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INVESTIGATION OF FOCUSED ION BEAM IMPLANTATION PROFILE OF Ga^+ IONS FOR APPLICATIONS IN SILICON PHOTONICS

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ABSTRACT

Use of focused ion beam (FIB) as a nanostructuring platform for fast prototype device development in the area of photonics has been attracting a considerable interest. In this study, we report a systematic investigation of focused ion beam (FIB) induced Ga^+ ion implantation in silicon on insulator (SOI) structures. The local implantation of Ga^+ ions during milling is studied for a wide range of ion doses, ranging from about 10^{14} to 10^{17} ions/cm^2, using X-ray photoelectron spectroscopy (XPS). Ion implantation is realized on identically sized areas for each dose by varying the FIB parameters such as dwell time and loop number. It is found that the most of the Ga^+ is within the first 50 nm of Si. This suggests that it can be possible to potentially reduce optical losses caused by the ion implantation in any optical application. Methods such as thermal annealing and wet or dry chemical etching can result in removal of the 50 nm implanted layer of SOI, as a result removing the layer causing potentially high optical losses.

Keywords: Focused Ion Beam (FIB), Ga^+ ion implantation, SOI, Photonics

1. INTRODUCTION

The increasing interest in patterning materials at the nanoscale regime has been driving the development and use of alternative approaches such as focused ion beam (FIB) milling. FIB milling has been used for more than a decade in the microelectronics industry, however the attractiveness of this method in the area of photonics has only recently been recognized [1-9].

The main motivation for using this technology stems from the need for nanostructuring materials or material combinations that are hard to structure by use of more conventional methods such as those based on e-beam lithography, nanoimprinting or holography. Moreover, in comparison to other technologies for nanofabrication, FIB has the advantage of allowing fast prototyping, enabling fast proof of principle experiments. FIB technology can be used for reliable and well-controlled nanometer-size feature definition. The method involves physical removal of material by a beam of (most commonly) Ga^+ ions, and therefore can be adapted and optimized almost for any material system.

Some of recent reported applications of FIB processing for photonic devices include fabrication of laser facets in GaN [3], photonics crystals structures and Bragg reflectors in InP [6], $KY(WO_4)_2$ [9], $LiNbO_3$ [10], and Si-based materials [4, 5, 8, 11].

The main concern in employing FIB milling in fabrication of photonic structures is the effect of Ga^+ ion implantation on the optical performance of the devices. It is well known that the Ga^+ ions cause large optical losses through amorphization and ion implantation of the material [12, 13], while the exact mechanism is not yet well known.

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A recent study has investigated the effects of iodine-enhanced FIB milling of Si waveguides and the resulting optical losses in multimode waveguides [13]. In the current work, we extend this study and present a systematic investigation of Ga^+ implantation in Si. The study is expected to contribute to better understanding of Ga^+ implantation in its probable effects on optical waveguide structures.

2. EXPERIMENTAL

A dual-beam FEI Nova 600 FIB machine was used for the Ga^+ ion implantation experiments. The ion beam used in a milling process is generated from a liquid gallium ion source. The FIB milling current is controlled by adjusting aperture size in discrete steps. The spot size of the beam gets larger with increasing milling current with the lowest spot size being 7.5 nm at a current of 1.5 pA.

The writing field, i.e. the maximum area that can be scanned by the ion beam, of the FIB is divided in 4096 by 4096 pixels and its actual size depends on the selected magnification. In other words, the magnification determines the field of view as in a conventional optical microscope. For instance, at a magnification of 5000 times the resulting writing field or field of view (FOV) is of about 25x25 μm, with a grid spacing of 6.2 nm. There are various parameters that are to be well controlled in order to achieve nano-structuring process with desired characteristics. The most important ones can be listed as follows:

Dwell time - the stationary time on one pixel while milling.
Loop number - the repetitive pass number for the whole patterns.
Dose per area - total dwell time current averaged by area.
Pixel pitch - the distance between two adjacent pixels.

