

# TRENCH SIDEWALL IMPLANTATION WITH A PARALLEL SCANNED ION BEAM

## R. Kakoschke

Siemens AG, HLT312, D-8000 Munchen 83, FRG

and

R.E. Kaim, P.F.H.M. Van Der Meulen and J.F.M. Westendorp
Varian/Extrion Division, Beverly, MA 01915, USA.

Published in *IEEE Trans. Elec. Dev.*November 1989



# TRENCH SIDEWALL IMPLANTATION WITH A PARALLEL SCANNED ION BEAM

R. Kakoschke Siemens AG, HLT312, Otto-Hahn-Ring 6 , D-8000 Munchen 83, FRG

and

R. E. Kaim, P.F.H.M. Van Der Meulen and J.F.M. Westendorp\* Varian/Extrion Division, 123 Brimbal Ave., Beverly, MA 01915, USA

#### Abstract

The sidewalls of trenches on 100 mm wafers were doped by implantation with an implanter whose beam scan is accurately parallel over the whole wafer surface. The doping was characterized with a staining technique and transmission electron microscopy. All the trenches exhibited symmetrical doping, with the main differences between trenches from the center and edge of a wafer being due to non-uniformity of the trench etching rather than the implant step.

<sup>\*</sup>Present address: ASM Microelectronics Technology Center, Bilthoven, The Netherlands. Published in *IEEE Trans. Elec. Dev.* Nov. 1989

### INTRODUCTION

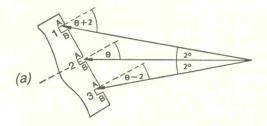
In order to increase the packing density of devices on VLSI circuits, deep trenches are commonly used for isolation between devices or for increasing the storage capacitance of DRAM memory cells [1,2]. In either application it is necessary to dope the sidewalls of the trenches: for isolation, the doping is required to adjust the threshold of the isolating junction provided by the trench; when the trenches are used to provide increased capacitance in a DRAM cell, the doping is used to achieve a conductive capacitor plate along the vertical length of the sidewalls. The use of ion implantation to dope the trench sidewalls [2,3,4] is attractive because use of implantation reduces the overall thermal budget of the VLSI manufacturing process. In addition, implantation is a well established technology.

However, the need to implant ions into the vertical sidewalls of trenches whose aspect ratio (depth/width) may be as high as ten, imposes stringent requirements on ion implantation equipment. In particular, the angle of incidence of the ions on the trenches has to be strictly controlled. In this paper we present for the first time results of trench sidewall doping performed with an implanter which has a parallel beam scan – use of such an implanter is a prerequisite for successful application of the trench doping technique in a production environment, especially for larger wafer sizes.

#### **EFFECT OF IMPLANT ANGLE VARIATION**

Figure 1 schematically illustrates implantation of trench sidewalls using a non-parallel ion beam. The angular variation of  $\pm 2^{\circ}$  shown in the figure is typical for 100 mm wafers in implanters which scan the beam electrostatically in two dimensions. The effect of the variation is that side A of trench 3 (Figure 1a) is implanted with a smaller angle between the beam and the sidewall than side A of trench 1. After the wafer has been rotated to implant the opposite sides of the trenches (Figure 1b), it is seen that both trenches 1 and 3 have opposite sidewalls implanted with different angles of incidence.

An implant angle change of only a few degrees can cause a major asymmetry in the ion dose delivered to opposite sidewalls of a trench [4]. There are 3 factors, each of which contributes to the



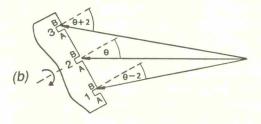


Figure 1. Schematic illustration of trench implantation with a non-parallel scanned ion beam at a nominal wafer tilt angle θ. The wafer in (b) has been rotated 180° relative to its position in (a).

dose error in the same direction: the dose is less where the implant angle between the beam and the sidewall is smaller:

- (i) The dose delivered to the sidewall is proportional to the sine of the implant angle. For an implant angle of 7° at the wafer center, a side-to-side angle variation of ±2° corresponds to almost a factor of two change in the dose in opposite sidewalls.
- (ii) Reflection of ions from the sidewalls increases sharply with decreasing angle [7,6], reducing the retained dose.
- (iii) The reflected ions contribute significantly to the dose in the opposite sidewall [3].

