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The design and fabrication of a wafer-scale microlens for multiple microcolumns

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Abstract: Many researchers have tried to develop microcolumns to improve the throughput of electron beam equipment, since we can increase the speed of inspection or lithography by operating multiple microcolumns at the same time. In particular, the concept of a wafer-scale microcolumn was proposed as one of the ideal types of multiple microcolumns, and we need to optimize the arrangement of microcolumns and the connecting wires for the practical fabrication of multiple microcolumns on a wafer. We have calculated the maximum number of microcolumns that can cover the full wafer considering the minimum wire width, and have designed a wafer-scale microlens module including the connecting wires, accordingly. In addition, we have developed the practical processes for fabricating a wafer-scale microlens module based on MEMS technology, and experimentally fabricated a wafer-scale microlens module using Pyrex wafers and boron-doped Si wafers.

Keywords: multiple electron beam, wafer-scale, MEMS, microlens, microcolumn

1. Introduction

Microcolumn have been developed to improve the throughput of electron beam equipment, since we can increase the speed of inspection or lithography by operating multiple microcolumns at the same time [1-2]. In particular, the concept of a wafer-scale microcolumn was proposed as one of the ideal types of multiple microcolumns[3-6], and we need to optimize the arrangement of microcolumns and the connecting wires for the practical fabrication of multiple microcolumns on a wafer.

Fig. 1 compares the structure of a single microcolumn with that of a wafer-scale microcolumn. We can fabricate each component consisting a wafer-scale microcolumn on a wafer as shown in Fig. 1(b). That is, the emitter, source lens, deflector, and Einzel lens structure is batch fabricated on individual wafers, and we need to assemble those components through proper assembly process to complete a wafer-scale multiple microcolumns. As an example, we schematically presented a wafer-scale microlens fabricated on a wafer in Fig. 2.

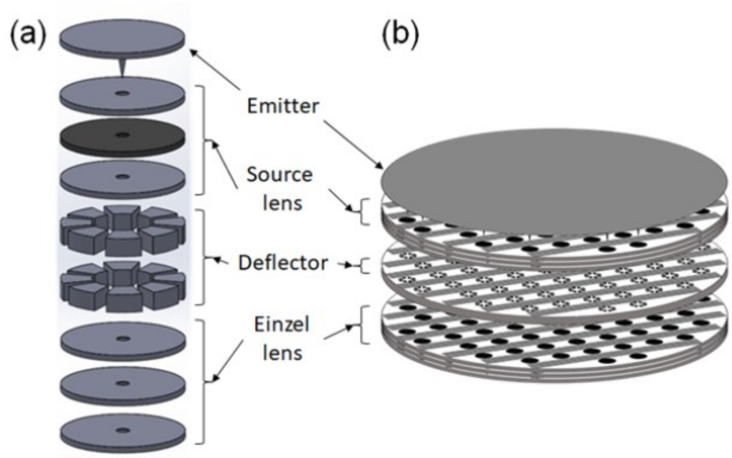

Figure 1. Structures of (a) a single microcolumn and (b) a wafer-scale microcolumn

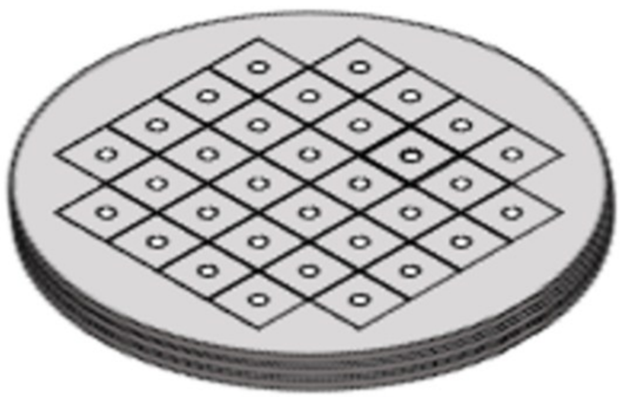

Figure 2. An example of a wafer-scale microlens

We have continually investigated on each component of a microcolumn and the design of the microcolumn itself to improve its performance. Commonly used tungsten emitters have problems in assembling processes since there are many emitters and lens apertures to be aligned. Therefore, we have developed a 2D CNT (Two Dimensional Carbon Nan Tube) tip and tested its performance [7]. As a wafer-scale deflector, we have fabricated the Si deflector by using MEMS processes, and tested various types of deflectors to obtain large FOV [6, 8] without sacrificing the resolution. In this study, we have studied the design of a wafer-scale microlens and developed the fabrication processes. There are several difficulties in manufacturing a full wafer-scale microlens module. The first one is that we must precisely align the small apertures of individual lenses. For example, to complete a set of Einzel lens, three Si wafers and three Pyrex wafers are required as shown in Fig. 5, and we need to align the six wafers. The second one is that we need to optimize the number of electric wires and their arrangement connecting to the microlens. Considering these difficulties, we have designed and fabricated the wafer-scale microlens module.

