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Indirect trench sidewall doping by implantation of reflected ions

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Ion implantation (i/i) technology is employed for silicon trench sidewall doping. The aspect ratio of trenches for high Mbit DRAM is very large (depth/width$\geqslant$10), so that very small glancing-angle i/i to sidewalls is necessary. In this case, reflected ions are large in number and are implanted to the opposite sidewall. It is very important to know the elemental depth profile in the opposite sidewall to understand the implantation mechanism. For the first time, we measured the depth profiles at several positions of the opposite trench sidewall by secondary-ion mass spectroscopy for arsenic and boron ion implantations. It is found that reflected ions are distributed near the facing region of the directly implanted region with smaller energies than the primary energy. These findings are compared with the simulations based on the MARLOWE program.

Narrow and deep trench capacitors are indispensable to high megabit DRAMs.[1] Ion implantation is a very attractive method for doping of such a trench with a high aspect ratio. We demonstrated that we can dope the sidewall uniformly over the entire 6 in. wafer by ion implantation at a small incident angle (grazing incidence) of 4° using a specially designed implanter whose scan error is less than $\pm 1.2°$.[2] For implantation to the sidewall of a narrow trench, however, the incident angle measured from the silicon surface is very small. In this case reflection and scattering increase,[3] and indirect implantation of inelastically and diffusely scattered ions plays an important role.

In this letter we analyze this doping for both cases of boron and arsenic. To understand the mechanism and to get quantitative data of the indirect doping, we measure the in-depth profiles of the dopants at several points of directly and indirectly doped sidewalls by secondary-ion mass spectroscopy (SIMS). We also simulate the reflection and scattering processes by the computer program MARLOWE.[4] Based on these analyses, we make clear the mechanism of the indirect doping previously suggested by Kakoschke *et al.*[5] We confirm that the uniformity of the sidewall doping leads to desirable capacitance-voltage (*C-V*) characteristics of the trench capacitors.[2]

Sectional scanning electron microscope (SEM) photographs are used to analyze the doping region in sidewalls and the n^+-doped regions are made clear by enhanced wet etching after annealing at 900 °C for 30 min. Depth profile measurement of real trench sidewalls by SIMS is very difficult because of their miniature sizes. Only one report has been made.[6] So two silicon slices, 10 mm wide and 30 mm long, are arranged to face each other separated by 1 mm for 4° implantation and 2 mm for 7.5° implantation as shown in Fig. 1. The points a, b, c, and d are measured. a, b, and c are 25, 20, and 10 mm apart from the bottom edge in the directly implanted side plate. SIMS measurement was performed on a CAMECA IMS-4f using Cs and O ions as primary ions. Electrical characteristics are measured for a surrounding high-capacitance cell (SCC) type capacitor developed here.

Figure 2 is a SEM photograph of 0.4-μm-wide trenches with 3.8 μm total depth whose right sidewalls are implanted by arsenic ions directly at an incident angle of 4° with respect to the sidewalls. The trench with flat vertical sidewalls is etched by a new ECR etching.[7] It is surprising that the opposite sidewalls seem to be doped uniformly. It is very important to know the concentration in the opposite sidewall for doping of narrow trenches precisely by ion implantation.

Figures 3(a) and 3(b) show the depth profiles at the points a, b, c, d in the insets for As implantation at 150 keV at 4° and 7.5° and with doses of 2.0×10^{15} and 1.07×10^{15} cm^{-2}, respectively. The doses were chosen such that the incident ion beam intensities per unit surface area are equal.

For the 4° implantation case, the peak concentration at the central indirectly doped region (a and b) is fairly high. It is a surprise that the concentration at the upper facing region is the same as that at the central region and the concentration at the specularly reflected region is extremely lower. At the facing region (a and b), the concentration at the incident angle of 7.5° is lower than that at the incident angle of 4°. One of the reasons may be the difference of the doping ratio, doped ions/total incident ions, in the directly implanted regions. The simulated doping ratios are 45% and 60% for 4° and 7.5° implantation, respectively. These are in good agreement with the available experimental result for 7.5°.[8] This factor must be taken into account for controlling the concen-

