

# **Exposure optimization in scanning laser lithography**

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n 1959, the integrated circuit (IC) was invented simultaneously by Jack Kilby of Texas Instruments and Robert Noyce of Shockley Semiconductor [Kilby, 2000]. This development has been considered one of mankind's most significant innovations.

The most popular and economical process for IC fabrication is the complementary metal-oxide semiconductor (CMOS) process [Baker, 2010]. Like other processes, the CMOS process involves a series of implantation, deposition, and etching steps to build the structure additively.

Each implantation or etching step is preceded by a photolithography step, where a resist layer is added and then selectively removed from the wafer. After the deposition or etching process is complete, the remaining resist is removed in preparation for the next process step.

An example of a simple CMOS process is the 1um XC10 process, illustrated in Fig. 1, which is offered by XFab AG, Germany. This process requires at least ten masking steps but up to 23 masking steps if features like high-voltage transistors, optical windows, or sensors are required.

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By 2017, the half-pitch of a transistor will have reduced to 32 nm. This requires an extreme-UV (EUV) light source and a sophisticated optical system to satisfy the required numerical aperture. The foremost problem with this development is the cost and complexity of the EUV light source and mask infrastructure. At present, a maskset costs upwards of US\$1 million and is predicted to increase tenfold as dimensions shrink and complexity increases. The cost of infrastructure is also predicted to dramatically increase, for example, the cost of a suitably powerful EUV light source is in the tens of millions of U.S. dollars, which is an order-ofmagnitude more expensive than the excimer lasers used previously.

There are two major consequences of the increasing development and processing costs of ICs. First, the best performance technology will only be available to the highest volume applications, such as computer memory and cell phone processors. Second, future innovations in device technology will be dampened by the prohibitive manufacturing costs.

The infrastructure and processing cost of microelectromechanical systems (MEMS) is also of major concern. In particular, prototyping services are time consuming and expensive, since a single MEMS device still requires a complete set of



**FIG1** A cross section of a CMOS inverter and a pressure sensor manufactured on the XFab XC10 process. (Figure reproduced with permission from XFAB, 2008.)

masks. If the requirement for masks and the optical delivery system could be eliminated, the cost of MEMS prototyping would be dramatically reduced. A decrease in development costs would be a major stimulant to MEMS innovation. EBL and IBL cannot be used to prototype a standard mask-based process, since the resist chemistry is different. The infrastructure cost is also significant.

In addition to EBL and IBL, maskless optical lithography is also

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## The rise of maskless lithography

To bypass the physical limitations and cost of mask production, a number of maskless lithography processes have been developed [Lin, 2007]. The most promising technique for future IC processes is electron beam lithography (EBL) [Altissimo, 2010]. This process involves the selective modification of a resist layer by electron bombardment in vacuum. Like a scanning electron microscope, the beam is scanned over the surface, which eliminates the need for a mask.

The foremost difficulty associated with EBL is the slow process speed. However, this may be improved by using many parallel beams. Further difficulties include placement inaccuracy due to drift, substrate heating, charging, and proximity effects [Menon et al., 2005]. Ion beam lithography (IBL) is a similar technique but suffers from even slower speed and worse drift. developing. In its simplest form, a laser beam is focused to a spot size of approximately 500 nm and scanned over the surface. A faster method for maskless optical lithography is zone plate array lithography. In this technique, a controllable grating array creates a dot-matrix-like image on the photoresist. By scanning the wafer while changing the image, a larger complex image can be realized. To date, feature sizes of 150 nm have been demonstrated with zone plate lithography. However, the feature size is limited by the wavelength of the light source, which must be con-



**FIG2** A circular pattern exposed using a scanning fiber.

tinuous-wave. Future improvements will be possible with the availability of shorter wavelength continuouswave lasers. Other problems with zone plate lithography include limited image contrast and "stitching errors" at the boundary of each image [Menon et al., 2005].