There are several different approaches on how to define the geometry of the structure to be milled. The simplest one is to use the built-in geometrical shapes of the software of the machine and draw the desired structure directly on the screen and mill it on the layer of interest. This basic method, however, lacks repeatability and most importantly does not allow for precise control of the above-mentioned critical parameters. The second method is to make use of a stream file. A stream file is a predefined mask file that contains milling time, pixel information, and pixel sequence for the desired geometry. The most common approach to create a stream file is to convert a bitmap picture into set of coordinates by using special software. This also results in limitations since the pixel sequence in this method cannot be well controlled, however for complicated geometrical structures the bitmap conversion approach can still be feasible. For the structures of interest in this project, it is possible to create the stream files of the structures to be milled by using programming tools.

For this purpose we have developed a code that allowed for a complete control over the critical parameters such as dwell time, loop number, dose per area and milling sequence. In all of the implantation work reported below a stream file approach was used.

Based on preliminary tests for balance between milling time and accuracy, the current was fixed at 48 pA and the acceleration voltage was set to 30 keV. The dose per area, defined by the total current dwell time averaged over the milled area, was varied and programmed to achieve the desired ion doses for each experiment.

3. RESULTS AND DISCUSSION

The Ga^+ ion implantation profile has been investigated using Physical Electronics Quantera XPS. The ion implantation has been realized using FIB as discussed in the experimental section.

The main reason for diminished optical performance of FIB milled structures is the local implantation of Ga^+ ions. TRIM (transport and range of ions in matter) calculations [13] and previous ion implantations studies in Si predict large number of implanted ions and amorphization of the Si layer [14-16]. Ga^+ ion is known to have a low solid solubility in Si and a low amorphization dose. The critical dose for continuous amorphous layer formation is reported to be about 1×10^{14} ions/cm^2 [14, 15]. The typical ion doses involved in FIB milling can be higher by few orders of magnitude (typically ranging from 10^{16} ions/cm^2 to more than 10^{18} ions/cm^2).

Since we are interested in the implantation of ions during the actual milling of nanostructures, we have chosen to investigate doses in the range between 5×10^{14} ions/cm^2 and 1×10^{17} ions/cm^2. The minimum dose that was chosen corresponds to the case of ion implantation with no detectable milling, while the highest dose used resulted in substantial material removal. A uniform area of 25×25 μm^2 of planar SOI structure was irradiated with FIB for each of the six different doses, as listed in Table 1.

Table 1. List of Ga^+ ion doses used throughout the experiments.

Experiment #	Ga^+ ion dose (ions/cm^2)
1	5×10^{14}
2	5×10^{15}
3	1.25×10^{16}
4	5×10^{16}
5	1×10^{17}
6	2×10^{17}

The optical microscope picture of the ion-implanted experiments on Silicon on insulator (SOI) are shown in Figure 1.

