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Development of free-electron lasers for xuv projection lithography*

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ABSTRACT

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 $\geq 1\%$, XUV FELs should be able to supply sufficient average power to support high-volume chip production. Recent developments of the electron beam, magnetic undulator, and resonator mirrors are described which raise our expectation that FEL operation below 100 nm is almost ready for demonstration. Included as a supplement is a review of initial design studies of the reflecting XUV projection optics, fabrication of reflection masks, characterization of photoresists, and the first experimental demonstrations of the capability of projection lithography with 14-nm radiation to produce lines and spaces as small as 0.05 μm .

1. INTRODUCTION

Advanced lithographic technologies capable of producing $\leq 0.25 \mu\text{m}$ features and with high wafer throughput will be needed to meet the demand for larger, faster, and more complex integrated circuits for 1995 and beyond. 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 projection photolithography. Moreover, the major obstacles faced by x-ray proximity lithography, especially those involving the transmission mask and x-radiation effects on certain FET circuits, have yet to be resolved adequately for production requirements. XUV lithography based on an FEL could be a less costly alternative for production of application-specific integrated circuits (ASICs) such as logic circuits. Near the end of this century, it could as well become the preferred technology for high-volume production of dynamic and static random access memory (DRAM and SRAM) integrated circuits with 0.1- μm features.

Additional reasons that suggest that XUV projection lithography with an FEL source could be very important for the future of integrated circuit production. First, this technology will be a direct extension of deep-ultraviolet (DUV) projection lithography with excimer laser sources, which is now being readied for the next-generation of microcircuit manufacturing facilities. DUV lithography, even with the ArF laser at 193 nm and an optimistic process parameter $K_1=0.7$, will reach a minimum-feature limit $\geq 0.25\text{-}\mu\text{m}$ in commercial production as a result of maintaining the total depth-of-focus at $\geq 1 \mu\text{m}$. Extension of lithographic processes to XUV wavelengths below 100 nm with an FEL will enable resolution well below 0.25 μm while still satisfying these practical production requirements. Second, even finer resolution $\leq 0.1 \mu\text{m}$ can be attained by extending the FEL operating wavelength to near 10 nm. Such a scalable exposure tool will be useful over a number of generations of microcircuits. Third, the process exposure latitude should be sufficient for commercial requirements by imaging the XUV photons onto surface photoresists. Op de Beeck et al.² have characterized the surface-imaging DESIRE process as maintaining constant linewidth of $0.25 \mu\text{m} \pm 10\%$ for an

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adequate $\pm 7\%$ range of photon exposure. **Fourth**, the technical challenges and risks for XUV-FEL projection lithography are different from those of x-ray proximity lithography. Thus, development of both technologies makes practical sense. **Fifth**, the XUV reflecting masks needed for $\sim 5:1$ reduction projection optical systems will be much less costly (4 to 5 times less) than the 1:1 transmission masks needed for x-ray proximity lithography.³ Finally, XUV-FEL sources build on the past decade of research and development of FEL technologies.

As shown in Fig. 1, XUV projection lithography with an FEL has the potential to attain resolution R less than $0.1\ \mu\text{m}$. (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 $K = K_1/K_2^{0.5}$). An attractive feature of the FEL is that it can be progressively upgraded to attain shorter wavelengths for correspondingly higher-resolution lithography. Using process parameters $K_1 = K_2 = 0.8$, which are appropriate for today's high-volume commercial production, and holding the total depth-of-focus constant at $1.0\ \mu\text{m}$, resolutions of 0.25 , 0.10 , and $0.05\ \mu\text{m}$ can be attained by operating FELs at 85 , 13 , and $4\ \text{nm}$, respectively. (The corresponding minimum feature sizes on the integrated circuits, after resist processing, typically will be slightly smaller at 0.2 , 0.08 , and $0.04\ \mu\text{m}$.) Memory chips with such small features will have a major impact on future computing capabilities. For example, a $25 \times 25\ \text{mm}$ DRAM chip with $0.1\text{-}\mu\text{m}$ features would have $\sim 1\ \text{GByte}$ memory capacity which is equivalent to that of a present-generation CRAY computer. We expect that XUV-FEL-based lithography systems could serve the semiconductor industry for a number of generations of microcircuits, perhaps to the year 2020, by continuously extending today's optical lithographic methodologies.

