

Optical lithography: Introduction

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Guest editors

The dramatic increase in performance and cost reduction in the electronics industry are attributable to innovations in the integrated circuit and packaging fabrication processes. The speed and performance of the chips, their associated packages, and, hence, the computer systems are dictated by the lithographic minimum printable size. Lithography, which replicates a pattern rapidly from chip to chip, wafer to wafer, or substrate to substrate, also determines the throughput and the cost of electronic systems. A lithographic system includes exposure tool, mask, resist, and all of the processing steps to accomplish pattern transfer from a mask to a resist and then to devices. For further reading, we suggest several excellent reviews of the optical lithography of integrated circuit fabrication [1-3].

From the late 1960s, when integrated circuits had linewidths of 5 μm , to 1997, when minimum linewidths have reached 0.35 μm in 64Mb DRAM circuits, optical lithography has been used ubiquitously for manufacturing. This dominance of optical lithography in production is the result of a worldwide effort to improve optical exposure tools and resists. Although lithography system costs (which are typically more than one third the costs of processing a wafer to completion) increase as minimum feature size on a semiconductor chip decreases, optical lithography remains attractive because of its high wafer throughput. This topical issue of the *IBM Journal of Research and Development* focuses on optical lithography from manufacturing, development, and research perspectives.

Electron-beam (e-beam) and X-ray lithographies have been considered as alternatives to optical lithography. However, wafer throughput with e-beam lithography is too

slow for use in current semiconductor wafer production [4]. Currently e-beam lithography is regarded as complementary to optical lithography. Optical lithography depends on e-beam lithography to generate the masks. Because of its intrinsic high resolution, e-beam lithography is at present the primary lithographic technique used in sub-quarter-micron device research.

X-ray lithography has been aimed at production since its inception. Efforts to displace optical lithography with X-ray lithography began in the 1960s [5], because of a presumption that the resolution of optical lithography was only suitable for dimensions greater than 1 μm . In addition to resolution limits, optical lithography had to solve the difficulties of lamp constraints and level-to-level overlay alignments.

In the early 1970s, Wilczynski of IBM assembled a small group to address the resolution limits of optical lithography. In optical projection lithography, resolution is given by the equation

$$W = k_1 \lambda / NA,$$

where λ and NA are the exposure wavelength and numerical aperture of the optical lithography tool, and k_1 is a constant for a specific lithographic process. In 1975, Wilczynski's group, using an exposure wavelength of 405 nm (Hg H-line) at an NA of 0.32, succeeded in demonstrating a step-and-repeat optical projection camera at a linewidth of 1 μm [6]. This pivotal demonstration led optical tool vendors to make continued improvements in optical lithography that have sustained the technology since that time. The strategy to meet the continued demands for higher resolution and larger depth of focus is

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to migrate from visible light at 436 nm (Hg G-line) to deep-UV (248-nm) wavelengths for resist exposure. This trend is continuing to wavelengths of 193 nm and possibly beyond.

As the wavelength becomes shorter, the light source becomes more complex and expensive. Initially, the light source was a mercury lamp filtered for G- and H-lines, and later for the I-line (365 nm). Lithography at a wavelength of 248 nm spurred the development of a reliable and line-narrowed KrF laser, though mercury lines near 250 nm have been used in catadioptric systems (a combination of mirrors and lenses). A 193-nm ArF excimer laser source is still under development. Either new lasers must be developed or an expensive synchrotron will be required to generate enough EUV (extreme ultraviolet, 13 nm) and X-ray photons to meet throughput requirements. Therefore, it is still unknown when EUV or X-ray will be widely accepted for production.

To address the issue of level-to-level overlay, i.e., the precise aligning of successive masks with previous patterns on a silicon wafer, Kirk and Wilczynski of IBM demonstrated the advantages of using dark-field alignment [6], an important scheme that is standard on many of today's exposure tools. It is important to note that both optical and X-ray lithography rely on optical alignment schemes.

