HANDBOOK OF

Microlithography, Micromachining, and Microfabrication

Volume 1: MICROLITHOGRAPHY

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PREFACE

Microlithography and microfabrication are rapidly finding applications in many areas, from sensors and actuators to biomedical devices, in addition to their uses in microelectronics device manufacturing. Lithography is the key technology that has driven the dynamic growth of the IC industry over the past two decades. To date, optical lithography continues to be the mainstream technology for the IC industry, and is being used in production by leading-edge high-volume manufacturers to support 0.25-μm minimum feature size. Although the exposure system using 193-nm optical lithography is expected to extend to 0.13 μm, the industry remains undecided as to the choice of an exposure system beyond 0.13 μm. The options include extreme ultraviolet (EUV or projection x-ray), e-beam projection, massive parallel direct write, and 1X proximity x-ray. The field of lithography will continue to be very dynamic, and demands an authoritative handbook for process development and production to aid in the training of scientists and engineers.

Microlithography and micromachining are also driving microelectromechanical systems (MEMS) technology, which is rapidly developing. Within the next decade the cost of micromachined devices will drop to the point where there will be an explosive demand for these devices for use in such industries as automotive, chemical, aircraft, and disposable medical products. MEMS will also find applications for in-situ process monitoring, environmental health and safety monitoring, and numerous other sensor and actuator systems. Use of lithography for fabrication of many microelectromechanical devices frequently requires processing procedures that range from the fabrication of high-aspect-ratio structures down to ultrafine structures.

Although there are a number of books on lithography, a need exists to compile all the diverse information into an easily accessible handbook-type format. SPIE Press is publishing the handbook of Microlithography, Micromachining, and Microfabrication in two volumes. Volume 1 addresses microlithography, and Volume 2 covers micromachining and microfabrication. Volume 1 focuses on the application of microlithography techniques in microelectronics manufacturing. We hope it will be a useful tutorial introduction to the key microlithography technologies for researchers and engineers who are not necessarily experts in the field, as well as a good sourcebook for those who are.

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P. Rai-Choudhury
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Introduction

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Microlithography is a term developed to denote a particular branch of lithography that is specifically applied to integrated circuit fabrication. The term came into use shortly after the invention of the integrated circuit (IC) in 1958. Starting from fabricating ICs with dimensions in the hundreds of micrometers, industry is now poised to make circuits whose critical dimension is orders of magnitude smaller, with dimension control in hundredths of a micrometer. The number of transistors has grown by eight orders of magnitude, and is now approaching nine. The fast pace of progress makes it difficult to capture the most advanced achievements into a comprehensive reference book, but there is a continuous need for such documentation. A significant effort has been made by the authors of this handbook to review the state of the art, so relevant materials are assembled consistently within a single volume. Expert microlithographers can marvel at the accomplishments made in the field of microlithography, and continue to build upon their ever-expanding technology, while those entering the IC fabrication industry can have a tutorial overview of all the major microlithography technologies.

The rapid development in microlithography started in the early 1970s and has spanned over two decades. Microlithography began as optical lithography. The resist on the wafer was delineated by replicating the pattern on the mask. This pattern on the mask was made by exposing with a focused spot of light from a microscopic objective brought to the locations requiring exposure. This spot-scanning technique was a substantial improvement over the primitive technique of cutting and pasting a mask pattern before it is reduced to a usable mask. Even with the spot-scanning mask technology, reduction imaging continued to be used in the mask-making process, leaving the wafer-exposing equipment simple by remaining in the 1X domain. It was soon realized that generating an electron beam, which is much smaller than an optical spot, and moving it rapidly, is inherently easier. As a result, e-beam lithography quickly replaced optical lithography in mask making, except for the recent development in masking using multiple scanning laser spots. A review of optical projection imaging is presented by Levinson and Arnold in Chapter 1. E-beam systems are covered by McCord and Rooks in Chapter 2, and Skinner et al. treat mask fabrication issues in Chapter 5.

