Secondary ion mass spectrometry depth profiling of nanometer-scale p^+-n junctions fabricated by Ga$^+$ focused ion beam implantation

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We have used secondary ion mass spectrometry (SIMS) as an analytical tool to measure the depth distribution of 2–10-keV focused ion beam Ga implants into crystalline Si. Depth profiling was carried out by SIMS using 2-keV Cs$^+$ bombardment at 60° with respect to normal and monitoring positive secondary ions. Implant ranges correlate well with those calculated by TRIM but are shallower by 20–25 Å; in contrast ΔR_p values are identical to those calculated by TRIM. Rapid thermal annealing has been used to electrically activate the Ga and SRP measurements have been used to determine junction depths.

I. INTRODUCTION

The demands of shrinking device geometries require that techniques be devised to form increasingly shallow *p-n* junctions. In silicon-based MOS devices, it is anticipated that 0.25-μm gate devices will require junction depths of less than 75 nm. In addition, these junctions must exhibit low leakage current and low sheet resistance to perform acceptably. Focused ion beam (FIB) implantation[1] is a developing technology that will allow excellent lateral control of implant area as well as being more flexible than conventional ion implanters in selection of ion impact energies. By utilizing Ga, a heavy *p*-type dopant in Si, shallow implants can be formed in Si by low energy implantation with much less channeling than conventional B or BF_2 implants.

Measuring the depth distribution of a low energy Ga implant is a challenging depth profiling problem, because of the requirement of excellent depth resolution in a minimal analysis area. We have utilized secondary ion mass spectroscopy (SIMS) to successfully profile implants performed using accelerating energies as low as 2 keV in implanted areas 540×540 μm. The depth resolution is optimized by utilizing a high mass primary beam (C_s) at a glancing impact angle and low bombarding energy. Important criteria for the SIMS measurements are both high depth resolution and minimal beam equilibration depth at the beginning of profiling. The latter requirement is particularly important because much of the essential information about low energy implants will be found within 100–200 Å of the surface. Because Ga has a high positive ion yield, the sensitivity using C_s ion bombardment is sufficient to measure profiles over four orders of magnitude.

Several studies have addressed comparative depth resolution using different sputtering beams for III–V compound structures, but few have been carried out on silicon. These studies have found that O ion bombardment typically yields the best depth resolution at a given primary beam energy. However, for impact energies of 1–4 keV there is not a significant decrease in depth resolution when high mass bombarding species are used.[2] In addition, depth resolution improves by using a high angle of incidence for the sputtering beam.[3]

Beam equilibration with the sample occurs at the initiation of a depth profile as the initial distribution of the implanted primary beam species is encountered during sputtering. The equilibration depth is a function of primary beam energy, angle of incidence, and mass of the bombarding ion. Studies of this surface transient have shown equilibration depths of 100–200 Å for O_2^+ ion bombardment of silicon but less than 100 Å for higher energy C_s^+ bombardment.[4,5] Little systematic work has been published on the equilibration depth using C_s bombardment as a function of energy or impact angle. However it is apparent that the minimum equilibration depth will be achieved by using a high mass bombarding species, such as C_s, at low energy and a high angle of incidence.

II. EXPERIMENT

The FIB implants were performed in *n*-type ⟨100⟩-oriented Si wafers, *P*-doped with a background concentration of 2×10^{15} at/cm^3. All implants were performed using an unseparated Ga beam current of 400 pA to obtain a dose of 1×10^{15} at/cm^2. An area of 540×540 μm^2 was selected for these experiments as a compromise between implant time and area required for the secondary ion mass spectometry (SIMS) measurements. Beam focus was not an important criteria in the implantation of such large areas. Several samples were annealed after implantation in an AET-ADDAX RV system at 600 °C for 30 s to study the effects of rapid thermal annealing on the implant distributions and to provide electrically active samples for spreading resistance measurements.

The SIMS measurements were performed using a Perkin-Elmer 6300 SIMS system equipped with both duoplasmatron and C_s ion sources. In order to minimize the equilibration depth and ion mixing effects of the primary beam, a C_s^+ ion beam was used at 60° incidence relative to the surface

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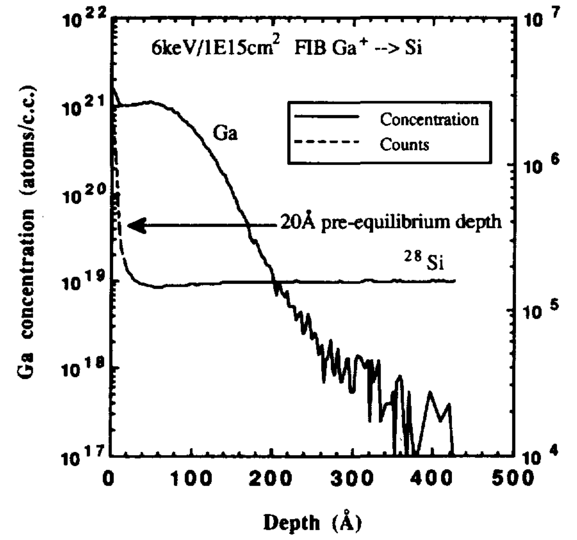

FIG. 1. Depth profile of 6-keV-FIB Ga implant in silicon.