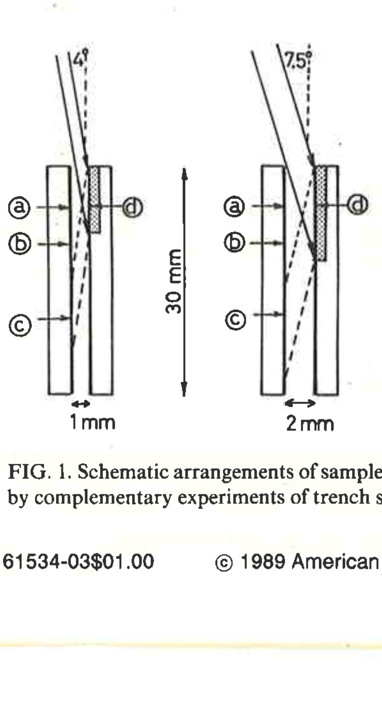

FIG. 1. Schematic arrangements of samples for depth profile measurement by complementary experiments of trench sidewall doping.

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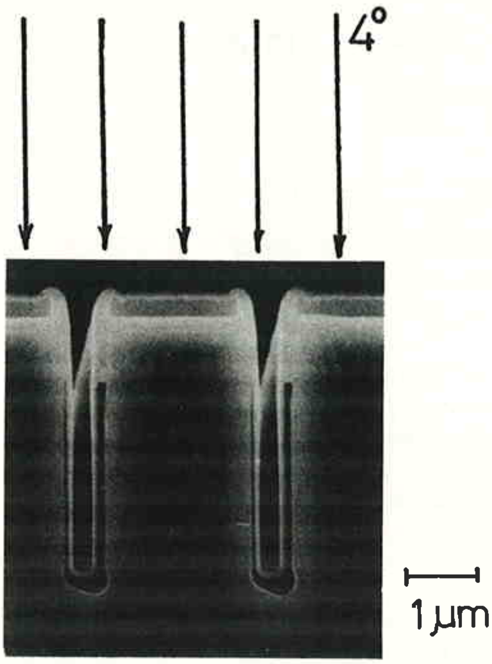

FIG. 2. SEM photograph of trenches whose right sidewalls are implanted by As at 4°; the n^+-doped regions are made clear by enhanced wet etching.

tration in a sidewall. The implanted "ranges" in the opposite surfaces are shallower than directly implanted ones for both cases, respectively. This, together with a geometrical consideration, indicates that lower energy ions scattered at larger angles contribute to the indirect doping.

Figure 4 shows the depth profiles at points a, b, c, d in

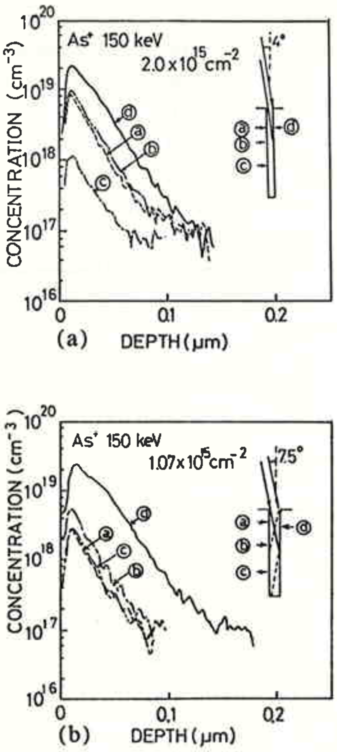

FIG. 3. Depth profiles of As implanted to parallel Si slices shown by insets at 150 keV at incident angles of (a) 4° and (b) 7.5°.

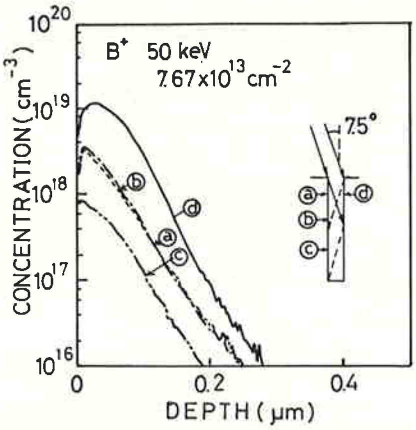

FIG. 4. Depth profiles of boron implanted to parallel Si slices at points shown by the inset at 50 keV at incident angle of 7.5°.

the inset for boron implantation at 50 keV, at 7.5° with doses of 7.67×10^{13} cm^{-2}. In the case of boron atoms, about 20% of the total implanted ions are doped faced regions (a and b). The specularly reflected region is lower, similar to the case of arsenic.

