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XUV free-electron laser-based projection lithography systems*

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ABSTRACT

Free-electron laser sources, driven by rf-linear accelerators, have the potential to operate in the extreme ultraviolet (XUV) spectral range with more than sufficient average power for high-volume projection lithography. For XUV wavelengths from 100 nm to 4 nm, such sources will enable the resolution limit of optical projection lithography to be extended from 0.25 μm to 0.05 μm and with an adequate total depth of focus (1 to 2 μm). Recent developments of a photoinjector of very bright electron beams, high-precision magnetic undulators, and ring-resonator cavities raise our confidence that FEL operation below 100 nm is ready for prototype demonstration. We address the motivation for an XUV FEL source for commercial microcircuit production and its integration into a lithographic system, including reflecting reduction masks, reflecting XUV projection optics and alignment systems, and surface-imaging photoresists.

1. INTRODUCTION

In the latter half of this century, advanced lithographic technologies capable of producing $\leq 0.25 \mu\text{m}$ features with high wafer throughput will be needed to meet the expected demand for larger, faster, and more complex integrated circuits. Until recently, it was not possible to see how optical projection lithography could attain such high resolution over a usefully large field and with a practical depth of focus, mainly due to lack of a short-wavelength photon source with sufficient average power. However, the emergence of the free-electron laser (FEL) changes this situation.¹ When extended into the extreme ultraviolet (XUV - wavelengths from ≤ 10 - to 100 nm), FELs driven by rf linear accelerators should readily fulfill the wavelength and average-power source requirements of commercial projection photolithography.²

The incentives for developing XUV projection lithography, particularly with an FEL source, are compelling. First, this technology will extend optical projection lithography from its present limits with deep-ultraviolet (DUV) excimer laser sources and transmitting imaging optics to exposure wavelengths below 100 nm using all-reflection imaging optics. DUV lithography with the ArF laser at 193 nm will produce minimum features of $\sim 0.25 \mu\text{m}$ if a very small total depth-of-focus (DOF) of 0.5 μm and an optimistic process parameter $K_1=0.7$ are acceptable in commercial production. Use of an XUV FEL source below 100 nm will not only enable resolution well below 0.25 μm , but also will permit use of small numerical apertures (NA) and large DOF $\geq 1 \mu\text{m}$. Second, even finer resolution $\leq 0.1 \mu\text{m}$ can be attained by tuning the FEL operating wavelength to near 10 nm. Such a scalable exposure tool will be useful over a number of generations of microcircuits. Third, an rf-linac-driven FEL will uniquely supply the average power needed to offset the inherently lossy projection optics ($\sim 1\%$ net throughput) in the extreme ultraviolet. As described in Section 3.4, the average XUV power from one FEL will be sufficient to drive many steppers simultaneously, each processing ≥ 30 (12-inch dia.) wafer levels per hour. Fourth, the process exposure latitude should be sufficient for commercial requirements by imaging the XUV photons onto surface photoresists. For example, Op de Beeck et al.³ have characterized the surface-imaging DESIRE process as maintaining constant linewidth of $0.25 \mu\text{m} \pm 10\%$ for an adequate $\pm 7\%$ range of photon exposure. Fifth, the $\sim 5:1$ reduction reflecting masks that will be needed for XUV projection optical systems will be robust, much easier to fabricate, and less costly (4 to 5 times less⁴) than the 1:1 transmission masks needed for x-ray proximity lithography. Sixth, an FEL has neither a chemical waste disposal problem, as do excimer and

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dye lasers, nor plasma debris contamination of the optics as do laser-produced plasma sources. (As with synchrotron sources, however, radiation shielding will be required for personnel safety.) Finally, XUV-FEL sources build on the past decade of intensive research and development of FEL technologies.

An attractive feature of the FEL, indicated in Fig. 1, is that it can be progressively upgraded to attain shorter wavelengths for correspondingly higher-resolution lithography. Operating an FEL at wavelengths of 60, 13, and 4 nm, while holding the total depth of focus constant at 1.0 μm , and using process parameters $K_1=K_2=0.8$ (appropriate for today's high-volume commercial production), will enable resolutions of 0.2, 0.1, and 0.05 μm , respectively. (Standard definitions are: $R=K_1\lambda/\text{NA}$ and total depth of focus $2Z=K_2\lambda/\text{NA}^2$, which yield the convenient form, $R=K[2Z\lambda]^{0.5}$ with $K=K_1/K_2^{0.5}$). The corresponding minimum feature sizes after resist processing, typically will be slightly smaller at 0.2, 0.08, and 0.04 μm . Memory chips with such small features will have a major impact on future computing capabilities. For example, a 25x50 mm DRAM chip with 0.1- μm features would have ~2 GByte memory capacity which is equivalent to that of a present-generation CRAY computer.

