Features of the transformation of small square zones during their thermomigration through a silicon wafer (100)

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A new effect has been experimentally discovered and studied during the thermomigration of a linear aluminum-based zone, shaped as a square with a side length of less than $520\,\mu$m, through a {100} silicon wafer. The effect manifests itself in a complex transformation of the molten zone and the formation of an epitaxial channel with a goblet-like shape. The channel boundaries form two curvilinear $p-n$ junctions within the wafer, each possessing distinct electrophysical properties. The outer junction contains segments with the same sign of curvature as the rounded edges of conventional $p-n$ junctions produced by planar diffusion. The inner $p-n$ junction exhibits the opposite (negative) curvature sign, which cannot be achieved in standard junctions. It is shown that such curvature of the inner junction leads to an expansion of the space-charge region in the lightly doped n-type material and to an increase in the breakdown voltage of the $p-n$ junction.

Keywords: thermomigration, silicon, square zones, transformation, breakdown voltage.

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Thermomigration (TM) of an orthogonal grid of aluminum-based linear zones through a silicon wafer produces closed epitaxial channels (cells) extending through the wafer, which are useful for power semiconductor devices [1–3]. However, the method's reproducibility is reduced by occasional discontinuities at zone intersections.

References [4,5] used intersection-free linear zones forming separate, unconnected squares, termed square zones. These zones provided highly reproducible formation of p-type cells, but during TM the opposite sides converged synchronously at an angle of $22-27^\circ$ to the temperature gradient perpendicular to the wafer. Zone deflection from the normal was found to result from different crystal dissolution mechanisms along the inner and outer contours of the closed zone's dissolution front. These mechanisms produce asymmetric front faceting, which deflects the zone trajectory. Consequently, TM of a square zone through a silicon wafer produces a cell shaped as a truncated pyramid. Although this does not affect the cell's functionality, it reduces silicon utilization efficiency in device fabrication.

Here we experimentally discovered a new transformation effect in small square zones with side lengths $< 520\,\mu$m. As in earlier experiments, the silicon surface was ultrasonically cleaned before deposition. An aluminum film $8-10\,\mu$m thick was deposited by magnetron sputtering, followed by photolithography and chemical etching to form closed squares with strip widths of $80-100\,\mu$m, aligned along the crystallographic $\langle 110\rangle$ directions. The wafers were (100) n-type phosphorus-doped silicon with a resistivity of $4.5\,\Omega\cdot$cm, with a dislocation density of $\sim 10^2\,\mathrm{cm}^{-2}$, a thickness of 0.5 mm, and a diameter of 100 mm. TM was performed in vacuum using a heater with a uniform temperature gradient of $50-70\,$K/cm at temperatures of $1170-1370\,$K for $120-30\,$min, respectively. After TM, wafer planarity was restored by grinding away defective layers $30-50\,\mu$m thick from both front and rear surfaces. The aluminum concentration in the epitaxial channel was $(1-2)\cdot 10^{19}\,\mathrm{cm}^{-3}$.

During TM, in addition to the convergence of opposite sides of the outer contour, square zones undergo a transformation of the inner contour: it evolves from a square into a circle whose radius decreases to zero during migration. This causes the zone sides to merge, forming a localized (point) zone that migrates stably along the temperature gradient. Consequently, the epitaxial p^+-channel takes on a goblet-like shape with an unrecrystallized bowl of n-type silicon inside. Figure 1 shows the silicon surface with the initial aluminum zone of side length $465\,\mu$m and three successive sections parallel to the wafer plane, at depths of 30, 90, and $400\,\mu$m below the front surface, illustrating the main transformation stages.

Figure 2, *a* shows cross sections of channels formed by TM of small square zones with side lengths of 365, 415, 465, and $520\,\mu$m. The region of original silicon inside the channel increases in both width and depth as the square zone size increases, while retaining smooth contours. If the square zone side exceeds $520\,\mu$m, a cell extending through the wafer is formed (Figure 2, *b*).

