Narrow surface transient and high depth resolution SIMS using 250eV O_2^+

Ab Razak Chanbasha[1] and Andrew Wee Thye Shen[2]

Department of Physics, Faculty of Science, National University of Singapore, 2 Science Drive 3, Singapore 117542.
Email: 1. scip1390@nus.edu.sg 2. phyweets@nus.edu.sg

ABSTRACT

Ultrashallow junctions in semiconductors and multi-quantum wells (MQW) in lasers demand high depth resolution for accurate depth profiling. SIMS has been widely used in depth profiling and the use of ultralow-energy SIMS has demonstrated a narrower surface transient and an improvement in depth resolution. In this work, we use an ATOMIKA 4500 SIMS depth profiler with O_2^+primary ions at an ultralow-energy (E_p) of 250eV and incidence angles (θ) between 0 - 70º without oxygen flooding. A sample with 10 delta layers of $Si_{0.7}Ge_{0.3}$ nominally grown 11nm apart is used. We observe that for applications like characterizing of ultrashallow junctions, θ ~ 0º provides the narrowest surface transient (z_{tr}) of 0.7nm, which is marginally better than at θ ~ 40º with z_{tr} of 1.0nm. The depth resolution denoted by the full-width at half maximum (FWHM) of the $^{70}Ge^+$ peaks is comparable at both θ ~ 0º and 40º at 1.6nm and 1.4nm respectively. However, in the case of MQW profiling, whereby the quantum wells are normally located deeper, θ ~ 40º is preferable. At this angle, the average sputter rate of 47nm min^{-1} nA^{-1} cm^{-2} is significantly higher, more than double that at θ ~ 0º and a better depth resolution with decay length (λ_d) of 0.64nm/decade compared to 0.92nm/decade at θ ~ 0º. Moreover, the dynamic range possible is also better at θ ~ 40º. θ ~ 60º is not ideal, even though there is no sign of the onset of roughening. Although the higher sputter rate is an advantage, the depth resolution deteriorates as the profile gets deeper.

INTRODUCTION

The ion bombardment process in SIMS will inadvertently give rise to an initial transient state where the sputter yield and ionization probability are not constant [1,2]. Reliable data can only be obtained after this transient depth. The surface transient width (z_{tr}) can be reduced by lowering the impact energy (E_p) and /or increasing the incident energy (θ) [3,4].

With the use of delta-doped samples, we can evaluate the depth resolution by measuring the full width at half maximum (FWHM) of a peak profiled and the decay length (λ_d) which is the distance over which the intensity drops by a factor of e. Depth resolution is mainly influenced by atomic mixing, a bombardment induced relocation of target atoms. To minimize this effect, the penetration depth of the probing ion must be reduced. This can be achieved by reducing the probe energy [5] and/or changing the incidence angle to oblique [6].

Typically at ultralow-energy, normal incidence is advocated [2,7]. At normal incidence, a narrow transient width prevails and the onset of roughening does not occur thus providing a good depth resolution. However, a major disadvantage is speed of analysis as the sputter rate is low.

EXPERIMENTAL

- Sample: Ge delta-doped (Ge-δ) Si sample comprising ten $Si_{0.7}Ge_{0.3}$ delta layers of 0.4nm thickness (nominally) grown by atmospheric pressure chemical vapour deposition (APCVD) at 700ºC. The first layer is at a depth of 12nm and subsequent depths of the deltas are at multiples of 11nm.
- Equipment: ATOMIKA 4500 SIMS Depth Profiler [9]
- Operating parameters: 250eV O2+
  θ ~ 0 - 70º at 10º interval
  Beam current - 48nA
  Raster size - 200 x 200mm
  Electronic gating - 6% by area

RESULTS & DISCUSSION

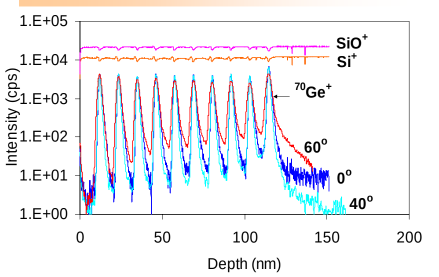

Figure 1. Depth profile of $^{30}Si^+$ and $^{44}SiO^+$ at θ ~ 0º with $^{70}Ge^+$ at θ ~ 0º, 40º and 60º normalised to the first peak of θ ~ 0º.

