Low energy off-axis focused ion beam Ga$^+$ implantation into Si

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(Received 29 May 1991; accepted 16 July 1991)

Off-axis focused ion beam (FIB) implantation of Ga$^+$ has been performed at low energies to study the channeling effect. FIB implantations were performed at 3, 5, and 10 keV into crystalline (100) Si at tilt angles of up to 15° toward the ⟨110⟩ axis. The Ga atomic depth profile was measured using secondary ion mass spectrometry with a 2-keV-Cs$^+$ primary beam incident at 60° from the sample normal, in order to minimize ion beam mixing effects during sputttering. The Ga depth profiles show significant reduction in channeling with implantation tilt angle. The fractions of the Ga dose found in the tail of distribution for the 5 keV implant were ~16% and 10% for the 0° and 15° off-axis implantation, respectively. Corresponding values reported for 5-keV B$^+$ implantation under the same conditions are ~50% and 19%, respectively. Thus, low energy FIB Ga implantation is seen to not only have a much lower penetration depth than B, but also to produce more effective channeling suppression.

I. INTRODUCTION

The fabrication of shallow layers and *p-n* junctions can be obtained by low energy broad beam or focused ion beam implantation. For the formation of nanometer-scale Si p^+-n junctions, conventional implantation using ^{11}B demands extremely low energy and suffers from substantial channeling[1,2] even at tilt (off-axis) and rotation angles in excess of 15°–20°. Moreover, such a large tilt angle would result in undesirable shadowing effects during device fabrication while wafer rotation is difficult to accommodate in automated ion implanters. FIB implantation parallel-to-sample-normal of heavy group III elements has been shown to produce nanoscale junctions, as low as 15 nm for 5 keV Ga$^+$.[3] This was accomplished in part due to the effective amorphization of the crystalline Si substrate during Ga$^+$ FIB implantation. Electrical properties of these low energy FIB-implanted junctions indicate excellent characteristics,[4] with leakage current density of ~10 nA/cm^2, breakdown voltage of ~100 V, and ideality factor of ~1.01.

In this paper, we report on an investigation of Ga channeling in Si at low energies by FIB implantation at various tilt angles. The Ga$^+$ FIB implants were performed using a MicroBeam Inc. NanoFab 150. A description of the FIB system can be found elsewhere.[3] Ga acceleration voltages of 3, 5, and 10 keV were used for implanting doses from 10^{13} to 10^{15}/cm^2 into regions of $540\times540\ \mu$m^2. The focus ion beam divergence at the sample was simulated in the column using SIMION.[5] At 3 keV, a divergence of 0.37° was calculated. The samples used were (100) oriented Si with phosphorus background concentration of $(1–2)\times10^{15}$ cm^{-3}. The crystal orientation was confirmed by x-ray diffraction. Immediately prior to FIB implantation only a native oxide layer (≈1–2 nm) was present on the Si samples. Tilt angles of 3°, 6°, 9°, 12°, and 15° from the ⟨100⟩ axis towards the ⟨110⟩ axis were used in these experiments. While (100) axial channeling is minimized in this configuration, planar channeling along the (110) planes is still expected to result in some "tailing" of the distribution. To completely minimize channeling, one must provide wafer tilt towards one of the higher index directions, such as the ⟨210⟩ axis, which avoids alignment with any planar channel and thus presents the incident ions with a near-random distribution of lattice atoms. In a sense this involves a combination of tilt about the ⟨110⟩ axis, followed by wafer rotation of the appropriate angle. Since this procedure is rather difficult to implement in our FIB system, we have limited our present experiments to the effects of ⟨110⟩ tilt.

The concentration as a function of depth of the implanted Ga ions was obtained from secondary ion mass spectrometry (SIMS) using a Perkin-Elmer 6300 system. Since at the low implantation energies used the majority of the implanted Ga ions are to be found within 10–20 nm of the surface, the SIMS depth profiling of such a small volume becomes an extremely challenging analysis.[6] We have optimized the depth resolution by employing a primary beam in the SIMS analysis consisting of low energy (2 keV) ^{133}Cs$^+$ ions incident at 60° from the sample normal direction. The Si matrix ion SIMS signal reaches an equilibration depth within 2–3 nm of the surface. This shallow equilibration depth enables us to accurately measure the "tail" of the distribution. The Ga ion count rate was converted to a Ga density using a conventionally Ga implanted standard. The depth scale calibration was obtained by measurement of the Cs$^+$-sputtered craters with a stylus profilometer.