2. Design Procedure

Fig. 3(a) and (b) shows two types of wafer-scale microlens designs for multiple microcolumns. The design (a) is the microcolumn array arranged to the maximum and the design (b) the optimized placement of microcolumn array; the number of lens electrodes is 132 for design (a) and 64 for design (b). For both (a) and (b) designs, we can apply the operational voltage of the electrostatic lens to the electrical wire connected to the individual lens electrode, which can be seen in the magnified images, insets of the images (a) and (b). In this work, we selected the design (b) to fabricate some sample wafer-scale lenses. Although the total number of lenses per wafer is reduced, it is easy to manufacture the wafer-scale lens module composed of anodic bonded three wafers that include many lenses and wires. To supply voltage to the lenses, the wiring is placed at the edge of the wafer as shown in inset of Fig. 3(a). We have designed this structure so that the electric wires do not interfere with each other when the wafers are stacked.

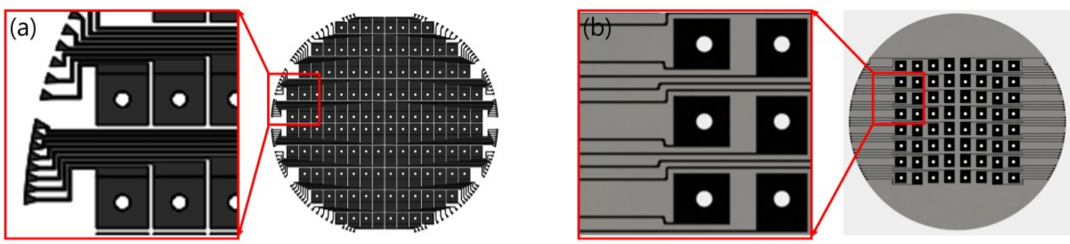

Figure 3. The design of the wafer-scale microlens for (a) the microcolumn array arranged to the maximum number, and (b) the optimized placement of microcolumn array. The number of lens electrodes is 132 for design (a) and 64 for design (b).

3. Results and Discussion

3.1. The simulation to optimize the number of columns and wire width

Fig. 4(a) illustrates the way of calculating the allowed number of columns depending on the center-to-center distance (C-C distance) between the neighboring columns (neighboring lens apertures). We have designed the wafer-scale microcolumn so that each column fills the entire wafer as shown in Fig. 3(a) or Fig. 4(a). The maximum number of columns is determined by the C-C distance. Fig. 4(b) presents the simulation result showing the maximum number of columns depending on the C-C distance and the wire width suitable for that C-C distance. As shown in Fig. 4(b), the number of columns increases as C-C distance decreases. In a wafer-scale microcolumn structure, the lenses and wires are arranged on one layer at the same time, which means that the narrower the space between the columns, the smaller the line width of the wires. We have summarized the relation between the number of columns and C-C distance in Table. 1.

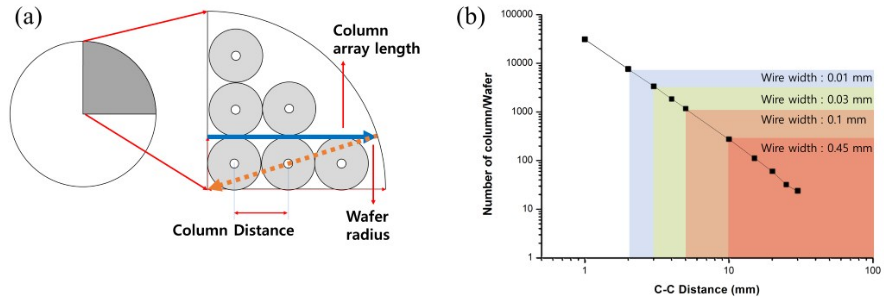

Figure 4. (a) The modeling of calculating the number of columns depending on the center-to-center distance between neighboring lens apertures (C-C distance), and (b) the simulation result showing the maximum number of columns depending on the C-C distance and the wire width suitable for that C-C distance.

Table. 1. The relation between the number of columns and C-C distance.

C-C Distance (mm)	Number of Columns (ea.)	Wire Width (mm)
10	276	0.45
5	1,176	0.1
2.5	4,844	0.019

When the spacing between columns is reduced by half, the number of columns increases by about 4 times or more, but the line width decreases to about 1/5. This is due to the increase in the number of columns due to the decrease in the spacing, and the increase in the number of required wiring. According to the currently designed wafer-scale microcolumn structure, we used Pyrex wafer as the insulating spacer by forming both 3 mm circular through holes for the electron beam passage and lens-electrodes thereon. For the stable structure and strength of Pyrex, the current wafer-scale microcolumn structure design is expected to have a limit of about 5 mm between columns.