Best depth resolution is at θ ~ 40º and poorest is at θ ~ 60º

Peak-to-valley ratio (PVR) at θ ~ 40º is marginally better than at normal incidence but clearly, the PVR at θ ~ 0º and 40º are better than that at θ ~ 60º.

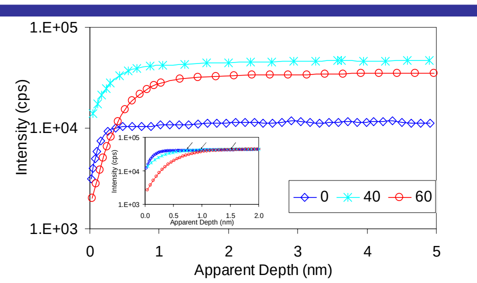

Figure 2. Depth profiles of $^{30}Si^+$ at θ ~ 0º, 40º and 60º.The arrows show the end of the transient width (95% of equilibrium signal). The insert shows the $^{30}Si^+$ profiles normalized to the profile obtained at θ ~ 40º.

Narrowest z_{tr} ~ 0.7nm ± 0.2nm is at normal incidence, it increases marginally to 1.0nm ± 0.2nm at θ ~ 40º and doubles at θ ~ 60º to z_{tr} ~ 1.5nm ± 0.1nm.

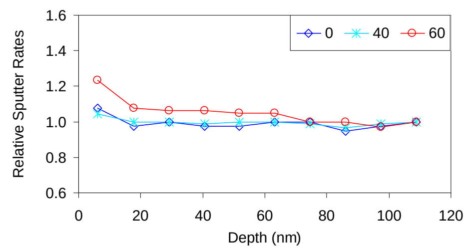

Figure 3. Plot of the sputter rate normalized to the sputter rate at the 9th to 10th delta.

At θ ~ 0º and 40º, the sputter rate is stable as a function of depth except at the surface.

Lowest sputter rate is 20nm min^{-1} nA^{-1} cm^{-2} at normal incidence.

The sputter rate increases with incidence angle, reaching a maximum at θ ~ 50º [11].

As a consequence of the lower sputtering yield at θ ~ 0º and 40º, a higher concentration of oxygen will be retained at the surface, forming SiO_2 [11]. Subsequent oxygen deposition results in rapid outward growth of SiO_2 [11,12]. This is a possible explanation for the lower z_{tr} obtained at θ ~ 0º and 40º compared to at θ ~ 60º

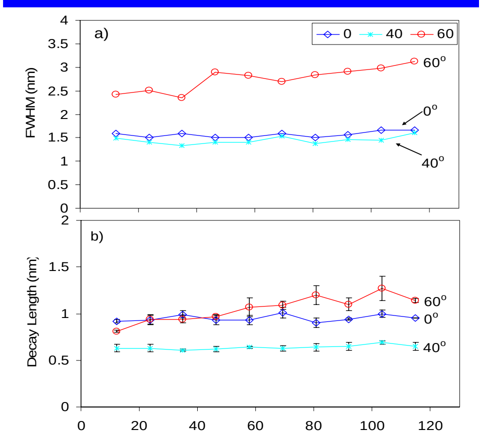

Figure 4. Plot of depth resolution against depth measured in terms of a) FWHM b) decay length, λ_d.

Best depth resolution at θ ~ 40º. At θ ~ 0º and 40º, FWHM is constant with depth.

At θ ~ 60º, the FWHM remains constant to only about 40nm before deteriorating further with depth.

FWHM at θ ~ 0º and 40º is better than at θ ~ 60º

Best FWHM is at θ ~ 40º. Average FWHM for θ ~ 0º, 40º and 60º is 1.6nm, 1.4nm and 2.8nm respectively.

Lowest λ_d is at θ ~ 40º and is relatively constant with depth, ~0.64nm/decade.

At θ ~ 0º and 60º, the λ_d do not differ by much. However, beyond 50nm depth, the λ_d at θ ~ 60º deteriorates greater than that at θ ~ 0º.

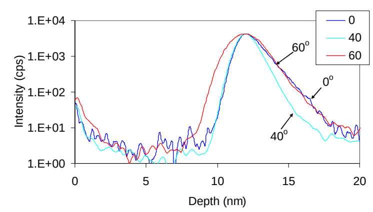

Figure 5. Depth profile of $^{70}Ge^+$ up to the first Ge-δ, showing that at θ ~ 40º, the peak broadening is the least.