II. EXPERIMENTAL RESULTS AND DISCUSSION

The Ga depth profiles obtained from the SIMS analysis of 5 keV implantation for a nominal dose of 1×10^{15}/cm^2 at angles of 0°, 3°, 6°, and 15° are shown in Fig. 1(a). The actual

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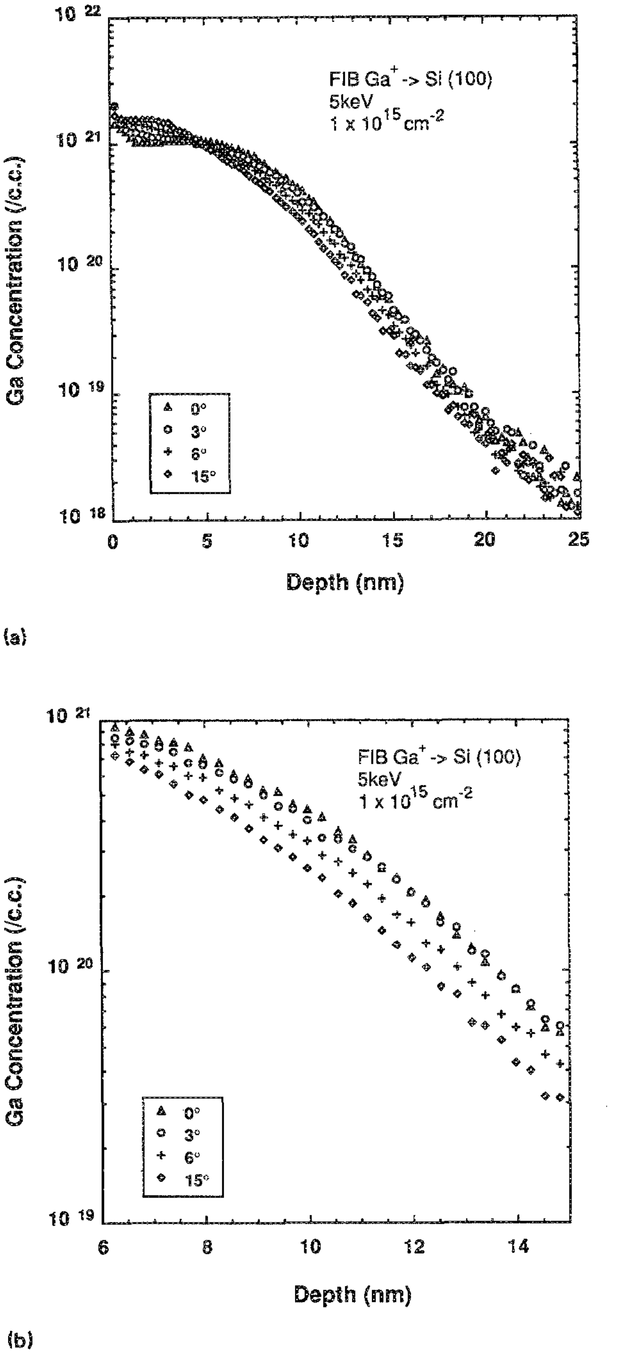

FIG. 1. SIMS depth profile of 5-keV FIB Ga$^+$ at 1×10^{15}/cm^2 dose: (a) full profile; (b) profile section on expanded scale.

dose for each profile was first obtained by integrating the measured concentration over the depth of the profile. These measured doses are shown in Table I. Then each profile was normalized to produce an equivalent 1×10^{15}/cm^2 dose. The effect of tilt angle is not readily apparent in Fig. 1(a), as the curves for all angles are quite close to each other. A clearer view of the effect of off-axis implantation is seen in Fig. 1(b), where a section of the depth profile from 6 to 15 nm is shown on an expanded scale. While a tilt angle of 3° appears to have only a marginal effect, an angle of 6°, and especially 15°, results in reduced channeling.

