FEL APPLICATIONS IN EUV LITHOGRAPHY

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Abstract

Semiconductor industry growth has largely been made possible by regular improvements in lithography. State of the art lithographic tools cost upwards of twenty five million dollars and use 0.93 numerical aperture projection optics with 193nm wavelengths to pattern features for 45 nm node development. Scaling beyond the 32 nm feature size node is expected to require extreme ultraviolet (EUV) wavelength light. EUV source requirements and equipment industry plasma source development efforts are reviewed. Exploratory research on a novel hybrid klystron and high gain harmonic generation FEL with oblique laser seeding will be disclosed. The opportunities and challenges for FELs to serve as a second generation (year 2011-2013) source technology in the semiconductor industry are considered.

INTRODUCTION

Over the last 30 years the numerical aperture of lithographic projection optics has increased from 0.28 to 0.93 and exposure wavelengths have decreased from 436nm to 193nm. Resolution has scaled from a few microns to tens of nanometers and leading edge microprocessors now contain 1.7 billion transistors. However, sub-wavelength patterning is requiring proximity correction, wave-front phase engineering, and water immersion for higher numerical apertures which is rapidly increasing technology cost. Extreme ultraviolet (13.5 nm wavelength) lithography is the leading candidate for next generation lithography [1]. Figure 1 shows some early resist images from a micro-exposure tool being used at Intel. However, the absence of a completely suitable EUV source remains a key challenge for high volume manufacturing.

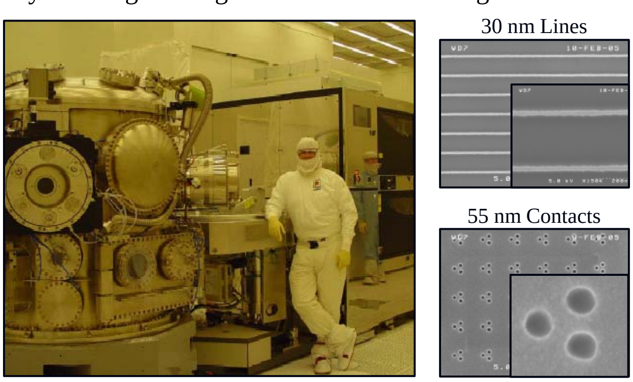

Figure 1: EUV micro exposure tool and resist images.

PRESENT SOURCE SOLUTOINS

The semiconductor equipment industry is currently pursuing both electric discharge produced plasma (DPP) and laser produced plasma (LPP) sources [2,3]. In these techniques 20-40 kilowatts of energy is pumped into a ~mm^3 volume containing a Xe, Sn, or Li fuel. Near 100 Watts of collectable in-band EUV power is expected from this method. However, out of band radiation exists in the IR to X-Ray range and light is radiated in 4π. Heating, contamination, and ablation of relatively expensive collector optics requires mitigation. Power of 50 Watts has been demonstrated for brief periods with projected collector lifetimes of a few days between required cleaning. A path to 100 Watts and one year mirror lifetime is still uncertain. Although continuous improvement will occur there is a need for a second generation EUV light source that is clean, narrow band, and forward directed. At the present time synchrotrons are used for actinic interferometry and interference lithography as plasma sources lack the necessary coherence for these applications [4,5].

Source Requirements

Industry consensus requirements jointly developed by ASML, Canon, and Nikon, are shown in Table 1 [6]. These requirements represent expectations for first generation light sources. Capital costs should be in the range of 1 – 4 million dollars per tool with operating consumable costs in the range of 0.25 – 1.0 million dollars per tool per year. System size is an implicit requirement of cost. These are relatively difficult specifications and considerable development work is required for all solutions being considered.

Table 1: EUV Source Requirements.

Metric	**Specification**
Wavelength	= 13.5 nm ± 1%
In-band power	≥ 115 Watts
Repetition rate	≥ 7 – 10 KHz
Integrated energy stability	≤ 0.3%, 3σ of 50 pulses
Maximum Etendue	≤ 3.3 mm^2 Sr.
Out of band energy	≤ 3 – 7% (130 – 400 nm) ≤ TBD (for > 400 nm)

FEL Directions

The EUV source requirements represent both a challenge and an opportunity for future free electron laser research. The use of mini-undulators has been proposed using ~half GeV energy accelerators with few mm period wigglers. [7] High energy accelerators are however larger then would be desired for a clean room or sub-facility environment. At lower energies optical wigglers [8], Cerenkov radiation [9], and resonant transition radiation [10,11,12] has been recognized as a potential source technologies, however, these methods have so far not lased or demonstrated the efficiencies necessary for high power operation. Recent developments in high gain harmonic generation (HGHG) FELs have opened up potential methods to address some of these difficulties [13].

