DEUTSCHES ELEKTRONEN-SYNCHROTRON

DESY 01-179
November 2001

VUV Lithography Based on SiC Reflective Optical Systems and SASE FEL Coherent Light Sources as a Natural Extension to Shorter Wavelengths of Present-Day Optical Lithography Technology

C. Pagani

INFN Milano - LASA, Italy

E. L. Saldin, E. A. Schneidmiller

Deutsches Elektronen-Synchrotron DESY, Hamburg

M. V. Yurkov

Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia

ISSN 0418-9833

NOTKESTRASSE 85 - 22607 HAMBURG

DESY 01-179
November 2001

ISSN 0418-9833

VUV Lithography Based on SiC Reflective Optical Systems and SASE FEL Coherent Light Sources as a Natural Extension to Shorter Wavelengths of Present-Day Optical Lithography Technology

C. Pagani [a], E.L. Saldin [b], E.A. Schneidmiller [b], M.V. Yurkov [c]

[a] *INFN Milano - LASA, Italy*

[b] *Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany*

[c] *Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia*

Abstract

The semiconductor industry growth is driven to a large extent by steady advancements in microlithography. According to the newly updated industry roadmap, the 50 nm generation is anticipated to be available in the year 2012. This paper discusses the basic concepts of VUV lithography (VUVL), a relatively new form of lithography that uses vacuum ultraviolet radiation (VUV) with a wavelength in a range of 50 to 100 nm to carry out projection imaging. This approach uses a Self Amplified Spontaneous Emission (SASE) Free Electron Laser (FEL) as a source of radiation, a reflective mask, and a 4X reduction all reflective imaging system. The reflective elements for VUVL use SiC mirrors to produce normal incidence reflectivities nearly 40% . The mask in a VUV system also uses the same type of SiC material. Recent advances in SASE FEL systems suggest the feasibility of flexible sources for microelectronic production facilities. Any lithography must satisfy cost-ownership requirements. A VUV SASE FEL source is economical for high-volume production, because it can feed multiple steppers. The average SASE radiation on wafers is about 1 W, and throughput of each stepper is 90 wafer/hr. Estimated SASE FEL source portion of total cost is about \$ 0.5 per 300 mm wafer. We believe that the underlying simplicity of the technology, particularly the mask and mirror and low source portion of total cost will make VUVL a cost effective solution for lithography at 100 nm and below. Since the wavelength of SASE FEL source is adjustable, selection of new materials needed for photoresists may be much easier than for the case of fixed wavelength source. SiC mirrors with characteristics required for VUVL optics are produced by industry. All components of the proposed SASE FEL source equipment have been demonstrated in practice. This is guaranteed success in the time requirement.

Preprint submitted to Elsevier Science *30 October 2001*

1 Introduction

The electronic industry is supported by the semiconductor industry, and the semiconductor industry is supported by the equipment industry where lithography has been the critical link. The speed and performance of the chips are dictated by the lithographic minimum printable size. Lithography, which replicates a pattern rapidly from chip to chip, also determines the throughput and the cost of electronic systems. Lithography is perhaps the most critical of the processing steps since about half of the capital equipment cost for a wafer fabrication is in lithography. Any future lithography technology must address the issues of a tool cost, throughput, mask costs, and process costs in order to be viable.

Current lithography for high-volume manufacturing employs optical projection. In projection photolithography, the mask is moved to near the light source. The presence of the different transparent and opaque regions patterns the light source. This patterned light beam is then passed through a reducer lens, which is focussed on the sample. The reducer acts to decrease the size of the light beam, and hence the size of the pattern. The pattern that is written on the sample is therefore smaller than the pattern than is in the mask. The actual size of the pattern is determined by the reducing factor of the lens, and can be a factor of four or more smaller than the mask pattern. The most advanced lithography tools use a wavelength of 193 nm. This will take the integrated circuit (IC) industry to 130 nm scale features. For IC features of 100 nm and beyond a new lithographic concept is required.