Optical lithography requirements are most evident in a manufacturing environment as the wavelength of light for resist exposure is decreased to provide high-resolution DRAM minimum feature sizes. In this issue of the *IBM Journal of Research and Development*, Holmes et al. review how IBM led the effort in switching to deep-UV (248 nm) in the 1980s. IBM worked with tool vendors and internally developed high-resolution, high-sensitivity deep-UV resists in order to make this transition. Advanced DUV photolithography in a pilot line environment is discussed by Ausschnitt et al. They present the collaborative development of 16Mb (0.5- μm) and 64Mb (0.35- μm) DRAM generations by IBM, Siemens, and Toshiba.

The paper by Singh et al. documents the innovations in high-numerical-aperture optical designs at IBM. Fused silica is the only lens material available at wavelengths of 248 nm and 193 nm, unless one resorts to calcium fluoride and lithium fluoride. As a result, most lenses are monochromatic (to a bandwidth of several picometers). As the wavelength becomes shorter, optical designs evolve from all-refractive lenses (for G, H, I, and 248 nm) to catadioptric systems, and finally to all-reflective systems (for 13 nm). This is the first detailed presentation of a collection of lens configurations by IBM.

Lincoln Laboratory has pioneered systematic research on how fused silica is damaged by radiation at a wavelength of 193 nm, and has collaborated with IBM on

193-nm resist research. Rothschild et al. review 193-nm lithography at the MIT Lincoln Laboratory.

As part of his Ph.D. research at the University of Arizona, Goodman carried out extensive computer aerial image simulations [7] based on the Hopkins theory of partially coherent imaging [8–10]. Image irradiance of an arbitrary, complex two-dimensional object can be simulated by taking into account residual lens aberrations, depth of focus, partial filling of the pupil, phase-shift masks, various illumination schemes, etc. Aerial image simulation is important, because the simulated results are deconvolved from resist properties. For this reason, it is currently in wide use. The paper by Brunner studies the impact of lens aberrations on optical lithographic quality using image simulations.

The continuing advances in optical lithography depend not only on tool design and improvements, but also on the concomitant development of innovative resist materials and associated processing which defines the chip circuitry. Even with the highest-resolution stepper available, the aerial image projected through the mask is degraded because of diffraction and lens aberrations. The resist must compensate for this pattern distortion by converting a "blurred" aerial image to a "sharp" binary stencil so that closely packed circuitry features can be defined. This can be accomplished by designing "high-contrast" resist systems that respond over a narrow range of exposure intensity to eliminate the blurred edges of the aerial image. In addition to providing high contrast to achieve resolution, the resist exposure sensitivity must be optimized for the wavelength of the optical tool. The high absorption of the resists developed for the G-, H-, and I-line exposure tools would require such a large increase in exposure dose at 248 nm that wafer throughput would ultimately be affected.

Resist systems must also provide etch resistance, thermal stability during processing, ease of developing, and adhesion to the substrate. There are many synthetic paths to UV-sensitive polymers that will cross-link, degrade, or undergo molecular rearrangement when irradiated. This irradiated or exposed area can be either soluble (positive resists) or insoluble (negative resists) relative to the unexposed area. Both positive and negative systems combining all of the attributes described above have been necessary to achieve the small dimensions and linewidth control required for increased speed and circuit density. The development of resist materials to meet these demanding requirements is a significant challenge. Over the past forty years, scientists have been able to provide a wide variety of materials and processes to answer the resolution, sensitivity, and processing needs of each succeeding chip generation.

