Electronic Materials Letters, Vol. 6, No. 2 (2010), pp. 55-58
DOI: 10.3365/eml.2010.06.055 Published 30 June 2010

Two-Dimensional Dopant Profiling in p+/n Junctions Using Scanning Electron Microscope Coupled with Selective Electrochemical Etching

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Scanning Electron Microscopy (SEM) combined with selective electrochemical etching was used to assess two-dimensional (2-D) dopant profiles in p+/n junctions that formed by using BF_2 implantation followed by annealing. It was discovered that the electrochemically delineated junction depth (d_j) increased with an increase in the BF_2 implantation energy. It was also found that, considering the mechanism of selective electrochemical etching, d_j represents the junction edge that corresponded to the electrically-activated B atoms. The simulated 2-D dopant profiles of the experimental conditions were directly compared with the SEM results, and the implications of the discrepancies are discussed in this paper.

Keywords: dopant, two-dimensional, selective electrochemical etching, SEM, junction

1. INTRODUCTION

The ion implantation process has been successfully used to shrink Metal-Oxide Semiconductor Field-Effect Transistors (MOSFETs) device dimensions down to the deep-submicron level.[1] Recent developments in this field have focused on obtaining accurate information about the dopant distribution and the depth of junction . In particular, the assessment of the lateral diffusion of dopants in the gate area of the devices has become critical in obtaining the desired electrical characteristics and the calibration of process simulators. Generally, the Secondary Ion Mass Spectroscopy (SIMS) and Spreading Resistance Profiling (SRP) have been the most widely used methods for extracting dopants or carrier distributions out of the p-n junctions. These methods have been largely restricted to one-dimensional (1-D) depth profiles, although some special SIMS techniques have revealed two-dimensional (2-D) dopant distribution with a spatial resolution that is not sufficient. To overcome such a limitation, many attempts have been made to assess 2-D dopant profiles using electron microscopy combined with selective chemical etching,[2-5] Scanning Capacitance Microscopy (SCM),[6] Scanning Tunneling Microscopy (STM),[7] Kelvin Probe Force Microscopy (KPFM),[8] and electron holography.[9] Among these attempts, electron microscopy combined with selective chemical etching has received significant attention because of its simple experimental procedure and easy data interpretation. Until now, 2-D dopant profiling based on selective chemical etching, in combination with electron microscopy analysis, has focused on the n+/p junctions due to the large sensitivity range of the dopant ($10^{16} \sim 10^{21}$ cm^{-3}), which is suitable for the direct characterization of commercial devices. On the other hand, several efforts have been made to delineate 2-D dopant distribution in p+/n junctions by using Ultraviolet (UV) illumination or Direct Current (DC) bias-assisted selective chemical etching combined with Transmission Electron Microscopy (TEM).[4,10] However, the artifacts, such as the thickness variation of the TEM specimen and the ion milling damage that occurred during the TEM specimen preparation, could be a main barrier in obtaining reliable 2-D results. Furthermore, since the TEM specimen preparation is hard and time consuming, the use of a Scanning Electron Microscopy (SEM) is more useful and effective in revealing 2-D junction profiling than TEM.

In this work, we demonstrated 2-D dopant profiling in p+/

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n junctions by using selective electrochemical etching with SEM for the first time. The experimental data were directly compared with the simulation results, which was necessary in order to create a database from which the parameters of the simulation programs could be extracted.

2. EXPERIMENTAL PROCEDURE

Test structures were made for the junction pro-filing study. A series of MOSFETs that had p+/n junctions was fabricated on n-type Si (100) wafers with a doping concentration of 10^{17} cm^{-3}. To form gate stacks, 10 nm-thick SiO_2 films were thermally grown, upon which 160 nm-thick Si_3N_4 films were deposited. Si_3N_4 was chosen as a gate electrode due to its high resistance to the etching solution. After patterning gate stacks with a space of 1.5 mm using photolithography, combined with dry etch, the implantation of BF_2 was performed under two conditions: energies of 20 keV and 65 keV to a dose of 10^{15} cm^{-2}. These samples were then annealed at 950°C for 30 min in a flowing N_2 ambient. Finally, amorphous Si layers were covered on all the samples in order to protect the surfaces from damage that can occur during the specimen preparation and the selective etching process. In order to directly reveal 2-D dopant profiles in the p^+/n junctions, a Scanning Electron Microscopy (SEM, JEOL JSM-5800), coupled with selective electrochemical etching, was performed. The selective chemical etching technique used was based on the works of Choi *et al.,*[4] who demonstrated that selective electrochemical etching based on the anode oxidation of Si can lead to the delineation of p+/n junctions with a detection of dopant levels at 10^{17} cm^{-3}. For selective electrochemical etching, cross-sectional SEM specimens were prepared by using a conventional “sandwich” technique that was electrochemically etched using a mixture of $HF:HNO_3:CH_3COOH$ (1:100:10) for 5 s under a DC bias of +0.8. For comparison, dopant distributions in the test structures were simulated by using a Silvaco process simulator that used the default values.