An alternative to the controllable grating array discussed previously is the use of a micromirror array. The micromirror array effectively replaces the mask in a standard optical system. However, an extremely high demagnification factor of greater than 200 times is required to transfer the micron-sized features of the mirror to the nanometer-sized features of the target. Unfortunately, since refractive optics are required, this technique cannot be extended to wavelengths below 157 nm. Further problems include the number of required pixels (10 million) and the need to correct for the response of each individual pixel.

Rather than focusing light through an objective lens, it can also be directed through a sharpened optical fiber or probe as shown in Fig. 2. Below one wavelength from the fiber tip, the emitted light forms an evanescent field with highly localized intensity. If the fiber tip is positioned within a few nanometers from the surface, the near-field intensity can be used to expose the resist with nanometer precision.

Since the light delivery does not require any optics or free-space transmission, the resolution is not diffraction limited like other optical lithography techniques. Probe-based exposure also avoids some of the disadvantages associated with EBL.

> For example, there is no charging, proximity effects, or scattered electrons; and most importantly, probe-based exposure is compatible with standard photoresist chemistries.

> A number of challenges exist with probe-based and scanning laser photolithography. First, the throughput is extremely low compared to mask-based methods. However, advances in nanopositioning systems have

allowed scan rates to exceed 1,000 Hz, which can allow thousands to millions of features to be written per second [Fleming and Leang, 2014]. The probes have also been optimized to maximize throughput and resolution in lithographic applications [Routley et al., 2015].

Another major difficulty is the problem of finding a suitable exposure pattern that optimizes the fidelity of developed features. In other words, where, when, and how long the laser should be activated while the substrate is being scanned. This is a challenging problem that involves modeling and optimizing the nonlinear optical and chemical behavior of the exposure and development process. In the next section, this modeling process is introduced. A nonlinear programming approach is then employed to find an exposure pattern that minimizes the difference between the desired and developed feature geometry [Fleming et al., 2016].

#### Exposure modeling

Once the desired feature size becomes similar to the wavelength of the illumination source, diffraction and interference play a major role in the developed feature geometry. In standard lithographic techniques, these problems have been tackled by resolution enhancement techniques (RETs) that aim to minimize the differences between the desired and exposed pattern. Methods for prewarping the mask, known as optical proximity correction, can be categorized into rule- and optimization-based methods. The rule-based methods improve proximity effects based on rules derived from simulations, experiments, or a combination of the two. Optimization-based techniques use a forward model that maps input light intensity to a developed feature. An optimization technique then modifies the input pattern to improve the developed resolution.

At present, these methods require significant computing power and don't guarantee convergence to the optimal solution. In maskless lithography, the exposure problem can be thought of as an attempt to create sharp images by scanning a blurry spot of light over the photoresist. It turns out that the properties of the photoresist actually make this feasible. age energy received. The simplest model is a threshold function that indicates 100% conversion when the dosage is above a threshold. A more realistic model of the exposure is a smooth function that relates the energy to the fraction of converted

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#### Beam modeling

The first step is to develop a model of the exposure process that is compatible with optimization methods. In scanning laser lithography, the beam profile represents the optical power as a function of distance from the center. In our experiments, the beam profile is represented by a two-dimensional Gaussian function:

$$B(x,y) = \frac{2P}{\pi w_0^2} e^{-\frac{2(x^2+y^2)}{w_0^2}},$$
 (1)

where *x* and *y* indicate the transverse axes of the beam at focal point  $w_0$ , and *P* is the total power in the beam. An example of this function is plotted in Fig. 3.

#### Photoresist modeling

The photoresist model quantitatively characterizes the chemical reactions of the photoresist based on the dosphotoresist. A sigmoid function is employed for this purpose:

$$\widehat{Z}(x,y) = (D(x,y)) = \frac{1}{1 + e^{-\gamma(D(x,y)-T)}},$$
(2)

where  $\widehat{Z}(x, y)$  is the fraction of converted photoresist, *T* is the threshold energy, and the parameter  $\gamma$  dictates the steepness of the sigmoid. When this parameter is large, the function resembles a binary exposure model.