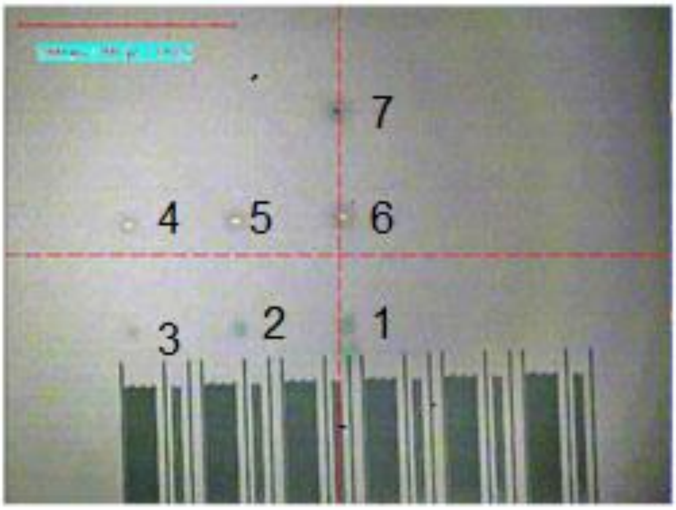
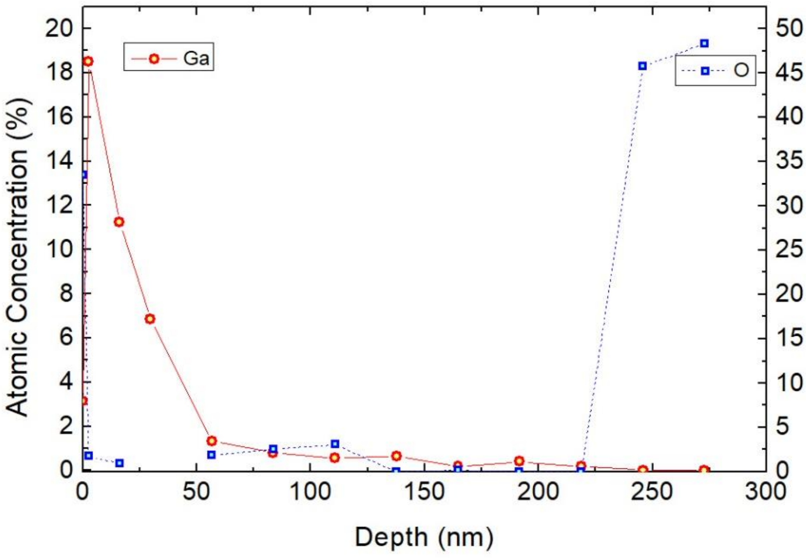


Figure 1. Optical microscope image of the ion implanted regions on SOI with the dose experiments as listed in Table1. The experiment 7 was used for control purposes.

The incorporation of Ga^+ ions in Si was analyzed using depth profiled X-ray photoelectron spectroscopy (XPS) and the milling rate has been corrected to correspond to the thickness of analysis.

Figure 2 (a) depicts the implantation profile of gallium and oxygen in the SOI sample for various doses and Figure 2 (b) summarizes the variation of atomic percentages of Si, Ga and O in the sample for experiment 5.

(a)



(b)

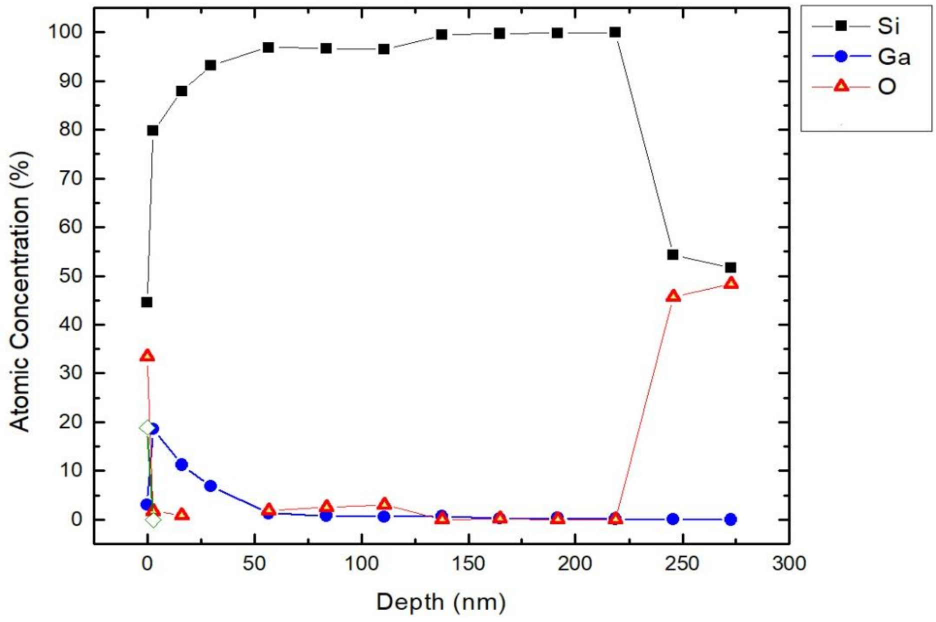


Figure 2. **(a)** The FIB implantation profile of gallium and oxygen in the SOI sample for dose of experiment 5; **(b)** variation of atomic percentages of Si, Ga and O as a function of thickness of the SOI sample for experiment 5.