3.2. *Fabrication Process of wafer-scale microlens module*

We have fabricated a few wafer-scale microlens modules by using the MEMS processes described in Fig. 5. At first, we formed a highly boron doped layer on a Si wafer by using a high energy implanter (Axcelis GSD/HE) as shown in Fig. 5(a), which will be used as an lens electrode and/or electric connecting wires. Secondly, we have carried out proper photolithography process to make patterns for the lens electrodes, the apertures at the center of lens electrodes, the electric wires, and the alignment keys on a Si wafer as presented in Fig. 5(b). After carrying out the photolithography process, we have formed the lens, wire patterns, and the align key by etching the boron-doped layer by using a DRIE (deep reactive ion etching, STS VPX-Pegasus), and the result is presented in Fig. 5(c). Next, in the process of Fig. 5(d), we have bonded the patterned Si wafer in Fig. 5(c) with a Pyrex wafer by using anodic bonding technique. During this process, we have bonded the boron-doped layer (patterned layer) to the Pyrex wafer not to the bare Si wafer. Before the process of Si-Pyrex anodic bonding, we have patterned the align keys on the Pyrex wafer for the alignment with Si wafer and made the holes (3 mm in diameter) for the electron beam passages. This Pyrex layer plays the role of insulating supporter of the thin lens electrode as well as the spacer controlling the distance between the lens-electrodes as schematically described in Fig. 5(f) as we can control the thickness of the Pyrex plate to meet our microcolumn design. After the process of Fig. 5(d), we have polished out the Si bare wafer through CMP (Chemical Mechanical Polisher) process remaining only the boron-doped patterned layer as shown in Fig. 5(e), which completes the fabrication of one wafer-scale lens plate. Finally, we assemble the three wafer-scale lens plates in order to make one wafer-scale lens module, for example one Einzel lens set, through anodic bonding of the three plates. During this anodic bonding process, we have used the aligner and the align key on the Pyrex wafer. Fig. 6 shows the fabricated wafer-scale lens through the processes described in Fig. 5.

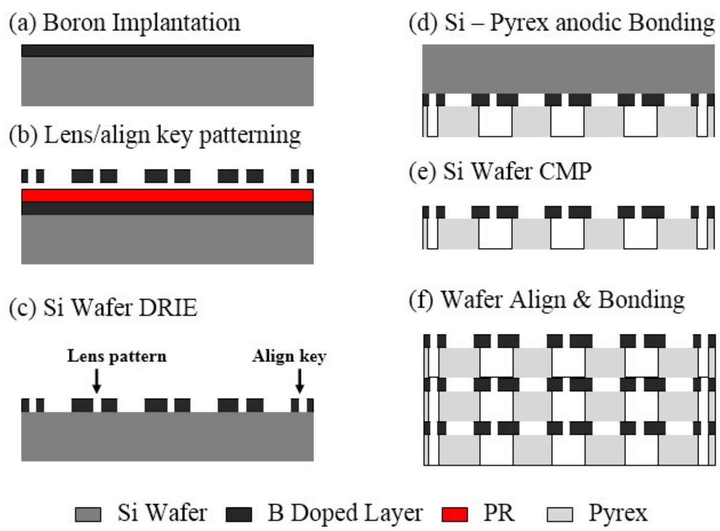

Figure 5. The MEMS processes for the fabrication of a wafer-scale microlens module

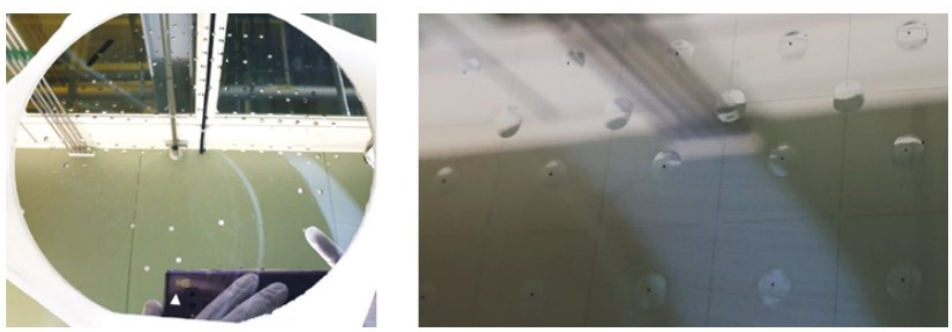

Figure 6. Fabricated wafer-scale lens after CMP process

4. Summary

We have designed and fabricated the wafer-scale microlens module for wafer-scale microcolumns. The wafer-scale microlens is designed in consideration of the arrangement of microcolumns including the number of columns and the wire width. The wafer-scale microlens lens module was manufactured through appropriated MEMS processes using Pyrex wafers and boron-doped Si wafers. The Pyrex wafer with through holes and the Si wafer with patterned lens structures were bonded to complete the wafer-scale lens. And the three sets of wafer-scale lens on a Pyrex wafer can be assembled to complete a wafer- scale lens module.

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