#### **Process model**

A simplified model of the exposure process is illustrated in Fig. 4. Physically, the exposure profile E(x) represents the time interval where the laser shutter is open, which is proportional to the resulting dosage since the beam power is constant. Another possibility is to



**FIG3** The normalized beam power function, where the center is located at x = 3 and y = 2.



**FIG4** A simplified one-dimensional model of scan-based photolithography. In this example, the exposure pattern E(x) is three discrete exposures of equal energy. The resulting dosage D(x) is the sum of each exposure point convolved with the beam profile B(x). Finally, the photoresist function  $f(\sigma)$  maps the cumulative dosage D(x) to the exposed feature  $\widehat{Z}(x)$ .

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directly modulate the laser power from 0 to 100%.

The light intensity (in W/m<sup>2</sup>) is a Guassian function described in (1). To calculate the dosage D(x)(in J/m<sup>2</sup>) at a single point, the intensity is multiplied by the exposure time, that is  $D(x) = t_{on}B(x)$ . Where multiple exposures  $(t_i)$  are involved at arbitary locations  $(x_i)$ , the total dosage is

$$D(x) = \sum_{i=1}^{N} t_i B(x - x_i).$$
 (3)

Equation (3) is observed to be a convolution operation that can be generalized to discrete or continuous exposures in one or more dimensions. That is, in general

$$D(x, y) = E(x, y) \otimes B(x, y), \qquad (4)$$

where  $\otimes$  is the convolution operator. When the exposure function is discrete, the dosage can be expressed as

$$D(x,y) = \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} E_{i,j} B(x - x_i y - y_j).$$
 (5)

Once the dosage is known, the fraction of converted photoresist (0 to 1) can be computed by applying the photoresist function to the dosage. That is, the exposed feature  $\widehat{Z}(x, y)$  is

$$\widehat{Z}(x,y) = f(D(x,y)), \qquad (6)$$

where f(D(x, y)), is defined in (2).

#### Optimization

The aim of the optimization is to compute an exposure pattern that minimizes the difference between the desired and predicted features. The target shape *Z* is defined over a finite grid with  $N \times N$  locations, such that  $Z_{i,j}$  is the desired value (typically either 1 or 0) at row *i* and column *j* of the image matrix. This grid corresponds to points in the transverse x, y-axes, where  $_{X}(k) = k\Delta_x$  and  $y(k) = k\Delta_y$  with  $\Delta_x$  and  $\Delta_y$  defining the *x* and *y* axis resolutions.

With the process model described previously, it is possible to define a measure of distance between the desired image matrix Z and the predicted one. This distance becomes part of a cost function that can be minimized to determine the optimal exposure pattern. At the same time, it is important that the exposure pattern does not produce high dosage levels, which is achieved by simultaneously minimizing the feature errors and applied energy. The exposure profile must also be constrained to positive values since negative values aren't physically realizable.

The above problem is a nonlinear and, importantly, nonconvex programming problem. In the absence of the thresholding function the problem reduces to a quadratic program (QP) with simple positivity bound constraints. However, the sigmoid thresholding function, while smooth, is neither convex nor concave and renders the problem more difficult to solve.

Nevertheless, this optimization problem can be solved by employing a barrier function approach where the inequality constraints are replaced with a weighted logarithmic barrier function [Fiacco and McCormick, 1968]. This method also requires the computation of a gradient vector that can be obtained efficiently using a Hessian approximation. An in-depth description of the optimization process can be found in [Fleming et al., 2016].

#### Example exposure

In this example, the optimal exposure profile will be obtained for the feature plotted in Fig. 5. The target exposure is 0.9, which implies a 90% conversion of the photoresist. The optimization assumes a beam width of 500 nm with unity power. The photoresist development threshold is 1 with a steepness of  $\gamma = 5$ .