If the sidewall doping is asymmetrical it becomes difficult to select an acceptable window for the process. For example, for DRAM capacitors the trench sidewall has to be doped to a level of 10<sup>19</sup> cm<sup>-3</sup> in order to achieve a conductive capacitor plate with sufficient capacity in the operating range. On the other hand, the doping must not be too high since this can alter the growth rate of the oxide which is grown subsequent to the doping.

#### **EXPERIMENTAL**

Implants were performed with a medium current serial implanter [8,9] which is shown schematically in Figure 2. This implanter employs a hybrid electrostatic/mechanical scan to spread the beam with uniformity better than 0.5% over wafers up to 200 mm in diameter. In the horizontal direction, a parallel beam scan is achieved by means of a non-uniform field dipole magnet, while in the vertical dimension the wafer is mechanically translated with a 0.5 Hz With this system the reciprocating motion. implant angle variation across a wafer is determined only by the deviation from parallelism of the horizontally scanned beam [10]. This deviation is less than 0.25° over the width of the 100mm wafers used in this work.

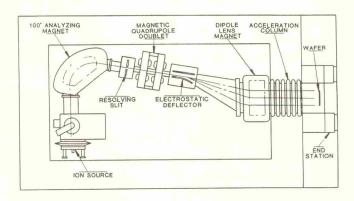


Figure 2. Beamline layout of the implanter.

Test structures with 5 $\mu$ m deep trenches of circular cross-section 1 $\mu$ m in diameter were formed on 100mm wafers by reactive ion etching. The wafers were implanted with 80keV As ions to a total dose of 1  $\times$  10<sup>16</sup> ions/cm<sup>2</sup>. Table 1 shows the implant conditions for each of four wafers.

After implant the wafers were annealed by rapid thermal annealing for 15 seconds at 1200°C in an oxygen atmosphere. The temperature ramp-up included a 20 second plateau at 900°C to grow a protective oxide cap which prevents out-diffusion of the dopant at the higher temperature. The anneal was followed by enhanced wet etching of the silicon for 3 seconds in 19:1 HNO<sub>3</sub>:HF, a technique [3] which makes the doped regions of silicon visible by scanning electron microscopy. In the micrographs obtained with this technique, the observed thickness of the doped region correlates with the doping concentration, the boundary of the

TABLE 1

Wafer No.	Tilt Angle (degrees)	Dose/Step (ions/cm <sup>2</sup> ) ( x 10 <sup>-15</sup> )	Rotations (degrees)
1	15	10.0	0
2	7	2.5	0,90,180,270
3	15	2.5	0,90,180
	15	1.25*	270
4	7	1.25	0,90,180,270
	15	1.25	0,90,180,270

<sup>\*</sup> Incorrectly implanted

etched region corresponding to an isoconcentration line of approximately  $2 \times 10^{19}$  cm<sup>-3</sup>.

The dependence of the thickness of the etched region on ion dose was modelled using SUPREM III. Post-diffusion doping profiles were calculated in the planar case (ie. only implantation and diffusion normal to the trench sidewall were taken into account). The calculations were repeated for different as-implanted depth distributions corresponding to energies between 10 and 80 keV, and the results showed that the final dopant profiles are dominated by diffusion, with only minor dependence on the as-implanted distribution. In fact the final distributions corresponding to 10 and 20 keV were nearly identical. At the energy (80 keV) and tilt angles (7° or 15°) used for the trenches in this work, the projected energy normal to the sidewalls is less than 10 keV, and it can therefore be assumed that the final dopant profile is diffusion dominated. Consequently low energy reflected ions contribute to the observed doping in the same way as the primary ions. Using the diffusion-dominated profile, and assuming that etching occurs up to a particular isoconcentration contour, the etched thickness can be estimated. Figure 3 shows the calculated thickness of the etched region as a function of ion dose, for three presumed isoconcentration contours. These calculations were made for a 30 minute oven anneal, but the results are assumed to be approximately valid also for the rapid thermal annealing used in this work. This result, and the calculations of Figure 3, have also been verified by SIMS measurements (not shown here).

