Focused Ga^+ beam direct implantation for Si device fabrication

H. Hamadeh, J. C. Corelli, and A. J. Steckl
Center for Integrated Electronics, Rensselaer Polytechnic Institute, Troy, New York 12180-3590
I. L. Berry
Department of Defense, Fort George G. Meade, Maryland 20755

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A focused ion beam (FIB) has been used for Si submicron device fabrication. *p-n* junctions and two terminal resistors were fabricated using a 60 keV Ga^+ ion beam of diameter as small as 0.2 μm. Typical resistor dimensions were 50–160 μm in length and 0.2–0.5 μm in width. The Ga^+ dose ranged from 5E13 to 5E14 Ga/cm^2. *I–V* measurements showed the correct dependence of resistance on resistor length, width, and impurity concentration. We have studied the broadening of lines implanted in Si and SiO_2 using a fixed ion beam diameter as a function of dose level. Selective etch (H_3PO_3 at 180 °C for Si and HF for SiO_2) and SEM analysis showed an increase of 50%–75% in linewidth as the dose was increased by an order of magnitude.

I. INTRODUCTION

One of the most promising uses of focused ion beam (FIB) is for maskless ion implantation doping of semiconductors.[1–3] Focused ion beams are well suited for submicron device fabrication. The fabrication process is considerably simplified since masks are eliminated, thus keeping the semiconductor surface as clean as possible.

In this paper we present experimental results on direct ion implantation of Ga^+ in Si and SiO_2. A 60 keV Ga^+ ion beam focused to 0.2–0.5 μm was used in fabricating resistor/diode-type structures. Details of the FIB system used are published elsewhere.[4] Device characterization was performed using SEM examination and electrical measurements.

II. EXPERIMENTAL PROCEDURE

In fabricating the devices, an *n*-type (100) oriented, 15 Ω cm Si wafer was used. After etching alignment marks in the Si, boron was implanted into 200 μm square pads. The energy was 100 keV and the dose used was 5E14 B/cm^2. The spacing between the pads was 50–160 μm as shown in Fig. 1. The sample was then annealed for 1 h at 1100 °C in a nitrogen ambient. Photoresist was applied and patterned into 100 μm squares over the boron pads. The purpose of the photoresist was to identify the location of the boron implanted regions. The Ga^+ beam was then used to connect the boron pads by ten conducting lines, spaced 5 μm apart (Fig. 1). The length, width, and dose of the Ga^+ lines ranged from 100 to 200 μm, 0.2 to 0.5 μm, and 5E13 to 5E14 Ga/cm^2, respectively. The sample was implanted at 7° off the (100) axis to reduce channeling effects. The areal dose was determined by implanting multiple passes of 600 Å diam beam (full width at half maximum) to fill an area 0.20 μm wide. The areal dose is then obtained by dividing the implanted area by the area of the filled-in pattern. The latter is uniform over most of the linewidth except for a drop-off effect of 600 Å at the edges of the 0.20 μm linewidth. After Ga^+ FIB implantation, the resist was removed and the sample annealed at 800 °C for 15 min in a hydrogen ambient. Aluminum was then evaporated and patterned onto the 100 μm square contact pads. Figure 2 shows the process steps of the fabrication of the FIB test sample. Device characterization was made using SEM examination and *I–V* measurements.

III. RESULTS AND DISCUSSION

Figure 3 shows the *I–V* characteristics of the device shown in Fig. 1. The device consists of ten resistors (conducting lines) in parallel. The resistor length is 50 μm (equal to the spacing between the boron implanted pads) and the width is 0.2 μm. The resistance values in the insert are those of one resistor (line). As expected, we observed a decrease in resistance as the dose increases. Figure 4 is a plot of the resistance

