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Dopant/carrier profiling in nanostructures.

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1.Introduction

Understanding the fabrication and operation of nanostructures requires a detailed characterization of their structure, compositional distribution and electrical properties on the nm scale. Characteristic dimensions of these structures may range from solely one-dimensional layer structures, over 2D-confined devices and even 3D-structures like FINFET's and nanowires etc.. Obviously with increasing degree of dimensional restrictions, the metrology requirements increase dramatically from "simple" depth resolution problems to metrology with high 2D-spatial resolution to the need to probe in an extremely small confined volume (3D-devices). Along this technological spectrum, the problems linked with resolution, sample preparation, sample localization and finite signal intensity (limited to limited statistics) increase tremendously.
In this paper we focus on the case of semiconductor based structures and try to present an overview of the recent evolution in 1D, 2D, and 3D analysis.

2. One-dimensional analysis

Quantitative high depth resolution dopant (and composition) profiles of ultra shallow junction and very thin layers is the prime application of **1D-analysis**, whereby attempts to obtain information on the incorporation of dopants and impurities of various doping techniques (implant, vapor phase deposition, cluster beam implantation,..) as well as their diffusional behavior during subsequent thermal anneals. A simple sensitivity analysis indicates that one should perform this analysis with a depth resolution of at most 0.5 nm/dec. In view of the required sensitivity these kind of studies are performed almost exclusively with SIMS as it combines very high sensitivity, depth resolution and quantification accuracy. Nevertheless in order to meet the required target for depth resolution, one needs to reduce the extent of the collision cascade dramatically as this is the main cause for layer intermixing during the sputter erosion. This can be achieved by a reduction in impact energy from the routinely used 500-250 eV to less than 150 eV thereby approaching almost the energy threshold for sputtering < 150 eV. This operational mode is now termed EXLE-Sims, extremely low energy SIMS. The benefits of this energy scaling are substantial as under these conditions one can identify films differing only 0.5 nm in thicknes. At these low energies the sputter yield is dramatically reduced which not only leads to long analysis times but more importantly implies that the incorporation of the reactive species from the primary beam, is no longer controlled by the sputter yield of the matrix but rather by the ability of the excess atoms to form a stable layer or vice versa by their evaporation or desorption probability. An important result of this self induced stabilization is that the concentration of reactive species at the surface and their enhancement effect on ionization probabilities becomes nearly matrix independent thereby reducing the SIMS matrix effect considerable. For instance a dramatically improved interface analysis of As in the SiO_2/Si system can be observed whereby the ion intensities now reflect the As-concentration directly without any need for complex correction algorithms. Similarly it was demonstrated that a 10x more precise analysis can be made of the near surface removal of dopant atoms during cleaning steps. Whereas standard analysis shows a very strong As-surface peak (induced through the enhancement of the ionization probability by the oxygen from the native oxyde) the latter is almost completely suppressed under the EXLE-Sims conditions. The enhanced capabilities of EXLE-Sims also enabled to probe the Ge-segregation into the Si-layers when attempting the passivation of Ge-substrates with a few monolayers of Si. Detailed studies on the incorporation probabilities of Cs at low energies indicate however a strong dependence on the environmental conditions implying that traces of oxygen (10^{-9-8} Torr range!) can alter the Cs-retention over orders of magnitude.

3. Two-dimensional analysis

With shrinking transistor dimensions and diffusion-less anneals, 1D-analysis is often no longer sufficient and 2D-interactions gain significantly in importance. Moreover understanding detailed device operation requires an analysis of the lateral outdiffusion and the overlap between source/drain profiles and the gate structures. Such information can not be retrieved from 1D-analysis and thus 2D-profiling becomes a requirement. As indicated in the ITRS-roadmap, the requirements in terms of spatial resolution are quite challenging requiring sub-nm resolution for most applications. During recent years Scanning spreading resistance microscopy (SSRM) has emerged as the reference metrology tool for 2D-profiling able to satsify the ITRS requirements. SSRM is based on mapping the local resistivity variations using a conductive AFM-tip which is scanned across the cross sectional surface whereby the local spreading resistance is measured. Crucial in the SSRM concept is that a nearly Ohmic contact is made to the semiconductor as in that case the spreading resistance scales linearly with the local resistivity. The spatial resolution will be set by the

