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OVERVIEW OF X-RAY LITHOGRAPHY AT IBM USING A COMPACT STORAGE RING

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ABSTRACT

This paper describes the feasibility studies being conducted at IBM to use x-ray lithography for production of high density silicon chips. The system approach to x-ray lithography adopted at IBM considering the interaction of all the components: x-ray source, masks, resists, exposure tools, with the devices and processes is presented in this paper. In particular, the status of the Advanced Lithography Facility which houses the electron storage ring x-ray source procured by IBM from Oxford Instruments, is presented.

1.-INTRODUCTION

This paper describes the work at IBM to evaluate x-ray lithography (XRL) for the manufacture of submicron silicon chips. Several IBM locations are involved in this work including, Yorktown Heights, N.Y.; Burlington, VT.; Manassas, VA.; and East Fishkill, N.Y.. Several Universities are also supported by IBM in areas that include mask studies, modelling, radiation damage, and mask/wafer alignment techniques. IBM is also working with several companies under a DARPA contract, and collaborating with Motorola in an 18 month study program on XRL with several Motorola employees temporarily assigned to IBM facilities.

The decision to explore the feasibility of XRL utilizing a synchrotron storage ring[1] was taken at IBM in 1980, after many years of work utilizing conventional x-ray sources [2-5] inside IBM and at other companies. A systematic approach to XRL was then started[6] using as the x-ray source, a port on the VUV storage ring at the Brookhaven National Laboratory (BNL). This approach considered the interaction of all key system components: source, mask, beamline, stepper, resists, etc., necessary to fabricate submicron (0.5 μm) devices. Four level NMOS and eleven level CMOS devices were successfully fabricated [7-8]. The excellent results obtained at BNL, and the predicted [9] advantages of XRL over other lithographic technologies led to the realization of the Advanced Lithography Facility (ALF) at East Fishkill, N.Y.. The major components of the ALF's x-ray lithography system will be described below taken in account their interrelationships (system approach).

2.-X-RAY SOURCE

The x-ray source recently installed in ALF is a compact storage ring (HELIOS)[10] built by Oxford Instruments for IBM utilizing superconducting magnets. Compact storage rings have been built also in Germany[11], and Japan[12]. HELIOS is designed to operate at an energy of 700 Mev, ($\lambda_c = 8$Å) with an average current of 135 ma. Low energy electron injection into the ring is performed by a 200 MeV linear accelerator, ramping the energy up to 700 MeV by an electronic control system.

HELIOS is expected to deliver about 100 mW/cm^2 of x-rays between 8-10 Å incident on the resist with a properly designed beamline. This x-ray flux is considerably higher than any other conventional point source including electron bombardment[13-14] and plasma (gas[15-16] or laser [17-22]) x-ray sources. These point sources produce several orders of magnitude less output, and therefore are not suitable for a high throughput production system like the one to be evaluated in ALF. Nevertheless, these alternative sources offer the advantage of "granularity" and ease of installation with comparatively lower initial cost, and their future performance and development should be watched closely [23,24].

3.-EXPOSURE SYSTEM

In storage ring based XRL systems, exposures are performed in a stepper located at the end of a beam line used to transfer x-rays in a useable form to the stepper. The exposure system, or beamlines and steppers, are designed to work together with the x-ray source in order to optimize the resolution, and throughput of the x-ray lithography system.

The mask wafer aligner for a storage ring x-ray lithography system is operated with the semiconductor wafer mounted in a vertical position on some form of a vacuum or electrostatic chuck[25] held in close proximity to

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the precisely aligned patterned mask. One of the most critical components of the x-ray stepper is the alignment system. Alignment systems and steppers for ALF pilot lines are currently under development to satisfy 0.25 μm ground rules.

Presently, there are two kinds of beamlines installed by IBM at BNL. One of them labeled U6, (originally installed by the Research Division) includes an oscillating mirror which cuts off the unwanted high energy radiation, and scans the fan of radiation from the storage ring onto the mask/wafer assembly. An IBM built stepper [26] which operates in relatively high pressure helium gas (20 torr) was used in U6 for the fabrication of 0.5 μm devices with 11 x-ray exposed levels[27]. The other beamline[28] labeled U2, (presently in use) has a fixed mirror which shifts the beam from the horizontal plane, and cuts-off the high energy x-rays from the ring. The mirror provides a fixed quasi-circular segment of radiation onto the movable mask/wafer assembly of the SUSS stepper[29] operating in an atmospheric helium gas environment. Work in mirror evaluation[30] and design is being performed in collaboration with CXRL at the University of Wisconsin. Both beamlines have a Be window to separate the low pressure environment from the exposure chamber, and acoustic delay lines in conjunction with fast acting valves to protect the ultra high vacuum in the event of window failure.

