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Ultra-Low Energy Ion Implantation for 0.1 Micron CMOS Devices

David Armour
Applied Materials Implant Division, 3050 Bowers Avenue, Santa Clara, California 95054 - 3299, USA.
Phone: 408 986 2682, Fax: 408 563 7850, E-mail: Dave_Armour@amat.com

1. Introduction

The use of ultra-low energy ion implantation to produce the shallow junctions specified for 0.1μm devices requires the development of highly specialised implantation and annealing equipment together with an ability to control the damage related redistribution processes which limit the achievable junction depth. This redistribution, which is affected by defect-defect and defect-dopant atom interactions occurring both during implantation and post-implant annealing, is significantly affected by the proximity of the surface (silicon - silicon dioxide interface) for the sub - 1keV energies involved. The detailed behaviour of defects produced or trapped in this shallow region is not well understood and is further complicated by the need for high doping levels in the source/drain extensions.

An understanding of these processes is crucial to the development of reliable technologies for the production of very shallow, low capacitance, high conductance junctions. 0.1μm devices will require junction depths of less than 50nm and sheet resistances in the implanted region below about 500Ω/□. This paper reviews the present state of knowledge concerning the effects of radiation damage on the behaviour of dopant atoms implanted in the so-called eV implantation regime. For boron implantation, the energy range fom 50eV upwards has been studied and commercial scale processes using 200eV have been developed. For arsenic, for which the inherent range is considerably shorter than for the lighter boron, energies down to about 500eV have been used.

2. Defect behaviour in Silicon

It is now well established that there is a direct correlation between the extended defects that form after implantation and transient enhanced diffusion. The nature of these secondary defects which form at quite specific annealing temperatures has been found to depend on the implanted species, dose and energy and wafer temperature during implantation [1] [2]. Hence, to some extent, it is possible to control the type, configuration and density of these post-irradiation defects by appropriate selection of processing conditions. For the case of boron, for which most information is available, the problems are compounded by the significant dependence of the high effective diffusivity on implant dose. At low doses, where only point defects or small defect clusters are formed, extremely high diffusivities have been observed while at higher doses, where more complex secondary defects such as {311} rod-like structures, tangled dislocation networks or complete amorphous regions, are produced,the effective diffusivity falls progressively to the equilibrium value. The formation of these secondary defects is strongly dependent on the details of the annealing procedure. Below 600°C, defect structures large enough to be observed in transmission electron microscopy (TEM) are not formed and the reduction in damage, as seen by Rutherford backscattering (RBS) or medium energy ion scattering (MEIS), is considered to be due to either the mutual annihilation of simple point defects or the formation of small defect clusters [3]. At temperatures above about 750°C, the more complex defects which develop have been shown to evolve from sub-saturated levels of disorder and to be almost exclusively interstitial in character [4][5]. The dissipatiopn of these defects at temperatures above 900°C is responsible for significant dopant redistribution via the supply of self-interstitial atoms.

3. Defect and Dopant Atom Behaviour in Low Energy Implantation

Studies in the energy range between 50eV and 10keV have shown that above about 2.5keV two distinct damaged regions are formed [6][7]. In this energy range, for doses above 1E14 ions/cm^2, damage seen by RBS and ellipsometry is located both at the surface and around the projected range. Below about 1keV, only the surface damage can be detected. The use of MEIS in the high resolution, low angle, double alignment mode has provided detailed information concerning the dependence of this damage on both dose and energy. Fig. 1 shows, for example, that the depth over which the damage extends increases significantly more rapidly with dose than energy.

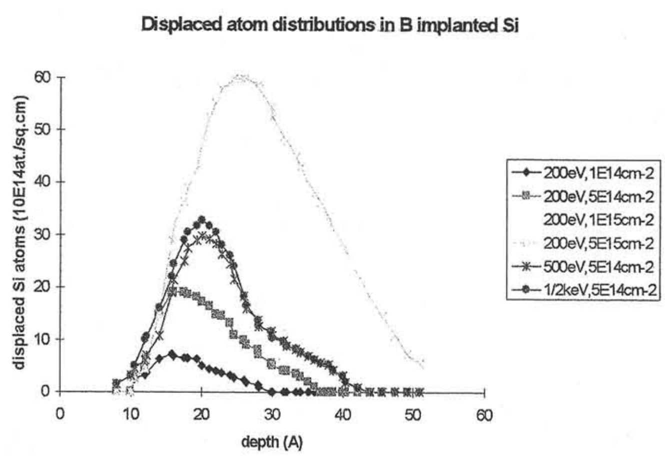

Fig. 1 Displaced atoms in boron implanted silicon measured by MEIS.

Comparison with both corrected secondary ion mass spectrometry (SIMS) profiles and TRIM calculations [8] confirms that the surface damage is located closer to the surface than both the implant and damage production regions. This near-surface concentration of displaced atoms may be explained by the accumulation of interstitial atoms produced along the ion track at the oxide interface, by the presence of knock-on oxygen atoms or by the precipitation of boron since the concentration exceeds the solid solubility limit of 1E20 atoms/cm^3 in this region. It has been shown that the contribution of knock-on oxygen is negligible [6] and the fact that the boron concentration exceeds the solubility limit over a considerably greater depth than the displaced atom region means that trapping of mobile interstitials at the interface is the most plausible explanation.

The redistribution of the implanted atoms during post-implant annealing represents a major problem from the point of view of the production of increasingly shallow junctions. Typical redistribution effects are demonstrated by SIMS measurements which compare as-implanted and annealed profiles. The increase in the depth of the dopant atom distributions is significant, for example, for a B^+ dose of 1E15 ions/cm^2 at 200eV a rapid thermal anneal for 20 seconds at 1050°C shifts the B profile at 1E18 atoms/cm^3 40nm deeper than an anneal at 900°C. This effect, together with channelling, which has been predicted theoretically and observed experimentally down to energies as low as 50eV [9][10], represents the major fundamental limitation to junction depth reduction.

The diffusion mechanisms responsible for this redistribution have been extensively investigated both theoretically and experimentally. Molecular dynamics calculations [11] and measurements using silicon samples containing boron δ-layers, grown by molecular beam epitaxy [12], have provided information on an atomic scale regarding the interaction between point defects and dopant atoms. Implant induced transient diffusion, in which long range interstitial B atom migration initiated by kick-out reactions with self-interstitials occurs, has been observed at temperatures below 600°C. However, as the implant energy is reduced to the point where the range is commensurate with the thickness of the surface damage region, there is evidence that high dopant activation and effective damage annealing can be achieved using very short annealing times which significantly reduce the effects of transient diffusion.

4. Summary

The need to exponentially scale CMOS source/drain junctions to shallower depths as critical device dimensions are reduced is one of the main challenges to the production of 0.1μm devices. Ion implantation and annealing equipment capable of exploiting the unique characteristics of the surface damage region has already been developed. Production worthy systems capable of meeting the requirements of 0.18 and 0.13μm technologies are currently available and the basic structural features of 0.1μm devices in terms of junction depths of less than 50nm can now be obtained. The growing understanding of the complex dopant atom - defect interactions which occur during the production and annealing of the surface damage layer is continuing to contribute to the development of production worthy 0.1μm fabrication processes.

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