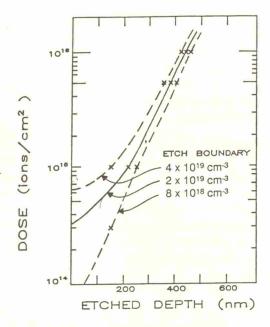


Figure 3 - Calculated thickness of stained region as a function of ion dose.

#### RESULTS AND DISCUSSION

Figure 4 shows a trench from the center of wafer no. 1, which was implanted from one side only at a tilt angle of 15°. The arrow in the photograph is a trajectory at 15°, and it can be seen that the lower boundary of the heavily doped layer on the directly implanted sidewall agrees well with the line defining the onset of shadowing. By measuring the observed thickness of the heavily doped layer, and using the contour for  $2 \times 10^{19}$  cm<sup>-3</sup> in Figure 3, the retained ion dose in the layer is estimated to be  $2 \times 10^{15}$  cm<sup>-2</sup>. The projected

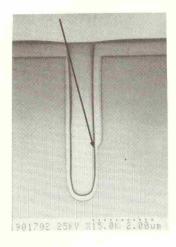


Figure 4. Trench from center of wafer no. 1, implanted at 15° tilt without rotation.

dose, given by the surface dose  $\times$  sin15°, is  $2.6 \times 10^{15}$ , indicating a high degree of retention. The opposite wall, which is only accessible to reflected ions, shows uniform doping with a dose of about  $6 \times 10^{14}$  cm-2. There is also evidence of doping at roughly  $10^{14}$  cm- $^2$  on the sidewall below the directly implanted region. This doping is due to double reflections.

The trenches in Figure 5 are from wafer no. 2, which was implanted at 7° tilt with four rotational steps. The most noticeable difference between trenches from the center and side of the wafer is in the shape of the trenches themselves, which is caused by spatial non-uniformities in the reactive ion etching process used to make the trenches. In particular, the steps in the sidewalls of the trench in Figure 5b are an artifact of the reactive ion etch. The sidewall doping is uniform and symmetrical for both trenches, but the dose is slightly larger in Figure 5a  $(8-9 \times 10^{14})$  than in Figure 5b (6-7  $\times$  10<sup>14</sup> cm<sup>-2</sup>). This difference in doping may be caused by the different trench shapes: the sidewalls on the trench from the wafer edge deviate by about 0.5° from vertical, reducing the effective implant angle. The difference in dose due to this angle change ( $\sin 7^{\circ}/\sin 6.5^{\circ} = 1.08$ , together with the reduced retention at the smaller angle), is sufficient to account for the observed difference in thickness of the doped layers. Note that the doping thickness on the directly implanted surface layer, which corresponds to the total dose of  $1 \times 10^{16}$  cm<sup>-2</sup>, is the same in all the micrographs.

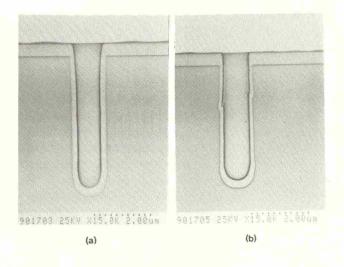


Figure 5. Trenches from wafer no. 2, implanted at 7° tilt with four-way rotation. (a) From wafer center. (b) From wafer edge.

When the tilt angle is increased to 15° with four-way rotation (Figure 6), the sidewall doping profile exhibits a step due to shadowing of the lower part of the trench. In this case the sidewalls on the trench at the center of the wafer are tilted about 1.5° from the vertical, increasing the implant angle on these walls. This explains why the directly implanted region in Figure 6a is slightly thicker than that in Figure 6b.

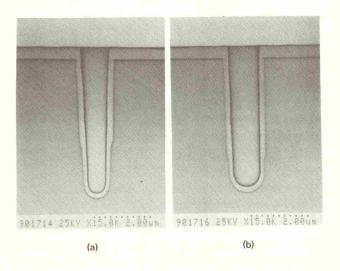


Figure 6. Trenches from wafer no. 3, implanted at 15° tilt with four-way rotation. (a) From wafer center. (b) From wafer edge.

