Application of Electron-beam Direct-writing Technology to System-LSI Manufacturing

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OVERVIEW: EB (electron-beam) direct-writing lithography has not only been used for semiconductor research and development but has also been applied to small-volume fabrication of custom LSI (large-scale integration) chips. The present paper first describes the EB direct-writing lithography system that has been developed and put on the market by Hitachi High-Technologies Corporation. It then describes an example application of the system to fabrication of silicon devices. Lastly, it outlines the current status and future developments concerning direct writing with the developed EB lithography system.

INTRODUCTION

AS the rapid pace of scaling down of semiconductor devices continues, the minimum device pattern size is already entering the sub-100-nm domain. Such dimensions are smaller than the wavelength of the light used in optical lithography tools. To form fine pattern sizes below such light wavelengths, special exposure methods using a reticle is thus applied in the lithography process. In this case, to improve the lithographic resolution, fine auxiliary patterns are required. Up until now (and into the future), manufacturing such state-of-the-art reticles has incurred great time and expense.

On the one hand, semiconductor devices such as memory chips must be produced in large volumes, and on the other hand, the demands of individual customers for custom LSI (large-scale integration) chips must be met. Production of custom LSI chips usually involves a small number of wafers; consequently, it is difficult to fabricate such devices at a reasonable cost. Moreover, it is tough to attain high precision with the use of a reticle, and the time period for manufacturing the reticle can run into several months. These problems concerning fabrication of custom LSI chips often lead to difficulty in meeting the delivery date agreed with customers.

These circumstances surrounding the fabrication of custom LSI chips have led to the demand for a lithography technique that does not require a reticle, thereby lowering production costs and shorting manufacturing lead-time. Eliminating the need for a reticle would free LSI production from the constraints imposed by the above-mentioned problems concerning reticle cost and delivery date. One lithography technique that does not require a reticle is known as direct-writing technology; namely, an EB (electron beam) is used to write a pattern directly onto the surface of a wafer. Hitachi High-Technologies Corporation has developed such an EB lithography system (see Fig. 1), and the rest of this paper outlines the apparatus and explains the direct-writing technique in detail.

Fig. 1—Appearance of EB Lithography System.
To attain high-precision writing, the apparatus's main unit and the control circuits to be controlled precisely are housed in a temperature-controlled chamber.

EB LITHOGRAPHY SYSTEM

Hitachi High-Technologies Corporation developed an EB lithography system, an apparatus for direct EB writing. Its main specifications are listed in Table 1 and some examples of the exposure results given in Fig. 2.

To attain the required resolution of 90 nm and below, the system utilizes an EB with an accelerating voltage of 50 kV. In regards to the shape of the beam, a variable-shaped beam with a maximum size of 2 by 2 µm or a cell-projection beam with a size of 4 by 4 µm are available.

The whole apparatus can be controlled via a workstation; namely, after the input data has been processed by special digital circuitry, it is sent to analog circuitry, and the beam is thus controlled. The new lithography system incorporates the following three main improvements compared to conventional lithography systems.

(1) New EB optical system: Resolution and controllability of the beam have been improved through higher-resolution EB optics and finer control of beam size and deflection position. Moreover, the new lithography system offers a variable-shaped beam as well as a cell-projection beam, so it is possible to electrically select 21 kinds of cell or mechanically select 525 kinds of cell.

(2) More compact apparatus: Since lithography equipment for shop-floor production is frequently set in a clean-room environment, it should be as compact as possible. Accordingly, the main body of the new lithography system is set in a 2-m by 3-m temperature-controlled chamber, reducing the floor space and stabilizing the influence of the circuitry on writing accuracy.

(3) Improved operability: Although it is often said that operation of EB lithography is complicated, the new lithography system is fitted with a GUI (graphical user interface) in accordance with the SEMI (Semiconductor Equipment and Materials International) standard; outstanding user-friendly operability is thus guaranteed.

In regards to performing lithography with an EB writing system, it is necessary to prepare the specified pattern data beforehand. Since data created by CAD (computer-aided design) involves overlapping patterns, the designed graphical feature sizes are not suited to processing by an EB writing system. It is thus necessary to ensure that the data is in a format suitable for EB lithography. This process — referred to as data conversion — requires that a huge amount of data be converted at high speed, so the lithography system is combined with a special workstation for performing that task.