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 includes a comparison of the average-power capabilities of the FEL with several other candidate photon sources relative to the expected lithographic requirements. The main Section 4 presents a substantial survey of recent development of the primary components of an XUV FEL. Following our summary remarks in Section 5, we present a supplemental Section 6 that describes the initial efforts to develop reflecting optics and photoresists for XUV projection lithography plus the first reports of projection lithographic experiments.

2. ELEMENTS OF XUV PROJECTION LITHOGRAPHY BASED ON AN FEL

Figure 2 shows the essential components of XUV projection lithography. An XUV FEL source, driven by an rf linear accelerator (linac), will provide sufficiently high-average power of partially coherent photons scalable from 100 to $4\ \text{nm}$. (Storage-ring FELs, due to energy spread induced by the lasing action on the recirculating electron beam, are not 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 from multiple reflections within a rectangular light pipe whose walls are coated with a reflective metal, e.g. Rh. A reflective mask (first suggested by Silfvast and Wood⁴) on a thick Si substrate (water cooled on the backside) is composed of a metal film 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. $\geq 1\ \text{cm}$, 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 POWER REQUIREMENTS

Numerical simulations of future XUV FEL oscillators driven by rf linacs by Goldstein et al.⁵ predict that, with modest duty factors of $\sim 1\%$, the average-power output should easily meet the requirements for XUV projection lithography. The total energy required to expose a $25 \times 25\ \text{mm}$ image area on a chip in one second will be only 60 to $600\ \text{mJ}$ for photoresists having sensitivities of 10 to $100\ \text{mJ}/\text{cm}^2$ such as PMMA ($\leq 50\ \text{mJ}/\text{cm}^2$ at $14\ \text{nm}$).⁶ However, the radiation source must also provide enough power to offset the losses of

the projection optical system which will be comprised of multilayer mirrors with relatively low reflectance and narrow bandwidth. For example, the throughput of a five-reflection projection optical system (four mirrors plus reflecting mask), each with 50% reflectance, will be only 3%. Furthermore, the net reflection bandwidth of N identical multilayer mirrors in series is $\sim 1/N^{0.5}$ that of a single mirror. The best soft x-ray reflectors yet produced, comprised of Mo/Si films, have a reflectance maximum at ~ 13 nm of 40% to 50% and bandwidth of 4%. So, the net bandwidth of a five-reflection optical system would be $\sim 2\%$.

Figure 3 compares the average power capabilities of several light sources relative to the expected needs of XUV projection lithography. Future rf-linac FELs should produce much higher levels of average power per unit bandwidth than can 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. One FEL should produce enough average power for distribution to multiple lithographic steppers (~ 10 or more, depending on the resist sensitivity) operating at the same time, via a rotating polygonal mirror beam director.

Storage rings with bending magnets will not produce sufficient power to satisfy the conditions listed in Fig. 3 even with a resist sensitivity of only 10 mJ/cm^2 . For example, compact, superconducting storage rings with 200 mA stored current^{7,8} will produce $\leq 0.04 \text{ W}$ at 13 nm in a 2% bandwidth and 50-mrad horizontal collection angle. For a specified wavelength, the radiated power from a bending magnet scales linearly with electron energy. Raising the beam energy to 1.1 GeV and stored current to 500 mA (a proposed normal-conducting storage-ring design with 1.6-T bending magnets⁹) will increase the power to 0.2 W at $13 \text{ nm} \pm 2\% \text{ BW}$. This is yet a factor of 5 to 10 lower than the indicated requirement. More power per unit bandwidth can be produced by undulator insertion devices. If the optimistic combination of a 10 mJ/cm^2 resist and a four-reflection optical system can be developed, then an undulator in a high-energy storage ring, such as the 1.5-GeV, 400-mA Advanced Light Source storage ring being constructed at Lawrence Berkeley Laboratory¹⁰, could just meet the power requirements for one stepper unit.

Laser-plasma sources can produce power levels comparable to that from bending magnets in storage rings.¹¹ 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. 3, with $\sim 5 \text{ mW}$ average power into a 0.35-sr solid angle. However, high-repetition-rate excimer lasers will be a better option. For example, a factor-of-forty higher production of 100 eV photons in a 1% BW (0.15 W) has been attained by focusing a 150-W KrF excimer laser ($1.5 \text{ J/25 ns/100 Hz}$) on a gold target.^{12,13} This latter source could prove useful for low-volume production requirements.

