

High sensitivity measurement of implanted As in the presence of Ge in $\text{Ge}_x\text{Si}_{1-x}/\text{Si}$ layered alloys using trace element accelerator mass spectrometry

S. A. Datar

*Ion Beam Modification and Analysis Laboratory, Department of Physics, University of North Texas,
Denton, Texas 76203*

Liying Wu

*Motorola Advanced Product Research and Development Laboratory, 3501 Ed Bluestein Boulevard, Austin,
Texas 78721*

B. N. Guo, M. Nigam, D. Necsoiu, Y. J. Zhai, D. E. Smith, C. Yang, and M. E. Bouanani

*Ion Beam Modification and Analysis Laboratory, Department of Physics, University of North Texas,
Denton, Texas 76203*

J. J. Lee

*Motorola Advanced Product Research and Development Laboratory, 3501 Ed Bluestein Boulevard, Austin,
Texas 78721*

F. D. McDaniel^{a)}

*Ion Beam Modification and Analysis Laboratory, Department of Physics, University of North Texas,
Denton, Texas 76203*

(Received 3 April 2000; accepted for publication 9 October 2000)

Various devices can be realized on strained GeSi/Si substrates by doping the substrate with different impurities such as As. As is an *n*-type dopant in both Ge and Si. As cross contamination can also arise during germanium preamorphization implantation due to inadequate mass resolution in the implanter. Thus, it is important to be able to accurately measure low-level As concentrations in the presence of Ge. Secondary ion mass spectrometry (SIMS) is the standard technique for these types of measurements but is constrained by mass interferences from molecular ions (^{74}GeH , $^{29}\text{Si}^{30}\text{Si}^{16}\text{O}$). The trace element accelerator mass spectrometry technique allows the breakup of interfering molecules. As is measured in a GeSi matrix with sensitivity significantly better than SIMS. © 2000 American Institute of Physics. [S0003-6951(00)02450-5]

The GeSi layered matrix offers an opportunity to exploit the advantages of heterojunctions in Si-based technology. The lattice mismatch in the GeSi heterostructure results in some novel optical and electrical properties. Various electronic and optoelectronic devices such as infrared detectors, quantum well metal-oxide-semiconductor field-effect transistor and tunneling devices can be fabricated on strained GeSi/Si substrates.^{1,2}

A key step in the fabrication of devices is the introduction of *n*- and *p*-type dopants into the semiconductor substrate. As is commonly used as an *n*-type dopant. Accurate characterization of the distribution of the implanted dopants in the substrate is necessary.

Secondary ion mass spectrometry (SIMS)³ is one of the most sensitive and commonly used techniques for impurity depth profiling. Conventional accelerator mass spectrometry (AMS) is used to measure the abundance ratios of long-lived radioisotopes such as ^{10}Be , ^{14}C , ^{36}Cl , ^{129}I , etc. to their stable counterparts at levels as low as 10^{-16} atoms/cm³.⁴ The use of AMS for dopant detection in semiconductors dates back to 1985.⁵ The trace element accelerator mass spectrometry (TEAMS) facility in the Ion Beam Modification and Analysis Laboratory at the University of North Texas is a

combination of both SIMS and AMS and may be used to measure trace amounts of stable isotopes.⁶ TEAMS can detect very low levels of impurities whose presence, even in trace amounts (parts per billion), affects device performance.⁷

It is difficult to quantify ^{75}As in a GeSi semiconductor alloy using SIMS because of molecular interferences (e.g., ^{74}GeH and $^{29}\text{Si}^{30}\text{Si}^{16}\text{O}$) which have the same nominal mass as As. Resolving ^{74}GeH from ^{75}As with SIMS requires ultrahigh mass resolution, which is extremely difficult for most SIMS instruments and reduces sensitivity. TEAMS uses a SIMS-like system as an injector for a tandem accelerator. To remove molecular interferences, the tandem accelerates negative ions (both molecular and atomic) to the terminal and uses a differentially pumped stripper gas to remove two or more electrons, producing molecular breakup.⁸

The TEAMS beamline uses a specially designed ultralow contamination cesium ion source for sputtering negative ions from the sample (Fig. 1).⁹ The $^{133}\text{Cs}^+$ ions are momentum/charge analyzed with a 90° magnet to prevent chemically similar ions (e.g., Rb, Li) and contaminant ions from the source hardware (e.g., Fe, W) from striking the sample. Together with a 90° analyzing magnet before the accelerator, it effectively constitutes a negative ion, magnetic sector SIMS instrument.

