Implant temperature dependence of transient-enhanced diffusion in silicon (100) implanted with low-energy arsenic ions

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Abstract

The diffusion of arsenic implanted into silicon at low ion energies (2.5 keV) has been studied with medium-energy ion scattering, secondary ion mass spectrometry and four-point probe measurements. The dopant redistribution together with the corresponding damage recovery and electrical activation produced by high-temperature (550–975°C) rapid thermal anneals has been investigated for a range of substrate temperatures (+25, +300 and −120°C) during implant. Initial results show an implant temperature dependence of the damage structure and arsenic lattice position prior to anneal. Solid-phase epitaxial regrowth was observed following 550°C, 10 s anneals for all implant temperatures and resulted in approximately 60% of the implanted arsenic moving to substitutional positions. Annealing at 875°C resulted in similar arsenic redistribution for all implant temperatures. Following annealing at 925°C, transient-enhanced diffusion was observed in all samples with more rapid diffusion in the +25°C samples than either the −120 or +300°C implants, which had similar dopant profiles. In the 975°C anneal range, similar rates of implant redistribution were observed for the +300 and +25°C implants, while diffusion in the −120°C sample was reduced. These observations are discussed qualitatively in terms of the nature and density of the complex defects existing in the as-implanted samples. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The fabrication of sub-micron electronic devices at and below 0.18 μm sets the requirement of increasingly shallow junctions, e.g 100 nm, and higher doping levels of 5E19 atoms/cm\textsuperscript{3} at the source–drain implant regions. If ion implantation is to be used effectively for this technology, ultra-low implant energies (<5 keV) are necessary to produce the shallower ion distributions required. Additionally, factors which contribute to dopant distribution, both during implantation and post implant annealing must be well understood. While it is now technically possible to achieve the low beam energies required for the doping of very shallow regions at production worthy dose rates, the occurrence of transient-enhanced diffusion (TED) can lead to junction depths significantly beyond the original range of the implanted dopants [1–3]. For boron this phenomena is known to depend on the ion damage created by ion implantation and has been associated with the movement of self interstitials released from extended defects (e.g. dislocation loops and \{3 1 1\} defects) during high temperature annealing. These
extended defects generally grow in size and decrease in density by ostwald ripening. As a result, the transient diffusion process, generally observed at about 900°C, is both temperature and time dependent.

The concentration, type and distribution of ion generated defect complexes found within a crystal following implantation can be varied by changing the implant temperature and dose rate [4, 5]. Additionally, the evolution of the implant damage during subsequent thermal processing is dependent on the nature of the initial damage distribution [6], the proximity of the surface [7], and the concentration of the implanted ions [8]. In the present study, the effect of substrate temperature (−120, +25 and +300°C) on the TED of arsenic during rapid thermal anneal (RTA) was investigated. Arsenic ions of 2.5 keV energy were implanted at normal incidence into silicon (1 0 0) samples to a dose of 1.5 × 10^{15} ions/cm², at a rate of 3 μA/cm². Significantly different damage profiles were produced at each implant temperature. Subsequent annealing at temperatures in the range 550 to 975°C produced varying levels of arsenic diffusion which depended upon the damage structure existing after implant. In all three samples a minor redistribution of arsenic occurred during solid-phase epitaxial regrowth (SPEG) of a near surface amorphous layer. At 875°C, TED produces a similar redistribution of arsenic for all three implant temperatures. During a 925°C anneal, the +25°C implanted arsenic was observed to diffuse to greater depths than that in either +300°C or −120°C samples. For the higher anneal temperature of 975°C, the +300°C implant diffused at a greater rate than the +25°C and −120°C arsenic implants. Although the arsenic profile redistributed in the −120°C sample at 975°C, it was significantly more stable than in the samples irradiated at 25°C and +300°C.

2. Experiment

Ion implantation was carried out using the ultra low energy, dual source, ion implanter at Salford University [9]. The ions were transported as 15 keV, 300 μA beams and decelerated to 2.5 keV at the target stage. Arsenic was implanted into p-type silicon (1 0 0), held at temperatures of +25°C (±2°C), +300°C (±5°C) and −120°C (±10°C), at 3 μA/cm² to a dose of 1.5 × 10^{15} ions/cm². A liquid-nitrogen tank located behind the sample holder was used to cool the samples and a hot tungsten filament centred behind the sample holder was used for heating. To eliminate neutral particle contamination of the silicon, target chamber pressures were maintained at 1 × 10⁻⁷ mbar during implantation with a base pressure of 1 × 10⁻⁹ mbar. Prior to implant the samples were cleaned in acetone in an ultrasound bath for 5 min.

The implanted samples were annealed to temperatures ranging from 550 to 975°C (±25°C) for 10s in a rapid thermal processor. Different pieces of silicon, implanted at +25, +300 and −120°C were annealed simultaneously at each temperature. Although, absolute temperatures are only known to within ±25°C, the relative temperatures between anneals are accurate to ±5°C. All anneals were conducted in a nitrogen atmosphere using ramp rates of 20–25°C/s.