4. FEL TECHNOLOGY DEVELOPMENTS

The essential elements of an FEL oscillator, illustrated in Fig. 4, are the 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 coherent, polarized, and nearly diffraction limited. The typical temporal format is a 10-1000- μs 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 with short coherence length would probably be utilized.

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^{14,15} to millimeter wavelengths as shown in Fig. 5. 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 Laboratory¹⁶⁻¹⁸ and Stanford University^{19,20} have operated rf-linac-driven FEL oscillators in the near infrared for several thousand hours. Experience with these two sys-

terms has provided invaluable insight and data with which to design rf-linac-driven FEL oscillators^{5,21-28} as well as high-gain amplifiers²⁹⁻³⁷ 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 μm with 300-400 A peak current).^{17,18} Such are the magnitudes of the parameters that will be required for operation 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 present interest for lithographic applications, 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.

4.1 Bright electron beam

The paramount importance of a high-brightness electron beam (2 X ratio of peak current and normalized emittance-squared) is evident from the following: Extending FELs to ever shorter wavelengths is inherently difficult since the gain decreases monotonically with the square-root of the wavelength, and below 100 nm, the available mirrors for resonators have comparatively low reflectance, generally $\leq 50\%$. With such mirrors, the small-signal power gain for a single pass through the magnetized undulator must exceed 400% just to reach the threshold for oscillation. Increased gain can be attained with long undulators comprising several hundred periods and peak current of >100 A. However, long undulators have reduced homogeneous gain bandwidth equal to $1/2N$, where N is the number of periods. Since the gain depends very sensitively on the transverse beam emittance and longitudinal energy spread, it is essential that the accelerators deliver very bright electron beams.^{38,39} For example, a 12-nm FEL oscillator designed by Goldstein et al.⁵ requires a beam brightness of $6 \times 10^{10} \text{ A/(m-r)}^2$, corresponding to a peak current of 300 A and normalized transverse emittance of $30\pi \text{ mm-mr}$ (90% of particles), with energy spread of 0.15% (FWHM).

Until the development and experimental demonstration of the laser photoinjector by Fraser and Sheffield,⁴⁰⁻⁴³ electron beams with the above properties had not been generated in an rf linac. As shown in Fig. 6, a photocathode is positioned on the end wall of the first accelerating cavity and is irradiated by a train of ps-duration, visible to ultraviolet laser pulses. By applying a very high accelerating gradient, e.g., 30 MeV/m, the photoelectrons attain a relativistic energy of 1- to >3 MeV in the first cavity, thereby minimizing their susceptibility to perturbations that cause emittance growth. Photocathodes with varying levels of quantum efficiencies (Q.E.) are being used: CsK₂Sb ($\leq 10\%$ Q.E.) at Los Alamos National Laboratory,⁴² yttrium (0.1% Q.E.) at Brookhaven National Laboratory,⁴⁴ and LaB₆ (0.01% Q.E.) at Stanford University.⁴⁵ The CsK₂Sb cathode is most susceptible to poisoning by contamination and must be operated in high vacuum of 10^{-10} Torr in order to have a practical lifetime with high Q. E. Recent lifetime measurements of this cathode while mounted within the photoinjector cavity at 2×10^{-10} Torr and without laser irradiation indicated that the Q.E. only declined from 10% to 8% in a 36-hour period followed by no change until the test ended at 68 hours.⁴⁶

The concentrated efforts of several research groups^{44,45,47} to implement photoinjectors on rf linacs designed for FELs should eventually make rf linacs reliable sources of high-current, low-emittance electron beams. If the high brightness of such beams can be maintained without degradation during acceleration to high energy, then the FEL gain will be high enough for oscillator operation at wavelengths as short as 4 nm.^{5,48,49} The first FEL experiments with a photoinjector, conducted by a Stanford University-Rocketdyne team, demonstrated lasing at 3.1 μm with laser-enhanced electron emission from a LaB₆ rf gun.⁴⁵ Meanwhile, a high-current photoinjector has been integrated into the Los Alamos Infrared FEL system. As reported by Feldman et al.⁵⁰ in these Proceedings, Los Alamos' initial measurements of the beam quality of a single, 10-nC micropulse at 17 MeV were in agreement with the normalized design emittance, $\sim 50 \pi \text{ mm-mr}$. An important goal is to minimize the temporal jitter of the mode-locked, frequency-doubled Nd:YLF drive laser which has a significant effect on stability of the accelerated beam energy.