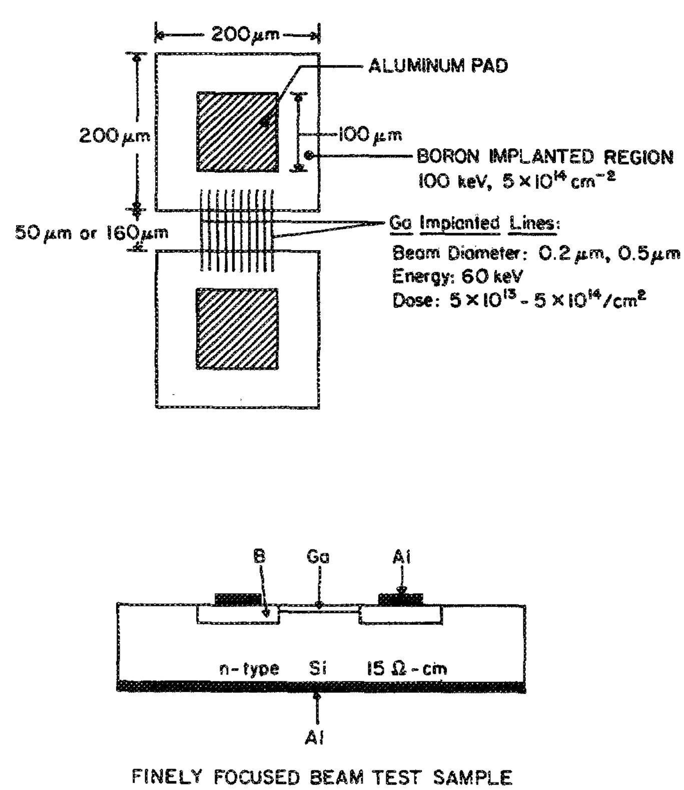

FIG. 1. FIB test structure.

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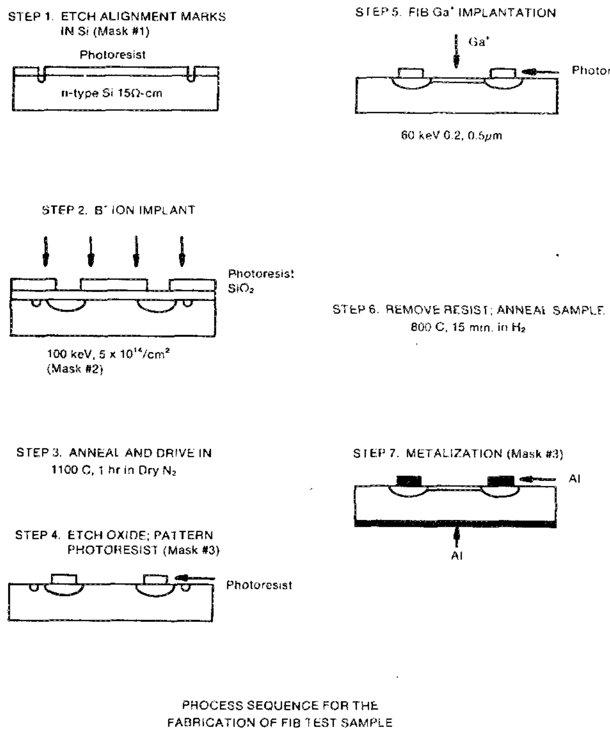

FIG. 2. Fabrication sequence of FIB test sample.

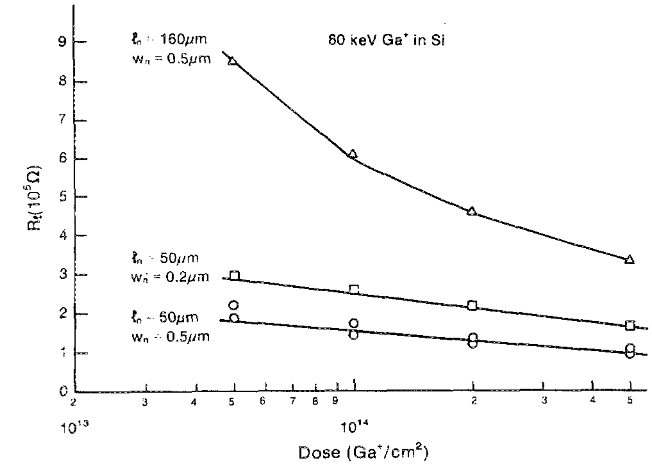

FIG. 4. Resistance per line R_ℓ vs dose for different device geometries.

per line R_ℓ as a function of dose for various device geometries. We notice that, for the same resistor length l_n, the resistance increases with decrease in nominal beam diameter W_n, and for the same beam diameter, the resistance increases with resistor length. This is correct dependence of resistance on resistor geometry. For identical devices, however, a variation of resistance about 10% at high dose (5E14 Ga/cm^2) and about 25% at low dose (5E13 Ga/cm^2) was observed between different chips. The dose uncertainty at low dose levels may be one reason behind the observed 25% variation. Another reason could be the presence of defects/resist residues on the region to be implanted with the FIB. Power supply failure during implanatation results in open lines which contributes to the variation in resistance. In order to study the effect of dose on the lateral profile of implanted Ga in Si and SiO_2, a fixed beam diameter was used to implant lines in Si and SiO_2 at various doses. A damage dependent etch (H_3PO_4 at 180 °C for Si and HF for SiO_2) was used to remove the implanted regions. An SEM was then used to measure the resulting linewidth. Figure 5 shows the dependence of linewidth on dose. Notice the increase in linewidth as the dose increases. This could be due to many factors, such as the effect of the tail of the Gaussian beam, which becomes pronounced at high dose, scattering in the substrate, lateral damage spread, and sputtering or enhanced etching at high dose. The same behavior is observed for lines implanted in SiO_2 (Fig. 6). Here, the charging of the SiO_2 affects the beam focusing at the target, which shows up

