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Trends in Research and Development of Lithography Technology for Next-generation LSIs

ATSUSHI OGASAWARA
Information and Communications Research Unit

3.1 Introduction

On April 12, 2001, the world's first EUV (extreme ultraviolet) lithography tool for the next-generation LSIs, which allows semiconductor manufacturers to print circuit lines below 0.1μm (100nm), was revealed at the Sandia National Laboratories of the U.S.

This tool was developed in collaboration with the U.S. DOE (Department of Energy) laboratories (Sandia, Laurence Berkley and Laurence Livermore) and a consortium called EUV LLC, which consists of Intel, Motorola, AMD, Micron Technology, Infineon Technologies (Germany) and IBM.

The tool currently allows mass production in accordance with the 0.07μm (70nm) rule, and is expected to support 0.03μm (30nm) in the future. Specifically, the current operating frequency of 1.5GHz with the Pentium 4 processor is expected to reach 10GHz in 2005 to 2006.

Japan's semiconductor technology, which conventionally developed with DRAMs as the technology driver, maintained its top position in terms of device scaling throughout the 1980s and the 1990s. This success has been made possible mainly due to the fact that Nikon and Canon, both of which have excellent optical technologies, have maintained their leading positions in the field of steppers (projection printing tools for circuit patterns) for LSIs.

In the late 1990s, the United States regained the world's top position from Japan in semiconductor share with its designing technologies represented by the MPU technology. Additionally, it has launched a campaign aimed at also capturing the top position in lithography technologies, which are expected to play the principal role in manufacturing technologies, in order to solidify its position in the next-generation LSIs market.

This article analyzes the United States' EUV lithography technologies, and touches upon Japan's course of direction in technological development.

3.2 Situation by Country in Lithography Technologies

3.2.1 Current Status of Lithography Technologies

Since the 1980s, Japan has boasted its overwhelming strength in the stepper market for semiconductor manufacturing, with Canon and Nikon maintaining approx. 30% and 40% shares, respectively. In the past few years, however, ASML of the Netherlands has made significant progress with the backing of Philips and Carl Zeiss, and in fiscal 2000, it overtook Nikon to capture the top share, 40%-plus. Thus, Japan is being overwhelmed from attacks by the U.S. and European powers not only in the next-generation LSIs market but also in the present-generation market.

Even in the development of existing optic-based lithography technology, Japan is being overtaken by ASML in terms of greater lens diameters and higher NAs (numerical apertures). This is largely owing to the fact that Schott Glas supports Carl Zeiss lenses with its material handling technique. Schott's expertise in optic fiber production is used in forming lens material crystals; thus, technologies that are not based on the conventional method of manufacturing camera lenses are being tested.

Chart 1: Roadmap of Lithography Technologies

	Light Source	Wavelength (μm)	Introduction timing (year)
Optical method	KrF	0.248	Currently mass-produced
	ArF	0.193	2000 ~
	F_2	0.157	2003 ~
Electron-beam projection	EPL	Variable	2006 ~
Extreme ultraviolet method	EUV	0.0134	2008 ~

Source: Data by Ohmi Lab, New Industry Creation Hatchery Center, Tohoku University

3.2.2 Roadmap of Lithography Technologies

Since line widths have been decreasing in the manufacture of LSIs, it was formerly thought that lithography technologies would be developed according to the roadmap indicated in Chart 1.

3.2.3 Situation in Japan

In Japan, research and development efforts for optical methods are being made from ArF to F_2, in accordance with the schedule indicated above. The industry leader Nikon is proceeding with the development of the F_2 method, and for the development of a post-optical generation method, it has chosen EPL to be developed in cooperation with IBM.

3.2.4 Situation in the United States

In the United States, however, the industry has concluded that it would be difficult to manufacture large crystals of CaF_2, which is one of the lens materials, in developing the F_2 method, and shifted to the EUV method. The decision was based on the grounds that if an F_2-based stepper was manufactured with the existing method (pulse oscillation), it would require tens of CaF_2 crystal lenses, each measuring 30cm in diameter and 20cm in thickness, in order to reduce the high energy density. It was judged that the F_2-based stepper would not be feasible because at that size, the production yield of the crystal would be very low, and the CaF_2 crystal, which has relatively low mechanical strength, would be deformed by its own weight.

EPL was another possibility for a next-generation method. However, EUV was chosen since with EPL, it would be difficult to manufacture a mask and the throughput would be lower than EUV. Also, it is said that the technology developed for a reconnaissance satellite was used in developing the EUV method of condensing beams. This implies the transfer of a military technology.

The course of direction of the whole U.S. semiconductor industry has become clear as IBM, which was developing the EPL technology in cooperation with Nikon, joined EUV LLC in March this year.

3.2.5 Situation in Europe

The European semiconductor industry is adjusting its stride to the United States as Infineon Technologies (Germany) has joined EUV LLC, and ASML has withdrawn from the development of EPL and starting cooperating with EUV LLC. However, the European industry slightly differs from U.S. in that it has not given up on the possibility of the F_2 method. For example, the ASML-Carl Zeiss-Schott alliance has developed a lens with a 0.9 NA for the manufacture of CaF_2 crystals with the F_2 method. The European industry is also characteristic in that it has superior crystal researchers in the former Eastern European and former Soviet Union countries and material technologies based on the latest optical fiber technologies, neither of which are found in the U.S. industry.