The credibility of XUV projection lithography was given a major boost in the last year by the experimental demonstrations of 0.1- μm and 0.05- μm features by an AT&T Bell Laboratories research team.⁵⁻⁷ Their XUV radiation source was a magnet undulator in the National Synchrotron Light Source VUV storage ring followed by a pinhole to attain full spatial coherence, and their projection optics was a 20:1-reduction, Schwarzschild two-mirror system fabricated and aligned by GCA Tropel. With an exposure wavelength of 36 nm, they attained 0.2- μm lines and spaces in a trilayer resist. Subsequent exposures at 14 nm with the mirrors coated with Mo/Si multilayers produced 0.1- μm and 0.05- μm features with small NA values of 0.08 and 0.12, respectively. This series of experiments demonstrated the potential resolution and sharp image definition attainable with XUV wavelengths and the practical capability to fabricate and align XUV reflective optics to attain diffraction-limited images, albeit over a small, 50- μm square field limited by the two-mirror projection system.

The remaining sections of this paper address four topics: Section 2 is a brief description of the components and arrangement for an XUV projection lithographic system, and Section 3 discusses the average-power requirements on the photon source, including a comparison of the capabilities of rf-linac-driven XUV FELs with several other candidate photon sources. Section 4 reviews FEL experience and component parameters for an XUV FEL for lithography. In Sections 5 and 6 we describe the initial efforts to develop reflecting projection optics and initial data on XUV exposures of photoresists for XUV projection lithography. Summary remarks are given in Section 7.

2. ELEMENTS OF XUV PROJECTION LITHOGRAPHY BASED ON AN FEL

Figure 2 shows the essential components of XUV projection lithography based on an FEL source. An XUV FEL, driven by an rf linear accelerator (rf linac), will provide sufficiently high-average power of spatially coherent photons scalable from 100 to 4 nm. (Storage-ring FELs, due to energy spread induced by the lasing action on the recirculating electron beam, will not be capable of producing sufficient average power required for projection lithography.) The output beam is transmitted through a moderate vacuum or helium gas atmosphere to minimize transmission losses. The requirement for uniform illumination in the wafer plane is attained by focusing the beam into a reflecting light pipe whose walls are coated with a reflective metal, e.g. Rh. After undergoing multiple reflections, the beam is recollected by a paraboloidal mirror and directed onto a reflective mask (first suggested by Silfvast and Wood⁸) deposited on a thick Si substrate (water cooled on the backside). The mask is composed of a single-layer or multilayer reflector, appropriate for the chosen XUV wavelength, and overcoated with an absorbing oxide or gold coating (patterned by photolithography) to achieve high contrast between reflective and absorptive areas. A reflective optical projection system, consisting of a minimum of two mirrors with between three and four reflections, provides diffraction-limited illumination over a large diameter, e.g. ≥ 1 cm, in the image plane. Due to high absorption in the XUV, single-layer or bilayer photoresists on the wafer will be optimized for surface imaging and subsequent pattern transfer by wet or dry etching processes.

3. XUV SOURCE POWER REQUIREMENTS

3.1 Projection system constraints

The total energy required to expose a $25 \times 25 \text{ mm}^2$ image area on a chip in one second will be only 30 to 120 mJ for photoresists having sensitivities of 5 to 20 mJ/cm², respectively. However, the radiation source must also provide enough power to offset the very large losses inherent for projection optical systems comprised of multiple, XUV multilayer mirrors with relatively low reflectance and narrow bandwidth. Several XUV reflecting projection optical systems have been designed to achieve a large ($\sim 1 \text{ cm}$ dia.) diffraction-limited image by use a small NA ~ 0.1 which makes compensation for the various optical aberrations possible with only five reflections (four mirrors plus reflecting mask). Upstream of the projection optics, an additional normal-incidence mirror will be needed to recollimate the FEL beam after passage through a reflective beam uniforming tube, and the source collection optics for other diffuse sources such as laser plasmas will require a two-mirror collection system. To date, the highest normal-incidence reflectance achieved for mirrors operating below 100 nm is $\sim 50\%$ for Mo/Si multilayer stacks at $\sim 13 \text{ nm}$, near the absorption edge of silicon. At the reflectance peak, the net transmission of a six- or seven-reflection system with these mirrors will be 1.6% or 0.8%, respectively. Furthermore, the net reflection bandwidth of N identical multilayer mirrors in series is $\sim 1/N^{0.5}$ that of a single mirror. The bandwidth of a Mo/Si reflector, shown in Fig. 3, is 6% FWHM.⁹ Therefore, the net bandwidth of a seven- reflection optical system would be $\sim 2\%$. When practical variations in mirror coating thicknesses are included, this bandwidth will be even smaller. The limited mirror bandwidth poses no restriction for the FEL which will be operated with a $\sim 1\%$ bandwidth. However, it strongly limits the power transmission from broadband sources like bending-magnets in storage rings or laser-produced plasmas.