4.2 High-precision, long, magnetic undulators

Long, high-precision magnetic undulators will be needed to attain sufficient gain for single-pass FEL amp-

lifiers or to overcome the resonator mirror and output coupling losses in FEL oscillators. Increasing the number of undulator periods results in higher gain, but the cumulative influence of uncorrected random magnet errors increases with length as well. To prevent serious degradation in FEL gain, the magnitude of individual magnet errors (strength and orientation) that can be tolerated decreases as the number of undulator periods increases, e.g. to below 0.1% for several hundred periods.^{51,52} Fortunately, several solutions for this problem have been devised. Elliott and McVey⁵² determined that the effect of magnet imprecision as large as 0.7% can be mostly overcome by measuring the beam position at a sufficiently large number of points along the undulator, e.g. every 25 periods, and by applying a like number of correction fields. Warren^{53,54} has developed a very sensitive pulsed-wire field-measuring technique that has proven useful in rapidly indicating the location and magnitude of needed corrections to reduce steering errors to a low level. Subsequently, Feldman and Warren⁵⁵ have wedded this system with a series of field-correcting dipole coils using computer control. From a series of rapid, on-line measurement of the field errors, an automatic correction is applied. This system is expected to prove invaluable for monitoring and correcting magnetic-field errors that may develop while the undulator is in use.

Attainment of high-precision uniformity of undulator magnetic fields has also been demonstrated by several other groups. Curtin et al.⁵⁶ used the technique of simulated annealing to computationally determine the optimum ordering of the individual SmCo₅ magnets within a 2-m-long undulator to minimize the trajectory wander. A deviation of less than 25 μm was obtained for a 40-MeV beam and 3.3-kG axial undulator field. Gottschalk et al.,⁵⁷ have demonstrated a correction technique that can reduce the rms field errors to only 0.1% by placing thin iron shims on individual magnets. Another effective scheme devised by Ramian et al.⁵⁸ uses a moving, robotic screwdriver to individually adjust the magnetic fields in response to measurements of field imperfections.

Since a photoinjector offers the promise of at least an order-of-magnitude increase in beam brightness over thermionic guns, it appears possible that FELs might be operated at a given wavelength with much lower electron beam energies than heretofore. Lower beam energies will directly reduce the accelerator length and cost which is essential if FELs are to become affordable for a wide range of applications. To this end, a number of groups are trying to build undulators with very short periods, e.g. 1-10 mm, while keeping the product of the peak axial magnetic field and undulator period near 1 cm-Tesla to maintain high FEL gain. Warren⁵⁹ has identified the pulsed electromagnet as the most promising design for this objective. The minimum period of such undulator designs is, however, limited by thermal transport away from the magnet wires, and the number of periods (which sets the tolerable limit on electron energy spread in an FEL), is limited by the ripple in the pulsed current supply. Further progress in this area is expected.

4.3 XUV resonator mirrors

If reliable, ultra-high-brightness electron beams and precise undulators with ~1000 periods can be realized, it should be possible to attain the large exponential gain ($>10^4$) needed for single-pass XUV amplifiers starting from spontaneous emission.^{31,32} However, FEL oscillators operate with much lower single-pass gain ($<10^3$) which can be achieved with lower electron beam brightness (10-100X lower) and shorter undulators (25-50% as many periods) both of which are now almost available. The last major elements needed for FEL oscillator operation in the XUV are resonator mirrors with retroreflectance arbitrarily set at $\geq 40\%$. At this level the mirror losses must be offset by $>600\%$ single-pass gain, which is attainable.