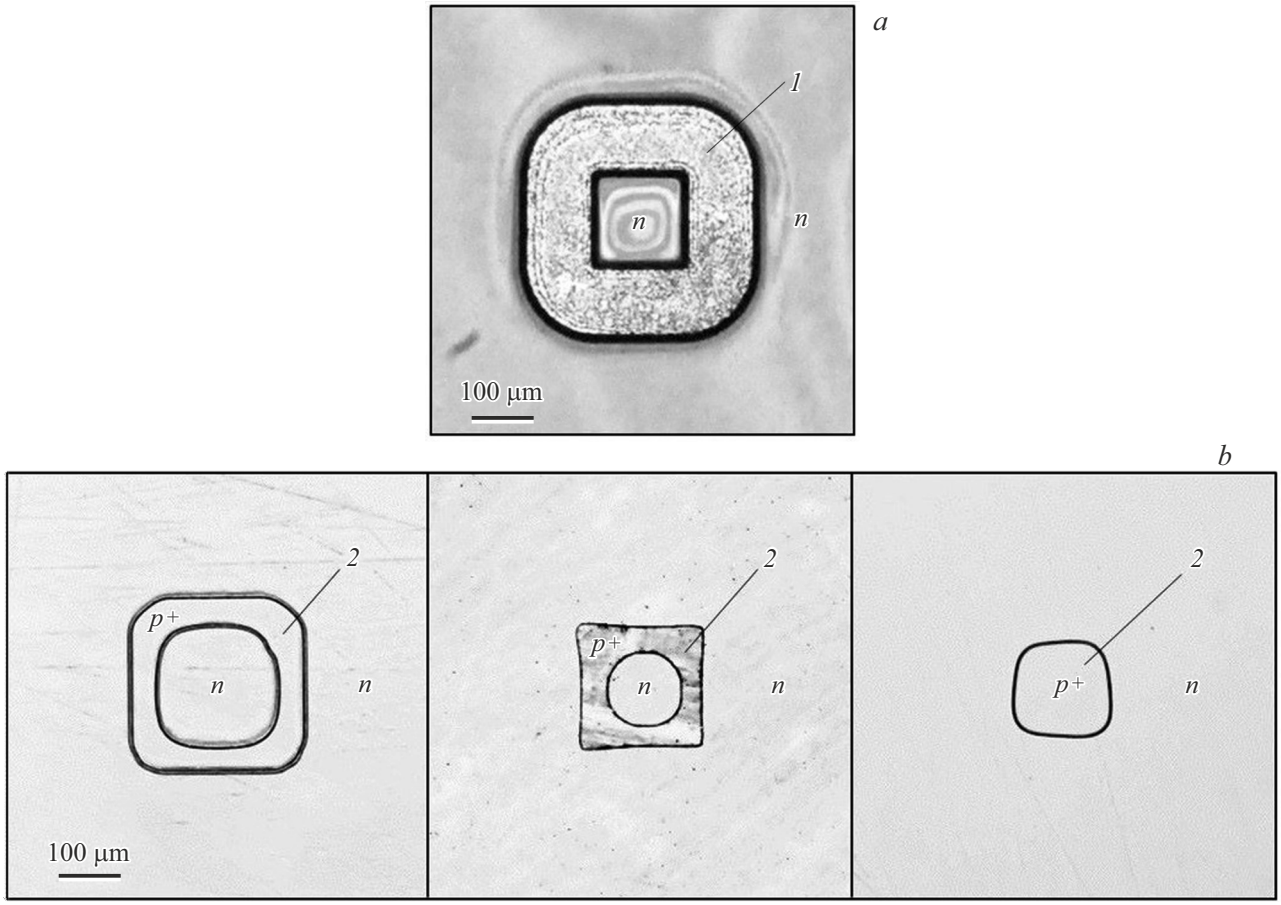


Figure 1. Photographs of the initial wafer surface (*a*) with an aluminum zone (*1*) and of the epitaxial p^+-channel (*2*) formed by TM of a small square zone, at different depths (*b*).