The question naturally arises as to how to improve the system transmittance. As seen in Fig. 3, the measured peak reflectance is only two-thirds of the 70% theoretical maximum calculated from the optical constants of Mo and Si for perfectly smooth surfaces. The difference is attributed to surface and interlayer roughness which, with the so-called Debye-Waller factor, can be modeled with a total effective roughness of 0.67 nm for this mirror. It is conceivable that reduced scatter could be realized by some coating procedure, such such as post ion-beam smoothing of each layer pair as demonstrated by Spiller,¹⁰ who suggested that the effective roughness might be reduced to as low as $\sim 0.3 \text{ nm rms}$. At this level, the specular reflection of the Mo/Si mirror in Fig. 3 would be 65% instead of the observed 50%. The ideal and measured bandwidths of a single reflector would remain the same at 6% FWHM. Then the net transmission of the optical system might be five to six times higher for six and seven reflections, respectively.

The possibility of using an optical system with fewer reflections than described above is a second way to increase power transmission to the wafer. However, for non-scanning illumination of large image areas $\geq 1 \text{ cm}^2$ with low image distortion, it appears that the minimum number of normal-incidence reflectors is six for the FEL and storage-ring undulator sources (one post uniformer collection mirror, the mask, and four reflections for imaging) and seven for the bending-magnet radiation and laser-plasma sources (two collection mirrors, the mask, and 4 reflections for imaging). For scanning systems such as the Perkin-Elmer Micralign I^{11,12}, which image a narrow radial arc 1-2 mm wide by 2- cm long, it may be possible to use one less imaging mirror (three instead of four) to increase the optical transmission by a factor of two. This possibility has yet to be analyzed.

3.2 XUV FEL output power capability

Figure 4 compares the average power capabilities of future rf-linac-driven FELs and several other light sources relative to exposure parameters close to those expected for XUV projection lithography near the end of this century. The choice of 20 mJ/cm² resist sensitivity is derived from recent reports by Taylor, et al.¹³ and Kubiak, et al.¹⁴, discussed in Section 6. Numerical simulations by Goldstein et al.¹⁵ of future XUV FEL oscillators driven by rf linacs predict that, with a moderate duty factor of $\sim 3\%$, the average-power output should meet and surpass the requirements for XUV projection lithography. One FEL should produce enough average power for distribution to multiple lithographic steppers (~ 10 or more, depending on the resist sensitivity and mirror specular reflectance) operating at the same time, via a reflective beam director such as a rotating polygonal mirror. It is clear that the output power of synchrotron radiation sources including bending magnets

in compact storage rings, magnetic undulators in future high-energy storage-ring research facilities, and laser-plasma soft x-ray sources all fall significantly below the level needed for 1-second exposures per chip. The basis for this conclusion follows.

3.3 Output power capabilities of alternate sources

Synchrotron radiation sources: At a specified wavelength, the power P radiated into unit spectral bandwidth from bending magnets in storage rings is proportional to the electron energy divided by the wavelength as:

$$P(W) = 49E(\text{GeV}) I_{av}(\text{amps}) \emptyset (\text{rad}) G_1(\lambda_c/\lambda) BW(\%) / \lambda(\text{nm}), \quad (1)$$

where G_1 is a distribution factor with peak value ~ 1 , and

$$\lambda_c(\text{nm}) = 1.864 / B(\text{Tesla}) E^2(\text{GeV}^2). \quad (2)$$

For example, a compact, 700-MeV superconducting storage ring with 200-mA stored current^{17,18} will produce 0.02 W at 13 nm in a 2% bandwidth and with a large, 50-mrad horizontal collection angle. Raising the beam energy to 1.1 GeV and peak fill current to 500 mA (a proposed normal-conducting storage-ring design with 1.6-T bending magnets¹⁹) will increase the power to 0.16 W at 13 nm $\pm 1\%$ BW into 50 mrad. Even more power per unit bandwidth can be produced by undulator insertion devices in a large storage ring, such as the 1.5-GeV Advanced Light Source (ALS) being constructed by Lawrence Berkeley Laboratory.¹⁶ This would be a more costly option, however. It should be noted that the average radiated power decreases exponentially with time as the stored current declines after each fill. In the optimistic case that the rings are refilled with beam at full energy, we estimate that the time-average stored current could equal 80% of the peak fill current.