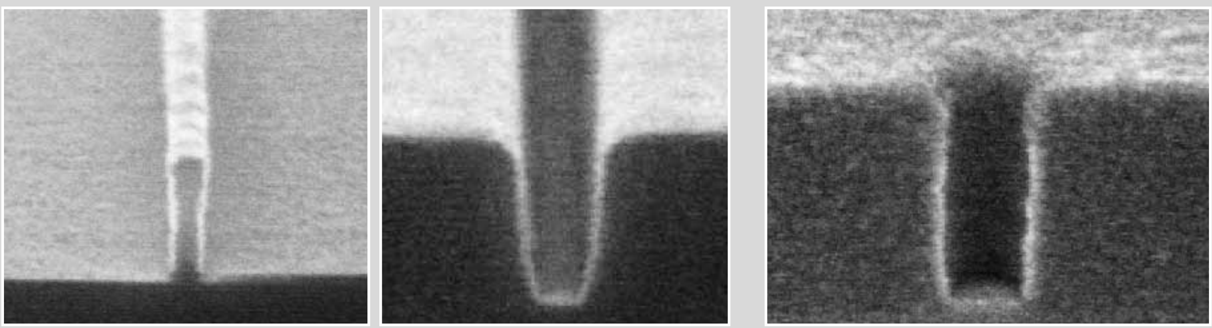
At present, the main application area of EB direct-writing technology is in the production of silicon

TABLE 1. Basic Specifications of EB Direct-writing Lithography System.

The basic specifications of the direct-writing system are listed in the table.

Parameter	Specification
Resolution (isolated line)	90 nm
CD accuracy (3 σ)	10 nm
Stitching accuracy (3 σ)	30 nm
Overlay accuracy (3 σ)	35 nm

CD: critical dimension



(a) 50-nm line-and-hole
Resist thickness: 250 nm

(b) 80-nm hole
Resist thickness: 300 nm

Fig. 2—Examples of Regist Images Exposed by Direct-writing System.
Examples of resolution obtained with positive and negative prints are shown.

devices. And using the C to C (cassette to cassette) loading method, the new lithography system can handle specimens up to eight inches in diameter. In the case of specimens other than silicon wafers [such as GaAs (gallium-arsenide) chips and magnetic-head devices], the configuration of the palette for holding the wafer inside the apparatus and the specimen-transfer unit only have to be changed.

In the case that lithography technology is used for fabricating device structures, among the many steps involved in the lithography process, several steps demand high accuracy, so direct writing is used for those steps; the other steps can be handled by conventional optical lithography. This means that a stepper and a scanner (or one of them) are applied in combination with EB lithography system. Regarding such so-called mix-and-match device fabrication, the new lithography system is equipped with a function that performs writing in accordance with the result of the optical exposure.

APPLICATION TO SYSTEM-LSI MANUFACTURING

There are many issues concerning the application of EB lithography technology to device development and system LSI manufacturing. Two particular issues are lithography reliability and manufacturing costs. The present circumstances regarding these two issues are taken up in the following two sections.

Lithography Reliability

In the case of direct-writing technology, to make the desired pattern shape, the EB is shaped, blanked, and scanned in accordance with the pattern data to make the desired pattern shape. In optical lithography, the pattern on the reticle is projected on the wafer. If the pattern on the reticle is precisely formed, the same pattern as the original can be transferred by the exposure process. On the contrary, in the case of direct writing, since the pattern is formed during the drawing, the control circuits of the system involved in forming the pattern, or controlling the actual behavior of the EB during exposure, must be extremely reliable.

As previously mentioned, in the case of the developed EB writing system, writing is performed according to data processed during the writing. And a large number of digital circuits are used to achieve this pattern-data processing and EB control. The LSI chips used in these circuits are composed of high-precision devices to ensure that the control system is highly reliable.

TABLE 2. Evaluation Results on Reliability of Direct-writing with Lithography System.

Measuring the CD uniformity across a wafer surface shows the reliability of the direct-writing system.

		0.102 (8.1)	0.103 (6.8)	0.104 (6.8)		
	0.104 (3.7)	0.105 (3.4)	0.106 (3.5)	0.107 (3.9)	0.107 (3.4)	
0.105 (5.0)	0.104 (5.9)	0.105 (4.4)	0.105 (3.1)	0.106 (5.7)	0.108 (5.3)	0.104 (7.3)
	0.104 (5.1)	0.106 (4.6)	0.105 (3.7)	0.107 (4.7)	0.107 (5.2)	
		0.101 (9.0)	0.102 (8.1)	0.102 (8.9)		

Upper value: CD uniformity (µm); average: 0.105
Lower value: CD uniformity variability; average (3 σ nm): 7.9
Measurement points: 50 per chip

At the same time, as a result of electrical noise from around the apparatus and the charging-up effect inside the electron optics, it is possible that the EB — which must be precisely controlled by the control circuits — cannot be controlled as predetermined. Accordingly, the reliability of the whole system performance, including the control circuits and the EB— is evaluated and confirmed by writing a fine line-and-space pattern and then performing an open/short-circuit check on it.