Many attempts have been made to replace optical lithography because of the concern that optical lithography will no longer be capable of achieving the smaller geometries that modern ICs demand. E-beam, x-ray, ion-beam, and extreme-ultraviolet (EUV) have been proposed, funded, and developed as possible technologies to meet these requirements. Progress and achievements are reported in chapters 2, 3 (Cerrina), and 8 (Peckerar et al.).

In the early 1970s, the critical dimension of ICs was in the regime of 2–5 μm. Wafer imaging was performed by replicating a mask, by placing the photoresist-coated wafer in contact with the mask and exposing with broadband and near-UV light in the spectrum between 300 and 450 nm. To reduce wear and tear of the mask that is subject to repeated contact with the wafer, the emulsion mask has been replaced with the chromium mask, which also helps to improve the edge definition. With these advantages, the chromium mask has become the workhorse of the IC industry. To further reduce wear and tear to the mask under repeated contact, the wafer was placed in close proximity (at a distance of 10–25 μm) to the mask instead of in hard contact with it, and optical proximity printing was born. The mask-to-wafer gap has become indispensable to maintain a profitable wafer yield. To maintain this gap and still continue to reduce the minimum feature size (MFS), the exposure wavelength was reduced to deep-UV centering at 250 nm, and further to soft x-ray on the order of 1 nm in wavelength.

The wavelength reduction and e-beam mask-making activities necessitated resist development for wafer-masking materials. Resists are required that react to the higher energy beams, maintain a usable throughput, and possess good processing characteristics, such as adhesion, uniformity, etch resistance, thermal stability, stripability, and long shelf life. Even within the main energy spectrum for microlithography, the photoresist continues to be improved by providing a choice of polarity, better developing characteristics, higher sensitivity, lower defects, and higher consistency. In Chapter 4 on deep-UV resists, Allen et al. describe the vast amount of work required to develop the resist for microlithography. Chapters 1 and 2 contain information on resists in the optical and e-beam disciplines, respectively. Chapter 8 discusses the status and requirements of resists for manufacturing devices smaller than 0.1 μm.

Optical lithography did not remain long in the proximity/contact printing phase. In 1974, 1X full-wafer projection printing using an all-reflective system was introduced. Because of the total separation between the mask and the wafer and better alignment, 1X projection all-reflective printing superseded proximity printing for minimum feature size, down to the vicinity of 1.5 μm. Attempts were made to extend 1X full-wafer projection printing to 1 μm in the 1980s, using deep-UV exposure. Even though optical imaging may be made to work in the 1X full-wafer projection printing regime, the need for a stringent tolerance 1X mask has switched the bulk of sub-1.5-μm imaging to reduction step-and-repeat projection printing, which was introduced in 1978 and has remained viable after six generations of MFS reduction. For economic reasons, 1X step-and-repeat projection printing, introduced in 1980, is still used to pattern all noncritical levels. Recently, the reduction step-and-repeat method is experiencing difficulties in further reducing the MFS, but still increasing the field size to accommodate the larger chips that usually follow higher densities. In the areas of large field sizes and high resolution, the reduction step-and-scan system, introduced in 1989, is starting to replace step-and-repeat printing. Because of the move from reflective systems with large bandwidth to narrow-bandwidth refractive systems used for step-and-repeat, multiple reflections within the resist layer becomes an important issue to understand and to overcome. Chapters 1 and 7 discuss this issue.

Even in the era of proximity printing, it was recognized that experimental work is expensive. The experiments also tend to be empirical, unless simulation of the physical phenomena of imaging is performed to assist in understanding the process and to guide the experiments. Leading the charge to turn microlithography from black magic to science is the work in theorizing and understanding proximity printing, even in the theoretically difficult region of exact contact, the resist exposure and development mechanism, two-dimensional partially coherent imaging for optical projection printing, x-ray partial coherent imaging, and e-beam proximity effects. Most of the simulation activities are reported by Neureuther and Mack in Chapter 7 on optical lithography modeling. E-beam and x-ray modeling are covered in Chapters 2 and 3, respectively.