The initial condition for the exposure function was obtained by exposing at every point where the feature is desired, which is shown on the top left of Fig. 6. This initial condition results in a gross over-exposure, which is evident in the dosage and feature geometry plotted in the top row of Fig. 6. After 20 iterations (middle row), the exposure function and feature geometry are observed to show significant improvement. After 80 iterations, the algorithm converges to an optimal solution with excellent correlation between the desired and predicted exposures. Since the beam-width is



**FIG5** The desired feature Z(x, y) used in the simulation has a target exposure of 0.9, which implies a 90% conversion of the photoresist. The exposure area is  $10 \times 10 \,\mu$ m with a resolution of 200 nm.



**FIG6** The optimization results with the initial conditions (i = 1), a midway point (i = 20), and the optimal result (i = 80). The exposure function, resulting dosage, and feature geometry are plotted in the left, middle, and right columns. The optimized feature is observed to closely match the desired feature plotted in Fig. 5.



**FIG7** The optical modeling results for the simplified two-dimensional model and slices taken from the three-dimensional model at the top layer, bottom layer, and a cross section taken through A). The cross section reveals the presence of an interference pattern formed in the cavity between the top and bottom surfaces of the photoresist.

similar in dimension to the feature resolution, the optimal exposure reduces to a line-scan along the major axes of the feature. Interestingly, the additional exposure points near the external corners of the feature are similar to the "hammerhead" points that are empirically added to masks to improve corner fidelity.

#### **Optical simulations**

To validate the proposed optimization process, three-dimensional optical simulations were preformed. The model was created within the COMSOL multiphysics framework, which solves Maxwell's equations in the frequency domain over a nonuniform mesh. To drastically reduce computation time, the photoresist was assumed to have fixed optical properties, ignoring photo-bleaching. The photo-bleached state's optical proprieties were used to produce the worst case optical scattering [Routley et al., 2015]. This assumption allowed for the point spread function (PSF) or beam profile to be properties. A  $1-\mu$ m-thick photo-resist layer was used with a glass substrate. The wavelength of the light source was set to 405 nm and the profile was a Gaussian beam with a width of 500 nm. The results shown

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modeled in two dimensions. The PSF was then revolved and convolved with the exposure function. Producing a three-dimensional representation of the dosage.

The photoresist under consideration is AZ-701 from Microchemicals GmbH, which provided the optical in Fig. 7 indicate that there is little beam divergence. With the top layer dosage and the bottom layer dosage having almost identical features. This low divergence is due to the large beam width when compared to the wavelength. The cross section indicates that there is optical



**FIG8** A three-dimensional representation of the resulting feature after the photoresist is developed. The vertical walls are slightly corrugated by an interference pattern created through the thickness of the film.

interference occurring in the photo-resist, due to reflections off the glass substrate.

These interference patterns can also be seen if Fig. 8, which represents

function, this method is applicable to all forms of serial lithography including e-beam, probe-based, and scanning laser.

Current research includes adapting the algorithm to handle images with a massive number of features and/or ultra-high resolution. It is also necessary to consider uncertainty in the optical and photoresist models, for example, variations in film thickness and photoresist constants, among others. Although technical challenges still exist, the development of this technology will dramatically improve access to a low-cost, ultrahigh resolution lithographic process. We hope that this

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the resulting feature after the photoresist is developed. It was produced by thresholding the three-dimensional dosage data at 0.9. In Figs. 7 and 8, the corners appear somewhat rounder than those found in Fig. 6; however, this is primarily due to the higher resolution used for the optical modeling.

#### Conclusion

Scanning laser and probe-based exposure offers an attractive alternative to standard lithographic methods for prototyping and lowvolume production. As the speed of nanopositioning systems increases, these methods will become increasingly competitive. Simple devices can already be exposed in less than a second and current research aims to create millions of features in a similar time frame.

This article focuses on the problem of finding an exposure pattern which optimizes the geometrical fidelity of the developed features. The solution is based on a nonlinear programming approach that can be solved with a gradientbased method. By changing the beam profile will stimulate the development of new fabrication processes and myriad new technologies and devices that rely on them.

#### Read more about it

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