Nano-Level Electron Beam Lithography*

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Abstract: The JEOL JBX-5000LS is a vector type machine. The system hardware features an ion-pumped column, a LaB_6 electron emitter, 25kV and 50kV accelerating voltage, and a turbo-pumped sample chamber. The resolution, stability, stitching and overlay of this system are evaluated. The system can write complex patterns at dimensions down to 30nm. The demonstrated overlay accuracy of this system is better than 40nm.

Key words: electron beam lithography system; resolution; overlay accuracy

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1 Introduction

Electron beam lithography (EBL)[1] is a specialized technique for creating the extremely fine patterns required by the modern electronics industry for integrated circuits. Since the first electron beam lithography machines were developed in the late 1960s, a lot of series of EBL tools have became commercially available for research and business application.

The JBX-5000LS[2] is a vector type electron-beam lithography system and its operation mode is roughly divided into two: the 4th lens-mode and the 5th lens-mode, each mode having a distinct feature. Usually, the 4th lens-mode is used for sub-micron electron beam lithography to write fine geometry on wafers. The 5th lens-mode is used for ultra-fine electron beam lithography to write ultra fine geometry on wafers.

The system employs a high-brightness electron gun using LaB_6, a single crystal cathode and an in-lens deflector. This feature allows the 4th lens-mode to form an electron beam spot with a diameter as small as tens of nanometers, enabling efficient sub-micron writing. In the 5th lens-mode, the electron beam spot diameter is less than 10 nanometers, and nanometer writing is possible. Several experiments have been carried out to evaluate the JBX-5000LS EB lithography system´s resolution, stability, stitching and overlay performance. Details of the experiments are reported in the following sectors.

2 High resolution patterning

There are several factors that determine the resolution of an electron beam system. First is the vital source d_v divided by the demagnification of the column, M, resulting in a beam diameter of $d_g = d_v / M$. In a system with a zoom condenser lens arrangement, the demagnification of the source can be varied, but increasing the demagnification also reduces the available beam current, such as scan-

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ning step, resist sensitivity and resize amount. For writing fine patterns, the exposure parameters should be carefully adjusted.

Beam current is determined by beam size. Normally, beam size is 1/4 to 1/5 of the minimum design rule of a writing pattern. Figure 1 shows the relation between beam size and beam current. In the single scan writing, since line-width is determined by beam size, resist thickness, etc., particular consideration is required when setting beam current.

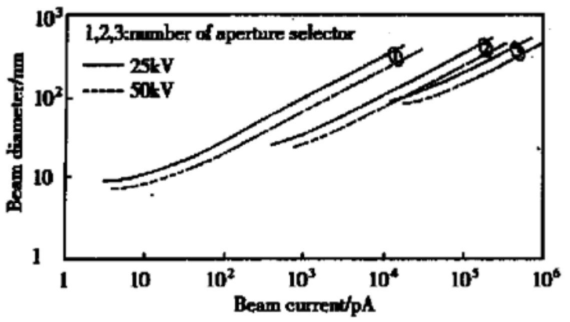

Fig. 1　Relationship between beam current and beam size for 5th lens

At pattern writing, beam shot interval can be controlled by changing scanning steps. Steps are selectable in the range of 2.5nm $\times N$ for the fifth lens or 25nm $\times N$ for the fourth lens, where N is a number of 1 to 20. In order to produce uniform edges of a written pattern, the scanning step should be set to a value to the allowable range as low as possible.

By referring to the values specified by resist supplier, suitable resist sensitivity should be determined from a series of experiments.

Pattern data from some kind of design program, such as CAD, must be converted into JEOL´s format, thus these patterns are finally divided into multiple rectangular data, trapezoid data, and single line data. A written pattern will be a bit larger than the designed pattern, because it is written by scanning a beam of finite dimensions. Specifying the extent of resizing and the value can eliminate this pattern broadening by which to shrink the pattern size in the split data. This is done by entering the resize amount when reading the pattern data from the disk or magnetic tape medium to the disk. Pattern sizes can be reduced in steps of 25nm (25kV) or 12.5nm (50kV) for the fourth lens, or 2.5nm (25kV) or 1.25nm (50kV) for the fifth lens. As a rule one-half value of scanning step is used for the size correction, but the amount of correction is more accurately determined from the results of test pattern writing.

To test the resolution of this system, based on above rule, a 950K-molecular weight PMMA[3,4], 2% solution in chlorobenenre, was spun onto a bulk silicon substrate, and then baked for 40min at 165℃. The exposure conditions are shown in following: field size 80μm, accelerating voltage 50kV, beam current 30pA, resist PMMA, line resist sensitivity: 2μC/cm, 5th lens, silicon wafer, 60μm aperture size, the resist thickness is 50nm, shot rank is 4. After exposure, the wafer was developed at 21℃, in MIBK (1) ∶ IPA (3)[5] mixture solution for 45s. The highest resolution patterns were obtained for both single line and dense line. For single line, the line width is 27nm and 28nm, respectively in x, y direction. For the dense line, an example feature are shown in Fig. 2.