IC industry is willing to invest billions of dollars to develop future lithographic technologies. There are four main next-generation lithography (NGL) technology contenders for 100-nm lithography and below. They are extreme ultraviolet lithography (EUVL), electron projection lithography (EPL), ion-beam projection lithography (IPL) and synchrotron-based proximity X-ray lithography (PXL). International SEMATECH hopes to build global consensus for a single NLG technology choice in near future. The huge cost of converting semiconductor manufacturing facilities to the new technology demands that the industry selects just one. In year 1999, International SEMATECH narrowed its choice of possible successors to optical lithography to two: EUVL and EPL [1]. Nevertheless, industry experts generally agree that it is too early to make a singular NLG decision. Now we can recognize the fallibility of recent NLG decision. Although, the recommendation for International SEMATECH to focus its funding efforts on the two selected technologies does not imply that development efforts in the other two selected technologies under consideration - X-ray and ion-beam projection lithography - should stop, the effect was to kill PXL development and infrastructure in the United States. However, at the XEL 2000 conference in Yokohama, where progress on all of four NLG technologies was reported, it was clear that Japan's PXL is many years ahead of the others. In contrast, the problems of EUVL and EPL are only slowly being revealed. It is not at all clear that either could succeed in semiconductor manufacturing, regardless of how much money and manpower is devoted to them [2].

The shift to smaller feature size traditionally was done by reducing the wavelength of optical lithography systems. As the wavelength becomes shorter, the light source become more complex and expensive. The present light sources under consideration for NGL include laser plasma sources and synchrotron radiation sources. A new era in the technology of powerful synchrotron radiation sources began in year 2000, with the first demonstration of the high gain linac-based SASE FEL at 100 nm wavelength. Radiation from a SASE FEL has much a common with radiation from a conventional optical laser, such as high power, narrow bandwidth and diffraction limited beam propagation. While the electrons from linear accelerator are propagating through a long periodic magnetic dipole array - a so called undulator - the interaction with electromagnetic radiation field leads to an exponential growth of the radiation emitted by the electrons. This amplification of radiation is initiated by an increasingly pronounced longitudinal density modulation of the electron bunch. In the beginning - without micro-bunching - all the N electrons in a bunch can be treated as individually radiation charges with the power of the spontaneous emission proportional to N. With complete micro-bunching all electrons radiate almost in phase. This leads to a radiation power proportional to N^2 and thus an amplification of many order of amplitude with respect to the spontaneous emission of the undulator. The experimental results presented in Ref. [3] have been achieved at the TESLA Test Facility (TTF) at DESY (Hamburg). The TTF team also demonstrated tunability of the SASE FEL in the wavelength range from 80 to 180 nm [4]. Today's current photon density gain achieved at 100 nm is about 60 dB [5]. In other words, the coherent energy enhances the spontaneous energy radiated into the 1% wavelength bandwidth by a factor of 10^6.

SASE FELs hold great promise as a bright sources of VUV-EUV radiation for applications such as a projection lithography. This paper discusses the basic concepts of VUV lithography (VUVL), a relatively new form of lithography that uses vacuum ultraviolet radiation (VUV) with a wavelength in range of 50 to 100 nm to carry out projection imaging. This approach uses a SASE FEL source of radiation, a reflective mask, and a 4X reduction all reflective imaging system. The reflective elements for VUVL use SiC mirrors to produce normal incidence reflectivities nearly 40% . Recent advances in SASE FEL systems suggest the feasibility of flexible sources for microelectronic production facilities. In the Ref. [6] we presented design considerations of SASE FEL based on superconducting RF linear accelerator which provides in the 50-100 nm wavelength range average output light power up to 10 kW within 0.5% bandwidth. Any lithography must satisfy cost-ownership requirements. A VUV SASE FEL source is economical for high-volume production, because it can feed multiple steppers. We believe that the underlying simplicity of the technology, particularly the mask and mirror and low source portion of total cost will make VUVL a cost effective solution for lithography at 100 nm and below. Since the wavelength of SASE FEL source is adjustable, selection of new materials needed for photoresists may be much easier than for the case of fixed wavelength source. SiC mirrors with characteristics required for VUVL optics are produced by industry. All components of the proposed SASE FEL source equipment have been demonstrated in practice. This is guaranteed success in the time requirement.

2 Favored NGL technologies

EUVL and PXL technologies are not the topic of this article. However, before explaining radically new way, some background is needed.