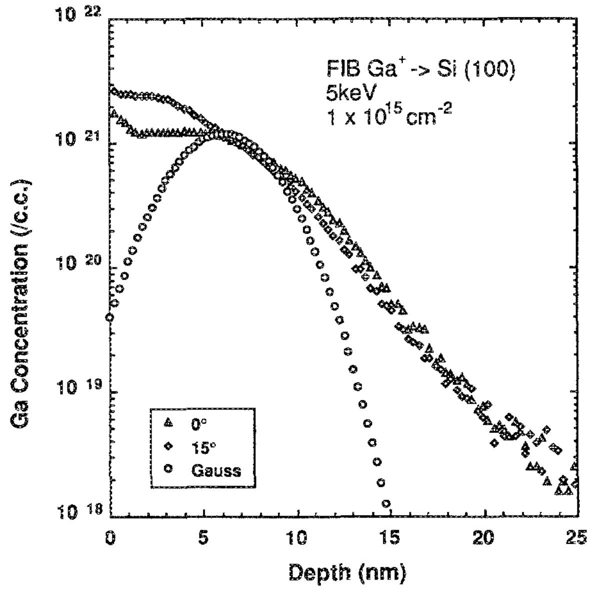

FIG. 2. Comparison of measured (SIMS) Ga depth profile and calculated Gaussian profile.

The extent of ion channeling is highlighted by comparing the experimental depth profiles to an ideal Gaussian distribution. An example is shown in Fig. 2, where the 5-keV Ga implant depth profiles at 0° and 15° are compared to a Gaussian profile using an R_p obtained by fitting a Pearson IV distribution[7] to the experimental data.

The Ga depth profiles obtained from SIMS analysis of the 3-keV Ga implantations are shown in Figs. 3 and 4 for doses of 1×10^{15} and 2×10^{14}/cm^2, respectively. By comparison to the 5 keV case, the off-axis implantations at 3 keV result in a tighter distribution with less apparent effect of tilt angle.

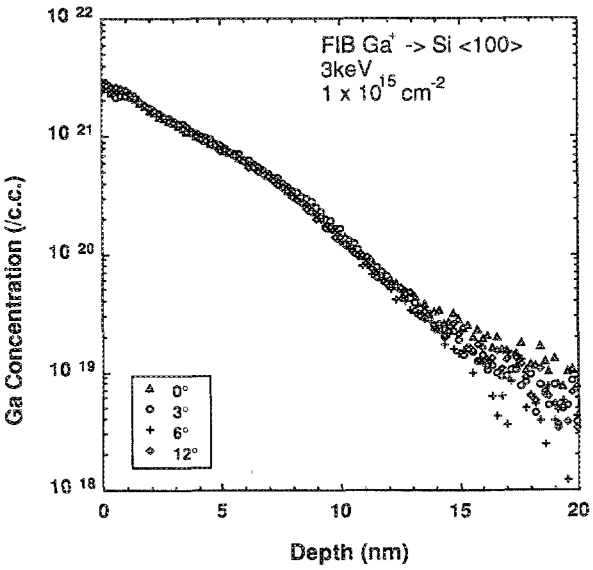

FIG. 3. SIMS depth profile of 3-keV FIB Ga$^+$ at 1×10^{15}/cm^2 dose.

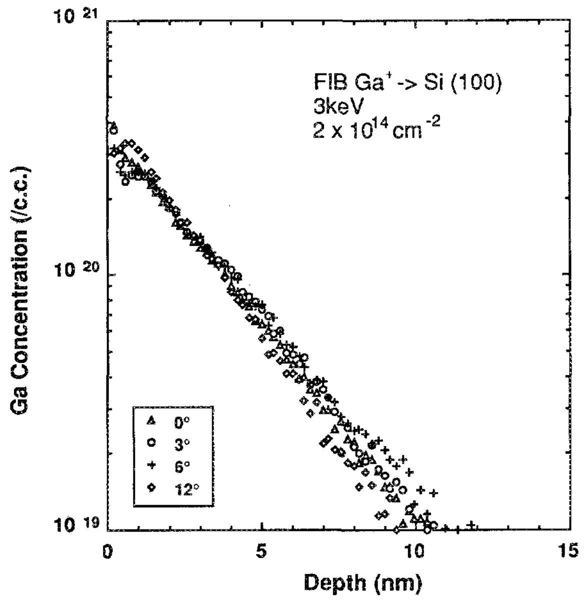

FIG. 4. SIMS depth profile of 3-keV FIB Ga$^+$ at 2×10^{14}/cm^2 dose.