Implanted samples, both prior to and following annealing, were analysed with medium-energy ion scattering (MEIS) [10]. The ion scattering technique, which is a high-energy resolution and, hence, high depth resolution variant of RBS/channelling, utilises double alignment of the probe beam along the (1 1 1) in and (2 3 3) out directions to give a scattering angle of 60.5° and a depth resolution of 11 Å. A 200 keV He probe beam was used to obtain the data and a reference random level was measured from a pre-amorphised sample. The double aligned measurements provided information on the distribution of non-substitutional arsenic and displaced silicon atoms in each sample. Depth scales were calculated using the method described by Chu et al. [11] using a surface energy approximation.

Complementary secondary ion mass spectrometry (SIMS) measurements were used to measure the total (both substitutional and non-substitutional) arsenic distributions. The analysis was performed with a Cameca IMS 4F using 2 keV O²⁻ primary ion bombardment (i.e. a 6.5 keV ion source potential and a target bias of 4.5 keV). Typically a 0.1 μA ion beam was rastered over a region of 250 μm. Positive secondary ions were collected from the centre of the sputtered region to reduce the signal from the crater edges. Oxygen flooding of the sample surface at 7 × 10⁻⁶ mbar was used to optimise and stabilise ionisation yields. The erosion rates for all the samples were calibrated against a standard arsenic implanted sample. The calibration was based on the assumption that the erosion rate was constant throughout analysis.

Four-point probe measurements were conducted to measure the average resistivity of the doped layer following arsenic activation. A 10s HF dip was used to minimise the surface oxide cover prior to the measurements. The raw data was corrected for the geometrical shape of the sample [12]. For the activated samples, the junction depth for 1 × 10¹⁵ atoms/cm², as determined by SIMS, was used to calculate the sample resistivity.

3. Results

MEIS measurements in Fig. 1 show that an amorphous surface layer is formed at implant temperatures of −120 and +25°C, as indicated by the ion yield reaching the random height (165 counts/5 μC). The −120 and
+25°C implants produce similar damage distributions: a continuous amorphous layer exists in both samples extending from the surface to a depth of ~85 Å in the +25°C implant and ~95 Å in the −120°C implant. It is observed that the silicon surface damage peak for the implant performed at +300°C does not quite reach the amorphous level in the MEIS spectrum. This surface peak feature is believed to be a thin amorphous region (~25 Å) which is unresolved for this particular system resolution. Due to the high levels of dynamic defect annealing which occur at elevated implant temperatures [4,5], the silicon damage peak for the +300°C implant is the smallest in area. The region behind the +300°C silicon surface peak, which in the depth region from ~40 to 100 Å contributes a significant yield to the MEIS spectrum, is not amorphous but highly damaged and is expected to contain complex damage structures [5].

The mean projected range of the non-substitutional arsenic detected by MEIS is ~55 Å. This value matches the arsenic range predicted by TRIM92 [13]. For the +25 and −120°C implants all the arsenic is detected by MEIS since it is contained entirely within the amorphous layer. The total arsenic distribution for all implant temperatures is shown in the SIMS spectra of Fig. 2 and, in conjunction with the aligned MEIS data, can be used to determine arsenic substitutionality. For the +300°C implant prior to anneal it appears that 30% of the arsenic has gone substitutional in crystalline regions of the damaged zone, however, it is possible that these atoms are occupying damage related sites in which they are not exposed to the MEIS probe beam.

For all implant temperatures the amorphous region regrows during the 550°C anneal, presumably by SPEG. During the regrowth the arsenic goes substitutional (and, therefore, becomes invisible in double alignment

Fig. 1. MEIS spectra of non- ( — ), 550°C ( ● ) and 925°C ( ◊ ) annealed material implanted at −120, 25 and +300°C (random level at 165 cts/5 µC).
MEIS) but does not diffuse to greater depths. A fraction of the dopant remains interstitial, possibly in the form of clusters. These atoms which are found in the region containing the remaining silicon damage are “snowploughed” towards the surface by the advancing amorphous-crystal interface during SPEG [14].

Following a 550°C anneal, the MEIS spectrum for the 300°C implanted sample shows the presence of damage at a depth (∼90 Å) corresponding to that of the amorphous-crystal interface in the as-implanted material. This so called end of range (EOR) peak could result from either a highly populated region of small clusters or a less dense network of larger defects. A smaller EOR peak is visible in the annealed spectrum for the +25°C implanted sample. Again the type and size of the scattering centres responsible cannot be determined in this analysis. No EOR damage is visible in the spectrum for the −120°C implant annealed to 550°C. For high-temperature anneals (> 925°C) the MEIS signal from the EOR defects in the +300°C sample disappears. In contrast, for the +25°C sample, the damage peak remains, indicating that a different, and more stable, type of defect structure exists in this sample compared to the sample implanted at +300°C.

