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Review article

X-ray lithography: Some history, current status and future prospects

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ABSTRACT

In this article we provide a brief history of some of the world's major efforts in X-ray lithography. We discuss the limitations and advantages of this approach in a variety of applications. These include the printing of mask layers in very-large-scale integrated circuits, the manufacture of high aspect ratio structures as a kind of "micro-3D printer," and the possible use of the technique for imaging on non-planar surfaces. We conclude with a discussion of the potential future of the approach in microlithography.

Contents

1. Background

X-ray lithography was proposed by H. Smith and Spears at MIT [1]. The first patent publication was 1973 and woke up interest in the technology all over the world. At Bell Labs, Murray Hill, N.J., this announcement coincided with the scale up in company effort to exploit its stake in transistor technology - a Bell invention [2]. Bell departments were asked to look outside their electro-optics and display efforts, and X-ray lithography offered a way to carry improvements in transistor technology forward. The first Bell Labs publications in XRL were in 1975–76 [4,3]. They were followed by the development of an X-ray system [5] utilizing a Pd stationary target cooled by nucleate boiling to overcome the long wavelength limitations of other X-ray targets proposed elsewhere. This system, including an X-ray mask with a polyimide substrate, was licensed to Micronix in Los Gatos, CA which commercialized the first US X-ray stepper to compete with the one developed by Suss in Germany.

The Pd target approach was followed by other companies in the U.S. In addition, Hewlett Packard, Hughes Aircraft and Westinghouse [6], worked in many different areas of XRL. Also, in the late '70s, experiments done at the Naval Research Laboratory demonstrated the usefulness of plasma-generated X-ray sources for lithographic applications [7]. Furthermore government agencies like the Defense Advanced Research Projects Agency (DARPA), under the direction of David O. Patterson, contributed with funds for the development of the technology in the late 80s and early 90s.

X-ray lithography (XRL) is an extension of optical lithography to shorter wavelengths. Due to the difference in penetration and reflection of X-rays in matter, XRL is usually per- formed in a projection transmission proximity printing mode instead of the usual reflection mode (mask pattern imaging), used by optical lithography. A mask with different local X-ray absorption areas is utilized to define the pattern to be replicated on a resist material previously deposited

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on a substrate (usually a silicon wafer). The absorptive regions are generally composed of up-plated heavy metals and the plating "guides" are the walls of exposed photoresist.

Depending on the chemical nature of the resist material, the X-ray exposed areas may cause cross linking (for negative resists) or bond breaking (for positive resists). After exposure, the resist pattern on the substrate can be developed utilizing the proper solvent. The exposed areas in a positive resist will dissolve and the unexposed areas will remain. Alternatively, the exposed areas in a negative resist will not be affected while the unexposed areas will dissolve. During operation, the X-ray mask is placed close to the wafer at a small gap and exposed to X-rays over the whole wafer area. To increase the throughput (wafers/hour), steppers are utilized for this purpose. Steppers are very precise machines that allow X-ray exposure of many small wafer field areas over the whole wafer and perform alignment (field to field) in the same wafer or wafer-to-wafer with fields with different patterns.

X-ray sources are critical for high-throughput X-ray lithography. Both point sources and storage rings have been utilized as stepper exposure sources. There are many kinds of point X-ray sources i.e., stationary and rotating anode, laser and gas plasma, etc. For a point source X-ray lithography system, the size of the gap and its variation over the wafer area determine the resolution and line width control required of the lithography stepper. For a storage ring X-ray lithography system (normal or superconducting), the X-ray beam simulates a fan with a very small width and angular spread. This near parallel X-ray beam allows more precise alignment and resolution capabilities in the stepper over larger field areas. Several companies were funded by DARPA in the '90s for X-ray source development. These included JMAR Technology for laser plasma and SRL for gas plasmas.