Laser plasma sources: These can produce average power comparable to that from bending magnets in storage rings.^{20,21} For example, a 10-J/1-ns/10-Hz Nd:YAG laser focused on a Cu target would produce the 100-eV blackbody spectrum, shown in Fig. 4, with ~ 5 mW average power at 13 nm within 1% BW and into a 0.35-sr solid angle. However, excimer lasers can operate at a higher repetition rate. Kubiak, et al.^{14,21} report that the Sandia-Livermore Laboratory 150-W KrF excimer system (1.5J/25-ns pulse at 100 Hz), focused to 300- μm diameter on a gold target, produces a time-averaged output flux at the test sample of 1.5 μW of 100-eV photons in a monochromatized 1.6% bandwidth. Approximately 30% of the incident radiation is converted to a soft-x-ray plasma radiator, and 0.5% of this radiates into a 1.6% bandwidth about 13 nm and into 2π -sr solid angle. A collection angle of 0.35-sr yielding $\sim 10\%$ collection efficiency for a Lambertian emitter should be possible. If the monochromator were replaced by a multilayer reflector projection system and if the plasma debris problem can be circumvented, this source could prove useful for low-volume production requirements for single steppers or scanners.

3.4 Potential wafer throughput for candidate photon sources

Estimates of the wafer level throughput using the above three types of sources are compared in Fig. 5 with that using FEL photon sources of 13 nm for projection lithography for the following conditions. First, the diameter of the wafers was set at 12 inches (chip patterns cover 80% of the area) which size is projected for production use by the year 2000. Secondly, the exposure wavelength was set at 13 nm at which Mo/Si multilayer projection mirrors have their highest reflectance ($\sim 50\%$) and where 0.1- μm resolution can be attained with a sufficiently large, 1- μm total depth of focus. To achieve a large, diffraction-limited image area of $\sim 1 \text{ cm}^2$, the projection system is comprised of five reflections (mask + four mirrors). This is preceded by a two-mirror system (0.35-sr collection angle, i.e., $\sim 10\%$ geometrical efficiency) for the laser plasma source, two collection mirrors for the bending magnet radiation (100% geometrical efficiency assumed), and a reflective beam uniformer tube with input focusing and output collimating mirrors (net throughput of $\sim 40\%$) for the undulator and FEL sources. The laser plasma source power was scaled upward assuming that a 1-kW drive laser will become available. Likewise, a large 1.1-GeV storage ring with 500-mA initial fill current and very large 100-mrad

horizontal collection angle was assumed. The undulator-magnet source has 98, 5.0-cm periods within a 1.5-GeV storage ring with 400-mA initial fill current as designed for the high-brightness, ALS insertion devices.¹⁶ The time-average current was set at 80% of the peak value to account for the exponential decay and reinjection time. An overhead of one minute was allowed per wafer for the stepper-scanner mechanical movements, including global alignment and chip field alignment.

Although the comparisons in Fig. 5 span potential resist sensitivities from 1 to 100 mJ/cm², the primary range of interest is 5 to 20 mJ/cm² where high-contrast, pinhole-free resists are expected to be developed. At these two sensitivity values, the wafer-level throughput with the laser-plasma and bending magnet sources are both projected to be about 1 and 0.3 wafer-levels/hr, respectively. The respective throughputs for the undulator source could be to be 4.5 and 1 wafer-levels/hr. If the mirror reflectivity could be substantially improved to 65% as discussed in Section 3.1, then the wafer throughput for the laser-plasma and bending magnet sources might be six times greater and that for the undulator five times greater than these values. In this optimistic case and with a 5 mJ/cm² resist, the undulator source would enable production of ~20 wafer levels per hour.

On the other hand, the output power of rf-linac-driven FELs at either 3% or 10% duty should be sufficiently large to permit simultaneous sharing between multiple projection steppers, each processing 30 wafer levels per hour. At 3% duty, the number of steppers would be 24 and 6, respectively, with 5 and 20 mJ/cm² resists. It appears that, for the above predicted projection lithographic conditions, the FEL will uniquely be able to satisfy the source requirements for high-volume production of large-area chips with 0.1-0.2- μ m minimum features needed in the last years of this century.