^{a)}Electronic mail: mcdaniel@unt.edu

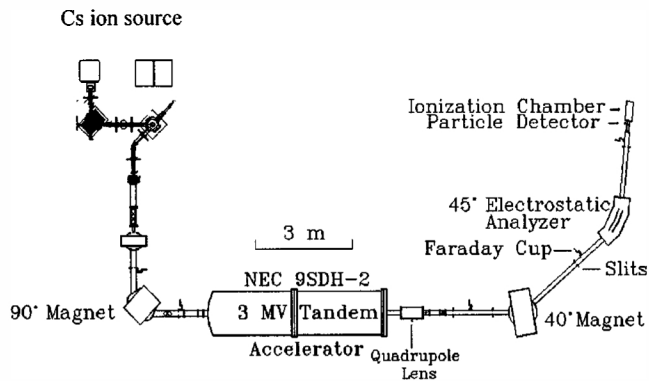


FIG. 1. Experimental layout of the TEAMS system.

After the accelerator, the elemental ions are momentum/charge analyzed with a 40° sector magnet, energy/charge analyzed with a spherical electrostatic analyzer and energy analyzed with a charged particle detector. The energy detector is used to resolve any remaining mass/charge degeneracies (e.g., $^{56}\text{Fe}^{4+}$ and $^{28}\text{Si}^{2+}$). The analyzing and focusing elements are under computer control and can be rapidly switched (\sim few seconds) to sequentially transmit different masses.

The cesium beam striking the sample etches a crater in the sample. The electronics and computer control allow only the secondary ions from the central 20% area of the crater on the sample to be counted, reducing sidewall effects. The raw data profiles that are actually measured are count rate versus time. Crater depths of each sample are calibrated with a surface profilometer. The count rate is then converted to concentration in atoms/cm³ with a conversion factor, which is detailed in Refs. 3 and 10, and the time scale is converted to a depth scale in angstroms. The yield (ions detected/atoms sputtered) for As in this measurement is $2.5e-8$, which is lower than SIMS and is expected due to transmission losses in the considerably longer beamline, and the fact that only one of the many positive charge states produced in the tandem accelerator terminal can be passed through to the detector. Table I describes some key experimental conditions. During the sample measurements, the Si count rate was measured as $^{28}\text{Si}^{3+}$ current in a Faraday cup in front of the ionization chamber. As was injected into the accelerator as the molecular ion AsSi^- (same as in the SIMS measurement) and detected in the ionization chamber as As^{4+} . Ge was detected as $^{74}\text{Ge}^{7+}$ for the GeSi alloy samples and $^{74}\text{Ge}^{4+}$ for the other nonalloy samples. The Si and Ge data for the alloy samples were multiplied by scaling factors to correspond to the appropriate matrix and are only approximate.

Figure 2 shows the results of As depth profile measurements from a mixed implant of 30 keV B, 80 keV P, and 100

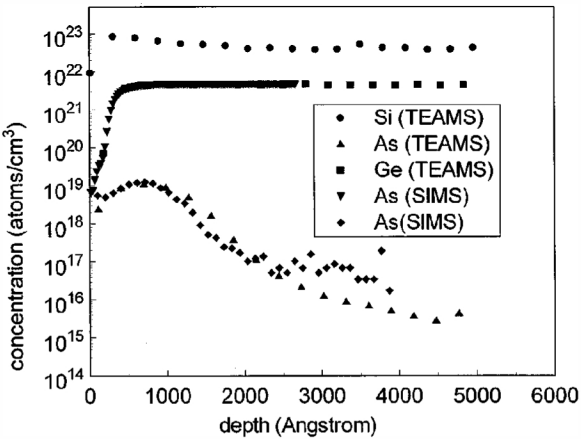


FIG. 2. TEAMS depth profile of As concentration for a mixed implant of 30 keV B, 80 keV P, and 100 keV As, all at a fluence of $1e14$ atoms/cm² in a $\text{Ge}_{0.25}\text{Si}_{0.75}$ film on a Si substrate (normalized data).