3. RESULTS AND DISCUSSION

Figure 1 shows the plots of B and carrier concentrations as a function of depth for test structures implanted with energies of 20 keV and 65 keV BF_2 to a dose of 10^{15} cm^{-2}, which were extracted from the simulated SIMS and SRP data. It is clear that both plots show similar behavior of B and carrier concentrations. A comparison of the 1-D SRP and SIMS data shows that the junction revealed by SRP is shallower than that measured by SIMS. For example, for a background doping concentration of 10^{17} cm^{-3}, the junction depths calculated from the simulated SRP and SIMS were found to be 280 and 300 nm for the 20 keV implanted test structure, and 319 and 341 nm for the 65 keV implanted test structure, respectively. It should be noted that the SRP data were in good agreement with the SIMS data in regions that had carrier concentrations higher than 10^{18} cm^{-3}. Below this concentration, there was a relatively large discrepancy between the SRP and SIMS results. This implies that all the implanted dopant atoms were not electrically activated by the annealing process used in this study.

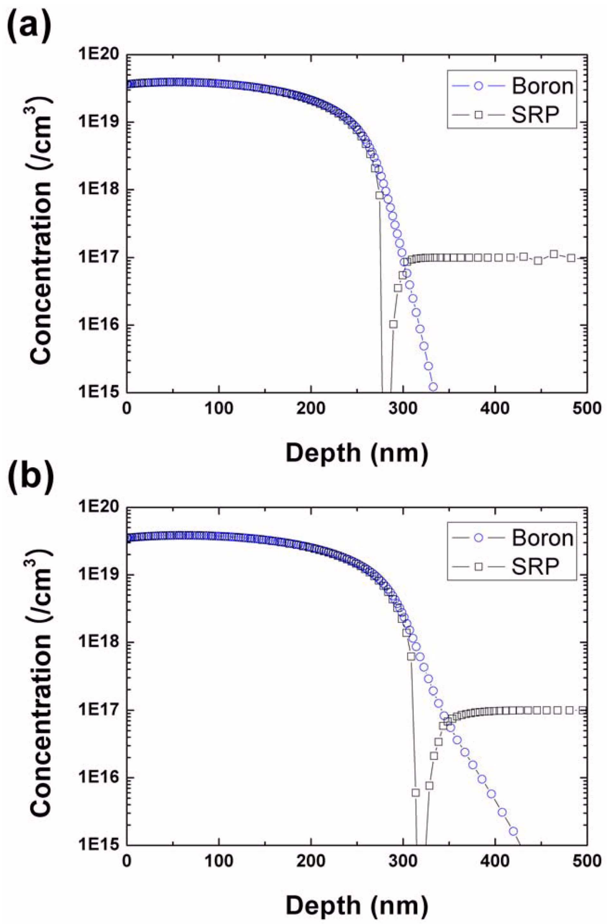

Fig. 1. Plots of B and carrier concentrations as a function of depth for the test structures implanted with energies of (a) 20 keV and (b) 65 keV BF_2 to a dose of 10^{15} cm^{-2}, which were extracted from the simulated SIMS and SRP data.