The beamlines to be installed in ALF are presently being procured, and they may be of either fixed or scanning mirror depending of the requirements of the stepper. However, a scanning mirror may provide a faster throughput system, since the possibility of mask/wafer misalignment during motion is eliminated.

4.-MASKS

The IBM x-ray mask technology developed at Yorktown was transferred to the Advanced Mask Facility (AMF) in Burlington, N.Y.. The IBM mask consists of an x-ray transparent boron doped Si substrate[31] about 2.5 μm thick with a thin absorber pattern obtained by electroplating gold[32] (about 0.6 μm) on a resist pattern delineated by an e-beam writing tool. The boron doped silicon substrates are obtained by conventional diffusion techniques on silicon wafers. The wafers are bonded to a support pyrex ring to provide stability. Work on mask ring behavior in a stepper has been reported[33] and work on modelling[34] is presently being performed in collaboration with the National Institute of Standards and Technology (NIST) to help establish a standard mount to be used in commercial steppers. In addition, studies on mask contrast enhancement[35], mask radiation damage [36], and mask replication are being performed in collaboration with the CXRL at the University of Wisconsin. The boron doped silicon substrates fabricated by the AMF are relatively strong[37], offer low mask distortion and excellent radiation hardness, however, they lack optical transparency for conventional alignment systems. In the IBM mask optically transparent alignment windows using a polyimide substrate[38-39] are located away from the silicon membrane area to allow room for the alignment microscope objectives. In order to decrease alignment errors it is advantageous to perform in-field alignment. For this reason, work in developing[40] and characterizing [41-42] mask substrate materials with suitable transparency is currently being pursued at IBM.

5.-RESIST MATERIALS

The high flux from storage ring x-ray sources allows efficient exposure of relatively thick single layers of conventional resists[43]. However, in order to further improve the system throughput and to reduce radiation damage during x-ray exposure of certain metal levels[44-50] more sensitive resists are desired. Work in resist materials[51-52] is presently being conducted with the goal to obtain high sensitivity (< 100 mJ/cm^2) resist materials capable of simple single level processing while preserving the required lithographic properties. Some of those resists are presently available at IBM, and their status has been reported elsewhere[53-54].

6.-SYSTEM CONSIDERATIONS

All the components mentioned above must be integrated with others to obtain an x-ray lithography system capable of successful operation in a production environment. The x-ray spectrum from the source must be chosen considering the following:

- Required thickness of the mask substrate materials
  The thickness of the mask substrate determines the maximum size of the membrane for safe operation. Therefore, it also determines the maximum field size, and the system throughput. Typically, a mask substrate about 3 μm thick is considered adequate for a 2.5 cm x 2.5 cm Si membrane. The minimum x-ray transmission of a mask substrate is usually about 50%, therefore a wavelength of about 10 Å will be needed.
- Required thickness of the absorber material
  From pattern writing and processing considerations, it is advantageous to work with a relatively thin absorber. In addition, for a given intrinsic stress in the absorber, the mask distortion is proportional to the absorber thickness[55]. Therefore, the source wavelength should be chosen to obtain the thinnest possible absorber compatible with the required mask contrast and proper resist exposure. In general, in between absorption edges, the longer the wavelength the thinner the mask absorber.

- Resist Sensitivity
  For resist systems in which cross-linking or chain scission is caused by photoelectrons, the use of longer wavelengths will give rise to higher resist sensitivity (for wavelengths between the resist absorption edges). The above may not be true for resist systems based in chemical amplification. The development of fast sensitive resists with good etching properties capable of being used in single level processing may have great cost implications in the choice of an XRL system [56]. However, the resist sensitivity is limited by quantum considerations regarding the number of photons required to expose a pixel.
- Maximum resist thickness for uniform exposure
  A uniform x-ray exposure through the resist thickness requires a relatively thin layer of resist, since then the x-ray absorption is approximately linear with thickness. For relatively thick resist layers, the x-ray absorption becomes none uniform, and the bottom of the resist is exposed less than the top. This will cause irregular resist profiles, and may affect the linewidth control during processing. Typically, some processing levels require resist layers up to 3 μm thick. In this case, uniform absorption (within a few percent variation) requires a relatively short wavelength ($<$ 10 Å).

For operation at longer wavelengths, a thin resist layer will be required in conjunction with one or more etch resistant thin film layers (multilevel resist schemes). However, this approach may not be attractive, since it has been shown[9] that the single layer resist process offers substantial cost advantages relative to the multilevel resist schemes.