Figure 5(a) shows a simulation of the number of reflected atoms versus reflection angle for 5000 incident atoms and Fig. 5(b) shows the energy carried by a reflected atom versus reflection angle for 4° implantation. The simulation shows that the majority of the reflected atoms are directed to the specular direction by nearly elastic scattering and diffusely scattered atoms at larger angles lose energies to larger extent. Thus the experimental results agree with the simulation fairly well. It is interesting that at smaller incident angles the contribution of low-energy ion indirect doping increases.

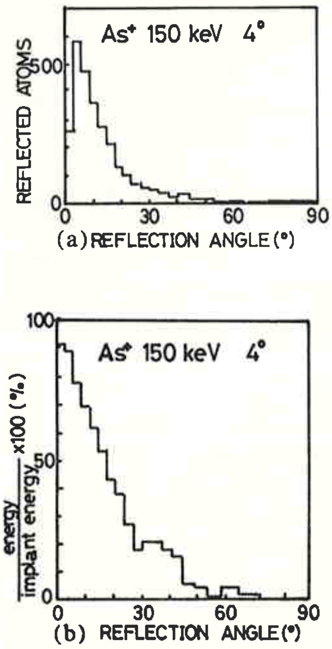

FIG. 5. (a) Number of reflected atoms vs reflection angle for 5000 incident atoms, and (b) energy carried by reflected atoms vs reflection angle for As implantation at an incident angle of 4° with energy of 150 keV, by Monte Carlo simulation.

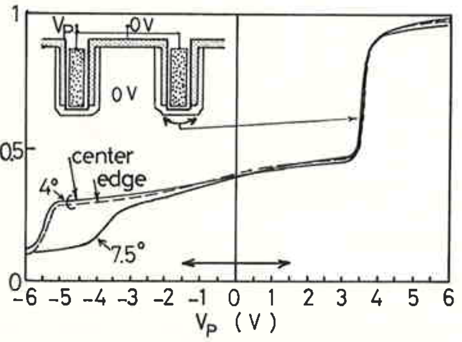

FIG. 6. *C-V* characteristics of the trench capacitors doped by fourfold ion implantations at incident angles of 4° and 7.5° for the center chip (solid line) and an edge chip (dashed line).

It appears surprising that the doping level in the specularly reflected region (c) is significantly lower than that in the upper part (a) for 4° implantation as the reflected atoms are sharply concentrated near the specular direction. This is understood as follows. The indirect doping intensity from a reflecting area ds is proportional to $(1/r^2)\cos(90-\theta)\times I(\theta)ds$, where r is the separation between the reflecting and doped points, θ is the incident angle at the doped point, and $I(\theta)$ is the doping ratio. At point c, r is larger and $\cos(90-\theta)$ and $I(\theta)$ are smaller than those at point a and so the doping level at point c is lower than that at point a.

We developed a trench capacitor[1] that uses only the uniformly doped sidewall: the upper part is covered by a SiO_2 sidewall and the bottom is removed by etching after sidewall doping. A central island is surrounded by an n^+-doped node and the bottom is B implanted after the etching for isolation. The *C-V* characteristics of the capacitors of 0.6-μm-wide trenches doped by fourfold implantation of As and B at incident angles of 4° and 7.5° to form high-capacitance structures as shown in Fig. 6. The solid and the dotted lines represent *C-V* curves of the device at the center and near the edge of the 6 in. wafer, respectively. The As doses are 3×10^{14} and 1.5×10^{14} cm^{-2} for 4° and 7.5° implantations, respectively. The increases at about -5.5 V and 3.5 V for 4° implantation indicate the electron accumulation at the n^+ node and the inversion at the trench bottom, respectively. It can be seen that the first rise for 7.5° implantation shifts to -3.5 V and becomes less steep. This indicates that the trench sidewalls are more heavily and uniformly doped by 4° implantation as expected by the present complementary experiments. The practical range for a 16 Mbit DRAM is shown by arrows. The region between the rises is quite smooth and flat reflecting uniform sidewall doping. The demonstrated uniformity of trench doping over the chips on a wide area of the 6 in. wafer is achieved by using a specially designed implanter whose scan error is less than $\pm1.2°$ over the wafer.

The depth profiles in indirectly doped sidewalls by reflected ions are measured for the first time. Excellent electrical characteristics are realized for 0.4-μm-wide trench capacitors doped by grazing ion implantations of As and 8 at 4° over the 6 in. wafer. Using the technique of 4° implantation, one can dope a trench whose aspect ratio is as high as 15.

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