3D-Simulation of an Enhanced Field-Funneling Effect on the Collection of Alpha-Particle-Generated Carriers in P^- on P^+ Epitaxial Substrates

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Abstract

We have investigated the soft-error phenomena in p^- on p^+ epitaxial substrates using three dimensional device simulator. We demonstrate for the first time that the field-funneling on the collection of alpha-particle-generated carriers in a memory cell is enhanced in a p^- on p^+ epitaxial substrate in comparison with that in a p^--type Czochralski substrate. In addition, we have found the reason why the epitaxial-layer thickness dependence of the charge-collection in a memory cell is opposite to that in a TEG (Test Element Group) structure having a large charge-collection area.

1. Introduction

A p^- on p^+ epitaxial substrate is one kind of epitaxial wafers which consists of a p-type silicon epitaxial layer grown on a p^+-type substrate. A p^- on p^+ epitaxial substrate has been employed for ULSI because of its high latch-up immunity and low density of grown-in defects which deteriorate the quality of gate oxides. On the other hand, it has been reported that the immunity of soft-error due to incident alpha-particles in a p^- on p^+ substrate is lower than that in a p^--type Czochralski (CZ) substrate[1]; however, the physical mechanisms of the soft-error phenomena in epitaxial wafers are not well understood. In this study, we have investigated the soft-error phenomena in p^- on p^+ epitaxial substrates using our in-house three dimensional device simulator (3D-MIDSIP). We demonstrate for the first time that the field-funneling on the collection of alpha-particle-generated carriers in a memory cell is enhanced in a p^- on p^+ epitaxial substrate compared with that in a p^- CZ substrate.

2. Simulation Procedure

Figure 1 shows structures of (a) TEG and (b) a memory cell for simulation, respectively. The simulated structures differ in the size of the surface n^+ diffusion layer, (a) $50\times50\mu$m and (b) $0.4\times0.4\mu$m. The dopant profile along the A-A′ axis is shown in Fig. 2. The third peak from the surface is the retrograde well (p well) which plays a major role in suppressing the collection of the minority carriers generated by an incident energetic alpha-particle[2]. In DRAMs, information is typically stored as a quantity of charge on a back-biased junction with an n^+ diffusion layer in a p-type substrate. After the initial potential and carrier distribution in the structures were calculated, the alpha-particle injection was then simulated by introducing a properly varying density of hole-electron pairs along the track of the particle. Next, a transient calculation with this modified initial condition was implemented. In the simulation , a quarter alpha-particle with 1 MeV or 5 MeV energy was injected along the A-A′ axis normally to the surface. The projected range is approximately 4 μm for an alpha-particle with 1 MeV energy and 23 μm for that with 5 MeV energy. We took advantage of the four-fold symmetry of these structures with respect to the A-A′ axis, saving the computational time as well as the amount of memory necessary for simulation. This is the reason why a quarter alpha-particle was injected in simulation.

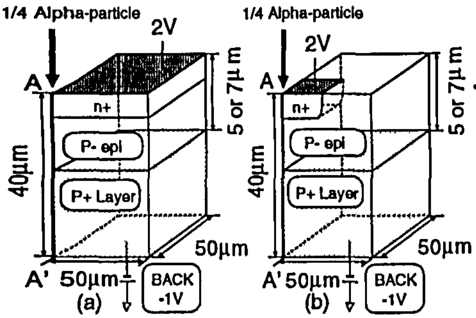

Figure 1: Schematic of the simulated structures, (a) TEG (Test Element Group) and (b) a memory cell.

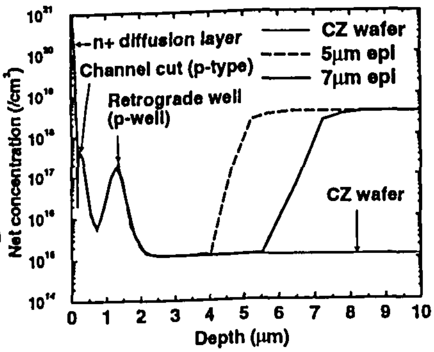

Figure 2: Simulated dopant profile toward depth direction.