- Diffraction and Electron Range Considerations
  The minimum printable feature size is limited by diffraction effects due to the wavelength spectrum of the x-ray source, combined with the source geometry, and the resist characteristics. Shorter wavelengths are preferred to decrease printed image blur due to diffraction. In general, diffraction and perhaps to some extent photo and Auger electron range considerations may limit x-ray lithography in the 7-10 Å wavelength to minimum features of the order of 0.1 μm.
- Required thickness of Be window
  The size of the window is limited by its thickness[3]. Short x-ray wavelengths allow the use of large window areas (thicker windows), capable of supporting 1 Atms. For example, at 8.33 Å, a 25 μm thick Be window has an x-ray transmission of about 50%.
- Printability of defects caused by foreign particles (Si, organic particles, dust).

One of the main features of x-ray lithography is its insensitivity to some kinds of defects[57-58]. However, in order to take full advantage of this feature, the wavelength of the x-ray source must be properly chosen. Shorter wavelengths allow a system to be more forgiving to defects. For the case of Si particles, there is an optimum wavelength range from 6.8- 10 Å which maximizes the allowed particle size (due to the Si absorption edge at about 6.8 Å).

Based on most of the above considerations, it is concluded that the preferred wavelength range for x-ray lithography using single levels of conventional resist materials is 7-10 Å. Other wavelengths have been proposed, but some trade-offs have to be made to meet system requirements. In particular, the conventional source system using a Pd target[59], required a three level processing chlorine based resist sensitive to the 4.37 Å wavelength of the Pd Lα line. On the other hand, longer than 10 Å wavelengths should not be completely ruled out, since its use may introduce less radiation damage, due to the relatively higher x-ray absorption of the upper device layers covering the oxide films. This may be more important than both defect printability, and the use of multilevel resist processing in some applications where annealing at elevated temperatures may not be possible, as will be discussed below.

Other considerations in the design of ALF include:

- Throughput dependence on field size (mask strength)
- Field Uniformity (resist linewidth control)
- Overlay Errors

  The maximum allowed overlay (registration) error between two lithographic levels depends on the minimum feature size of the devices being fabricated. The overlay error includes contributions from many sources listed below, which should be added in quadrature as independent contributions, and whose budget has to be determined for a particular process:

  - Mask distortion
  - Errors due to mask and wafer mounting
  - Mask Writing Errors.
  - Alignment System Errors
  - Run-out errors
  - Penumbral errors
  - Wafer processing errors
- Source Divergence Effects

  This issue has been shown[60] to play an important role for the extendibility of x-ray lithography below 0.25 μm. This is because coherence effects [61] may narrow the processing window for the simultaneous replication of several different features of different sizes below 0.25 μm, however, increasing the source size or its divergence helps in extending the process window for a given resist material [62].

- Device Radiation Damage

  Radiation damage as mentioned above may be a factor in determining the wavelength of the x-ray source. However, for any wavelength, there are several ways in which radiation damage during x-ray lithography may be reduced. Those include: a) the use of other than Al metallization techniques (ie. W) to allow annealing at temperatures higher than 400°C, b) the use of an intermediate x-ray blocking layer [44], c) high pressure hydrogen annealing, and d) the use of higher sensitivity resists. The latter is probably the simplest way, and the recent availability of good high sensitivity x-ray resists with adequate processing characteristics has ameliorated the concern on radiation damage during x-ray lithography.

- Mask inspection and repair tools and techniques[63]

  Presently, IBM is working internally and with vendors to develop mask inspection and repair tools and techniques to be used in the Advanced Mask Facility in Burlington, VT..

- Personnel safety

  Due to proper shielding, the radiation level of the populated areas in ALF is always below background (even during injection), allowing the facility personnel to remain inside the building at all times.

- Metrology

  This is one of the most important issues, and applies to any lithographic technology (optics, e-beam, or x-rays). New tools and techniques must be developed to measure the relevant parameters of sub-half-micron device fabrication.

7.-SUMMARY

In conclusion, all the required components for ALF have been designed and fabricated considering their interrelations using an integrated system approach. However, some none fundamental problems must be solved before the technology can be implemented in the manufacturing sub half micron devices. Those problems are currently addressed, and they include the development of more accurate e-beam writers, mask inspection and repair tools, steppers and alignment techniques; exploring the possibility of obtaining 1X x-ray masks from NX reticles (using optical tools or perhaps x-ray projection[64-65] systems); studies of wafer induced distortion and magnification correction techniques; and optimization of source divergence parameters. Some of the work at IBM is being performed with the U.S. government, vendors, and selected Universities. In addition, IBM is pursuing collaboration with other semiconductor companies towards the goal of demonstrating the feasibility of XRL for the manufacturing of sub half micron silicon chips, and be ready in the event that the established and continuously extended optical lithography technology reaches its limitations.

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