2.1 *EUV lithography*

The most logical approach to extending the capabilities of lithographic systems is to proceed with standard projection systems and move to steadily smaller wavelengths. In principle, EUVL is a logical extension of optical lithography to very short wavelengths. Extension of conventional refractive optical lithography to wavelength below 150 nm is problematic due to absorption in the refractive elements. To solve the absorption problem associated with lenses, researches turned to mirrors that reflect and focus the light on the chip. EUVL uses radiation at wavelength of 14 nm to obtain lithographic printing down to 30 nm resolution. The reflective elements for EUV use multilayer mirrors to produce reflectivities up to nearly 70% . The mask in an EUV system is reflective and also uses the same type of multilayers. A plasma-source is used to illuminate the mask, which is imaged by a system of mirrors onto resist-coated wafer with a reduction factor of four [7].

At very short wavelengths, however, problems begin to appear. The optical systems require mirrors with unprecedent tolerances with respect to figure and finish. That is, the shape of mirror must be corrected in addition to the surface being smooth. The specification are in the Angstrom and, in some cases, sub-Angstrom (i.e Bohr radius) range posing serious challenges for mirror fabrication. The main problem with EUVL is not the resolution. The big problem is the production of mask. To reflect the 14 nm

EUV wavelength, the silicon wafer mask blank is coated with 80 alternating quarter wavelength layers of molybdenum and silicon. An absorber is then deposited and patterned to complete the mask. The most serious issues for EUV masks are in creating multilayer coatings with no defects. Even very small (30 Å) defects in the multilayers can print unwanted features on the wafers [8].

EUVL presents numerous challenges related to understanding and developing materials for its successful implementation. Glass ceramic composite material is used as the mirror substrate material for EUV optics. Little is known about characteristics of the polished surfaces of this complex materials at the subnanometer scale. Properties such as long term stability, delayed elasticity, atomic structure, near surface damage need to be studied and measured at the Angstrom level. Typical multilayer film in use today consists of 80 or more layers of Mo and Si each with thickness on order of 30 Angstroms. Degradation of the interfaces caused by interfacial reactions, diffusions, alloy formation, etc. will result in time dependent decrease in reflectivity. Since tool throughput is dependent on the nR, where R is the film reflectivity and n is the number of mirrors in the optical system (n = 7-9), even 1% changes in R will have significant impact on performance.

As the wavelength becomes shorter, the light source become more complex and expensive. EUV is generated by laser-produced plasma source created by focusing radiation from a Nd:YAG laser onto Xe clusters produced by a pulsed gas jet system. The conversion efficiency is about 1% of incident laser light into an EUV band of 2.5% relative spectral bandwidth at 13.4 nm, and solid angle of 2π sr. An elliptical condenser collects about 3% of available 2π sr EUV radiation and projects it onto the mask in the camera chamber [7,10]. Because the photons in the EUV system are reflected at least seven times (two condenser mirrors, reflective mask, and four projection mirrors) before they hit the wafer, the losses mount until only < 4% of the original photons hit the target, which makes for long, costly exposure times. Problem that need to be resolved to enable a cost effective system using EUV lithography is a high-power source. Existing laser generated plasma sources are too low in output.

2.2 X-ray Lithography

Proximity X-ray lithography is, in effect, a method used to obtain a one-to-one X-ray shadowgraph of mask and recording the mask image in the underlying resist. PXL utilizes nominal 0.8-0.4 nm wavelength radiation. It uses relatively broadband bending magnet synchrotron radiation with relatively simple beamline optics. The simplicity of X-ray lithography, which accrues trough the absence of reduction optics, is offset by complexity

in the mask. For X-ray lithography the mask is 1:1 with the wafer, and consists of an absorber pattern on a thin, two microns thick, membrane. The mask is approximately 10 microns above the wafer. The membrane is either silicon carbide (SiC) or diamond.