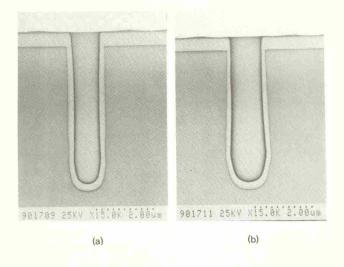


Figure 7. Trenches from wafer no. 4, implanted at 7° and at 15° tilt with four-way rotation.
(a) From wafer center. (b) From wafer edge.

The trenches in Figure 7 were implanted with 8 steps, consisting of four-way rotations at 7° and at 15° tilt. The uniformity of sidewall doping is good, with a barely noticeable trace of the step in doping due to shadowing at 15° tilt.

#### CONCLUSIONS

As a result of the implanter's parallel beam scan, none of the trenches from the center or edge of the wafer showed any side-to-side asymmetry when four 90° rotations were used. Although these measurements were made with 100 mm wafers, symmetrical doping should be attainable for all trenches on wafers up to 200 mm in diameter.

For the trench aspect ratio in this work, a tilt angle of 15° is too large since there is non-uniformity due to shadowing of the lower part of the trench. When the tilt angle was 7° the sidewall doping uniformity was excellent, but because of the acute angle of incidence the doping concentration was sensitively dependent on small angular deviations of the sidewalls from vertical. A tilt angle of approximately 10° would probably have been optimum for these trenches.

A combination of 7° and 15° tilt angles gave uniformity which was slightly inferior to 7° alone, but use of such a combination may be advantageous for trenches with higher aspect ratio where the tilt angle needed to implant the lower region of the trench becomes very small.

The authors are grateful to Dr. M. Engelhardt (Siemens ZFE EL PT 13) for preparing the test structures, and to Mrs. I. Neumann (Siemens HL T 431) for SEM analysis.

#### REFERENCES

- [1] "Technology and Reliability Problems of Trench Cell Capacitors", S.Roehl, Springer Series in Material Science (Semiconductor Silicon), Vol. 13, 288, Eds. G.C.Harbeke, M.J.Schultz (Springer-Verlag, Berlin Heidelberg 1989). Proceedings of the Summer School (Erice, Trapani, Sicily).
- [2] K.H.Kuesters, G.Enders, W.Meyberg, H.Benzinger, B.Hasler, G.Higelin, S.Roehl, H.M. Muehlhoff, W.Mueller; Proc. of the 1987 Symposium on VLSI Technology, Nagano (1987) p 93.
- [3] R. Kakoschke, H. Binder, S. Roehl, K. Masseli, I.W. Rangelow, S. Saler and R. Kassing, "Ion implantation into three-dimensional structures," Nucl. Instr. and Meth. in Phys. Res. B21 (1987) 142.
- [4] G. Fuse, M. Fukumoto, A. Shinohara, S. Odanaka, M. Sasago, and T. Ohzone, "A new isolation method with boron-implanted sidewalls for controlling narrow-width effect", IEEE Trans. Electr. Dev. **ED-34** (1987) 356.

- [5] G. Fuse, H. Ogawa, Y. Naito and K. Tamura, "Indirect trench sidewall doping by implantation of reflected ions", Appl. Phys. Lett. 54 (1989) 1534.
- [6] G. Fuse, H. Umimoto, S. Odanaka, M. Wakabayashi, M. Fukumoto and T. Ohzone, "Depth profiles of boron atoms with large tilt-angle implantations", J. Electrochem. Soc. 133 (1986) 996. ..page
- [7] K. Kato, "As-ion-implantation simulation for trench structures using a Monte Carlo method", IEEE Trans. Electr. Dev. ED-35 (1988) 1820.
- [8] Varian Extrion, Model E220.
- [9] D. W. Berrian, R. E. Kaim, J. W. Vanderpot and J. F. M. Westendorp, "The ASM-220 medium current implanter", Nucl. Instr. and Meth. in Phys. Res. B37 (1989) 500.
- [10] J.F.M. Westendorp, R. E. Kaim, G. B. Odlum, R. Schreutelkamp, F. W. Saris and K.T.F. Janssen, "Channeled implantation with a parallel scanned ion beam", Nucl. Instr. and Meth. in Phys. Res. **B37** (1989) 357.