4. FEL TECHNOLOGY DEVELOPMENTS

The essential elements of an FEL oscillator, indicated in Fig. 2, are the relativistic electron beam produced by an accelerator, a magnetic undulator in which the electrons oscillate transversely and emit (or absorb) light, and the resonator mirrors. By varying the electron energy or the magnet separation, the wavelength can be tuned continuously over a broad range. The laser radiation is linearly polarized and diffraction limited. The typical temporal format is a 10- to 1000- μ s macropulse train of picosecond pulses with 1- to 100-ns separation and with an arbitrary macropulse repetition rate. As a special feature, the FEL can be operated with the optical spectral bandwidth either narrowed to the Fourier transform limit of the ps pulses or broadened with sidebands to several per cent. For resist irradiations, the latter mode of operation with short coherence length would be advantageous.

4.1 Background on FEL development

Since 1977, more than one-dozen FEL oscillators and amplifiers have produced coherent radiation over a broad spectral range extending from 240 nm in the ultraviolet^{22,23} to millimeter wavelengths as shown in Fig. 6. These successes have encouraged FEL researchers to examine the parameters required for FEL operation in the XUV below 100 nm where no powerful, tunable, coherent-radiation source presently exists. In the last six years, Los Alamos National Laboratory²⁴⁻²⁶ and Stanford University^{27,28} have operated rf-linac-driven FEL oscillators in the near infrared for several thousand hours. Experience with these two systems has provided invaluable insight and data with which to design rf-linac-driven FEL oscillators,^{15,29-35} and possibly high-gain single-pass amplifiers,³⁶⁻⁴¹ for operation in the VUV and soft x-ray spectral ranges. An important distinction of the Los Alamos FEL is its very high 500-A peak current capability and correspondingly large single-pass optical gain from a short, 1-m undulator (250% small-signal gain/pass at 10 μ m with 300-400 A peak current).^{25,26} Such are the magnitudes of the parameters that will be required for operation of FEL oscillators in the XUV. Although FELs as a class must yet be extended in wavelength an additional factor of 2.5 to reach 100 nm (the longest wavelength of interest for future lithographic application), significant improvements of the primary components are either ready for implementation or have been conceived and provide confidence that lasing at such wavelengths is feasible. The status of these components (electron photoinjector, high-precision magnetic undulators, and XUV resonator mirrors) was reviewed in a recent publication by this author.²

4.2 Parameters of an rf-linac-driven xuv free-electron laser

The baseline parameters for 50-nm and 12-nm FEL oscillators, using present state-of-the-art technologies, are presented in Table 1. The output powers listed do not include the potential degrading influence of mirror distortion or power augmentation by side-band growth.

Table 1. Parameters for 50-nm and 12-nm FELs (rf-linac driven) for XUV lithography (see Ref. 15)

<u>Optical</u>		
Wavelength	50 nm	12 nm
Resonator end-mirror separation	30 m	30 m
Peak power output	20 MW	10 MW
Average power output @ 3% macropulse duty factor	200 W	100 W
<u>Accelerator</u>		
Frequency	1.3 GHz	1.3 GHz
Energy	260 MeV	535 MeV
Accelerating gradient	10 MeV/m	10 MeV/m
Charge per bunch	3 nC	3 nC
Micropulse duration, FWHM	10 ps	10 ps
Micropulse separation	30 ns	30 ns
Peak micropulse current	300 A	300 A
Average macropulse current	150 mA	150 mA
Energy spread, FWHM	0.16%	0.1%
Emittance, ϵ_n (90% of electrons)	31π mm-mr	23π mm-mr
<u>Undulator</u>		
Length	5 m	12 m
Period	1.6 cm	1.6 cm
Gap	4.7 mm	4.7 mm
Magnetic field, peak on axis (SmCo ₅), 2-plane focusing	0.75 T	0.75 T

Further development of various aspects of the rf linac, optical, and undulator technologies will be necessary to obtain smaller and less costly FELs for application to XUV projection lithography. As examples, attainment of brighter electron beams with advanced versions of the electron photoinjector will make possible sufficient optical gain with shorter undulators than listed in Table 1. Cryogenic or superconducting (SC) linac structures will reduce the rf power requirement, and operating with higher accelerating gradient, e.g. ≥ 25 MeV/m, will reduce the linac length. A compact accelerator configuration would be a recyclotron designed to reach the required beam energies by double-passing the beam through the accelerator structure, provided that the accelerator is designed for twice the listed macropulse average current and provided that the beam emittance can be maintained at the indicated level. Incorporation of electron energy recovery (for SC linac option only) would reduce the rf power requirement and the net electrical operating cost. Use of pulsed electromagnetic undulator designs to obtain shorter-periods, e.g. ≤ 9 -mm, and lasing on the optical harmonics will further reduce the required electron energy, the linac length, and the construction cost. Finally, use of cryogenic optics will reduce the beam-induced thermal distortion of the resonator mirrors which will permit the resonator length to be reduced to ~ 10 m. A conception of such a compact FEL designed to operate at 12 nm is shown in Fig. 7.