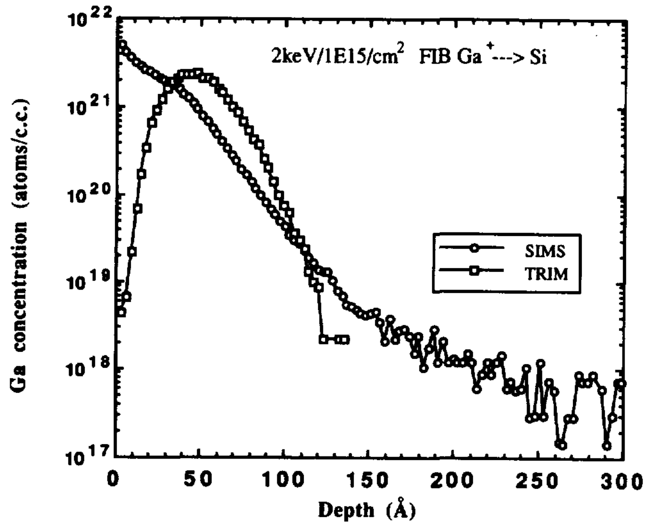

FIG. 2. Comparison of SIMS measured depth profile and TRIM-89 calculation for 2-keV-Ga implant in silicon.

normal and an accelerating energy of 2 keV. A beam current of 100 nA gave sufficient beam focus to allow profiling using a $700\times700\,\mu m^2$ area with acceptable sensitivity. The acceptance area of $450\times450\,\mu m^2$ was centered over the implanted area using an electron microscope image of the sample. Each profile was obtained by alternatively monitoring $^{69}Ga^+$ and $^{28}Si^+$. Conversion of Ga ion counts to concentrations was accomplished by using a medium energy Ga ion implanted standard. Calculated concentrations are accurate to within 10%. The depth scales were calibrated by sputtering a deep crater and measuring this crater depth with a Dektak stylus profilometer. This measurement allowed calibration of the depth scales to within 15%. Spreading resistance profiling (SRP) measurements were performed for selected samples in order to compare atomic and carrier concentration profiles.

III. RESULTS

A depth profile of a 6-keV FIB Ga implant, typical of those obtained in this study, is shown in Fig. 1. The quantitative Ga profile is plotted relative to the left axis and the corresponding Si matrix ion profile is plotted in counts relative to the right-hand side axis. The sharp drop in the Si signal near the surface is the combined result of removal of the native oxide on the wafer surface and buildup of the primary beam implant with the sample. One important feature of this profile is that the matrix ion signal reaches an equilibrium value within 20–30 Å of the beginning of the profile. This shallow equilibrium depth is necessary for accurate Ga profile measurements when the implant peak is within 100 Å of the surface. A comparison between the measured Ga distribution and a TRIM-89[6] calculation are shown in Fig. 2. Several features of this comparison are worth noting. First, the high surface concentration of Ga is thought to be a real feature of the implanted sample. However it is possible that surface contaminants may produce molecular ion interferences that mask the true Ga concentration at the surface. In addition, this surface peak is primarily within the native oxide and may represent partitioning of the Ga into the oxide during implantation. Second, the measured peak depth is significantly less than the calculated peak depth. This may result from inadequacies of the TRIM modeling at low energies where experimental data are scarce. Finally, the measured distribution shows significantly more tailing than is suggested by extrapolation of the calculated distribution. This is not surprising given that the calculation assumes an amorphous target and the implant was performed in crystalline material. The tailing may also be an ion mixing effect produced by sputtering. However ion channeling is thought to be the predominant cause of the tail.

Depth profiles of Ga FIB implants performed at implant energies from 2–10 keV are shown in Fig. 3. As was pointed

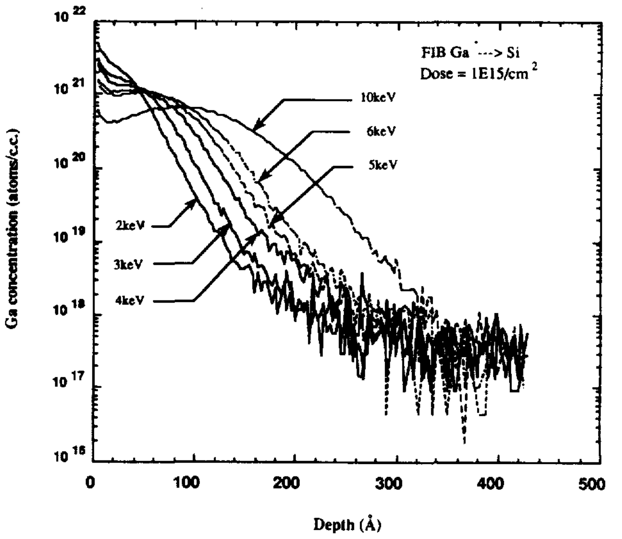

FIG. 3. SIMS profiles of 2–10-keV-FIB Ga implants in silicon.