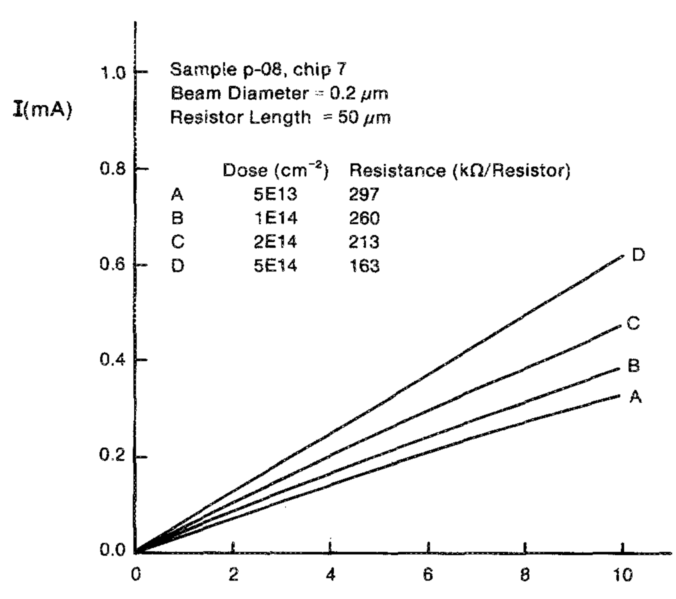

FIG. 3. *I–V* characteristics of device shown in Fig. 1 (l_n = 50 μm, W_n = 0.2 μm).

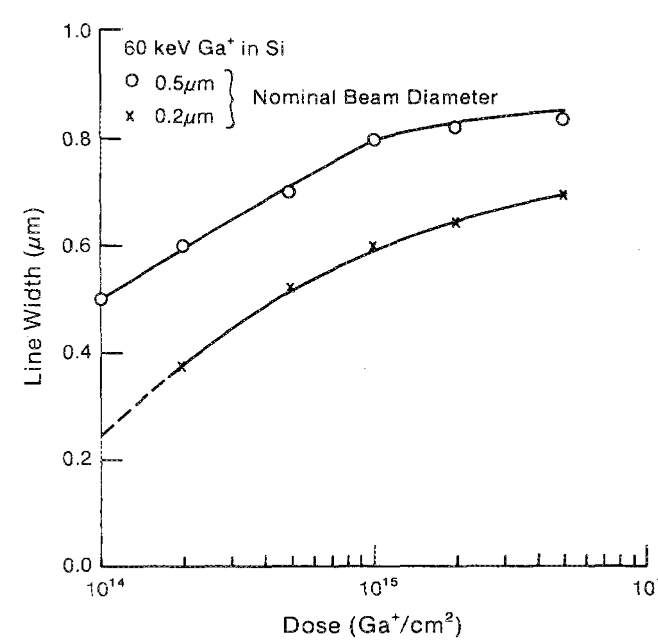

FIG. 5. Width of implanted lines in Si vs dose.

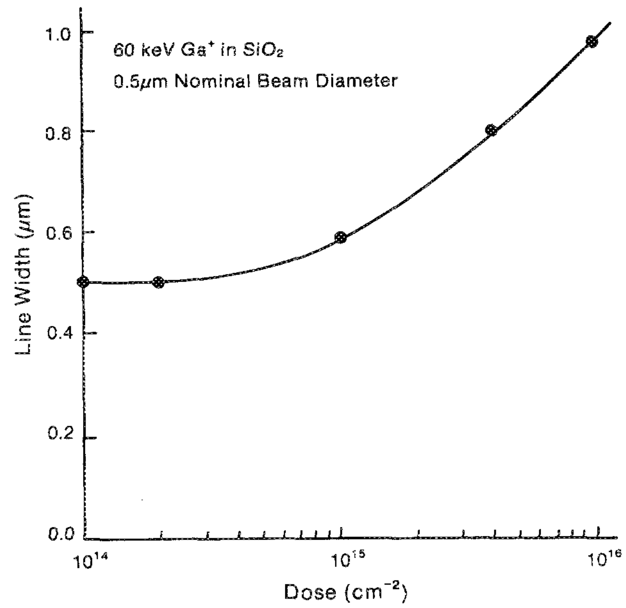

FIG. 6. Width of implanted lines in SiO_2 vs dose.