INTEL HYBRID KLYSTRON HGHG FEL

The approach considered here is the hybrid of a klystron and high gain harmonic generation FEL. Our goal is to explore the limits of what may be possible when utilizing a relatively low energy electron beam. The approach would employ a photoelectron gun, optical wiggler, chicane, accelerator, and EUV FEL as shown in Figure 2. Electrons from the gun are first momentum modulated at low energy (≤100 KeV) with an oblique high peak power laser. The beam can be seeded with a harmonic of the wiggler wavelength if sufficient wiggler power to start-up from the Compton back scattered wave is not present. The advantage of working at a low energy is an increased velocity modulation and the potential for Lorentz compression of the bunch period after subsequent acceleration. Magnetic correction of electron divergence is required between the bunching and radiating sections of the system, as with other Klystron designs [14]. Accelerating the electron beam after seeding a density harmonic is, as far as the authors know, novel and requires further study. An FEL mechanism such as from another optical wiggler, resonant transition radiation, Cerenkov radiation, or parametric radiation is then used to generate 13.5 nm radiation from the pre-bunched relativistic beam.

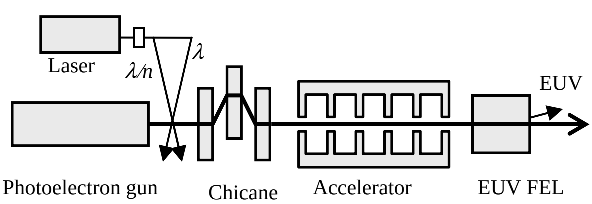

Figure 2: Schematic of the Intel FEL.

Optical Wiggler Pre-Bunching

An oblique, polarized, short pulse, and high peak power laser is focused to generate an appreciable wiggler field. The electron beam is bunched at the Compton wavelength. Benefits and drawbacks exist when using an oblique angle of incidence. This added degree of freedom allows setting the Compton wavelength at a harmonic of the wiggler laser, and seeding becomes possible without requiring an additional laser system. Overlapping the beam and wiggler is also simpler with off-axis illumination. This is because the oblique laser can have a near diffraction limited spot in one direction, as shown in Figure 3, which lessens the emittance and energy spread requirements of the electron beam. The maximum spot size of the electron beam is set by the height, H_W, of the optical wiggler cross-section and not the length, L_W, which is considerably smaller from anamorphic focusing. Neglecting space charge and magnetic focusing, the electron beam divergence is given by $\theta_b \sim \varepsilon / r_b$ where ε is the emittance and r_b is the radius of the electron beam. Thus good overlap occurs with an emittance of $\varepsilon \sim \theta_b\, r_b = \theta_b\, H_W$ which is significantly relaxed from $\varepsilon \sim \lambda_W$ required to overlap symmetric co-axial beams. The number of periods in the optical wiggler is set by the near diffraction limited length of the wiggler, *N*~ 50-100 periods, reducing the energy spread requirements to ~1/(2*N*).

There is, however, a drawback to seeding the electron beam in this way. The interaction time is low, and sensitivities to angular errors that result from divergence in both the electron beam and the optical field are increased. The emittance which produces a phase slip of $\pi/2$ is $\varepsilon = r_b\left[ArcCos\left(\frac{(2\pi N-\pi)Cos(\theta)}{2\pi N}\right)-\theta\right]$ where N is the number of periods and θ is the Compton seed angle. This emittance limit is 3 π-mm-mRad using 100 periods, a 0.5mm radius, and 40 degree angle of incidence. Emittance values below this (1.7 π-mm-mRad) have been produced by others with micro-pulses containing 1 nC of charge using a state of the art Photocathode and ~24 pS, 30 μJ pulses from a Nd:YLF fourth harmonic at up to 1 MHz [15]. The optical field also has a divergence. Assuming a Gaussian mode, the half divergence angle is $\sim \lambda_W / \pi L_W$. For 100 wiggler periods at 1053 nm, this gives a 105.3 micron interaction length and an optical divergence of 3.2 milliradians.

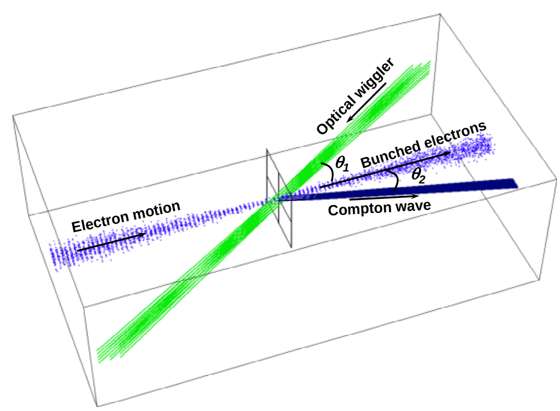

Figure 3: Bunching section of Klystron.