Below 100 nm, few materials have reflectance exceeding 40% for normal incidence. For wavelengths from 60-100 nm, polished chemically vapor-deposited (CVD) silicon carbide (SiC) deposited on hot SiC substrates exhibits a reflectance between 40% to 50% at normal incidence.⁶⁰ In the same spectral region, the reflectance of polished type-I diamond reportedly exceeds this by a few per cent.⁶¹ From 80 nm to 100 nm, the reflectance of unoxidized Al films goes from 40% to $>90\%$.⁶² Finally, in the range from 10 to 20 nm, multilayer reflectors of Mo and Si are available commercially with reflectance typically between 40 to 50%.⁶³

An additional requirement for FEL resonators is that the total beam-induced thermal distortion of the mirror

surfaces must be restricted to a small fraction ($\sim 1/4$) of the operating wavelength so that high mirror reflectance $\geq 95\%$, i.e., absorptance $\leq 5\%$, is essential.⁵ The multifacet XUV metal mirror design proposed by Newnam⁶⁴ should satisfy both requirements (retroreflectance $\geq 40\%$ and $\leq 5\%$ absorptance per facet). This mirror system exploits the phenomena of total external reflectance at large angles of incidence. As pointed out by Vinogradov et al.,⁶⁵ materials with both real and imaginary parts of the refractive index sufficiently less than unity can provide surprisingly high retroreflectance by a sequence of reflections beyond the critical angle, typically larger than 60° . Unoxidized Al and crystalline Si, for example, have the necessary optical constants to attain $\geq 40\%$ retroreflectance from 35 nm to 100 nm.

Los Alamos researchers have experimented primarily with aluminum thin films deposited with an electron gun on polished silicon substrates in ultra-high vacuum (UHV) of $\sim 10^{-10}$ torr to minimize surface oxidation. At 58.4 nm using a He-discharge source and 80° incidence, Scott⁶⁶ measured the in situ reflectance of single, Al-coated mirrors to be $98.7 \pm 2\%$. Under similar conditions, the net retroreflectance of a nine-facet Al-coated retroreflector, was $89 \pm 3\%$, in agreement with the single-facet measurement. This value of retroreflectance is more than a factor-of-two higher than reported for any other XUV mirror in the vicinity of 60 nm. Additional UHV single-mirror measurements at 30.4 nm wavelength indicated that this same nine-mirror array should have a retroreflectance value of $\sim 33\%$.

Oxide formation on aluminum films is retarded in sufficiently high vacuum and in the absence of ionizing radiation. After one month in a vacuum of 5×10^{-10} torr (primarily He from the He-discharge radiation source), ellipsometric measurements by Scott et al.⁶⁷ indicated that only 0.25 monolayer of surface oxide had formed. The remaining problem of carbon film growth on Al films during XUV illumination has not yet been adequately examined. It is possible that initial clearing the UHV system of carbonaceous compounds by the rf discharge technique developed by Johnson et al.,⁶⁸ followed by in situ deposition of the reflecting films, will yield conveniently long lifetimes with high reflectance.

Besides high reflectance over a broad spectral range, the multifaceted metal reflector offers two additional advantages. First, single-layer coatings, such as Al, can be deposited on the multifaceted Si substrates mounted within the ring resonator and, without breaking vacuum, can be overcoated or treated with an ion beam to remove the oxide after a period of use. Second, this retroreflector design is inherently resistant to thermal and optical wavefront distortions, as well as to laser-induced damage. This is due to the high reflectance of S-plane polarized light from metal surfaces at large angles-of-incidence and the $\cos\theta$ spatial dilution of the beam intensity over the tilted surface. The net wavefront distortion from a flat multifaceted retroreflector decreases by an additional $\cos\theta$ factor as the number of facets increases.⁶⁹

The first conception of a FEL ring resonator incorporating multifaceted retroreflectors is shown in Fig. 7. As indicated, the reflective coatings will depend on the spectral operating range: ~ 35 -100 nm using Al or crystalline silicon films and 9 to 14 nm with Ag, Ru, and Rh films.⁷⁰ Recently, Gabardi and Shealy⁷¹ have analyzed the optical stability and diffraction losses of several modifications of this design for a range of XUV wavelengths.

4.4 Parameters of an rf-llnac-driven xuv free-electron laser

The baseline parameters for 50-nm and 12-nm FELs, using present state-of-the-art technologies, are presented in Table 1. It would be economical to reach the required beam energies by double-passing the beam through the accelerator structure in a recyclotron configuration, provided that the accelerator is designed for twice the listed macropulse average current. The output powers listed (see Ref. 5) do not include the degrading influence of mirror distortion or augmentation by side-band growth.