At IBM Yorktown in 1980, the XRL interest was in using the storage ring as an X-ray source. The IBM effort grew throughout the years manning an XRL dedicated beam line at Brookhaven National Lab and finally building an XRL facility in East Fishkill, N.Y. to house the HELIOS superconducting storage ring in 1991. The X-ray effort at IBM grew in the 1990s fabricating high resolution DRAM devices demonstrating the X-ray lithography capabilities and purchasing X-ray steppers to be installed in East Fishkill. In addition, a large effort was established in IBM Burlington, VT to fabricate X-ray lithography masks following the NIST standard approved by many companies. These masks met the lithography requirements of the time. Starting in the early 90s IBM monitored and funded XRL efforts from several Universities including Wisconsin and LSU.

The IBM was joined in this effort by Motorola. It was clear at the time that to create such a major change in a costly technology would require broad collaboration among a number of user companies, equipment and material suppliers. But after some time, the companies could not come to terms either on the financial arrangements funding the work or on the ultimate disposition of the intellectual property it generated. The collaborative effort ended in the mid-90s. Thus, a diversity of company business plans and a divergence of the long range goals of these organizations impeded technology development. This is a recurrent theme in the fielding of major technology change and a theme that had a particularly adverse affect on XRL.

2. Patterning limitation in X-ray lithography

In this section, we discuss the fundamental limits we encounter in our ability to pattern arbitrary features in photoresist. There are a number of factors limiting resolution in an X-ray lithography system. First, we have the equivalent of the optical system limits of diffraction and depth of focus. The diffraction limit is given as [9]:

$$\delta_1 = k_1\sqrt{\lambda G} \tag{1}$$

Here, δ_1 is roughly equivalent the Airy diffraction limit, k1 is a process related constant (usually taken as 1.5), λ is the wavelength of the incident X-ray and G is the mask-to-wafer gap separation. For a relatively hard (Al Kα) photon λ is about equal to 10^{-8} cm (an Ångstrom) and G is around 5×10^{-4} cm. Thus, the diffraction-limited resolution is about 3.35×10^{-6}, or 335 Å. This is quite close to the experimentally derived result obtained by Early et al. in the middle 80s [8].

The second parameter cited for optical systems is depth-of-focus. In a point source X-ray system this is related to penumbral blur, as visualized in the figure below (Fig. 1).

From this figure, we see that:

$$\delta = \frac{1LG}{2D} \tag{2}$$

Thus, the undercut (and the feature boundary) will shift as we change the source-to-wafer and the gap spacing. We can define a depth-of-focus in terms of a minimal tolerable undercut change for some change in either of these parameters. But for any reasonable system design, the total undercut is miniscule. For a point source, we can anticipate about a meter source-to-wafer separation a gap of about 5 μm and a feature size of less than a micron. This leads to fractions of an Ångstrom undercut for a micron sized feature. For synchrotron sources, the effective mask-to-wafer separation is more like 10 m, leading

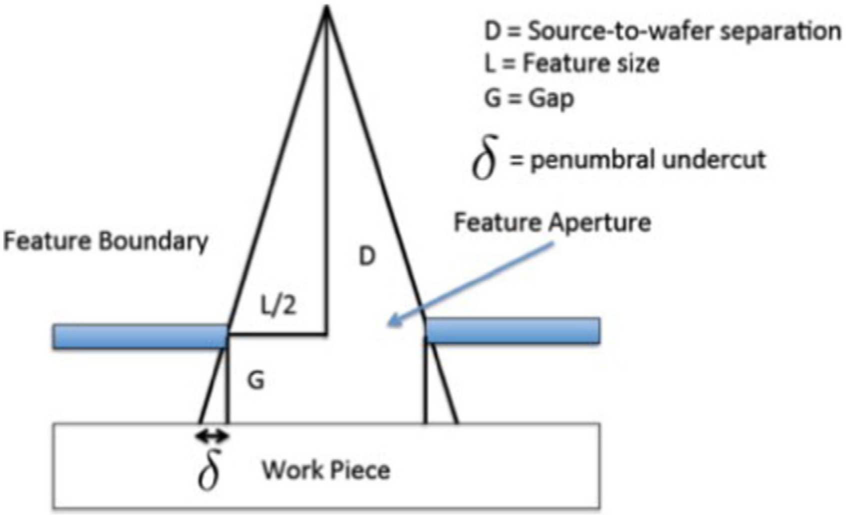

Fig. 1. Penumbral undercutting of a mask feature in X-ray lithography.