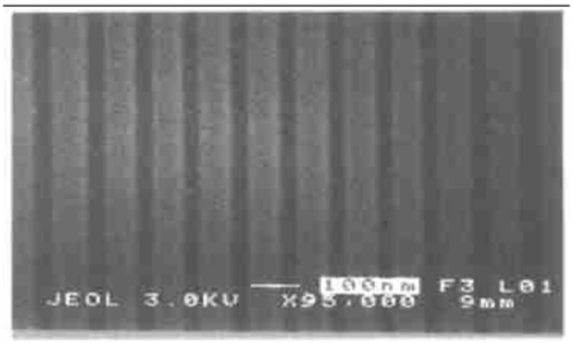

Fig. 2　Line/space pattern exposed by JBX-5000LS

3　System stability

The drift of the electron beam with respect to the laser-interferometer stage was carefully measured before attempting field-stitching and overlay measurements. There are several potential causes for beam drift which may vary over time: thermal effects in the column or the stage, charging in the column, chamber, or on the sample itself. The drift measurements were carried out with a conductive sample, and repeated on several different days.

Beam drift is composed of position shift and the amount of beam current. The drift in the data obtained by detecting of the reference mark position is regarded as the drift in position, but more strictly speaking, it is a drift of the entire system since the position drift of the mark itself is included. The drift in amount is measured by the Faraday cup and it depends on the conditions in the column (such as running time after cleaning, material of the work-piece, resist thickness, etc.)

At least 2h prior to beginning drift measurements, a patterned sample was placed on the substrate chuck and the sample had four globe registration marks P, Q, R, and S: gold bar, 100μm wide by 1500μm long with the shape of a cross. This permitted *X* and *Y* registration at four locations on the substrate. The four marks were arranged on top, bottom, left and right position. The use of four marks enabled the determination of drift values for position and rotation of the substrate with respect to the electron drift beam, as well as thermal expansion of the substrate.

The four marks on the substrate were scanned sequentially at 2min intervals for about 1h. The marks were always scanned at the field center to minimize intra-field distortion errors. An example of their positional drift is in Table 1. From this and other experiment results, the positional drift was found to be less than 4nm/min. The thermal stability was typically better than 0.15℃ during the experiments. A water cooling system was employed to make the thermal stability of this system.

Table 1 Electron beam drift over time, relative to center locations on the sample

t/min	10	20	30	40	50
X/nm	14	29	47	89	121
Y/nm	-19	-38	-58	-97	-154

The e-beam lithography system inevitably exhibits drifts in beam current and beam position in greater or lesser degree. Usually, the e-beam system is low efficiency and needs long time to expose a pattern. Even when the drift was less than 4nm/min, the total drift was really large after several hours' exposure, so the drifts must be corrected for fine pattern writing. To compensate for the current drift, the beam current is measured during pattern writing by a Faraday cup built into the stage. The measurement is made at fixed intervals, which are specified in terms of the number of chips or a field. At this interval, the ratio of this measurement to the beam current value previously measured at saving of pattern writing conditions is determined. Then the beam scanning speed is controlled according to that ratio, the dose is constant in the entire resist area.

Drift in beam position lowers field stitching and registration accuracy. In direct writing, beam position is corrected by detecting marks of each chip. In mask writing, which involves no reference mark on the work-piece, a cross mark of the reference mesh on the stage is used as the reference mark. In either case, the mark positions are detected at fixed intervals as in dose correction, and correction is made for the difference of the detection results from those of the previous detection.

4 Stitching and overlay accuracy

The field stitching perform of the JBX-5000LS system was evaluated in a vernier pattern. Before writing this pattern, the focus was calibrated carefully. To minimize field-calibration errors, the JBX-5000LS's auto-calibration program was executed several times, and the average values were used as the field setting. The pattern exposure condition as follows:

Field size: 80μm, accelerating voltage 50kV, Beam current: 100pA, Resist: PMMA, Resist sensitive: Line = 3.0nC/cm Area = 600$\mu C/cm^2$, Object lens: 5th lens, Substrate: silicon, Aperture size:

60μm, Resist thickness: 100nm. Finally, the result is shown in Fig. 3. The field stitching accuracy is better than 40nm.