Compared to other next lithography alternatives, a key advantage of X-ray lithography is the long history of technology development. Over this time period a large experience base has accrued to clarify the key technical challenges in detail. Among these challenges X-ray mask technology for volume manufacturing has been considered a critical issue. In contrast to optical lithography mask, X-ray lithography masks are thin membranes. Energy absorption during exposure needs to be controlled to maintain pattern integrity on the membrane. Given that the X-ray mask pattern is the same feature size as the final pattern on the wafer, the ability to reliably write the pattern with an e-beam tool has also been in question. Now PXL masks has demonstrated defect levels, which two order of magnitude above target level $10^{-2}/cm^2$.

The preferred source for PXL manufacturing is the synchrotron with multiple beamlines. Sumitomo Heavy Industries has developed a new synchrotron based on several years experience in the design and construction of synchrotrons for PXL. It employs normal magnets, and operate with a beam of 500 mA and a beam lifetime of 19 h. A simple radiation shield is build into cover of the unit, which accommodates 20 beamlines. The exposure intensity is 40 mW/cm^2 over 30 × 30 mm^2 field, which translates into an exposure time of about 2 sec per field [2]. The exposure time and throughput goal are 0.45 sec and 40 wafer/hr, respectively.

PXL is economical for high-volume production. The most expensive component, the synchrotron X-ray source, is expected to support ten or more steppers. The accelerator, each beam line, and accelerator building cost are $ 20M, $ 1.5M, and $ 10M, respectively. The depreciation term for accelerator, beam lines and building is 10 years. Assuming that 10 steppers are installed per storage ring, the source contribution to exposure cost is $ 1.4/wafer [11].

3 VUV lithography a reality for 100 nm production and beyond

3.1 VUV optics

VUV lithography, a novel approach to lithography that has been seen as the primary competitor to EUVL, is discussed in this section. In principle, VUVL is also a logical extension of optical lithography to short wavelengths. The wavelength range 40-120 nm is called Vacuum Ultraviolet, and the VUV-lithography utilizes light of 50 100 nm wavelength. This is the peak reflectivity wavelengths of silicon carbide (SiC). The idea of VUV lithography is to use SiC reflective optical systems and powerful VUV SASE FEL source [6]. SiC has a reflectivity at normal incidence of about 40% in the VUV wavelength range between 50 and 100 nm. It can be polished to a supersmooth surface with rms roughness of 2 Å. This material is very hard, stable and has high electrical conductivity and excellent thermal properties, such that surface distortions caused by high average absorbed power are negligible.

The mask in a VUV system is reflective and also uses the same type of SiC surface. A powerful SASE FEL source is used to illuminate the mask. Once the image is reflected from the mask, its travels through the projection optics system. The four SiC mirrors of the projection optics system reduce the image and form it onto the wafer with reduction factor of four. The resolution of a lithography system is usually expressed in terms of its wavelength and numerical aperture (NA) as

$$\mathrm{Resolution} = k_1 \frac{\lambda}{\mathrm{NA}} ,$$

where the k_1 is dependent on the process being used. In IC manufacturing, typical values of k_1 range from about 0.5 to 0.6 today. The idea of VUV lithography is to use large NA reflective optical elements at wavelength about equal to the smallest circuit dimensions. For example, an VUV system with wavelength of 50 nm and NA of 0.5 can yield 50-nm resolution. Another major limitation besides resolution in optical lithography is the depth of focus (DOF), which is governed by the equation

$$\mathrm{DOF} = k_2 \frac{\lambda}{(\mathrm{NA})^2} ,$$

where $k_2 \simeq k_1$ is a constant for a specific lithographic process. Historically, the "Comfort Zone for Manufacture" corresponds to the region for which DOF $> 0.5\ \mu$m [9]. Recently, however, it has been necessary to extend 193 nm imaging technologies to ever smaller DOF values down to 200 nm. Depth of focus values associated with VUVL for the printing of critical dimensions (CD) values ranging from 100 nm down to 50 nm will be DOF = 200 - 100 nm, i.e. comparable to the DOF associated with 193 nm lithography to print CD's down to 130 nm [9].

Compared to the multilayer EUV optics, a key advantage of VUV optics is the long history of technology development of SiC mirrors. Over this time-period a large experience base has accrued to clarify the key technical problems in detail. Now SiC mirrors with characteristics required for VUVL are produced by industry and are widely used at synchrotron radiation beam lines.