5. SUMMARY

Future rf-llnac-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 $\geq 1\%$, XUV FELs should be capable of

supplying sufficient average power to support high-volume chip production. Recent developments of the electron beam, magnetic undulator, and resonator mirrors raise our expectation that FEL operation at <100 nm is almost ready for demonstration. We highly recommend continued development of various aspects of the rf linac, optical, and undulator technologies to obtain smaller and less costly FELs for application to XUV projection lithography. As examples, attainment of brighter electron beams with the photoinjector will make possible sufficient gain with shorter undulators. Use of cryogenic optics will reduce the beam-induced thermal distortion of the resonator mirrors that will allow decreased resonator length to ~10 m. 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. Incorporation of electron energy recovery (for SC linac option only) will reduce the rf power requirement and the net electrical operating cost. Finally, use of pulsed electromagnetic undulator designs to obtain shorter-periods, e.g. <9-mm, and lasing on the third harmonic will reduce the required electron energy, the linac length and, thus, the construction cost. Figure 10 is a conception of such a compact FEL designed to operate at 12 nm for XUV projection lithography.

Table 1. Parameters for 50-nm and 12-nm FELs (rf-linac driven) for XUV lithography (see Ref. 5)

<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	300 W	150 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	20 ns	20 ns
Peak micropulse current	300 A	300 A
Average macropulse current	150 mA	150 mA
Energy spread, FWHM	0.15%	0.1%
Emittance, E_n (90% of electrons)	30π mm-mr	20π 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

6. APPENDIX: RECENT DEVELOPMENT OF XUV-PROJECTION LITHOGRAPHY

6.1. XUV projection optics systems

Reduction imaging optical steppers, which can project microcircuit features much smaller (2 to 10X) than the dimensions of practical reticles, will be essential for achieving ≤ 0.2 μm 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. D. Shafer has conceived a preliminary design for a reflective projection system that should achieve a resolution of 0.1 μm using ≤ 20 -nm irradiation.⁷²⁻⁷⁴ This two-mirror/four-reflection design has a reduction factor of 3.33 and provides diffraction-limited (DL) resolution over a 10 x 10 mm² image. Other designs for five-reflection projection systems (four mirrors plus reflection mask) capable of producing DL-image areas of ~1 cm² with XUV photons have been mentioned informally, but suf-

icient details have yet to be presented publicly. 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.⁷⁵ It is possible that a step-and-scan projection system, such as the new Perkin-Elmer Micrascan I,⁷⁶ will reduce the instantaneous field-size requirement. Not considered here is the requirement that such systems be able to provide circuit level-to-level alignment precision equal to 1/3 or 1/5 of the future 0.1- μ m minimum feature dimensions - a formidable challenge to system engineers and metrology.⁷⁷

As discussed in Section 3, a five-reflection projection optical system with 50% reflectors will have a reflected throughput of only 3%; with 40% reflectors, it will be 1%. Even with the high 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 will probably be designed for the wavelengths where satisfactory normal-incidence reflectors exist. This will include $\sim$ 13 nm at which wavelength the reflectance of Mo/Si multilayers is maximum at 40-60%. Other wavelength options include 85 nm and 60 nm. At 85 nm, the reflectance of aluminum mirrors with a 5-nm protective overcoat of transparent indium⁷⁸ will be $\sim$ 60% and increases to 80% at 100 nm. For wavelengths $\geq$ 60 nm, additional possibilities are type-I diamond⁶¹ and CVD-SiC films⁶⁰ with 40-50% reflectance. However, the coating technology necessary for low-temperature depositions of diamond and SiC on highly figured optics has not yet been developed.^{79,80} At very short wavelengths, such as 4 nm, considerable effort will be required to attain adequately high normal-incidence reflectance ($\sim$ 40%) because of increased scatter losses.

Since radiation shorter than about 185 nm is absorbed by the atmosphere, irradiations of resists by any XUV exposure system will have to be performed in either a rare gas such as helium or in a vacuum. The potential problem of carbon contamination of XUV-irradiated surfaces will determine how good a vacuum will be required. If aluminum reflectors are used for lithographic exposures in the spectral region $>$ 50 nm, oxygen and water vapor may also have to be excluded to prevent oxidation if In overcoatings do not provide an impermeable barrier.