We observe that almost all the gallium is within about the first 50 nm of Si for all doses and that an extremely high doping level occurs in the top few tens of nanometers, where the silicon is expected to be amorphized. The obtained results are in good agreement with previous observations in literature [16].

Similar trend and has been observed for all the implanted doses. Summary of specifically Ga^+ ion implantation profile as a function of thickness is presented in Figure 3.

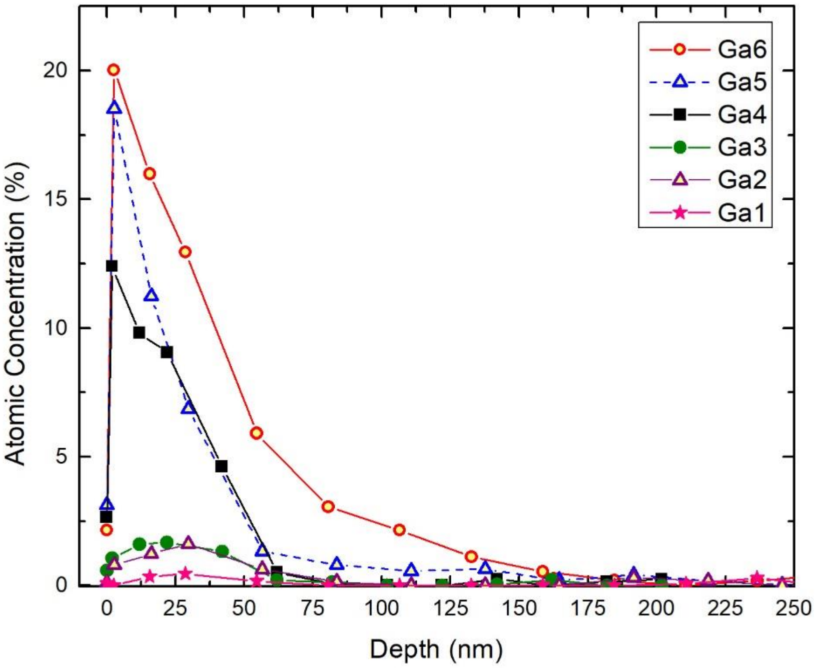


Figure 3. Ga$^+$ ion implantation profile as a function of SOI thickness for the six different ion doses.

The results suggest that there is significant Ga+ implantation for all the doses used in the experiments. Most of the Ga+ is found within the first 50 nm of Si. This suggests that it can be possible to potentially reduce optical losses caused by the ion implantation in any optical application. Methods such as thermal annealing [17]and wet or dry chemical etching can result in removal of the 50 nm-implanted layer of SOI, as a result removing the layer causing potentially high optical losses.

3. CONCLUSIONS

We have performed a systematic investigation of focused ion beam (FIB) induced Ga$^+$ ion implantation in silicon on insulator (SOI) structures. The ion implantation has been realized on identically sized areas for each dose by varying the FIB parameters such as dwell time and loop number. The local implantation of Ga$^+$ ions during milling was studied for a wide range of ion doses, ranging from about 10^{14} to 10^{17} ions/cm^2, using X-ray photoelectron spectroscopy (XPS). It was found that the most of the Ga$^+$ is within the first 50 nm of Si. This suggests that it can be possible to potentially reduce optical losses caused by the ion implantation in any optical application. Methods such as thermal annealing and wet or dry chemical etching can result in removal of the 50 nm-implanted layer of SOI, thus removing the layer causing potentially high optical losses.

REFERENCES

[1] Tseng AA, "Recent developments in nanofabrication using focused ion beams," Small 1, 924-939 (2005).