Industry experts generally agree that the biggest challenges and risks for the next generation lithography systems involve the mask. The technology that successfully overcomes the problems of mask production has a good chance of becoming the preferred choice. The VUV mask is produced by applying VUV-absorbing metal layer to flat SiC substrate and then etching away the metal to form the image of the circuit. We believe that the underlying simplicity of the mask technology will make VUVL a promising technology for lithography at 100 nm and below.

3.2 VUV source

Present level of accelerator and FEL technique allows to solve the problem of powerful laser for VUV lithography. FEL is a device in which electromagnetic radiation is amplified by the electron beam moving in the undulator. FEL devices can be divided into two classes: amplifiers and oscillators. FEL amplifier amplifies the input electromagnetic wave from the external master laser. The FEL oscillator can be considered as an FEL amplifier with feedback. For the FEL oscillator in the optical wavelength range the feedback is carried out by means of an optical resonator. An attractive feature of the high gain FEL amplifier scheme is the absence of no apparent limitations which would prevent operation at short wavelength range. Since the amplification process develops in vacuum during one pass of the electron beam through the undulator, the problem of the absorption of the radiation in the cavity mirrors does not exist at all. An important problem is that of input signal. Since the desired wavelength is very short, there is no laser to provide the input electromagnetic wave. Nevertheless, fluctuation of the electron beam current density can serve as the input signal in the FEL amplifier. These fluctuations always exist in the electron beam due to the effect of shot noise. An FEL amplifier which starts up from shot noise is frequently known as self-amplified spontaneous emission (SASE) FEL. Detailed description of SASE FEL theory and the photon beam properties can be found in [14]. The development of VUV 'litho' sources has been speeded up by recent dramatic progress in SASE FEL technology. The experimental results, which have been achieved at DESY [3–5] and at Argonne National Laboratory [12], form reliable experimental basis for industrial VUV SASE FEL discussed below.

In [6] we performed design consideration of 10 kW-scale VUV SASE FEL. The design consists of a 12 MeV electron injector, a one pass 1 GeV accelerator, and a uniform undulator. The exhaust electron beam from the FEL is decelerated for the energy recovery and dumped at final energy 10 MeV. In this design the beam dump energy is below the photon-neutron production threshold, so the problem of radio-nuclide production in the dump does not exist. The technical approach adopted in this design makes use of superconducting RF linear accelerator (SRF accelerator). With SRF linac, a SASE FEL would acquire high average power, thanks to the input beam continuous-wave (CW) nature. The energy recovery of most of the driver electron beam energy would further increase the wall plug power to output VUV radiation power efficiency up to 1%. The electron beam qualities required for VUV SASE FEL operation can be met with a conservative injector design using a conventional thermionic DC gun and subharmonic bunchers. Average current produced by the injector is 10 mA. The SASE FEL provides a continuous train of 0.5 ps micropulses, with 2 mJ of radiation energy per micropulse at repetition rate 6 MHz. The radiation from SASE FEL is spatially coherent. The bandwidth of the output radiation would be about 0.5%. When considering a possible technical realization of the injector we have used only those technical solutions which have been used 10 years ago. The SRF modules for the main accelerator have been produced by industry. This is advantageous for compressing development time.

Let us discuss the problem of output optical system for the VUV SASE FEL. Average radiation power at the exit of SASE FEL is about 10 kW. To provide the possibility of application for VUV steppers, the laser beam should be divided. In principle, there could be a lot of possibilities to divide initial CW radiation beam. Here we consider one of them. The initial radiation beam is transformed into 100 parallel beams of 1 ms macropulse duration and repetition rate of 10 Hz. It could be done, for instance, by means of rotating mirrors. For maximum efficiency the mirrors should be manufactured of highly reflecting material such as SiC. In the range 50-100 nm the SiC mirror reflectivity at grazing angles 10-15° is about 90% for s-polarization, and 80% for p-polarization. This material has excellent thermal properties such that surface distortions caused by the average absorbed power are negligible. Separation of the radiation beams is performed in two steps. At the first step the beam should be divided by the system of 10 rotating mirrors into 10 beams of 1 ms pulse duration and repetition rate of 100 Hz. At the second stage, each of the 10 beams is separated into 10 beams. The radiation power losses in the mirror is about 10%, so the integral losses of the radiation power in the dividing system are about 20%, and the output optical system produces 100 laser beams of 100 W average power (macropulse duration 1 ms, macropulse energy 10 J, repetition rate 10 Hz) which are directed to the VUV steppers.