Table 2 shows the evaluated CD uniformity of a 110-nm level LSI formed on a wafer by the new system. 50 points on the chip were measured, and the average and standard deviation of the CDs for several chips are listed in the table. It is clear from the table that the new lithography system can expose fine patterns with low CD deviation.

Note that the realization of such good pattern uniformity is due to the stability of the EB lithography system. On top of that, it is also necessary that other processes such as development must be accurate.

Production Cost

Applying lithography technology to the production of custom LSI chips must be cost effective. Accordingly, there have already been several studies that compare the production costs for several different lithography tools. These studies focused on the difference between the costs of direct-writing lithography and the costs of other lithography methods[2,3]. In short, the two main cases when the

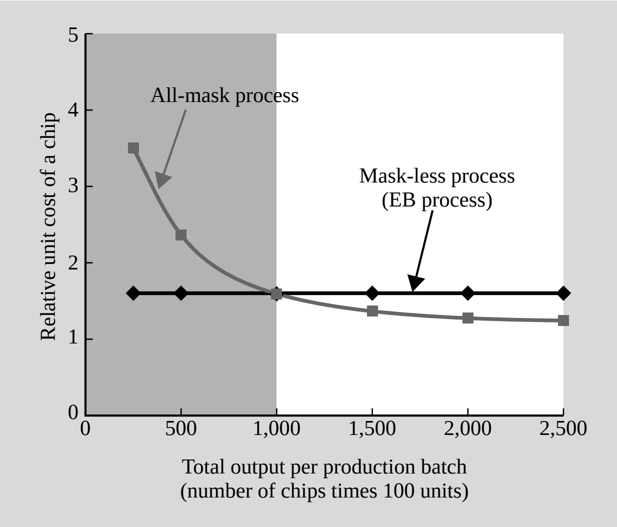


Fig. 3—Comparison of Costs of Lithography with or without Using Mask for Writing.
At the intersection of the two cost lines, equipment cost, reticle cost, throughput, chip cost, etc. become the parameters that determine the choice between the two lithography techniques. In the example shown, the intersection point corresponds to a chip production volume of about 1,000 units.

direct-writing method is advantageous in terms of cost-effectiveness are summarized below:
(1) When the number of LSI chips to be produced is small (so the use of a reticle increases the device cost)
(2) When the TAT (turnaround time) of the reticle is long (so a device cannot be fabricated in a short time, especially in the case of sample products)

In these two cases, it becomes advantageous to use the direct-writing lithography method since it does not need a reticle. And in terms of cost-effectiveness, direct writing is superior to optical lithography in the case that the number of chips to be fabricated is not so large. In such a case, the reticle cost per chip would increase, leading to higher production cost for optical lithography. The relative production costs (i.e., the cost per chip versus the aggregate number of chips produced) for both lithography methods are compared in Fig. 3. It is clear from the figure that when the number of chips is small, the cost per chip is significantly lower in the case of direct-writing lithography. In contrast, in the case of optical lithography, when the number of chips increases, the cost per chip drops. The production volume at which the costs per chip for both methods intersect changes according to the assumed conditions, such as equipment cost, reticle cost, running cost, yield, and throughput. As shown in the figure, when the number of chips to be produced is over 1,000, optical lithography becomes a more cost-effective method.

CONCLUSIONS

Since direct-writing technology has such high resolution, up till now it has been used in the field of device research and development. Only recently has commercial EB direct-writing system been introduced into production on the shop floor. In the near future, for such reasons as device diversification, shortening of device lifetimes, and steep rises in costs, applications of direct-writing technology, which does not need a reticle, will become more widespread. Note that although this paper describes the application of direct-writing technology to silicon devices, this technology is also being utilized for pattern formation in such fields as magnetic heads, GaAs devices, and optical devices.

Regarding future applications of direct-writing lithography for shop-floor production, the most important point is to improve the reliability of this technology. As well as offering higher fabrication accuracy, the new system must be easy to operate.

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