Beginning in the early 1960s, Eastman Kodak was the first to provide resists specifically designed for the

electronics industry. These were negative-resist systems which cross-linked upon exposure to light. Their resolution was limited because of pattern swelling in solvent-based developers. They were replaced in the 1970s by positive resists developed by Azoplate which utilized diazoketones and novolak resins that could be exposed using "near-UV" optical tools and developed in water-based solutions. Improvements in the chemistry and processing of these systems have provided resists that are still widely used to fabricate half-micron devices. However, in the late 1980s introduction of "deep-UV" tools at 248 nm required new resists specifically designed to address future high-resolution and sensitivity requirements. Over the next ten years, research on these advanced materials produced resists that are currently used to manufacture 64Mb memory chips at 0.35- μ m ground rules. Excellent overviews of resist materials are available [1, 11]. Chemists are now turning their attention to optical resist requirements for the future. New materials are needed that will extend the current resolution limit of 248-nm optical tools. The next generation of optical tools at 193 nm will require a totally new resist chemistry, with etch resistance and thermal stability that will provide resolution to 0.13 μ m by the year 2005.

The resist papers in this issue provide a history of materials development in IBM, their use in manufacturing, and advanced research activities. The first two resist papers describe the research path to the positive and negative resists currently used to manufacture IBM logic and memory chips at 0.35- μ m dimensions. The paper by Ito documents the history and development in IBM of the chemical amplification "deprotection" resists developed for 248-nm lithography. The paper by Shaw et al. reviews the chemistry and process improvements that extended the use of "near-UV" resists, and the path to the development of the high-performance "deep-UV" negative resist, CGR, used in logic manufacturing. Allen et al. describe the design approaches and current status of single-layer photoresists for 193-nm lithography, which requires major departures from the chemistry typical of 248-nm resists.

Another major limitation besides resolution in optical lithography is the depth of focus (DOF), which is governed by the equation

$$DOF = k_2 \lambda / NA^2,$$

where k_2 is a constant for a specific lithographic process. As resolution is increased through the use of higher-NA tools, the depth of focus can decrease to less than 1 μ m. However, this depth may be comparable to the height of the device topography. Multiple-layer resist and top-surface imaging, which present a planarized top surface for exposure, can provide substantial relief in this respect at the expense of process complexity. The paper by Seeger

et al. discusses the past, present, and prognosis for planarized thin-film imaging.

In the late 1980s, there was a renewed interest in the use of phase-shift masks to refine resolution and/or to improve depth of focus. Characterization of phase-shift masks requires phase information, in addition to the traditional dark/bright binary amplitude information, and the use of resist as a measurement tool requires a long feedback loop to debug the mask. This problem was compounded by the numerous illumination schemes introduced by tool vendors during the same time frame. Budd et al. review a new tool, known as the AIMSTM (Aerial Image Measurement System), for lithographic mask evaluation. This tool measures the aerial image at the exposure wavelength using the same pupil-filling factor as the stepper, and can thus simulate the exposure tool faithfully while providing a much faster feedback loop for debugging the mask. This tool is now available commercially from Zeiss as the Microlithography Simulation Microscope, MSM100.

Optical lithography dedicated to packaging has not received much attention (resists and materials for packaging applications were reviewed in 1989 [12]). Since 1971, IBM has built its own lithography tools for use in packages with thin-film top layers. In the late 1980s, in response to the need for via hole sizes smaller than those producible by mechanical drilling, laser ablation was developed at IBM [13]. Doany et al. describe a 1 $\times$ large-field scanning laser ablation tool that can ablate via holes down to 8 μ m. This tool was developed in the IBM Research Division and transferred to the IBM Microelectronics Division.

A conventional chrome mask cannot withstand the UV flux during laser ablation without itself being ablated. Speidell et al. describe new multilayer dielectric masks that are used in laser ablation technology.

The layers for conventional printed circuit boards are built in parallel. Each layer patterns its conductor on a dielectric substrate independently, and all of the patterned layers are then laminated together. This parallel layer approach achieves a faster turnaround time and avoids yield loss associated with each sequential fabrication step. However, high-density, thin-film top layers are usually built sequentially. Doany and Narayan review a laser release process which builds high-density thin-film metal-polyimide layers in parallel.

The use of self-assembling materials (SAMs) is being explored at a research level as a new approach to pattern formation. Biebuyck et al. describe this method of pattern formation, which requires no light, but relies on microcontact printing to transfer the pattern from an elastomeric stamp.

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