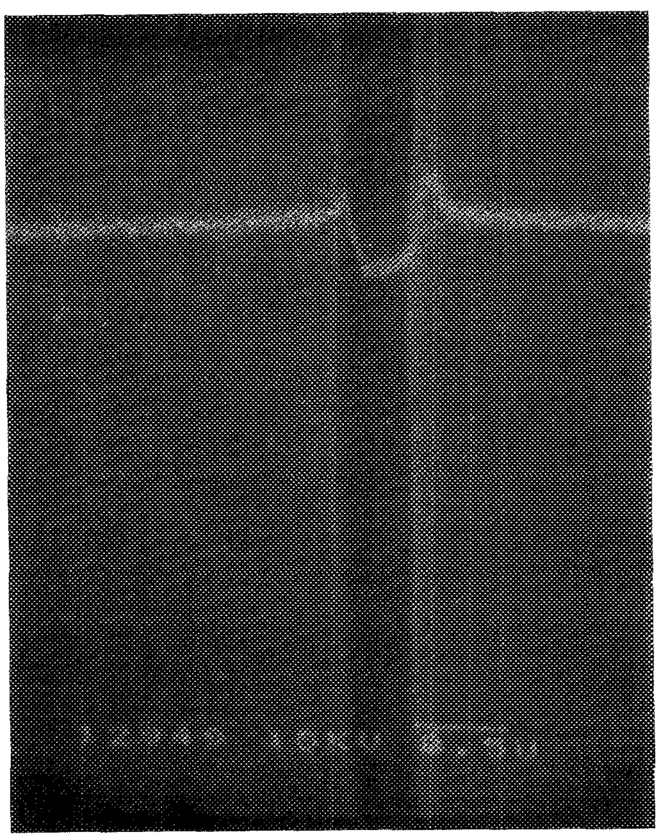

FIG. 7. Line engraved in Si using a 60 keV Ga^+ FIB. The beam diameter is 0.2 μm. The dose is 2E14 Ga/cm^2. An SEM line scan is superimposed. Sample treated in H_3PO_4 at 180 °C.

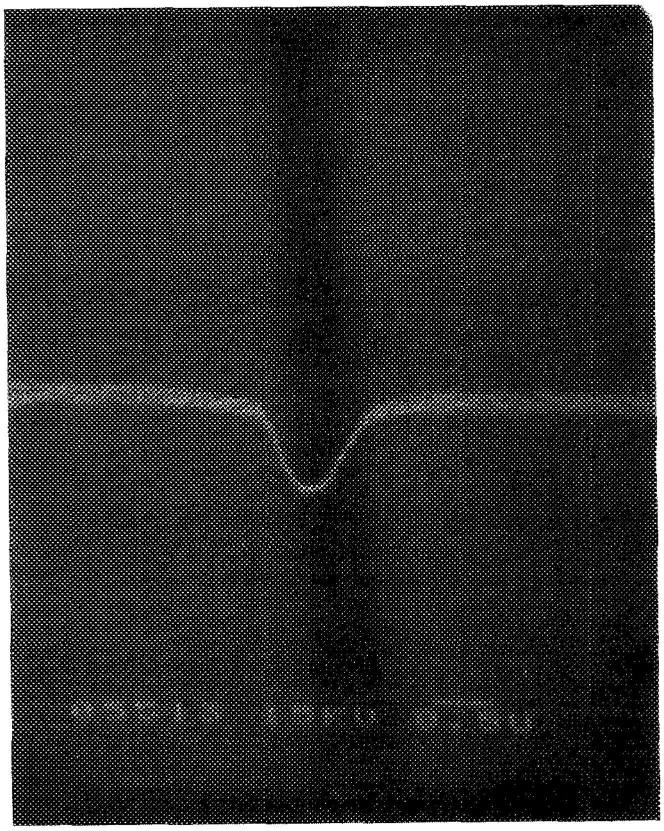

FIG. 8. Line engraved in SiO_2 using a 60 keV Ga^+ FIB. The beam diameter is 0.5 μm. The dose is 4E14 Ga/cm^2. An SEM line scan is superimposed. Sample treated in HF.

in broadening of engraved lines. The definition of linewidths given in Figs. 5 and 6 are the full width at half maximum taken from the SEM micrograpahs. Figures 7 and 8 are SEM pictures of lines engraved in Si and SiO_2 using a beam diameter of 0.2 and 0.5 μm and a dose 2E14 and 4E14 Ga/cm^2, respectively. The reason for the non-Gaussian shape in Fig. 7 is due to the nonlinear etch rate of H_3PO_4 with damage in Si.

IV. SUMMARY

A 60 keV focused Ga^+ ion beam of 0.2–0.5 μm in diameter was used to fabricate *p-n* junctions with two-terminal resistors in Si. Device characterization showed the correct dependence of resistance on dose and resistor geometry. Lateral profile of implanted Ga in Si and SiO_2 using a fixed ion beam diameter showed an increse in linewidth with increasing dose.

ACKNOWLEDGMENT

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