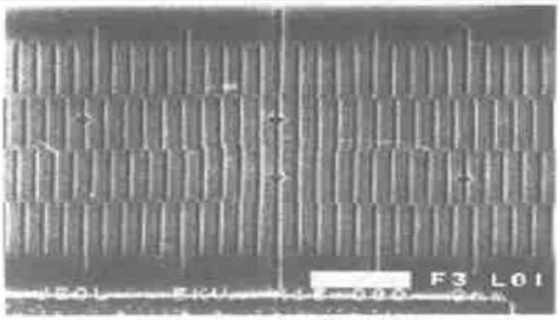

Fig. 3 Field stitching performance of JBX-5000LS system The stitching accuracy is better than 40nm.

To evaluate the overlay performance of JBX-5000LS, the multilevel pattern was employed in this experiment. Two levels of writing were done: pattern of global-registration marks, field-registration marks, and the first set of overlay (level 1), pattern of the second matching set of overlay marks (level 2).

The level 1, including global registration marks, field registration marks and first set of overlay pattern are exposed in the same time. The pattern was transferred in metal using a liftoff process. After the liftoff step, the wafer was coated with single layer resist, then pattern for the second level of overlay is written.

In writing level 2, pattern writing is performed after detecting the appropriate marks on the wafer and thereby determining the distance and direction of stage travel, pattern writing start position, and deflection direction and amplitude. In operation, the positions of global marks P, Q, R, and S are detected to determine the wafer expansion/contraction and rotation. The stage travel direction is corrected by the rotate amount obtained, and the stage travel distance is corrected by the work-piece expansion/contraction amount determined from PQ and RS; based on these correction values, pattern writing is performed. At first, the stage moves to the first chip, where the chip marks M_1, M_2, M_3 are detected. From the results of detection of this three marks, corrected values are determined for adjusting the amplitudes and direction of the x and y deflection, so that they conform to the size and direction of the chip marks and deflections are corrected accordingly.

The sample was developed again after the level 2 of patterning, and then subjected to liftoff processing. All patterns were transferred in metal to the silicon substrate, and measured the overlay accuracy in SEM. The results are summarized in Table 2, where X is the average overlay error, 2σ is measured accuracy, which means that 95.4% of the measured overlay accuracy will be within this range. The overlay measurements at 800μm and 1600μm field size were also done and the overlay accuracy were little worse than at 80μm field size. Finally, the average overlay accuracy is better than 40nm.

Table 2 Overlay accuracy of JBX-5000LS at 80μm field size and 5th len

Chip No.	Overlay/μm							
	W1	W2	W3	W4	W5	W6	W7	W8
1	-0.010	-0.010	0.000	0.000	0.000	0.000	0.000	0.000
2	-0.010	0.000	-0.010	-0.010	0.010	-0.010	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.010	-0.010	0.000	0.010	-0.010	0.000	0.000	-0.010
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	-0.010	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	-0.010	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.020	0.000	0.010	0.020
10	-0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.010	-0.010	0.000	0.000	0.000	0.010	-0.010	-0.010

Table 2 (Continued)

Chip No.	Overlay/μm							
	W1	W2	W3	W4	W5	W6	W7	W8
12	0.010	0.000	0.000	0.000	0.000	0.010	0.000	-0.010
13	-0.010	-0.010	-0.010	0.000	0.020	-0.010	-0.010	0.030
14	-0.030	0.010	-0.010	-0.010	0.010	-0.010	0.000	0.010
15	0.020	0.010	0.000	0.000	0.010	0.000	0.000	0.010
16	0.010	-0.010	0.000	0.000	0.010	0.010	0.000	0.020
X	-0.010	-0.003	-0.002	-0.001	0.004	-0.001	-0.001	0.003
2σ	0.023	0.014	0.008	0.009	0.016	0.011	0.009	0.021

5 Conclusion

The JEOL JBX-5000LS is an electron beam lithography system designed for various applications in the research field, including GaAs FETs, optical elements, X-ray masks, Si devices, and quantum effect that require ultra fine pattern exposure. It is a computer-controlled electron-beam lithography system. The system hardware features an ion-pumped column, a LaB_6 electron emitter, 25kV and 50kV accelerating voltage, and a turbo-pumped sample chamber.

The resolution, stability, fields stitching and overlay accuracy performance were evaluated. The system can pattern 30nm features. The field stitching and overlay performance is excellent.

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纳米电子束曝光*

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摘要: JEOL JBX-5000LS 是矢量扫描的电子束曝光机. 系统采用 LaB_6 灯丝, 可以工作在 25kV 和 50kV 的加速电压下. 对该系统的分辨率、稳定性、场拼接和套刻精度进行了系列研究, 得到了分辨率为 30nm 的图形, 图形的套刻精度也优于 40nm.

关键词: 电子束曝光系统; 分辨率; 套刻精度

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