4.3 Lithography system granularity and FELs

One of the important advantages of an integrated circuit manufacturing facility based on multiple lithography units, each with its own light source, is its relative freedom from the "shut-down" effects of a single-point failure. For an FEL light source driving multiple (10-15) steppers, there are two approaches that can be used to mitigate this potential vulnerability.

Multiple FELs: It is possible to use two FELs and co-mingle their beams so that the illumination on each reflective mask would be composed of light from each FEL. Each FEL could be operated at reduced power to enhance reliability. In such a mode, the failure of a single FEL would result in no reduction in wafer throughput (by temporarily increasing the power of the second FEL to make up for the failed unit) or, at worst, a modest reduction in throughput. Total shutdown of the facility would not occur. This option trades a factor of two increased capital cost for FEL systems for immunity from shutdown.

Redundancy within a single FEL: In an FEL, we expect that the subsystems and components that have the highest likelihood of failure are the injector system, the rf power supply components, and the optical alignment of the oscillator resonator. (The relatively high reliability of the linear accelerator itself, the single major component of the FEL system, has been established from decades of experience at many accelerator facilities.) The overall FEL reliability can be increased significantly by providing redundancy in these areas. For example, one could install an operationally ready back-up injector, on-line spare klystrons and ancillary components in the rf power supply, and a pre-aligned standby optical resonator. In most failure cases, the switchover time can be made short. The cost of providing this redundancy should be significantly less than the cost of a spare FEL.

5. XUV PROJECTION OPTICAL SYSTEMS

5.1. Provision for uniform illumination in the image plane

An all-reflective beam uniformer indicated in Fig. 2 will redistribute the spatial output of the XUV FEL radiation to obtain uniform illumination at the resist plane. One possible configuration for the uniformer is a 30-cm-long, hollow, evacuated tube consisting of four 5-mm-wide walls with square cross section. Prior to assembly, the inside surfaces are coated with an XUV reflective coating of, for example, rhodium for 12 nm and either rhodium or osmium for 60-nm radiation. An off-axis reflecting paraboloid will direct the FEL radiation to a focus at the entrance to the uniformer resulting in multiple reflections during transit. Different radial sections of the beam will have five, four, three, two, one, or no reflections, and the net throughput for 60-nm radiation is estimated to be 89% (92%) for Rh (Os) surfaces and 98% at 12 nm with Rh surfaces, calculated by use of tabulated listings of the optical constants.⁴² At the exit, a second off-axis paraboloid will direct the spatially uniform beam onto the mask. These beam uniformers are effective devices if the radiation has a sufficiently short coherence length to preclude interference effects such as speckle. Fortunately, the FEL spectral bandwidth can be operated with a broad bandwidth of ~1% for resist exposures. Thus, the coherence length will be only 1- to 10 μm which, with multiple pulses and an appropriately designed beam uniformer, should not result in significant interference patterns in the mask illumination.

5.2. XUV reflection masks

A reflection mask on a relatively thick (~1 cm) substrate will not have the thermal distortion and fragility problems inherent with the thin transmission masks used for x-ray proximity lithography. Silicon is a good candidate for the substrate because of its high thermal conductivity and the very smooth polished surface that can be achieved (~1 Å rms roughness) which minimizes light scattering. For 12-14 nm and normal incidence, multilayer reflectors will be necessary with the ~50% reflectance already noted for Mo/Si layer designs. As has been demonstrated by Hawryluk et al.,⁴³ the desired mask pattern can be produced lithographically in a gold film overcoat which has very low reflectance (~0.01%) for 10-30 nm. They achieved a high, ~500:1 contrast in this way. For 60 nm and normal incidence, the reflecting areas could be a metal-oxide patterned over single-layer films of type-I diamond⁴⁴ or CVD-SiC⁴⁵ (40-50% reflectance) similar to the mirror coatings suggested for the projection optics.

