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Combining dynamic modelling codes with medium energy ion scattering measurements to characterise plasma doping

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ABSTRACT

Plasma doping ion implantation (PLAD) is becoming increasingly important in the manufacture of advanced semiconductor device structures but a fundamental understanding of PLAD is complicated. A model of PLAD into planar substrates has been constructed using the one dimensional computer code TRIDYN to predict collision cascades and hence substrate compositional changes during implantation. Medium Energy Ion Scattering (MEIS) measurements of dopant profiles in PLAD processed samples were used to calibrate the input ion and neutral fluxes to the model. Rules could then be proposed for how post implant profiles should be modified by a cleaning step. This learning was applied to a three dimensional TRI3DYN based model for PLAD implants into FinFET like structures. Comparison of the model to dopant profile measurements made by time of flight (TOF)-MEIS revealed the angular distributions of neutral species and doping mechanisms acting in three dimensional structures.

1. Introduction

Plasma doping ion implantation (PLAD) is becoming increasingly important in enabling the manufacture of advanced semiconductor devices. PLAD is simple in concept: a negatively biased substrate immersed in a plasma is doped by ions and neutrals from that plasma. However, a fundamental understanding of PLAD is complicated because high fluence implantation, deposition, sputtering and ion beam mixing have to be taken into account during the implant after which additional passivation, cleaning and annealing steps have to be considered. The fluxes and compositions of neutral species that deposit on the substrate surface during PLAD cannot be directly measured and although the ions can be counted in a Faraday detector placed around the wafer, their compositions are unknown. The measurement of post PLAD dopant profiles should allow the neutral and ion compositions and fluxes to be determined but such profiles are difficult to measure. Profiling methods such as Secondary Ion Mass Spectroscopy and Dynamic X-ray Photoelectron Spectroscopy suffer from sputter mixing and matrix dependent effects unlike Medium Energy Ion Scattering which can readily yield absolute numbers of dopant atoms. This study reports how the interpretation of MEIS profile measurements was helped significantly by using TRIDYN [1], an established, one dimensional, dynamic code that modelled substrate evolution during implantation by calculating collision cascades using the binary collision approximation.

The angular distributions of arriving ions and neutral species does not greatly influence dopant profiles produced in planar substrates, but can affect the doping of 3D structures. Ions, accelerated across the plasma sheath, arrive in a direction normal to the wafer surface. Neutral atoms originating from the background gas can be modelled with cosine angular distributions, but neutrals originating from other sources, such as chamber walls, can have different angular distributions. In this study, PLAD dopant profiles in FinFET like structures were measured using a TOF-MEIS system. TRI3DYN [2] is a newly developed, three dimensional version of TRIDYN, in which collision cascades initiated by particles, whose incident angular distributions can be varied, are also calculated using the binary collision approximation. The three dimensional substrate is described by voxel elements which are changed throughout the model as a result of the injected ions, sputtered atoms and collision cascade mixing. Results from TRI3DYN models were compared to the MEIS dopant profile measurements and TEM images to give information on neutral species angular distributions and

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indicated implantation mechanisms occurring during PLAD processes.

2. PLAD process

Bare silicon wafers, biased at 7 keV, were implanted with arsenic in a VIISta PLAD system [3] in Gloucester, MA using a plasma generated from a gas mixture of 5% AsH_3 in H_2 to a total ion fluence of 1×10^{16} cm^{-2}. Wafers patterned with features that included 110 nm pitch, 130 nm tall FinFET like structures were PLAD implanted with arsenic from a mixture of 5% AsH_3 in Xe/H_2 at a bias of 2 keV to a total ion fluence of 5×10^{15} cm^{-2}. Although this study did not involve pre-implant lithography steps, the samples underwent an industry standard SPM (sulphuric acid hydrogen peroxide mixture) wet chemical clean in a Nexgen Technologies wet bench to represent the production step of photo-resist removal. Following a "spike" anneal (1050 °C held for 1.7 s) in a nitrogen atmosphere in a Mattson AST 3000 annealer, a dilute hydrofluoric (DHF) acid step was used to remove surface oxide.

3. Dopant profile metrology

MEIS measurements on planar wafers were carried out on the University of Huddersfield MEIS system [4] using 100 keV He^+ ions and a scattering angle of 90°. Double aligned spectra were collected for He ions directed at a 54.7° entrance angle along the [−1 −1 1] channel direction and exiting along the [1 1 2] blocking direction. The samples were tilted for a 61.7° entrance angle and also twisted by 7° when collecting random orientation spectra, examples of which are shown in Fig. 1a).

The FinFET structures were measured by Korean Materials and Analysis Corporation using their TOF-MEIS system [5] which has a sample imaging capability and small primary beam spot size so that the structures contained in a square die of 250 μm side could be measured. 100 keV He^+ ions were again used for the primary beam but a 130° scattering angle was used and scattered ions were analysed using a time of flight system rather than a toroidal energy analyser as at Huddersfield. Randomly oriented spectra were taken for entrance angles of 25° and 65° in a direction twisted 5° away from the normal into the fin sidewalls and with an entrance angle 25° in a direction twisted 5° away from parallel to the fin sidewalls. Examples of TOF-MEIS spectra for PLAD processed fins are shown in Fig. 1b).