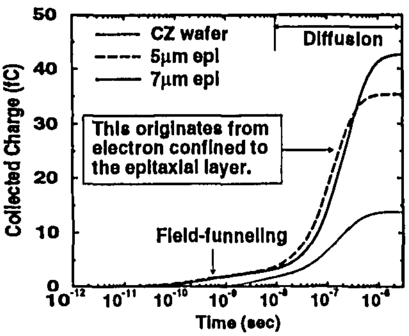

Figure 3: Transient charge-collection behavior in the TEG due to a quarter alpha-particle strike with 5 MeV energy.

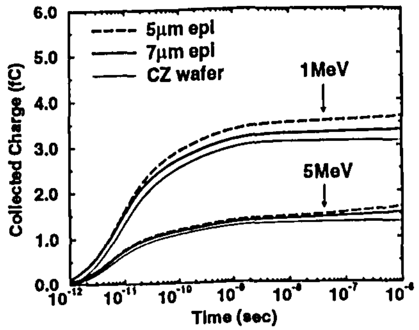

Figure 4: Transient charge-collection behavior in the memory cell due to a quarter alpha-particle strike with 1MeV or 5 MeV energy.

3. Results and Discussion

In this section, the simulation results are presented. Note that the lifetime of an electron is approximately $1\mu s$ in 3.6×10^{18} /cm^3 p$^+$ layer; both field-funneling and charge-diffusion occurring within $1\mu s$ can cause a soft-error.

Figure 3 and 4 show the simulation result of the transient charge-collection behavior in the TEG and the memory cell, respectively. In Fig. 3, the generated charge is collected majorly during the time interval from 10ns to 500ns, indicating that the overwhelming part of the collected carriers is contributed by charge-diffusion. On the other hand, in Fig. 4, the charge is collected majorly during the time interval from 0ps to 200ps, indicating that the overwhelming part of the collected carriers is contributed by field-funneling. Moreover, Fig. 4 implies that the field-funneling is enhanced in the epitaxial substrates in comparison with that in the CZ substrate. This is what we call *an enhanced field-funneling effect.*

Figure 5 shows the simulated charge-collection in the TEG along with the measured charge-collection [1]. The total amount of the collected-charge is simply proportional to the thickness of the epitaxial layer. The simulation qualitatively reproduces the

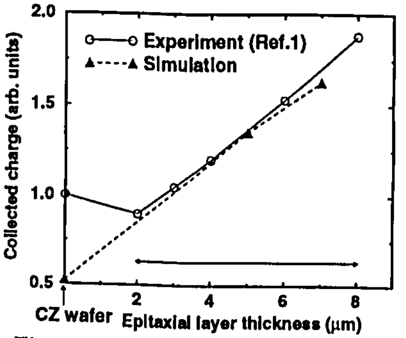

Figure 5: Epitaxial layer thickness dependence of charge-collection in the TEG.

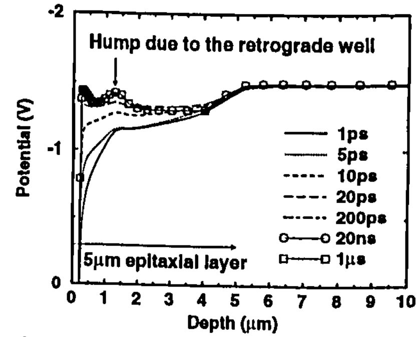

Figure 6: Transient potential distribution in the memory cell after a quarter alpha-particle strike with 5 MeV.

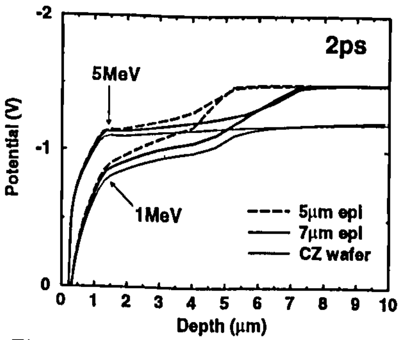

Figure 7: Potential profile in the memory cell at 2ps after a quarter alpha-particle strike.