TABLE I. Comparison of Pearson IV parameters measured by SIMS and calculated by TRIM for 2–10 keV implants.

Implant energy (keV)	R_p (Å)	ΔR_p (Å)	R_p (Å) (TRIM)	ΔR_p (Å) (TRIM)
2	27	22	48	22
3	36	27	60	26
4	44	33	71	30
5	54	36	81	33
6	60	40	90	36
10	93	54	124	48

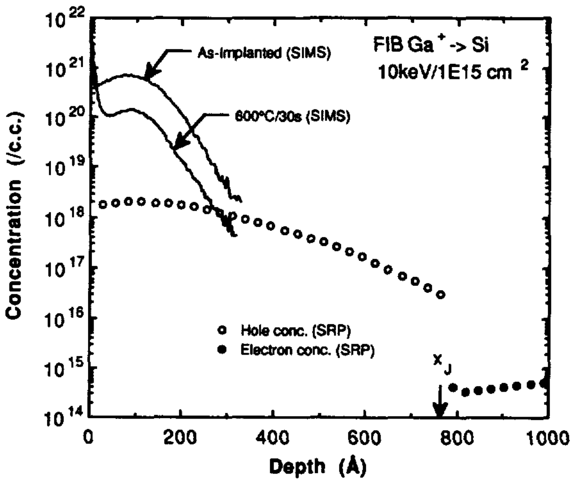

FIG. 4. Comparison of as-implanted distribution with annealed distribution for a 10-keV-FIB Ga implant in silicon. The measured spreading resistance profile (SRP) is shown for comparison.

out earlier, implant peak depths correlate well with those calculated using TRIM but are typically shallower by 20–30 Å. The Pearson IV moments of the 2–10 keV implants are given in Table I, which also compares the measured R_p and ΔR_p values with those calculated by TRIM. The peak depths calculated by TRIM are systematically less by 20–30 Å from those measured by SIMS, but the ΔR_p values are in excellent agreement.

It is the regular relationship between peak height, peak depth, and implant shape with increasing energy that leads us to believe we are accurately measuring the Ga distribution in these implants. This comparison also clearly demonstrates that SIMS can be used to measure implants in silicon having peak depths of less than 200 Å. The degree to which the profiles have been broadened by ion mixing effects is less clear. Certainly some of the profile shape is the result of channeling in crystalline silicon, and some is the result of ion mixing during the SIMS measurement. Although it has been shown that O ion bombardment yields the minimum depth resolution of any bombarding species in GaAs, corresponding measurements have not been performed in silicon.[2] Somewhat less ion mixing and better depth resolution might be obtainable by O ion bombardment. However, the pre-equilibrium depth would be significantly greater than for C_s ion bombardment, resulting in loss of accurate information near the Ga implant peak.

A comparison of SIMS profiles of an as-implanted and annealed 10 keV implant with a spreading resistance profile is given in Fig. 4. The profile of the annealed sample shows that even with minimal annealing, the Ga strongly redistributes toward the surface. The comparison between SIMS and SRP suggests that only about 1 part in 10^{-3} of the implanted Ga becomes electrically active after annealing. However a number of effects, some of which are discussed in other papers in this symposium, may cause an underestimation of the carrier concentration in the *p*-type region. Possible causes for underestimation of carrier concentrations include: use of carrier mobility determined for B rather than for Ga, underestimation of carrier mobility due to high Ga concentrations, and carrier spilling. If these factors are taken into account we estimate that carrier concentrations may be a factor of 5–10 higher than those indicated in Fig. 4. This would still indicate that 5%–10% of the implanted Ga is electrically active. The SRP profiles does not show the near-surface enrichment of Ga which is apparently electrically inactive. More extensive electrical characterization of FIB Ga *p-n* junctions presented elsewhere[7] indicates that considerably shallower junctions can be fabricated by reducing the Ga^+ energy below 10 keV.

IV. SUMMARY

SIMS has been used to measure the distribution of Ga implanted in silicon at energies from 2–10 keV using a focused ion beam. The measurements were carried out in areas 540×540 μm square. Implant peak depths correlate well with but are offset from those predicted by TRIM-89 calculations. Correlation of SIMS profiles with SRP profiles of annealed samples suggest that 5–10% of the implanted Ga is electrically active and that significant interstitial Ga redistribution occurs during rapid thermal processing. Focused ion beam implantation of Ga offers the prospect of fabricating Si PMOS circuits with p^+-n junction depths of significantly less than 1000 Å.

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