Peak broadens via the trailing edge when comparing θ ~ 0º to θ ~ 40º. Peak broadens further at both the leading edge and trailing edge when profiled at θ ~ 60º. This explains the poorer depth resolution at θ ~ 60º.

The peak broadening could be a result of erosion inhomogeneity [13] and/or the presence of micro-roughening [14]. At θ ~ 0º, Si will be fully oxidized more than at θ ~ 40º, Ge has a tendency to segregate down to the SiO_2 and Si interface thus explaining the larger λ_d than at θ ~ 40º [15].

Combining the information obtained, we conclude that the best depth resolution is obtained at θ ~ 40º.

The dynamic range averaged over the first nine deltas are 4.7 x 10^2 at θ ~ 0º, 3.3 x 10^3 at θ ~ 40º and 1.4 x 10^3 at θ ~ 60º.

CONCLUSIONS

•At θ ~ 0º, the narrowest surface transient (z_{tr}) of 0.7nm is achieved. It is ideal for applications such as characterizing of ultra-shallow junctions.

•The depth resolution denoted by FWHM of the $^{70}Ge^+$ peaks is comparable at both θ ~ 0º and 40º.

•At θ ~ 40º, the average sputter rate is more than double that at θ ~ 0º. Better depth resolution is also observed with decay length (λ_d) of 0.64nm/decade compared to 0.92nm/decade at θ ~ 0º. Profiling at this angle is preferred for MQW where the quantum wells are normally located deeper.

•Moreover, the dynamic range possible is also better at θ ~ 40º.

•At θ ~ 60º, it is not ideal, even though the higher sputter rate is an advantage since the depth resolution deteriorates with depth.

References

[1] M. G. Dowsett, T. J. Ormsby, F. S. Gard, S. H. Al Harthi, B. Guzman, C. F. McConville, T. C. Q. Noakes, P. Bailey, Appl. Surf. Sci.203/204 (2003) 363.
[2] K. Wittmaack, Philos. Trans. R. Soc. London A 354 (1996) 2731.
[3] P. F. A. Alkemade, Z. X. Jiang, C. C. G. Visser, S. Radelaar, W. M. Arnoldbik, J. Vac. Sci. Technol. B 16 (1998) 373.
[4] Z. X. Jiang, P. F. A. Alkemade, E. Algra, S. Radelaar, Surf. Interface Anal. 25 (1997) 285.
[5] M. G. Dowsett, Appl. Surf. Sci. 203/204 (2003) 5.
[6] R. Liu, A. T. S. Wee, D. H. Shen, H. Takenaka, Surf. Interface Anal. 36 (2004) 172.
[7] M. G. Dowsett, T. J. Ormsby, G. A. Cooke, D. P. Chu, J. Vac. Sci. Technol. B 16 (1998) 302.
[8] R. Liu, C. M. Ng, A. T. S. Wee, Appl. Surf. Sci. 203/204 (2003) 256.
[9] J.L.Maul, S.B.Patel. in: G. Gillen, R. Lareau, J. Bennett, and F. Stevie (Eds.), Secondary Ion Mass Spectrometry SIMS XI, Wiley, Chichester, 1998, 707 -710.
[10] M. G. Dowsett, T. J. Ormsby, D. I. Ellinet, and G. A. Cooke. in: G. Gillen, R. Lareau, J. Bennett, and F. Stevie (Eds.), Secondary Ion Mass Spectrometry SIMS XI, Wiley, Chichester, 1998, 371 - 374 .
[11] A. R. Chanbasha and A. T. S. Wee, Surf. Interface Anal.37 (2005) 628.
[12] K. Wittmaack, Surf. Interface Anal.24 (1996) 389.
[13] J.B.Clegg and I.L.Gale, Surf. Interface Anal.17 (1991) 190.
[14] T. J. Ormsby, D. P. Chu, M. G. Dowsett, G. A. Cooke, S. B. Patel, Appl. Surf. Sci. 145 (1999) 292.
[15] Z. X. Jiang, J. Lerma, D. Sieloff, J. J. Lee, S. Backer, S. Bagchi, J. Conner, J. Vac. Sci. Technol. B22 (2004) 630.