To obtain an understanding of the effect of tilt angle on the extent of channeling we have computed an effective dose present in the tail of the distribution. This was obtained by integrating the difference between the SIMS and Gaussian profiles for depths where the experimental values exceed the Gaussian. This procedure is similar to that used by Michel *et al.*[1] for channeling in low energy B$^+$ implantation. The calculations for the residual Ga doses in the distribution tails of on- and off-axis implantations at various tilt angles are summarized in Table I. Because of inherent difficulties in profiling such shallow junctions, the SIMS data exhibits fluctuations which result in up to $\pm10\%$ error bars in the calculations of percentage channeling. A number of observations can be made. First of all, it is apparent that the off-axis tilt angle has only a weak effect on the level of channeling at these low implantation energies. This is probably due to the small amorphization dose for Ga implantation into Si which allows relatively little channeling to occur. For 5-keV Ga$^+$ on-axis implantation the percentage of the dose in the tail is 16%, while for a tilt angle of 15° only 10.3% of the total dose is found to have channeled. It is interesting to compare these 5-keV-Ga$^+$ residual dose values with those reported[1] for 5 keV B$^+$. The B ions were actually implanted into Si wafers tilted towards the ⟨210⟩ axis, which provides a more random direction than the ⟨110⟩ axis tilt we have used for Ga implantation. Nevertheless, it appears that the Ga off-axis implantation is more effective in preventing channeling than B off-axis implantation. Indeed, the percentage channeling for on-axis Ga implantation is somewhat less than for B implantation with 15° tilt angle. The second trend to be pointed out concerns the effect of energy on channeling. The level of channeling, as computed by this method, decreases at low energy. This is opposite the normal trend observed for higher energy (>25 keV) implantation, where the effectiveness of off-axis tilt increases with increasing energy.

III. CONCLUSIONS

Low energy, off-axis Ga focused ion beam implants into (100) Si wafers have been performed at various tilt angles about the ⟨110⟩ axis. The effect of tilt angle on channeling has been shown to be minimal at these energies, with relatively little channeling observed even for on-axis implantation. This should simplify the processing of shallow junctions and layers in MOS and bipolar circuits by eliminating the customary implantation tilt angle, while improving device characteristics by removing the shadowing effect.

The authors are pleased to acknowledge the contributions of D. Irvin in performing the FIB implants and of H. Wang for the SIMION simulations.

TABLE I. Residual integrated Ga in distribution tail.

Energy (keV)	Nominal dose (cm^{-2})	Measured dose (SIMS) (cm^{-2})	Tilt angle (degrees)	Dose in tail (10^{14} cm^{-2})	Percent dose in tail	Percent B in tail (Ref. 1)
3 keV	1×10^{15}	1.31×10^{15}	0	1.59	12.1%	
		1.35×10^{15}	3	1.70	12.6%	
		1.23×10^{15}	6	1.77	14.3%	
		1.08×10^{15}	12	1.28	11.8%	
5 keV	1×10^{15}	1.09×10^{15}	0	1.71	16%	49.5%
		1.33×10^{15}	3	2.04	15.6%	...
		1.21×10^{15}	6	1.55	13%	33.2%
		1.26×10^{15}	15	1.28	10.3%	18.5%
10 keV	1×10^{15}	8.67×10^{14}	0	1.59	18.4%	
		6.95×10^{14}	3	1.34	19.3%	
		7.88×10^{14}	6	1.40	17.8%	
		7.14×10^{14}	12	1.48	20.7%	

[1] A. E. Michel, R. H. Kastl, S. R. Mader, B. J. Masters, and J. A. Gardner, Appl. Phys. Lett. **44**, 404 (1984).
[2] M. Hane and M. Fukuma, IEEE Trans. Electron Devices **37**, 1959 (1990).
[3] A. J. Steckl, H. C. Mogul, and S. Mogren, J. Vac. Sci. Technol. B **8**, 1937 (1990).
[4] A. J. Steckl, H. C. Mogul, and S. Mogren, J. Vac. Sci. Technol. B **9**, 2718 (1991).
[5] D. A. Dahl and J. E. Delmore, *The SIMION PC/AT User's Manual, ver. 4.0* (Idaho National Engineering Laboratory, Idaho Falls, 1989).
[6] S. W. Novak, C. W. Magee, H. C. Mogul, and A. J. Steckl, J. Vac. Sci. Technol. B (to be published).
[7] H. Maes, W. Vandervorst and R. Van Overstraeten, in *Impurity Doping Processes in Silicon*, edited by F. F. Y. Wang, (North-Holland, Amsterdam, 1981).