keV As each at a fluence of $1e14$ atoms/cm² in a GeSi alloy grown on a Si substrate. SIMS results are also plotted on Fig. 2. The SIMS data were taken on a Cameca 6f at Motorola Inc. in Austin, TX. The SIMS and TEAMS data agree very well. For the SIMS measurement, the instrument was operated in high-mass resolution mode ($m/\Delta m=4000$), with a sample chamber vacuum of $5e-10$ Torr. To reduce the hydride interference, the samples were dried overnight in the sample chamber. Even with all precautions, the sensitivity of the SIMS data is limited. TEAMS can measure the profile with over an order of magnitude greater sensitivity. The magnitude of the TEAMS peak is slightly lower, due to detector saturation as explained below. The TEAMS data also show a slower dropoff after the peak (1000–2000 Å). This is due to the higher cesium impact energy for the TEAMS analysis (25.6 keV) as compared to the SIMS analysis (14.5 keV). The higher impact energy is a problem for analysis of shallow implants since it causes a loss of depth resolution but does not otherwise limit the sensitivity for concentration measurements. Also, the density of points is lower because B and P were also profiled simultaneously, although they are not shown in the figure for clarity. Although difficult to see on the log scale, the Si count rate decreases slowly from the initial peak, due to a 100 Å thick Si cap on the surface, while the Ge count rate rises to a constant value. For comparison, Fig. 3 shows the results from an 80 keV, $1e12$ atoms/cm² As implant in Si. The count rate is lower by the corresponding

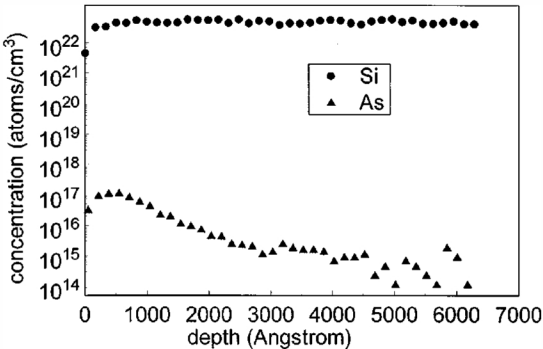


FIG. 3. TEAMS depth profile of As concentration for a 80 keV, $1e12$ atoms/cm² implant in Si.

TABLE I. Measurement parameters.

Cesium energy	10 keV
Cesium beam current	800 nA
Cesium beam diameter	100 μm
Crater size	1.5 mm \times 1.5 mm
Sample bias	−15.6 kV
Sputtering rate	2.7 Å/s
Sample chamber vacuum	1.0 $e-8$ Torr
Accelerator terminal potential	1.7 MV

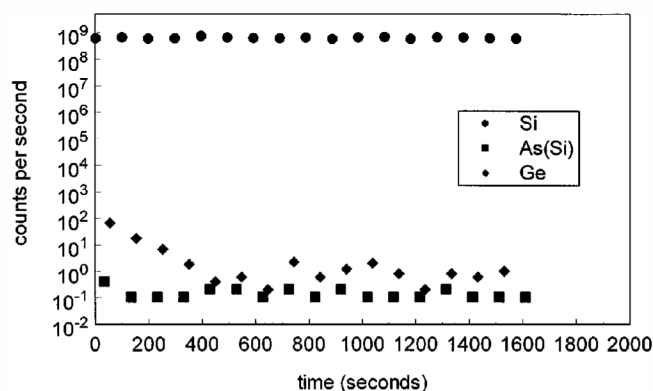


FIG. 4. Raw As and Ge count rate vs time plots from a nominal blank (FZ silicon).