3.3 Course of Direction in Next-generation Lithography Technologies

3.3.1 Problems of the EUV Technology

As described above, the U.S. and European strategies are all being oriented toward EUV as the next-generation lithography technology. However, this does not mean that the EUV method is the favorite next-generation lithography technology for the following reasons.

Chart 2: Photon Energy

	Wavelength (μm)	Frequency (PHz)	Photon energy	
			eV	Ratio to KrF
EUV	0.0134	22.4	92.53	18.506
F_2	0.157	1.910	7.90	1.580
ArF	0.193	1.553	6.42	1.285
KrF	0.248	1.209	5.00	1.000

Source: Data by Ohmi Lab, New Industry Creation Hatchery Center, Tohoku University

Chart 3: Band Gaps of Materials

Material	Band gap
CaF_2	9.41eV
Al_2O_3	8.95eV
SiO_2	8.95eV

Source: Data by Ohmi Lab, New Industry Creation Hatchery Center, Tohoku University

(1) High energy damage

Since EUV is a microwave (0.0134μm), a single photon can generate high energy of 92.5eV (Chart 2).

As indicated in this table, EUV generates energy 18.5 times higher than the existing KrF. This level of energy is far greater than the band gap of any lens material or optic material shown in Chart 3, and will excite electrons that contribute to the coupling to damage the material. To solve this problem, a miller with high reflectivity is used to condense light. However, any lens-based method will cause light to directly enter the mask surface, even if a miller is used. Since a multi layer film of MoSi is used in the mask, it is highly likely that it will generate high temperature as it receives high energy.

Therefore, the materials constituting the mask and the device may deteriorate, leading to an increase in the overall cost.

(2) Precision of the mask

Since the mask has a multi layer structure, it requires very high precision and the throughput in the manufacture of the mask will remain low.

(3) Contamination from the EUV light source

Metal vapor may adhere to the optical system.

3.3.2 Possibility of the F_2 Method

Although the United States has almost abandoned the F_2 method, if the light source for the present pulse wave method is converted to a continuous wave system, the sharp power peak can be controlled and the present performance can be achieved with a smaller CaF_2 crystal by reducing the load on the optical system. Since the largeness of CaF_2 crystals that are formed is the biggest problem of this method, if an F_2 excimer laser capable of continuous oscillation is developed, it will be possible to develop a system optimized for mass production. The line width can be dropped to 0.05μm using a 0.9 NA lens.

3.3.3 Possibility of the Electron Ray Method

Although the electron ray method is increasingly considered unsuitable for the next-generation lithography technology both in the U.S. and Europe, this method has advantages that are not found in the optical and EUV methods. With the electron ray method, a higher NA lens will be used in response to miniaturization. The higher the NA, the shallower the focal depth becomes. In other words, the range for adjusting the focus in the vertical direction becomes smaller. Even with the EUV method, images are formed on the wafer, and, therefore, a similar phenomenon occurs.

However, this problem can be solved by directly drawing electron beam. If the devices developed in the future have the dimensional structure, the electron beam method will likely attract strong attention as a lithography technology capable of solving this problem

3.4 Conclusion

If Japan follows the United States and Europe in adopting EUV as the next-generation lithography technology, it will be inevitably disadvantageous. However, since the F_2 method and the electron ray method also have many advantages and possibilities, it will not be correct to regard them negatively.

In particular, Japan is taking the dominant lead in the development of continuous-oscillation excimer laser technologies, and has been the most advanced in application technologies for electron rays. In addition, it has made research efforts in Xray exposure technologies, which is not explained in this article.

Concerning research and development of semiconductors in the United States, business, academic and governmental collaborations such as EUV LLC, and business and academic alliances such as Stanford University's CIS (Center for Integrated Systems) are effectively functioning for the development of next-generation LSI technologies.

Even Japan can seize the chance for victory if it implements next-generation semiconductor and lithography strategies that can answer the questions: what is the mainstay of next-generation LSIs (commodity products like conventional memories or system LSIs for diversified-item, small-volume production), and what is the form of devices that are being increasingly miniaturized (still the planar structure or the 3-dimensional structure).

LSI technology is the core of data processing and communications technologies, and it is the technology that Japan needs to control in order to maintain its top position in both economy and technology given that IT technologies are spreading into every sphere of society.

* **Notable Trends**

AMSL's Acquisition of SVG to Fortify the U.S.-Europe Alliance

On May 3, the Bush administration announced that it approved ASML's plan to acquire SVG in California.

It appears that SVG is playing an important role in helping EUV LLC develop a mass production machine for EUV. The company is known as the main supplier of steppers for Intel. ASML had submitted the acquisition plan (announced in October 2000), and the U.S. government committee CFIUS (Committee on Foreign Investment in the United States) conducted an investigation from March 7.

Since SVG has an agreement with the military, it was thought that the administration would disapprove the plan from a security standpoint. Thus, the decision of the Bush administration has drawn much attention.

With the latest movement, the strengthening of the U.S.-Europe coalition in the semiconductor industry is becoming a reality.

* **Sources:**

Center for Integrated Systems (CIS)
Stanford University
Ohmi Lab, School of Engineering, Tohoku University