To further move microlithography into the realm of well-understood science, the placement and size of the images produced have to be measured to a high degree of precision and accuracy regardless of the type of microlithography imaging system producing them. Metrology itself has become a science, an indispensable part of microlithography, and even a bottleneck at times. Metrology standards and the measurement of overlay and critical linewidths are covered by Lauchlan et al. in Chapter 6.

Looking further into the future, Chapter 8 considers the limits of each discipline for making devices with 0.1 μm minimum feature size and smaller, including quantum effects. These disciplines include optical, e-beam, and x-ray lithography, resists, metrology, yield assessment, ionizing radiation effects, and dry-etch damages. An interesting proposal is made to use massively parallel arrays of atomic force microscopes (AFMs) for quantum device manufacturing.

Instead of viewing them as photons, electrons, or ions, microlithographic systems can be separated into pattern-generating systems and replicating systems. The pattern generating systems take a mask design in software form and expose a physical pattern on the mask blank. Flexibility of the system makes it suitable to generate the mask for mass replication. This feature also encourages many lithographers to speed up the system to use as a maskless direct-write tool for wafer exposure. However, the sequential nature of pattern generation makes it difficult to compete with the throughput of a replication system, regardless of how much faster the individual beam can be accelerated. Attempts have been made to use many sequential pattern generations in parallel. A noted accomplishment is in pattern generation using multiple laser beams. However, the throughput is still not competitive to that of a replicating system. Attempts in multiple e-beams have had limited success. Therefore, it appears that pattern-generating systems are best suited for mask making, and replication systems are best suited for reproducing the mask patterns. To bridge the advantages of the two techniques one possibility is to use cell projection, as reported in Chapter 2.

The replication systems can be separated into two main categories, 1X and reduction systems. The 1X systems usually require simple imaging optics. For example, the 1X projection printing system enjoys the symmetry of optics and short focal length in both the mask and wafer sides, resulting in a small, low-aberration imaging lens. The proximity printing system, the ultimate example, uses no imaging system. The basic problem of a 1X replication system is that the 1X mask has to be built with stringent specifications to achieve an identical linewidth tolerance and overlay performance on the wafer that a reduction system can produce. This is illustrated in Table 1, which shows the linewidth tolerance in percentage.

TABLE 1 Linewidth tolerance components in 1X and 4X replication systems.

	1X	**4X**	**1X perfect wafer lithography**
Resist image on mask	8%	1.6 %	8%
Etched image on mask	8%	1.6%	8%
Resist image on wafer	10%	10%	0
Etched image on wafer	10%	10%	10%
RSS total	**18.1%**	**14.3%**	**15%**

Using the same 8% linewidth tolerance on the 1X and 4X mask results in a much larger total linewidth tolerance on the wafer. Even a perfect wafer imaging system producing zero linewidth tolerance cannot produce the result better than a 4X system. To be competitive, the 1X imaging system has to be specified for linewidth tolerance identical to the 4X system. This results in the need to specify the linewidth tolerance 4X better on the mask. At the forefront of MFS, everything is pushed to its limit, including the mask-making capability. There is no margin in mask making to accommodate the requirement of a 1X system.

Similarly, the feature placement error requirement on a 1X mask is too stringent, as seen in Table 2. The placement error is the displacement of the feature from its ideal location that is caused by uncertainty of the beam position during mask making. An extremely good e-beam system has a placement error on the order of 50 nm. Considering that the overlay is between two levels, the overlay error contribution from the mask placement error is the root-mean-square of the errors induced in two masking levels to be aligned to each other, reflecting the statistical nature of the error.

TABLE 2 Overlay error components in 1X and 4X replication systems.