Figure 2 shows the SEM images that were taken from selective electrochemically-etched test structures ion-implanted with 20 keV and 65 keV BF_2 to a dose of 10^{15} cm^{-2}. The images clearly reveal the presence of etch contours formed as a result of the doping-dependent etching in the p-type doped regions. These images may represent the iso-concentration line that corresponded to the junction edge, since the reaction of selective electrochemical etching was strongly dependent on the energy band structure formed at the interface between the p-type Si and the chemical solution.[11,12] Both test structures showed similar behavior of the 2-D dopant distribution. In other words, the iso-concentration line was parallel to the Si substrate surface in the middle region of the well and was bent upward under the gate oxide, terminating at the gate oxide/Si substrate interface. The electrochemically delineated junction depth (d_{j},) measured from the distance from the amorphous Si/Si substrate interface to the iso-concentration line in the middle region of the well, was found to be 267 nm and 301 nm for the 20 keV and 65 keV implanted test structures, respectively. Compared to the simulated SIMS and SRP results (Fig. 1), d_j was more comparable to the junction depth extracted by the simulated SRP results than to the simulated SIMS results. This implies that selective electrochemical etching was effective in revealing electrically-activated dopants. The ratio of Lateral to Vertical (L/V) diffusion, measured at d_j in the lateral and vertical extensions of the SEM images, was calculated to be 0.61 and 0.57 for the 20 keV and 65 keV BF_2 implanted test structures, respectively. Additionally, compared to most of the previous studies that examined the 2-D dopant distributions in the n+/p junctions that formed using various As implantation processes, the L/V ratio extracted from the p+/n junctions that formed using the BF_2 implantation employed in this study was relatively higher.[13] This could be attributed to the faster diffusion of B atoms than As atoms during the thermal process.

Figure 3 represents the simulated 2-D dopant distributions taken from test structures implanted with 20 keV and 65 keV BF_2 to a dose of 10^{15} cm^{-2}. For convenience, three iso-concentration lines for B atoms that corresponded to 10^{19} cm^{-3}, 10^{18} cm^{-3}, and 10^{17} cm^{-3} were drawn to clearly resolve the junction boundary. For both test structures, the 2-D simulation results did not fit well with the experimental results (Fig. 2), although they showed similar trends. For example, the simulated profiles were slightly more bowed in the region under the gate, whereas the SEM profiles tapered toward the surface. Furthermore, the L/V ratio of simulation results wasrelatively lower than the ratio of the experimental results. The L/V ratio extracted from the simulation results was found to be 0.59 and 0.53 for the 20 keV and 65 keV BF_2 implanted test structures, respectively. This indicates that the simulated lateral profiles were not suitable for presenting the 2-D dopant profiles. In fact, the 2-D simulator is an engineering model platform in which a calibration algorithm that can obtain the computed results is required in order to match the available process measurements. Therefore, such a discrepancy between the simulated and experimental results could be associated with the lack of information about the lateral dopant pro-files in the junction.

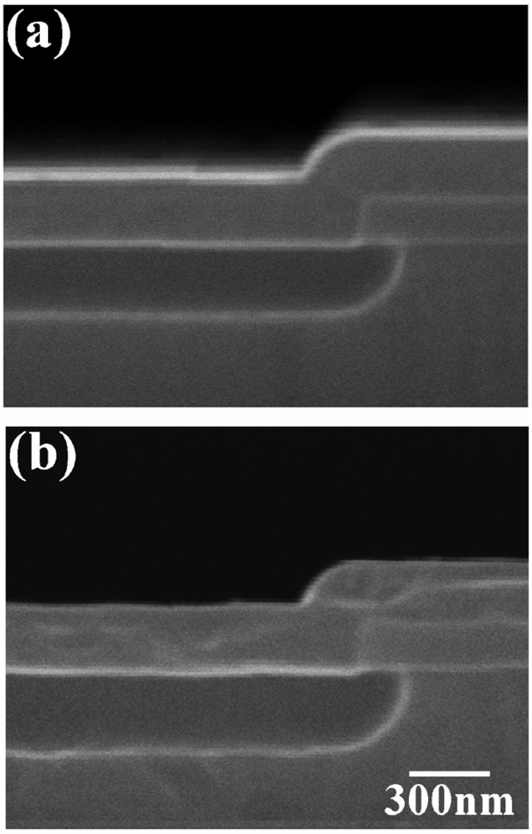

Fig. 2. SEM images taken from selective electrochemically-etched test structures ion-implanted with (a) 20 keV and (b) 65 keV BF_2 to a dose of 10^{15} cm^{-2}.