6.2. XUV reflection masks

A reflection mask on a relatively thick ($\sim$ 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 ($\sim$ 1 Å rms roughness) which minimizes light scattering. For 85 nm and normal incidence, the reflecting areas may be a oxide-patterned, UHV-deposited aluminum film overcoated with a thin layer of In similar to the mirror coatings suggested for the projection optics. For 12-13 nm and normal incidence, multilayer reflectors will be necessary with the $\sim$ 50% reflectance already noted for Mo/Si layer designs. As has been demonstrated by Hawryluk et al.,⁸¹ the desired mask pattern can be produced lithographically in a gold film overcoat which has very low reflectance ($\sim$ 0.01%) for 10-30 nm. They achieved a high, $\sim$ 500:1 contrast in this way. An outstanding issue is whether or not the reflective coatings can be fabricated free of high-contrast scattering or absorbing sites that, when imaged by the $\sim$ 5:1 reduction optics, could produce imperfections in the resists larger than about 1/5 the minimum feature dimensions. These are termed "killer defects."

Since $\sim$ 50% of the incident radiation will be absorbed into the mask, thermal distortion of the mask features has been evaluated. However, our analysis shows that absorption of $\sim$ 10 W over a 10-cm² mask area will cause a very small temperature differential ($\sim$ 0.1°C) between the front and back of the silicon substrate, and thermal drift can be prevented by cooling the back side with a very low rate ($\sim$ 1 liter/min.) of water flow.

6.3. Photoresists for the XUV

Surface-imaging resists will be the best candidates for XUV lithography, because all materials absorb strongly from $\sim$ 5 nm to 100 nm. One important benefit of surface imaging and high absorption is that interference effects due to reflections from the coated substrate will be negligible. After exposing a thin layer

of the resist with XUV photons, a dry-development process that involves anisotropic reactive-ion etching (RIE) can be used to obtain small features with steep sidewalls. First, gaseous silane is allowed to flood the surface and diffuse preferentially into the exposed areas (for negative resists), thereby selectively increasing the surface resistance to RIE with oxygen ions. A number of surface-resist processes are being developed, the best-known being the DESIRE process.⁸² It is expected that many of the resists that have been developed for electron-beam and x-ray lithographies will respond well to XUV photons, too. Also, thin, structured organic coatings, e.g., Langmuir-Blodgett films,⁸³ are being investigated to attain pinhole-free resists.

At this early stage of development of XUV projection lithography, there have been only a few laboratory exposures of resists to wavelengths in the 10- to 100-nm range. Kinoshita et al.⁸⁴ measured the depth of exposure of PMMA with 11.8-nm and 5.0-nm synchrotron radiation to be 0.08 μm and 0.3 μm , respectively. AT&T researchers measured the sensitivities of PBS, EBR-9, and PMMA resists at 36 nm to be 0.07, 0.7, and 16 mJ/cm², respectively, with the contrasts at 50% residual film thickness being 1.0, 1.5, and 1.8.⁸⁵ Their analyses of these same resists irradiated at 14 nm, where they are more transparent, indicated that the sensitivity values were twice as large and with higher contrast.⁶ Kubiak et al.¹³ have characterized four polysilane photoresists near the Si absorption edge of ~ 13 nm using a KrF laser-plasma soft x-ray source. Because of high absorption, presumably due to the carbon component, only shallow depths were exposed. As a result, low contrast was exhibited along with relatively high threshold sensitivity, ≥ 300 mJ/cm².