factor of 100. In addition, TEAMS measures the As concentration down to $\sim 2 \times 10^{14}$ atoms/cm³. Finally, Fig. 4 shows As and Ge profiles from a nominal blank (float-zoned silicon). The peak As count rate for the alloy sample was around 10 000 cps which is at the upper limit of the ionization chamber detector's capabilities and may represent an undercount from detector saturation. Plans are underway to install an attenuator in front of the detector to eliminate this problem in the future. At the same time, as the results from the blank and the low-level As implant in Si show, the detector can also measure count rates lower than one count per second. In fact, for the ionization chamber, the instrumental background is practically zero above the noise cutoff, while the efficiency is 100% for low-counting rates. Thus, the lowest detectable count rate is essentially limited by the acquisition time, which in turn is limited by the amount of available sample material. A more detailed discussion of extremely low-concentration measurements is given elsewhere.¹¹ Also, it is clear that while there is a residual Ge count rate after running a high concentration level Ge sample as can be seen from Fig. 4, the As and Ge signals can be easily resolved. Thus the actual detection limit is lower than $\sim 1 \text{ e}15$ atoms/cm³, although the As profile in the GeSi sample tails out at around

$\sim 2 \text{ e}15$ atoms/cm³ (Fig. 2). This is attributable to the homomemory effect,³ which is also seen in SIMS measurements. The low dose As implant clearly demonstrates the ability to measure the As concentration at the $1 \text{ e}14$ atoms/cm³ level.

TEAMS measurements can easily resolve As from all mass interferences possible in the GeSi matrix and achieve very good sensitivity for As depth profile measurements. The technique offers the possibility of making high-sensitivity concentration measurements that are difficult or impossible with SIMS. Since As is the most commonly used *n*-type dopant, this should greatly aid in the development of useful devices based upon the unique nature of the strained GeSi lattice. TEAMS can also help measure the effects of possible implanter cross contamination during germanium preamorphization implantation.

This work was supported in part by the ONR, NSF, and the Robert A. Welch Foundation.

¹T. L. Lin and J. Maserjian, Appl. Phys. Lett. **57**, 1422 (1990).

²K. L. Wang and R. P. G. Karunasiri, J. Vac. Sci. Technol. B **11**, 1159 (1993).

³R. G. Wilson, F. A. Stevie, and C. W. Magee, *Secondary Ion Mass Spectrometry* (Wiley, New York, 1989).

⁴D. Elmore and F. M. Phillips, Science **236**, 543 (1987).

⁵J. M. Anthony, D. J. Donahue, and T. H. Zabel, Nucl. Instrum. Methods Phys. Res. B **10/11**, 498 (1985).

⁶F. D. McDaniel, S. A. Datar, B. N. Guo, S. N. Renfrow, Z. Y. Zhao, and J. M. Anthony, Appl. Phys. Lett. **72**, 3008 (1998).

⁷J. R. Davis, A. Rohatgi, R. H. Hopkins, P. D. Blais, P. Rai-Choudhury, J. R. McCormick, and H. C. Mollenkopf, IEEE Trans. Electron Devices **ED-27**, 677 (1980).

⁸D. L. Weathers, F. D. McDaniel, S. Matteson, J. L. Duggan, J. M. Anthony, and M. A. Douglas, Nucl. Instrum. Methods Phys. Res. B **56/57**, 889 (1991).

⁹J. F. Kirchhoff, D. K. Marble, D. L. Weathers, F. D. McDaniel, S. Matteson, J. M. Anthony, R. L. Beavers, and T. J. Bennett, Rev. Sci. Instrum. **65**, 1570 (1994).

¹⁰S. A. Datar, Ph.D. thesis, University of Rochester, Rochester, NY, 1994.

¹¹S. A. Datar, S. N. Renfrow, B. N. Guo, and F. D. McDaniel, *AIP Conference Proceedings*, edited by J. L. Duggan and I. L. Morgan (American Institute of Physics, Woodbury, NY, 1999), pp. 632–635.