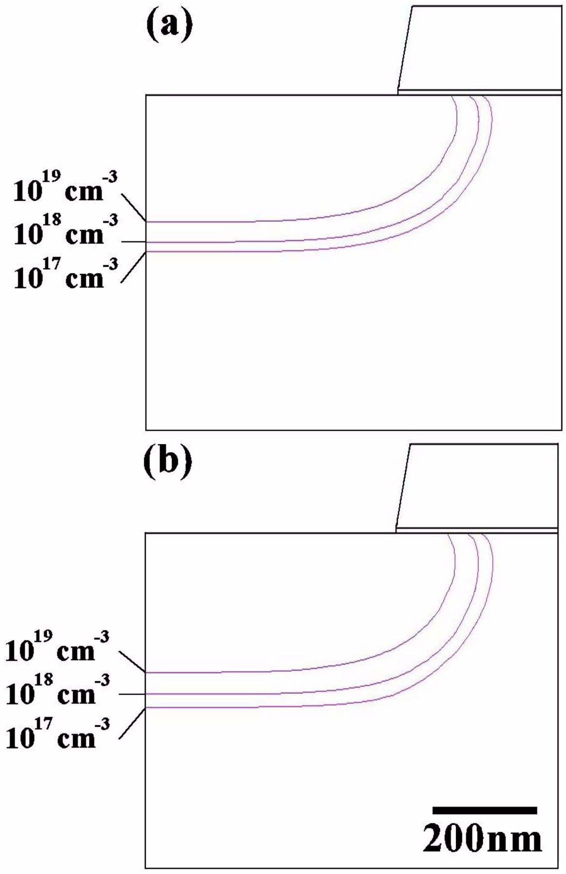

Fig. 3. Simulated 2-D dopant distributions taken from test structures implanted with (a) 20 keV and (b) 65 keV BF_2 to a dose of 10^{15} cm^{-2}.

4. CONCLUSION

We fabricated MOSFETs with p+/n junctions that formed from performing BF_2 implantation at energies of 20 keV and 65 keV with a dose of 10^{15} cm^{-2}. SEM coupled with selective electrochemical etching was employed in order to investigate the 2-D dopant distributions in the p+/n junctions. It was shown that selective electrochemical etching was effective in delineating the distribution of the electrically-activated dopant. The simulated dopant profiles exhibited a relatively large discrepancy with the experimental profiles, indicating further improvements needed for the numerical model for lateral diffusion enhancement.

ACKNOWLEDGMENTS

This work was financially supported by the Converging Research Center Program through the National Research Foundation (NRF) of Korea funded by the Ministry of Education, Science and Technology (2009-0082207), and the grant from the Industrial Source Technology Development Programs (2009-F014-01) of the Ministry of Knowledge Economy (MKE) of Korea.

REFERENCES

1. C. Hill, *J. Vac. Sci. Technol. B.* **10**, 289 (1992).
2. C. J. Choi and T. Y. Seong, *J. Electrochem. Soc.* **147**, 1525 (2000).
3. C. J. Choi, T. Y. Seong, K. M. Lee, J. H. Lee, Y. J. Park, and H. D. Lee, *Electrochem. Solid-State Lett.* **4**, G88 (2001).
4. C. J. Choi, T. Y. Seong, K. M. Lee, J. H. Lee, Y. J. Park, and H. D. Lee, *IEEE Trans. Electron Device Lett.* **23**, 188 (2002).
5. L. Gong, S. Peterson, L. Frey, and H. Ryssel, *Nucl. Instrum. Methods B*. **96**, 133 (1995).
6. Y. Huang and C. C. Williams, and J. Slinkman, *Appl. Phys. Lett*. **66**, 344 (1995).
7. K. J. Chao, A. R. Smith, and A. J. McDonald, D. L. Kwong, B. G. Streetman, and C. K. Shih, *J. Vac. Sci. Technol. B.* **16**, 453 (1998).
8. H. J. Shin, B. K. Lee, C. H. Kim, H. S. Park, D. K. Min, J. W. Jung, S. B. Hong, and S. D. Kim, *Electron. Mater. Lett.* **1**, 127 (2005)
9. A. E. Thesen, B. G. Frost, and D. C. Joy, *J. Vac. Sci. Technol. B.* **20**, 3063 (2002).
10. C. Spinella, V. Raineri, and S. U. Campisano, *J. Electrochem. Soc.* **142**, 1601 (1995).
11. S. K. Ghandhi, *The Theory and Practice of Microelectronics*, p. 154, John Wiley & Sons, New York, (1968).
12. A. J. Bard, and L. R. Faulkner, *Electrochemical Methods: Fundamentals and Applications*, p. 636, Wiley & Sons, New York, (1980).
13. R. Alvis, S. Lunung, L. Thompson, R. Sinclair, and P. Griffin, *J. Vac. Sci. Technol. B* **14**, 231 (1996).