Bunching occurs at the Compton back scattered wavelength $\lambda_2 = \lambda_W Sin(\theta_2)/Sin(\theta_1)$ where θ_1 and θ_2 are the acute incident and back scattered photon angles from $\beta(Sin(\theta_2)Cos(\theta_1)+Sin(\theta_1)Cos(\theta_2)) = Sin(\theta_1)-Sin(\theta_2)$ with $\beta = v/c$ the electron velocity v divided by the speed of light c. The bunching section can be designed for a 13.5 nm harmonic as shown in the first configuration of Table 2; however, the potential to compress a LINAC micro-pulse is an important opportunity for improvement. Here, a simplistic Lorentz compression of the micro-pulse containing an invariant number of sub-bunches will be used for evaluation. It should be understood that alternate compression methods exist. Complicating effects such as wake fields, space charge, dispersion and other degrading mechanisms would need to be overcome in either enhancement of a current harmonic or its compression. A bunching period with compression of $\lambda_B = \lambda_2 \, \gamma_1 / \gamma_2$ is used in configurations 2 and 3 of Table 2 where γ_1 and γ_2 are initial and final Lorentz factors. This reduces the bunch period to 13.5 nm and 27 nm in cases 2 and 3 respectively. In all of these configurations the Compton wavelength is also at a harmonic of the laser wiggler. This could in principal allow a single laser system to be designed that provides both a wiggler and seed wave to the bunching section of the FEL. Alternately, bunching may start from the spontaneous emission process with significantly higher wiggler powers. In either case it may be attractive to recover unused energy from the bunching wiggler to excite the photocathode after conversion to shorter wavelengths. For electron pulses to interact with their optical pulse successors in this type of energy recovery, an optical delay line between the wiggler and cathode is required with an interval that matches the micro-pulse period of the beam.

Table 2: Example Wiggler / Seed Configurations

#	λ_w [nm]	θ_1 [deg.]	V_1 [KeV]	λ_C [nm]	θ_2 [deg.]	V_2 [MeV]
1	1053	40	95.2655	351	12.37	7.0
2	532	45	40.77	266	20.7	10.361
3	1064	40	95.24	355	12.4	7.45

Electron bunching generated from this approach is explored here by solving the pendulum equation for the system in the single particle limit. The phase position of the electron with respect to the field is given by $\Delta\psi = 2\pi - k_C z Cos[\theta] + \omega_C t$ where k_C is the wave number and ω_C is the angular frequency of the Compton or introduced seed wave. The standard FEL pendulum equation is modified due to the non-collinear nature of the interaction and becomes $\frac{\partial^2 \psi}{\partial z^2} + \xi Sin[\psi] = 0$ with $\xi \equiv 2\left(k_o - \frac{k_C \theta^2}{2}\right) k_C \frac{a_w a_s}{\gamma}$ where a_w and a_s are the wiggler parameters for the optical wiggler and signal (seed) wave and k_o is given by the resonance condition $k_o = k_C\left(\frac{\theta^2}{2} + \frac{1 + a_w^2}{2\gamma^2}\right)$. This has been explored numerically for case #1 of Table 2 with a longitudinal energy spread of ±0.25%, a wiggler divergence of ±50 mRad, and 0.5mJ 10pS wiggler and seed pulse using 1mm×100µm wiggler cross-section. The results are shown in Figure 4, and an appreciable bunching of the beam is observed.

EUV Emission

The accelerated electron beam energies in Table 2 (γ_2 = 14.7 – 21.3) are particularly convenient for generating EUV (13.5 nm/91.85eV) photons using resonant transition radiation and CO2 laser back scattering.

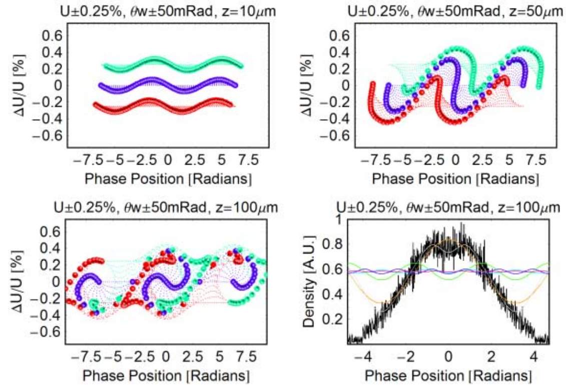

Figure 4: 351nm bunching of a 95.27 KeV beam.