Elemental profiles shown in this paper were extracted from MEIS and TOF-MEIS spectra collected from measurements on randomly oriented samples using POWERMEIS [6]. To fit the spectra from planar samples, POWERMEIS trial substrates were divided into layers containing As, Si and O atomic concentrations shown in Fig. 2 by the lines and symbols. The layer thicknesses were chosen to be consistent with the TEM images, and choice of layer compositions were guided by the outputs of a TRIDYN model. Atomic concentrations have been reported rather than atomic fractions to help indicate where the layer density is lower than for fully stoichiometric compounds.

To fit spectra from FinFET samples, POWERMEIS substrates were divided into cubic voxels of 2 Angstrom side and simple layers in the fin top, bottom and sidewalls were defined within these voxels. The use of TRI3DYN model outputs as suggestions for 3D POWERMEIS trial solutions (as done for the planar case) has not yet been investigated.

Brightfield TEM images were taken by Evans Analytical Group on parts of planar samples that were coated with Iridium before the TEM lamellae were produced. Energy dispersive spectroscopy (TEM/EDS) measurements were made for some of these samples, but are not discussed further in this paper. Fin samples were first coated with carbon before making the lamellae for brightfield TEM images.

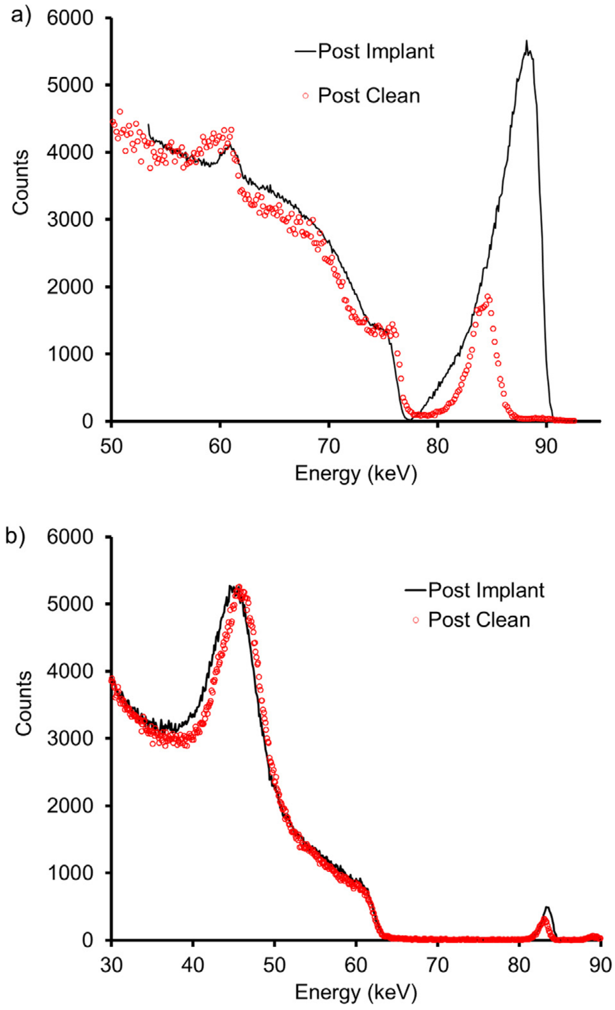

Fig. 1. a) MEIS energy spectra collected for two planar samples (random orientation) corresponding to process conditions shown by the TEM images of Fig. 2. The highest energy peaks are due to ions scattered by As atoms. Events below ~77 keV are from Si atoms with small peaks from O atoms superimposed around 60 keV. b) TOF-MEIS spectra for two fin samples measured at a 25° incident angle across the fins. Ions scattered from As atoms appear between 50 and 83 keV and the small peaks just visible below 90 keV are due to Xe. The Si edge is at ~63 keV and the large peak between 40 and 50 keV is characteristic of the geometry of the fins.

4. Planar PLAD implant results

The post implant TEM image of a planar PLAD process is shown in Fig. 2a). Ions and neutrals arrived from the left hand side of the image and the original position of the wafer surface before processing was 0 nm. Fig. 2a) shows an amorphous/crystalline interface at +10 nm created near the end of range of the As ions. The amorphous layer of uniform contrast from this interface up to the original wafer surface (0 nm) consisted of As ions and recoil implanted As neutrals mixed into the Si substrate. The "intermixed layer" between 0 nm to −10 nm contained As originating from both neutrals and ions from the plasma and Si atoms from the substrate. The TRIDYN model was constructed with assumptions for input fluxes of As ions, As atoms and other neutral species to simulate profiles that matched the measurements. TRIDYN suggested that the amount of Si present in the intermixed layer could not have

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