An outstanding issue is whether or not multilayer reflective coatings can be fabricated free of high-contrast scattering or absorbing sites that, when imaged by the ~5:1 reduction optics, would produce imperfections in the resists larger than about 1/5 the minimum feature dimensions. Prevention of these "killer defects" in the mask reflector will require an a defectless coating deposition procedure, such as an in situ scatter detector and repair technique as each layer is deposited. Otherwise, post-deposition repair of defects within a multilayer

structure would appear to be difficult. Lithography exposure systems that can achieve the desired resolution with illumination wavelengths ≥ 60 nm might use the aforementioned single-layer reflecting films of type-I diamond or CVD-SiC that should not be as difficult to repair. However, low-temperature coating technologies for diamond and SiC on highly figured optics are still being developed.⁴⁶⁻⁴⁸

Since ~50% of the incident radiation will be absorbed into the mask, the potential magnitude of thermal distortion of the mask features has been evaluated. Fortunately, our analysis shows that absorption of ~10 W over a 100-cm² mask area will cause a very small temperature differential ($<0.1^\circ\text{C}$) between the front and back of a 1-cm thick silicon substrate, and thermal drift can be prevented by cooling the back side with a very low rate (~1 liter/min.) of water flow. Additionally, the incident fluence on the mask within each 10-ps micropulse (separated by ~30 ns) will be $<0.1 \mu\text{J}/\text{cm}^2$, resulting in negligible thermal impulse.

5.3. Reflecting reduction imaging system

Reduction imaging optical steppers or scanners, which can project microcircuit features much smaller (2 to 10X) than the dimensions of practical reticles, will be essential for achieving $\leq 0.2 \mu\text{m}$ resolution with XUV radiation. For these systems to produce diffraction-limited images for XUV wavelengths below 100 nm, relatively low values of numerical aperture (0.1 to 0.3) will be required. Starting with a telescope designed by D. R. Shafer,⁴⁹ Rodgers and Jewell⁵⁰ have derived a 5X reduction projection optical design, composed of four, co-axial aspheric mirrors plus the reflecting mask, that has the potential to resolve 0.1- μm features over an image field up to 10 x 15 mm² with low distortion. Another two-mirror/four-reflection, centrally-obscured (40%) on-axis design by Shafer should also achieve 0.1- μm resolution using ≤ 20 -nm irradiation.⁵¹⁻⁵³ This system has a reduction factor of 3.33 and should provide diffraction-limited resolution over at least a 10 x 10 mm² image. As described by Yang, et al.,⁵⁴ the performance of obscured reflective projection systems can be optimized with annular illumination with partially coherent light. Another projection design uses four off-axis, aspheric mirrors plus a flat reflection mask to producing a diffraction-limited image over a ~1 cm² area with XUV photons.⁵³ The details of a reflective system designed for a smaller 0.2-cm² image area using 4.5-nm illumination were reported by Hawryluk and Seppala.⁵⁵ Alternately, a step-and-scan projection system, such as the Perkin-Elmer Micrascan I,^{11,12} might reduce the instantaneous diffraction-limited field-size requirement to a narrow, arcuate slit 2-cm long by 1- to 2-mm wide, which may be attained with one less projection mirror than required for full-field illumination.

As discussed in Section 3, a five-reflection projection optical system with 50% reflectors plus two collection mirrors will have a reflected throughput of only 0.8% in a limited, ~2% bandwidth. Even with the high-average power available from an FEL, the throughput of the imaging system should be maximized to avoid unnecessary attenuation of the beam, since this determines how many lithographic steppers can be served by one FEL source, simultaneously. Thus, projection optical systems in the XUV should be designed for the wavelengths where satisfactory normal-incidence reflectors exist, consistent with satisfactory photoresist response. This will include ~13 nm at which wavelength the reflectance of Mo/Si multilayers is maximum at 50%. Other wavelength options include ~60 nm, as mentioned in Section 5.2, and ≥ 4 nm. At the shorter wavelengths, such as 4 nm, it will be a challenge to obtain the required mirror surface figure for diffraction-limited images and to attain adequately high normal-incidence reflectance, e.g. 40%, because of increased scatter losses.

Irradiations of resists by any XUV exposure system will have to be performed in either a rare gas such as helium or in vacuum, because radiation shorter than about 185 nm is absorbed by the atmosphere. The potential problem of carbon contamination of XUV-irradiated surfaces will determine how good a vacuum will be required. This is a serious problem for optics used in synchrotron radiation experiments and has been described by many authors.

The generic requirements on future projection systems in terms of wafer alignment and level-to-level chip overlay/registration and alignment will be as challenging as the resolution goals. The common rule is that the systems must be able to provide circuit level-to-level alignment precision equal to ~1/5 of the minimum feature dimensions. For future 0.1- μm features, this poses a formidable challenge to system engineers and metrology experts.⁵⁶ In this regard, two metrology schemes proposed by Zladi, et al.⁵⁷ of the University of New Mexico,

Involving Moire fringes from diffracted He-Ne light from two gratings or a high-resolution Si-based optical position sensor, appear to have the precision capabilities required.