electrical contact radius. The ohmic contact formation is achieved by applying very high forces (> μN) such that below the tip a local phase transformation of the Si occurs towards the metallic β-Sn phase which will act as the effective ohmic contact. Molecular dynamics simulations of the tip-Si contact indicate that the extent of this transformed region is ~ 3-5 x smaller than the actual tip radius implying that the actual electrical radius is also 3-5x smaller than the physical radius. In order to sustain these high forces, very dedicated full diamond probes were developed. Detailed studies have demonstrated then a spatial resolution better than 1 nm which makes SSRM the sole 2D-profiling concept which combines high spatial resolution (<1 nm) with adequate sensitivity and quantification precision. The advanced capabilities of SSRM enable the complete characterization of the 2D-carrier profile in small devices and has been applied for the optimization of millisecond anneal processes and studies on advanced junction engineering with cocktail implants. Its precision and accuracy has reached such a level that it can now be used to fine tune and calibrate process simulators and that the obtained 2D-doping profiles can be used as input for a device simulator leading to the correct prediction of device parameters.
The appearance of complex 3D-structures like FINFET's and nanowires raises the methodology requirements again as the sample volume becomes very confined and localization of the structure of interest becomes very difficult as well. Therefore it has been necessary to develop procedures and test structures enabling to perform cross sectional analysis (using SSRM) on FINFETs and nanowires. In particular on FINFETs SSRM has been used extensively to probe and optimize conformal doping processes.

4. **Three-dimensional analysis**

For completely understanding 3D-effects and analysis devices like TFETs of nanowires, a true **3D-dopant** profiling method is necessary. Again the requirements are quite stringent as one needs to combine high 3D-resolution with adequate sensitivity and element identification. The most promising approach in this context is the Tomographic Atomprobe which is capable of visualizing individual dopant atoms with near-atomic resolution. In the atomprobe atoms are evaporated one by one under the influence of a very high electrical field (~ 50-100 V/nm) and projected onto a position sensitive detector whereby time-of-flight analysis provides mass identification. A simple geometrical analysis illustrates that the atomprobe works as a microscope with ~ 10^6x magnification leading to a theoretical spatial resolution in the order of 0.1-0.2nm! Numerous examples exist whereby the position of atoms on lattice planes can be identified and small cluster/precipitates (containing only 10-100 atoms) can be analysed. Detailed studies on depth resolution indicate that it outperforms SIMS in favorable cases substantially, leading to a depth resolution as good as 0.2 nm/dec for SiGe/Si structure. The advantage of the atomprobe is not only its ability to provide unparallel depth and spatial resolution but also its quantification properties. As atoms are only emitted as ions, near 100 % ionization is obtained and composition becomes entirely based on counting the emitted number of atoms. In principle no element dependent ionization artifacts are present nor does one has to rely on element dependent sensitivity factors for the quantification. Typical examples of recent atomprobe studies include the evolution of Ni-Si interaction during silicide formation, the analysis of dopant segregation during silicide formation, 3D-dopant metrology in finfets etc... Whereas for metals the Atomprobe can rely on voltage pulsing only, the limited conductivity of semiconductors requires the addition of laser pulsing. The latter does induce substantial artifacts due to preferential adsorption, carrier recombination, heat conduction which all make the evaporation sequence more complex and induces topographical effects. For instance the real ship shape now deviates from the theoretical hemispherical tip shape thereby violating the assumptions made during the 3D-reconstruction. The latter leads to errors on depth scales whereby layer thickness appear to differ substantially from the correct value. Moreover excessive heating may induce surface migration lowering the final spatial resolution. A judicious choice of laser wavelength, laser power becomes now a prime requirement to achieve optimum results.

5.Conclusions

The increasing complexity of advanced devices has created very important metrology challenges. Although solutions for 1D (EXLE-SIMS), 2D (SSSRM) and 3D (Atomprobe) are being reported achieving the required spatial resolution, sensitivity and quantification accuracy remains a challenge and careful interpretation of potential artifacts.