The development and test of the tools for VUVL is greatly facilitated by the fact that required parameters of the radiation source are practically identical to those being developed in framework of SASE FEL user facility at DESY [13]. The SASE FEL user facility at DESY will produce in the VUV-EUV wavelength range (10-70 nm) train of 0.5 ps micropulses with about 1 mJ of radiation energy per micropulse at repetition rate of 9 MHz. The 1000 MeV SRF accelerator will operate at 1% duty factor. The average output radiation power can exceed 50-100 W. Commissioning of this facility could start in year 2003 [5]. The SASE FEL at TTF would allow to test various novel hardware components and could be used for pilot tests of the sub-100 nm lithography technology.

3.3 Cost-of-ownership study on VUVL technique

Estimating the cost of ownership (CoO) for any lithography system is always a risky business, fraught with the necessity of making numerous guesses. Nevertheless, analysis presented below indicates that the CoO for VUVL should be significantly lower than for EUVL technology.

Superconducting linear accelerator used to generate the high power of VUV SASE radiation is relatively expensive, approximately $ 150 million dollars. However, a SASE FEL source is economical for high-volume production, because it can feed multiple steppers. A SASE FEL source is assumed to yield 12 kW average power and is expected to support 100 steppers. Table 1 shows the result of VUVL stepper throughput estimation. The output dividing system produces 100 radiation beams which are directed to the steppers. The stepper exposure area is 26x27 mm2, and the exposure steps in a 300 mm wafer are 80, assuming 80% wafer area utilization. The average SASE radiation on wafers is 1 W, and the resist sensitivity 5 mJ/cm2. The exposure time thus obtained is 0.03 sec. Assuming stepping motion $W_s = 0.2$ sec and overhead time 20 sec the raw throughput of this stepper is 90 wafer/hr

The accelerator, VUV beam line and accelerator building cost are $ 150M, $ 1.5M and $ 20M, respectively. The depreciation term for accelerator and beam line is 10 years, taking into account their application in plural device generations, and the depreciation term for building is 10 years. We assume that 5 persons takes care of accelerator by a cost of $ 50/hr. AC wall plug power consumption is about 1 MW.

Exposure cost can be acceptably low for high-volume production, where 100 steppers reduce the source portion of total cost to $ 0.5 per wafer single layer. The VUV mask and mirrors are significantly less expensive than EUV multilayer mask and mirrors and we believe that VUV lithography cost will be less than $ 20/wafer layer.

References

[1] R. DeJule, Semiconductor International, March 1999

[2] H. I. Smith, Semiconductor International, February 2001

[3] J. Andruszkov, et al., Phys. Rev. Lett. 85(2000)3825

[4] J. Rossbach, Proceedings of EPAC2000 Conference, Vienna, Austria, Jun2 2000, p.88

[5] M. Koerfer, "The TTF-FEL status and its future as soft X-ray user facility" presented at 23rd Int. FEL Conf.(Darmstadt, Germany 2001), Nucl. Instrum. and Method. A, in press.

[6] C. Pagani, et al., Nucl. Instrum. and Methods A 463(2001)9

[7] D. Attwood, "Soft X-rays and Extreme Ultraviolet Radiation" (Cambridge University Press 1999)

[8] L. R. Harriott, Proceedings of the IEEE, vol. 89, No. 30 March 2001, p.366

[9] J. E. Bjorkholm, Intel Technol. J. Q3(1998)1

[10] R. H. Stulen and D. W. Sweeney, IEEE J. Quantum Electron. 35(1999)694

[11] Y. Gomei, Semiconductor International, February 2001

[12] S. V. Milton, et al., Science 292(2001)2037

[13] J. Rossbach, Nucl. Instrum. and Methods A 375(1996)269

[14] E. L. Saldin, E. A. Schneidmiller, and M.V. Yurkov, "The Physics of Free Electron Lasers" (Springer-Verlag, Berlin-Heidelberg-New York, 1999)