The SIMS spectra in Fig. 2 show the behaviour of the arsenic as the anneal temperature is increased. No significant movement of the arsenic is observed until 875°C, suggesting that the arsenic redistribution takes place after SPEG of the amorphous layer is complete. At this stage, no appreciable difference is observed between the three implant temperatures. When annealed at 925°C, a major redistribution of the arsenic occurred for all implant temperatures. Compared to 550°C, the MEIS spectra shows a different distribution of arsenic in the near surface (oxide and oxide–silicon interface) region which is possibly related to the faster regrowth velocity during SPEG at 925°C. The SIMS spectra exhibit a plateau in the arsenic concentration; a feature usually seen following TED in material in which the implant concentration exceeds the
solid solubility limit [15]. In all the samples, the arsenic concentration saturates at $3 \times 10^{20}$ atoms/cm$^3$ when diffused into the sample. This corresponds to the solid solubility limit of arsenic in silicon at 925°C [15]. In contrast to lower anneal temperatures, the arsenic redistribution is now dependent on the substrate temperature during implant. In the +25°C sample, the arsenic distribution expands (to a depth of 800 Å) at a faster rate than in the +300 and −120°C implanted silicon, which show similar arsenic profiles.

During the 975°C anneals, TED continues for all implant temperatures. However, the more rapid diffusion is now observed for the +300°C implant. Diffusion of the −120°C implant is considerably slower than the other two implants at this anneal temperature.

Four-point probe measurements confirm that arsenic is activated by the thermal processing. As-implanted samples show no electrical activation, which is as expected due to their amorphous structure. After the 550°C anneal, all samples, irrespective of implant temperature, exhibit resistivities of $\sim 3.5 \times 10^{-4}$Ω cm. These values are anticipated for the substitutional concentration of $3 \times 10^{20}$ cm$^{-3}$ which is observed in these samples by SIMS (see Fig. 2). The arsenic is substitutional, as can be seen from a comparison of the MEIS and SIMS data, and the silicon damage has been recovered to close to the virgin level. On increasing the anneal temperature to 925°C, a slight reduction in the electrical activation is observed. This reduction is consistent with the MEIS results which show an increase in the amount of non-substitutional arsenic trapped in the surface region following the 925°C anneal.

4. Discussion

For the high-dose ($1.5 \times 10^{15}$ ions/cm$^2$) and low-energy (2.5 keV) arsenic implants used in this study, the variation in implant temperature led to significantly different dynamic defect annealing rates. As a result, the type (size and stability) and number of defects present in the as-implanted material changed with implant temperature. This ultimately led to implant temperature-dependent TED in the regrown crystals during high-temperature annealing.

Despite the different damage structures in the as-implanted material, annealing at 550°C led to identical silicon damage peaks and non-substitutional near surface arsenic yields in the MEIS spectra for all three implant temperatures. This similarity suggests that these near surface features are associated with SPEG, which is expected to be similar in all three samples. However, in the EOR region beyond the initial amorphous-crystal interface, different damage structures were observed following the anneal.

Relatively low levels of TED were first observed at 875°C. Interestingly, the arsenic redistribution at this temperature was not affected by the different damage structures produced during implantation. MEIS analysis of the 925°C samples show that non-substitutional arsenic moves back into the sample and the surface damage peak broadens at this temperature. It is possible that the phenomena responsible for these changes also occur at 875°C and are related to the uniform TED observed for all three implant temperatures.

At 925°C significant levels of TED have occurred (Fig. 3). The extent of the arsenic redistribution shows a marked dependence on the implant temperature, an effect that presumably reflects the different annealing characteristics of the different damage structures found at the EOR. Arsenic diffusion is most apparent in the +25°C sample, which is assumed to contain less complex defect structures [5] than the +300°C implant. The complex defect structures in the +300°C implanted material are probably more stable at this anneal temperature and therefore do not supply the same number of the point defects required for TED. Interestingly, the arsenic in the −120°C annealed sample has also diffused to a lesser extent than that in the +25°C sample. Although it is assumed that the simplest type of extended defects will be formed in the −120°C sample, a larger volume is amorphised by this implant. As a result, the width of the EOR defect band may be narrower than in the other samples and, therefore, fewer point defects may be available during annealing.
TED is still observed at 975°C, indicating that a source of point defects is still available at this temperature. The −120°C sample shows diffusion at a lower rate relative to the +25°C and +300°C implants, suggesting that the point defect flux is lower in this sample. However, the relative diffusion rate in the +300°C sample has increased compared to the one implanted at +25°C. It is assumed that this is due to an increase in the number of point defects which become available to promote TED as the more stable extended defects now start to dissociate. Although a significant level of TED is observed in the +25°C sample at this temperature it is at a reduced rate compared to the +300°C implant. Indeed, more prolonged or higher temperature annealing may produce further accelerations of the TED process in the +300°C implant as stable defects continue to dissociate, and a slowing in the +25°C sample as the reservoir of point defects contained in complex structures at the EOR become dissipated.

5. Conclusion

A strong dependence on the substrate temperature during implant has been identified for the transient-enhanced diffusion of arsenic in silicon. For 1.5 × 10^15 ions/cm², 2.5 keV arsenic ion implants, similar levels of arsenic diffusion were observed for samples implanted at −120, +25 and +300°C when annealed for 10s up to temperatures of 875°C. At higher anneal temperatures significant differences appear in the arsenic diffusion rates that are thought to be related to the different end-of-range damage structure of the samples.

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