[2] Marinelli C, Bordovsky M, Sargent LJ, Gioannini M, Rorison JM, Penty RV, White IH, Heard PJ, Benyoucef M, Kuball M, Hasnain G, Takeuchi T and Schneider RP, "Design and performance analysis of deep-etch air/nitride distributed Bragg reflector gratings for AlInGaN laser diodes," Appl. Phys. Lett. 79, 4076-4078 (2001).

[3] Kotani T, Hatada Y, Funato M, Narukawa Y, Mukai T, Kawakami Y and Fujita S, "Fabrication and characterization of GaN-based distributed Bragg reflector mirrors for low lasing threshold and integrated photonics," Phys. Status Solidi C 2, 2895-2898 (2005).

[4] Tanaka Y, Tymczenko M, Asano T and Nod, "Fabrication of two-dimensional photonic crystal slab point-defect cavity employing local three-dimensional structures," Jpn. J. Appl. Phys. 1 45, 6096-6102 (2006).

[5] Cabrini S, Businaro L, Prasciolu M, Carpentiro A, Gerace D, Galli M, Andreani C, Riboli F, Pavesi L and Di Fabrizio E, "Focused ion beam fabrication of one-dimensional photonic crystals on Si_3N_4/SiO_2 channel waveguides," J. Opt. A-Pure and Appl. Opt. 8, S550-S553 (2006).

[6] Callegari V Nellen PM, Kaufmann J, Strasser P and Robin F, "Focused ion beam iodine-enhanced etching of high aspect ratio holes in InP photonic crystals," J. Vac. Sci. Technol. B 25, 2175-2179 (2007).

[7] Reithmaier JP and Forchel A, "Focused ion-beam implantation induced thermal quantum-well intermixing for monolithic optoelectronic device integration," IEEE J. Sel. Top. Quant. 4, 595-605 (1998).

[8] Schrauwen J, Van Lysebettens J, Claes T, De Vos K, Bienstman P Van Thourhout D, and Baets R, "Focused-Ion-Beam Fabrication of Slots in Silicon Waveguides and Ring Resonators," IEEE Photonic Tech. L. 20, 2004-2006 (2008).

[9] Ay F, Iñurrategui I, Geskus D, Aravazhi S and Pollnau M, "Integrated lasers in crystalline double tungstates with focused-ion-beam nanostructured photonic cavities," Laser Phys. Lett. 8, in print (2011).

[10] M. Roussey, M. P. Bernal, N. Courjal, D. Van Labeke, F. I. Baida, and R. Salut, "Electro-optic effect exaltation on lithium niobate photonic crystals due to slow photons," Appl. Phys. Lett. 89, 241110 (2006).

[11] Hopman WCL, Ay F, Hu WB, Gadgil VJ, Kuipers L, Pollnau M and de Ridder RM, "Focused ion beam scan routine, dwell time and dose optimizations for submicrometre period planar photonic crystal components and stamps in silicon," Nanotechnology 18, 195305 (2007).

[12] de Ridder RM, Hopman WCL and Ay F, "Focused-ion-beam processing for photonics," ICTON 2007: Proceedings of the 9th International Conference on Transparent Optical Networks, Vol 2, 212-215 (2007).

[13] Schrauwen J, Van Thourhout D and Baets R, "Iodine enhanced focused-ion-beam etching of silicon for photonic applications," J. Appl. Phys. 102, 103104 (2007).

[14] Chu CH, Hsieh YF, Harriott LR and Wade HH, "Structural damage induced by Ga^+ focused ion beam implantation in (001) Si," J. Vac. Sci. Technol. B 9, 3451-3455 (1991).

[15] Tamura M, Shukuri S, Moniwa M and Default M, "Focused Ion Beam Gallium Implantation into Silicon," Appl. Phys. A-Mater. Sci. Process. 39, 183-190 (1986).

[16] Rubanov S and Munroe PR, "FIB-induced damage in silicon," J. Microsc. 214, 213-221 (2004).

[17] Arora BM, Castillo JM, Kurup MB, and Sharma RP, "Thermal Annealing and Electrical Activation of High-Dose Gallium Implanted Silicon," J. Electron. Mater. 10, 845-862 (1981).