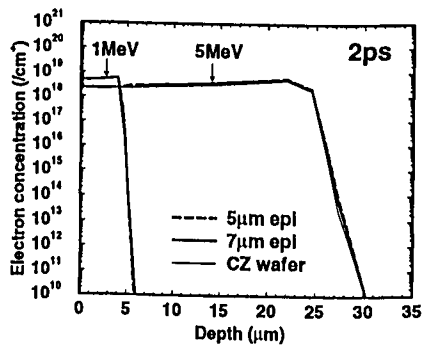

Figure 8: Electron distribution in the memory cell at 2ps after a quarter alpha-particle strike.

charge-collection, confirming the validity of the present simulation.

Figure 6 shows the potential distribution along the alpha-particle track at various times after a quarter alpha-particle strike in the memory cell fabricated on the 5μm epitaxial wafer. The region of potential change is no longer confined to a small area at the top of this structure near the pn junction, but has spread down along the alpha-particle track into the substrate. The potential distribution relaxes back towards its original location at 200ps. The distorted field funnels a large number of carriers into the surface n^+ diffusion layer. The hump due to the retrograde well plays a major role in suppressing field-funneling as well as charge-diffusion toward the surface.

Figure 7 and 8 show the potential and electron profile along the alpha-particle track in the memory cell at 2ps, respectively. In Fig. 7, the slope of the potential profile toward the surface increases as the thickness of the epitaxial layer decreases, leading to the result shown in Fig. 4 that the total amount of the collected-charge due to field-funneling increases as the thickness of the p^- epitaxial layer decreases. In Fig. 8, the amount of generated carriers is so large that the electron profile hardly reflects the dopant profile. Incident energy dependence of the collected-charge shown in Fig. 4 originates from its dependence of the amount of generated carriers at the surface.

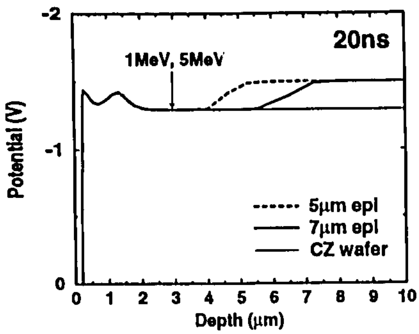

Figure 9: Potential profile in the memory cell at 20ns after a quarter alpha-particle strike.

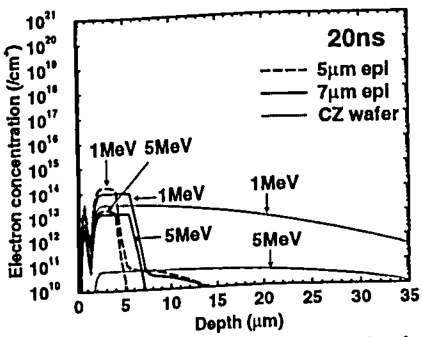

Figure 10: Electron distribution in the memory cell at 20ns after a quarter alpha-particle strike.

Figure 9 and 10 show the potential and electron distribution along the alpha-particle track in the memory cell at 20ns, respectively. In Fig. 9, there is no potential difference near the surface among the structures, indicating that the field-funneling is finished. On the other hand, in Fig. 10, the total amount of electron confined to the p^- epitaxial layer increases in proportion to the increase of the epitaxial layer thickness. Note that the electron profile in the TEG (not shown) exactly overlaps that in the memory cell shown in Fig. 10. The result shown in Fig. 3 appears if the area of the surface n^+ diffusion layer is large like the TEG. However, the contribution of the charge-diffusion to the charge-collection in the memory cell is much smaller than that of the field-funneling because the area of the surface n^+ diffusion layer is very small in the memory cell. This is the reason why the epitaxial-layer thickness dependence of the charge-collection in the memory cell is opposite to that in the TEG, as shown in Figs. 3 and 4. In the CZ substrate, the electron profile is averaged over the substrate thickness, leading to smaller charge-collection than that in the epitaxial substrate.

4. Conclusions

We have investigated the soft-error phenomena in a p^- on p^+ substrate using the three dimensional device simulator. The field-funneling is enhanced in a memory cell fabricated on a p^- on p^+ epitaxial substrate in comparison with that on a p^- type CZ substrate because the slope of the potential profile toward the surface increases as the thickness of the p^- epitaxial layer decreases. In addition, this effect is enhanced as the energy of an incident alpha-particle decreases.

References

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[2] K. Tsukamoto *et al.*, "High-energy ion implantation for ULSI, "*Nucl. Instr. and Meth.*, B59/60, pp.584-591, 1991.