6.4. Direct-write option

One interesting option possible with highly absorbing photoresists, when irradiated by the high peak power produced by an FEL in the XUV, will be photovolatilization of resist material (high-energy breakup of molecular bonds into elemental and molecular gases) at relatively low single-shot fluences. Zeigler et al.⁸⁶ determined that some polysilane compounds volatilize rather than ablate when irradiated by a focused, short-pulse laser. Volatilization is preferable because particulate debris causes defects in the integrated circuits. For either ablation or volatilization processes, large absorption coefficients make short wavelengths more effective, since energy deposited per unit volume is the important parameter. This was demonstrated in the resist exposure experiments of Davis and Gower⁸⁷ where the laser fluence requirements for photoablation decreased as the film absorbance increased with progressively decreasing laser wavelength from 248 nm to 193 nm to 157 nm in the VUV. At 157 nm, they found the threshold for 20-ns laser ablation of Isoline PM resist (0.006 micron per pulse) to be 15 mJ/cm². Below 100 nm the absorption coefficient of organic materials is very large, e.g. ~ 50 - $100 \mu\text{m}^{-1}$ for PMMA at 12 nm. The corresponding ablation threshold could be 1 mJ/cm² or less at which level the 0.1 mJ per micropulse predicted for a 12-nm FEL could photovolatilize 0.1- to 1 μm^2 areas. At intensities ~ 1 - 10 MW/cm², the FEL might also induce photobleaching that could extend the depth of exposure, making thick resists possible.

6.5. Integrated xuv projection lithography experiments

Two groups have reported encouraging progress in the first experiments to demonstrate the resolution capabilities of XUV projection lithography. H. Kinoshita et al.⁸⁴ of NTT in Japan reported the first integrated experiments of XUV projection lithography that attained 0.5- μm lines and spaces using 13-nm irradiation from a bending magnet in a storage-ring. A reduced image of a reflection grating was projected onto a bilayer resist structure with a Schwarzschild reflecting system coated with Mo/Si multilayer reflectors. Also using synchrotron radiation, but with a spatial coherence produced by an undulator, an AT&T Bell Lab research team has attained even higher resolution.^{85,88} They attributed their success, in large part, to very precise alignment of the two spherical mirrors of a 20:1 reduction Schwarzschild projection system by GCA Tropel. With an exposure wavelength of 36 nm, they attained 0.2- μm lines and spaces in a trilayer resist whose thin 60-nm-thick PMMA top layer registered the image pattern. Subsequent exposures at 14 nm with a numerical aperture (NA) of 0.08 resulted in 0.1 μm features, a feat which they subsequently surpassed by printing even smaller 0.05 μm features by increasing the NA to 0.12.⁸⁸ Although the images were only 50- μm square, this series of impressive experiments demonstrates the potential resolution and sharp image definition that will justify continued development of XUV projection lithography for eventual commercial production of microcircuits.

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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. The average-power capabilities within a 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 100 mJ/cm² sensitivities and future chip dimensions projected for production in the late 1990's.

Figure 4. Basic schematic of a free-electron laser oscillator showing the electron beam accelerator, magnetic undulator and optical resonator.

Figure 5. Successful free-electron lasers in the ultraviolet to the far infrared provide the basis for extension below 0.1 μm . (The power levels indicated for the two operating points in the VUV represent coherent spontaneous emission from an undulator driven by an external 0.532- μm laser are magnified by several orders of magnitude to fit on the graph.)

Figure 6. Basic concept of the laser-irradiated photoinjector. The photocathode is mounted in the first accelerator cavity where emitted electron pulses are rapidly accelerated by a high-gradient electric field.

Figure 7. Multifacet, all-metal mirrors based on total external reflectance at large angles of incidence ($\sim 80^\circ$) will provide the necessary $\geq 40\%$ retroreflection for FEL ring oscillators over broad spectral ranges in the XUV. Intracavity, grazing incidence, hyperboloidal mirrors diverge the beam to reduce beam-induced thermal distortion on the multifacet end mirrors and allow shorter resonator lengths. The off-axis paraboloidal figure of the upper facet of the multifacet mirrors collimates the reflected beam. After Newnam,^{26,64}

Figure 8. The measured retroreflectance⁶⁶ at 30.4 and 58.4 nm of a nine-faceted aluminum retro-mirror (deposited on Si substrates in 10^{-10} Torr vacuum) verifies the predicted performance, based on measured optical constants,⁶² and exceeds 50% for wavelengths greater than 40 nm.

Figure 9. The predicted retroreflectance, based on measured optical constants,⁷⁰ of rhodium multifacet reflectors (on Si substrates) should enable operation of FEL oscillators in the soft x-ray range of 10-14 nm.

Figure 10. 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. The FEL is designed to operate on the third harmonic at 12 nm using a pulsed electromagnetic undulator with 9-mm period and a ring resonator with nine-facet Rh mirrors deposited on cryogenically cooled Si substrates.