Electrons crossing the interface of distinct media emit transition radiation up to a region of $\omega \sim \gamma\omega_p$, where ω_p is the medium electron plasma frequency. Accurately spacing the interfaces allows for coherent superposition in a modest bandwidth for a thin annulus of observation. Two types of devices have been fabricated in experiments at Intel. These are metal/dielectric multilayers and vacuum/tri-layer foil stacks [16]. An example spectrum is calculated and shown in Figure 5.

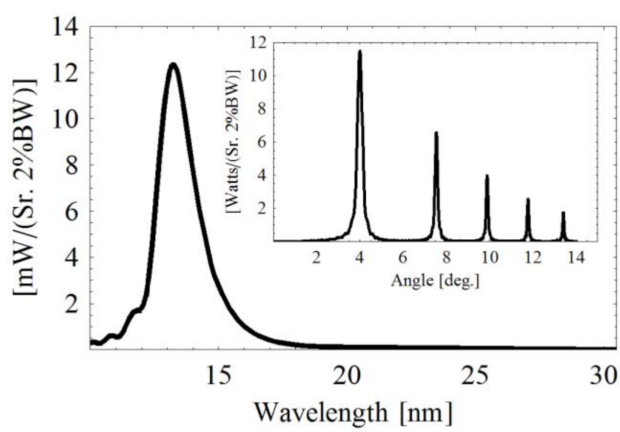

Figure 5: [MoN/Mo/MoN/vacuum]^20 stack (6/27/6/2100nm) emission at 7.0 MeV 0.91 mA.

Compton backscattering is a second convenient mechanism for generating EUV photons from a relativistic electron beam. Scattering a CO2 laser (10.6 µm) at 34.8 degrees from a 7MeV beam generates 13.5 nm light at an angle from the beam of 0.042 degrees.

The power that can be extracted from a bunched electron beam in free space with harmonic generation can be expressed by $P = \frac{\pi Z}{\gamma^4}\left(\frac{L}{\lambda}\right)^2 \langle I^2 \rangle$ where Z is the impedance of the medium (377Ω in vacuum) and L is the interaction length. For a bunched electron beam with micro-pulses of length τ_b, charge Q_b, and $\Delta n/n$ harmonic density content, the average current square is $\langle I^2 \rangle = \frac{rep.\_rate}{\tau_b} \times \left(Q_b \frac{\Delta n}{n}\right)^2$. Using L/λ=100, τ_b=10^{-11}, and a 1 MHz repetition rate, the expression for radiated power becomes $P = 1.2\times10^{6}\,\frac{Q_H^2}{\gamma^4}$ where Q_H is the harmonic component of the bunch charge in nC. Using a target power of 100 Watts at 7 MeV, the charge Q_H is found to be 2 nC. Thus, for bunching of ~10%, a micro-pulse charge on the order of 20 nC is required. The corresponding average electron beam current is 20 mA. Although large, this is much less than the ampere state of the art [17].

CURRENT DEVELOPMENT

A compact MEMS metal-vacuum stack and a metal-dielectric stack are explored as EUV FEL sources. A TEM of a metal-dielectric stack is shown in Figure 6.

A metal-vacuum stack composed ~2mm diameter diaphragms of 6/27/6nm MoN/Mo/MoN are fabricated to extract power from the bunched electron beam. Use of asymmetric capping layers, which prevent oxidation, is being investigated to promote unidirectional buckling of all of the layers to improve spacing at elevated temperature. The spacing is chosen according to the electron energy so that coherent superposition occurs.

An electron beam has been constructed to investigate both optical bunching of electron beams and TR emission from multilayer structures. The aim of the research is to generate EUV using compact FEL approaches.

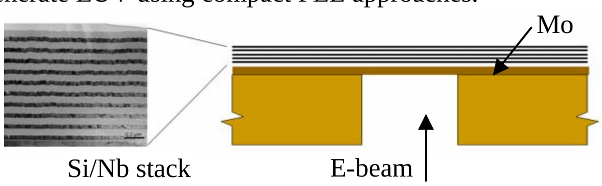

Figure 6: Diagram showing a high resolution TEM of a 100nm/60nm Si/Nb multilayer fabricated on top of a 24µm thin Mo foil supported on Al.

CONCLUSION

The main goal of this work is to challenge the FEL industry to create new ideas and solutions for a high power, clean, reliable, and a moderate-cost compact EUV source. We have proposed a hybrid klystron HGHG FEL to meet this challenge. To lower costs and reduce size, we have suggested relying on a moderate energy electron source, an optical wiggler, and a transition radiation demodulator. Our preliminary estimates show that the power emitted from such a device would be adequate of EUV lithography.

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