	1X	4X
Mask writer placement	72 nm (RSS between 2 levels)	18 nm (RSS between 2 levels)
Wafer alignment error	50 nm	50 nm
Stepper table error	30 nm (RSS between 2 levels)	30 nm (RSS between 2 levels)
Lens distortion	15 nm	30 nm
RSS total	**94 nm**	**68 nm**

This root-mean-square procedure applies as well to the stepper table error. During step-and-repeat imaging of the wafer, a table stepping error causes the mask image to be misplaced on the wafer, leading to misalignment to the image on the previous or subsequent level that is also subject to a table stepping error. The price to pay for allowing a larger overlay budget for a 1X system is too high.

Even though it requires a 1X mask, the proximity soft x-ray imaging system has been given attention and funding since the first system was used for making experimental magnetic bubble circuits in the mid-1970s and the first exposure with a storage ring in the late 1970s. In the two decades that followed, tremendous progress was made in mask making, mask repair techniques, the storage ring source, the beam line, the step-and-repeat alignment station, and resists. Chapter 3 provides excellent treatment of this subject. Other than proximity soft x-ray, there is no other 1X system being developed for submicrometer microlithography. The field of replication microlithography has narrowed down to candidates capable of reduction imaging. There are four systems, shown in Table 3 together with their advantages and concerns.

TABLE 3 Reduction replication systems and their advantages and concerns.

System	Advantages	Concerns
UV projection	Available light source Available mask technology—mask making, defect detection, and repair Available lens material, design, and fabrication capabilities Available resists	Depth of focus Alignment
EUV projection	Large depth of focus Potential for high resolution	Light source Lens Multilayer reflective mask Resists Window material Alignment
E-beam projection	Available light source Large depth of focus Potential for high resolution	Mask E-beam optics Proximity effects Radiation damage Resists Charging effects
Ion-beam projection	Large depth of focus Potential for high resolution	Ion-beam optics Mask Radiation damage Charging effects

A natural extension of UV projection lithography is to continue to reduce the wavelength from 365 nm, the Hg i-line, to 248 nm, the KrF excimer laser line, then to 193 nm, the ArF excimer laser line. Below 193 nm, several difficulties arise: (1) The atmosphere absorbs too much light; the imaging system has to be in vacuum. (2) Transmissive material becomes rare; reflective optics is required. (3) An entirely new set of resist requirements is inevitable. To date, the EUV wavelengths between 10 to 70 nm have been proposed; some have been demonstrated. To develop one of these systems for production there has to be (1) a light source brighter than a storage ring, (2) coating and window materials capable of withstanding such strong radiation, (3) high-reflectivity, low-defect multilayer reflective coatings, and (4) reflective lenses capable of reduction and field sizes competitive to UV lenses.

Another reduction possibility is to use e-beam for replication using a special mask such as the SCALPEL (scattering with angular limitation for projection electron lithography) system covered in Chapter 2. Unlike EUV systems, there apparently is a good e-beam source and the mask problem is not as insurmountable as that of EUV. The e-beam projection lens is easier than EUV, but is still a long way from matching the field size of a high-performance UV lens. It also suffers from traditional e-beam problems such as proximity effects, radiation damage, charging, and lack of a good resist.

Reduction ion-beam projection also has been demonstrated. It has negligible proximity effects, and a resist of required sensitivity is not difficult to develop. However, ion-beam optics are much harder and bulkier than existing systems. Also, continuous ion bombardment to the mask can be detrimental.

The next reduction system that may succeed a 193 nm step-and-scan optical reduction system for making 0.13 μm MFS is likely to be SCALPEL, if all its concerns are addressed. However, a reduction system may no longer be needed, because e-beam cell projection in combination with a shaped beam (as discussed in Chapter 2) is probably closer to successfully producing 0.13 μm MFS.

Historically, microlithography has been an innovative and rapidly advancing technology. To date, any effort to project its future often inspired activities to break through the limits identified by the projection. With the great changes in IC technology of the past two decades, it's difficult to project, or even imagine, the possibilities and great strides that will be made over the next two.