Materials Modification Implants for Advanced Devices

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The use of non-dopant implants in CMOS is increasing rapidly in order to continually advance device performance now that the era of simple device feature scaling has ended. Since non-dopants do not alter the electrical conductivity of the silicon, they are implanted for their physical or chemical effects on the device structure or the implanted dopants. For this reason, they are referred to as "materials modification" implants.   This article describes several diverse applications of materials modification implants in advanced CMOS devices.

The oldest and most widely used materials modification implant is pre-amorphization. Pre-amorphization is the use of an initial implant to deliberately destroy the ordered crystalline structure of the substrate in order to prevent channeling of subsequent implants. Germanium has been traditionally used for this application because of its high mass, but occasionally xenon is used. Because the atomic mass of Xe is almost twice that of Ge, Xe amorphization is very efficient, requiring doses of only $1\text{-}5\times10^{13}\text{cm}^{-2}$.

Recently, there is a lot of interest in carbon as a pre-amorphizing species. Because of its low mass, it is difficult to amorphize with C at normal wafer temperatures unless doses far exceeding $1\times10^{15}\text{cm}^{-2}$ are used. However, the amorphization threshold for C in Si is reduced to as low as $5\times10^{14}\text{cm}^{-2}$ if the wafer is cooled during implantation and the density of the C beam is sufficiently high. Spot beam implanters such as Optima HDx can easily amorphize Si using C implants at wafer temperatures in the range of -30°C to -50°C. Since C has additional uses in device fabrication (see below), using C to amorphize leads to the option of achieving two materials modification goals at once and eliminating a Ge implant.

After pre-amorphization, materials modification implants are used most frequently to control the diffusion and activation of dopant implants during annealing. It is well known that C, and to some degree F, retard the diffusion of dopants with high diffusivity such as B and P (Fig. 1). Carbon traps excess interstitials and therefore suppresses transient enhanced diffusion of both B and P (fig. 2) [1-5]. Minimizing the diffusion of these species during annealing is important in many regions of the transistor, particularly the halo (pocket), source/drain extension, and source/drain regions. For both nFETs and pFETs, a major goal of pre-halo co-implants is V_T variation reduction. For pre-SDE and pre-S/D co-implants, the objective is simultaneous minimization of lateral parasitic resistance (to maximize ID_{SAT}), junction depth (to reduce DIBL), and junction leakage (to minimize I_{OFF}). It is important to optimize the carbon dose, because excess carbon can produce defects that cause device leakage, and the observed leakage can be very sensitive to small changes in dose. Typical C doses for diffusion control are $3\times10^{14}\text{cm}^{-2}$ - $1\times10^{15}\text{cm}^{-2}$.

Despite their utility and increasing use as materials modification species, C and Ge can be difficult to run on traditional ion implanters. Problems with poor source life and low beam currents are

common. The Eterna ELS3 long life source from Axcelis is specifically engineered to maximize the source life, productivity, and cost-of-ownership of both carbon and germanium implants.

While carbon is the preferred co-implant species to suppress dopant diffusion, fluorine is also useful here. Fluorine behaves similar to carbon in that it also suppresses both the diffusion and activation of B [5,7-9]. Fluorine is always present as a co-implant whenever BF_2 is implanted. Some p-S/D and p-SDE implants are migrating from BF_2 to B to avoid B deactivation from F. Since the dose and energy of the F in a BF_2 implant are fixed relative to the B dose, F may be co-implanted separately to maximize process flexibility.
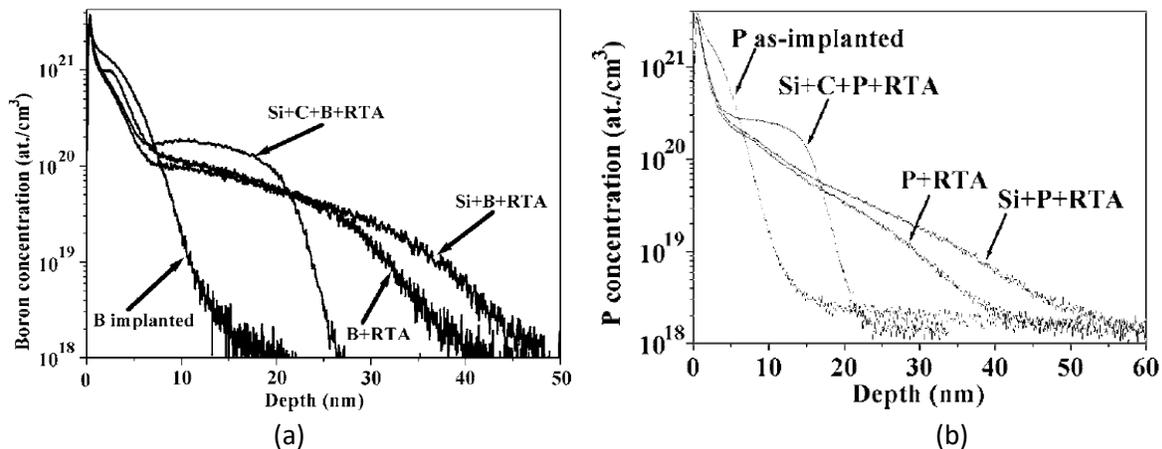

(a)   (b)

Figure 1: Suppression of (a) 0.5 keV B and (b) 1 keV P diffusion with a C co-implant (6 keV, $1x10^{15}cm^{-2}$). The B and P doses were $7x10^{14}cm^{-2}$; the RTA was a 1050°C spike anneal [71,72].

Another important application of materials modification is passivation of oxide traps. Fluorine implants passivate traps near the gate dielectric interface, resulting in lower gate-induced drain leakage (GIDL) [5,10]. This is especially important for leakage sensitive devices such as mobile DRAM.

In addition to controlling dopant diffusion, materials modification implants are used to engineer defect profiles. For example, nitrogen implants into the source-drain extension regions after gate stack formation produce lower and more repeatable leakage currents, due to the suppression of dislocation loop formation in the SDE regions [11-13]. This occurs because N tends to trap Si vacancies, which in turn reduce the Si interstitial concentrations available for extended defect formation. N is also believed to suppress B diffusion in the presence of F.

Other types of materials modification implants also exist. These include resist stabilization as part of a double-patterning lithography sequence, and densification of deposited films. The high versatility of the ion implantation process overall (species, dose, energy, angle, wafer temperature, etc.), ensures that the material modification implants described in this article will continue to be refined, and new ones will be introduced in future years.   The Axcelis suite of implanters can easily run all material modification implants required for advanced devices. Additionally, with the release of the Eterna ELS3 source, C and Ge implant capabilities are significantly enhanced.

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