6. PHOTORESISTS FOR THE XUV

Lithographic production of crisp, 0.1- μm features with XUV imaging will require photoresists with sufficiently high contrast ($\gamma \geq 3$), and adequately low absorption and exposure sensitivity. Also, the source average-power requirement will depend directly on the resist sensitivity. According to the analysis of a limited number of resists for soft x-ray wavelengths by Taylor et al.,¹³ conventional bulk-exposed resists may be viable only for wavelengths below 10 nm where the transmittance is adequate to allow at least a thickness of 0.5 μm which they consider as a minimum for planarization of the topography of the underlying layer. (A promising exception may be Shipley Company's System 905 which Kubiak et al.¹⁴ recently characterized for 14-nm irradiation as having a high contrast γ of 4.1 and low 18 mJ/cm² sensitivity for wet chemical removal of all but the lower 1/e thickness of a 0.42- μm layer.) Surface-imaging resists over a thick planarization layer may be the best candidates over the entire range from 5 to 50 nm. One important benefit of surface imaging and high absorption is that interference effects due to reflections from the coated substrate will be negligible. However, at 14-nm the irradiation thresholds for three, high-contrast ($\gamma > 4$), plasma-developed, positive-tone resists (UCB Plasmask P-150U, P-301-U, and MacDermid 1024), evaluated by the AT&T group, are above 200 mJ/cm².¹³ Taylor expects that addition of a chemical amplification agent to these surface-imaging resists could lower the effective sensitivities by a factor of $\sim 20\times$. Hopefully, high-contrast resists with 5 to 20 mJ/cm² thresholds will not exhibit statistical noise response nor pinhole defects, and can be economically processed.

7. SUMMARY

Future rf-linac-driven FELs, operating in the range from 4 nm to 100 nm, could be excellent exposure tools for extending the resolution limit of projection optical lithography to $\leq 0.1 \mu\text{m}$ and with adequate total depth of focus (1 to 2 μm). When operated at a moderate duty rate of $\geq 3\%$, XUV FELs should be capable of supplying sufficient average power to support high-volume chip production in a number of lithographic steppers simultaneously. Recent developments of the electron beam, magnetic undulator, and resonator mirrors raise our expectation that FEL operation is ready for laboratory scaling demonstrations. We expect that XUV-FEL-based lithography systems could serve the semiconductor industry for a number of generations of microcircuits, considerably beyond the year 2000.

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Figure 1. Extreme-ultraviolet projection lithographic exposure tools will be required to attain $\leq 0.1\text{-}\mu\text{m}$ resolution with a practical total depth of focus (DOF) of 1 μm . Diffraction-limited resolution for fixed DOF is proportional to the square-root of the exposure wavelength.

Figure 2. Conceptual schematic of projection lithography using an XUV FEL source. The stepper/scanner will use all reflective optics to project a demagnified image of a patterned reflection mask onto a surface-imaging photoresist.

Figure 3. Mo/Si multilayer mirrors attain nearly 50% reflectance at 13 nm for near-normal incidence. The net reflectance of a series of seven-mirrors (five-mirror projection system plus a two-mirror source collection system or input/output mirrors for a beam-uniformer tube) would be 0.8%. The FWHM bandwidth of a single mirror is 6%, and the net bandwidth of a series of six or seven mirrors will be 2%. This figure is reproduced with permission of J. Kortright of Lawrence Berkeley Laboratory.⁹

Figure 4. The average-power output capabilities per 1% bandwidth for several candidate XUV/soft x-radiation sources are compared with reference to the requirements for sub-quarter-micron projection lithography using photoresists with 20 mJ/cm² sensitivity and commercial chip dimensions projected for the late 1990's.

Figure 5. Projection lithographic exposure throughput of 12-inch-diameter wafers versus resist sensitivity for several sources of 13-nm radiation. Stepper alignment overhead of 1 minute/wafer was assumed.

Figure 6. Successful free-electron lasers that have operated in the visible to the far infrared since 1977 provide the experience basis for extension below 0.1 μm .

Figure 7. Conception of a compact XUV-FEL source for 0.1- μm -resolution projection lithography. Advanced accelerator components include a laser photoinjector and a high-gradient (25 MeV/m) rf-linac in a double-pass, recyclotron configuration to reach 250 MeV. This FEL design would operate at 12 nm on the third harmonic of 36 nm using a pulsed electromagnetic undulator with 9-mm period. The ring resonator features nine-facet Rh mirrors deposited on Si substrates and operated at a cryogenic temperature near 125 °K.

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