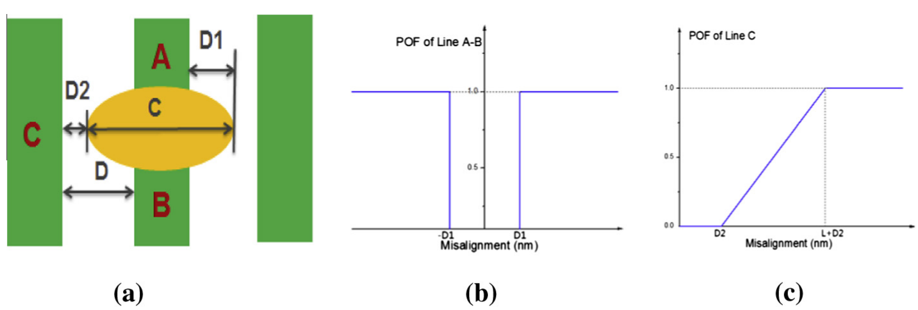

Fig. 2. The geometric model of a cut process and the POF curves (L: line CD). (a) Geometric description of a perfect cut process. (b) POF of the line to be cut. (c) POF of the other affected line.

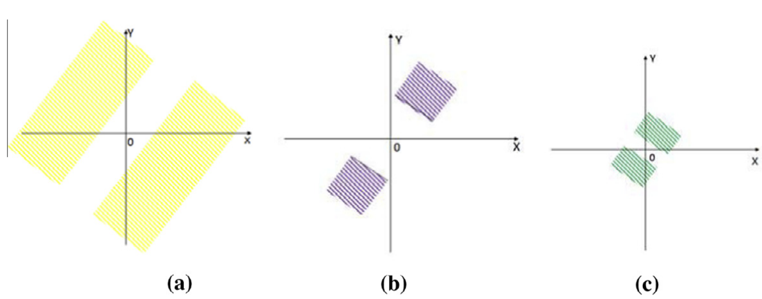

Fig. 3. The regions to calculate POF functions of lines A–B (a) and C (b–c).