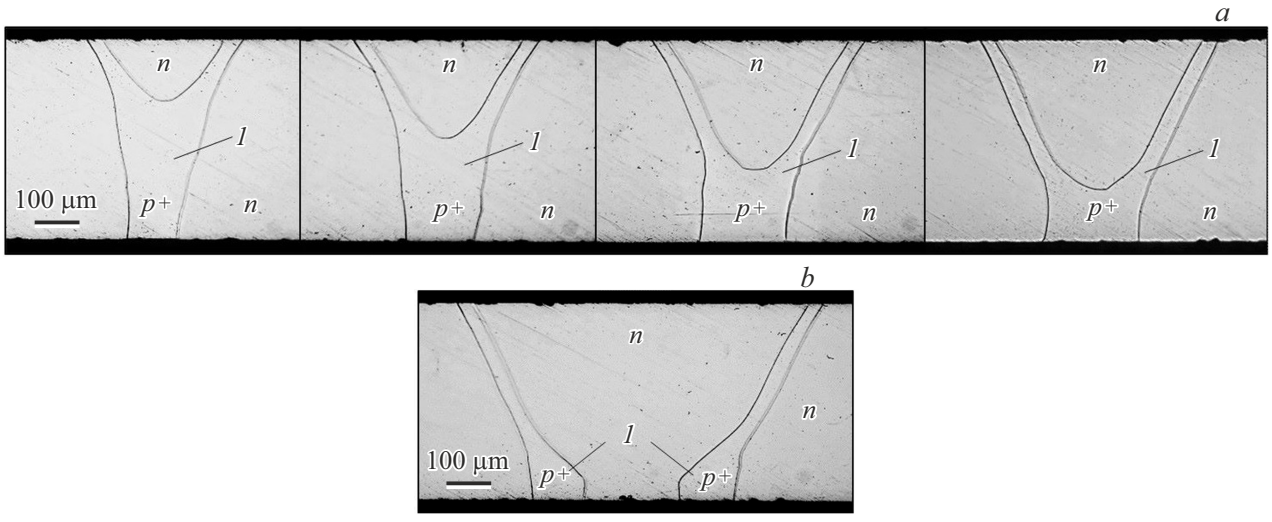


Figure 2. Photographs of cross sections of channels (*1*) formed by TM of small square zones (*a*) and a large square zone (*b*). The silicon wafer thickness is 430 μm.

The observed transformation of the inner contour of a small square zone appears to be caused by surface tension of the liquid zone. This is indicated by the dependence on square zone size and by the decrease in liquid-zone surface area. The surface area before penetration into silicon was determined from the shape and dimensions of the linear-zone cross section and the square perimeter. After the inner sides merged and a point zone formed, its surface area was estimated from the experimentally observed zone shape and dimensions. Conservation of liquid-phase volume was also assumed, neglecting aluminum loss through evaporation and doping of the epitaxial channel. The estimates showed that liquid-zone surface area decreases by 20–30 % during the transformation. Indeed, conversion of a small square zone into a point zone is energetically favorable because it minimizes the interfacial area.

Two curved, abrupt, asymmetrically doped $p-n$ junctions form at the channel boundaries: an inner and an outer junction. The latter has planar and rounded regions with the same sign of curvature (here termed positive, since the center of curvature lies in the heavily doped region) as the rounded portions of conventional planar-diffused junctions. The effect of positive $p-n$ junction curvature on its electrical properties is well understood [6]. At these rounded regions, the $p-n$ junction space-charge region narrows in the lightly doped substrate, reducing the breakdown voltage of the entire junction. The opposite (negative) curvature, i.e., a junction concave toward the substrate, cannot be produced by planar diffusion and has not previously been considered in the literature. Negative curvature should widen the space-charge region, reduce the electric field strength, and increase the $p-n$ junction breakdown voltage.

The inner $p-n$ junction has negative curvature over its entire area, including the regions meeting the wafer surface. To test the influence of negative curvature on $p-n$ junction rectification, current–voltage ($I-V$) characteristics were measured for inner and outer junctions formed by TM of small and large square zones. Measurements were performed by probing with an L2-56 semiconductor device parameter analyzer. One probe was placed on the p^+ channel and the other on the n region, inside or outside the epitaxial channel. Figure 3 shows typical reverse-bias $I-V$ characteristics, whose behavior depended strongly on the geometry of the $p-n$ junction. As expected, the highest breakdown voltage (~ 250 V) was obtained for the inner junction of goblet-shaped channels, which have negative curvature over their entire area (Figure 3, curve *1*). The inner $p-n$ junction of through-wafer cells had a lower breakdown voltage (~ 200 V), because, in addition to negatively curved regions, it contains planar regions that reduce the breakdown voltage of the entire junction. For the outer junctions (Figure 3, curves *2, 4*), which contain positively curved regions, the breakdown voltage difference (~ 185 and ~ 180 V) is associated with the greater curvature of the channel formed by the point zone compared with the channel formed by the large square zone.

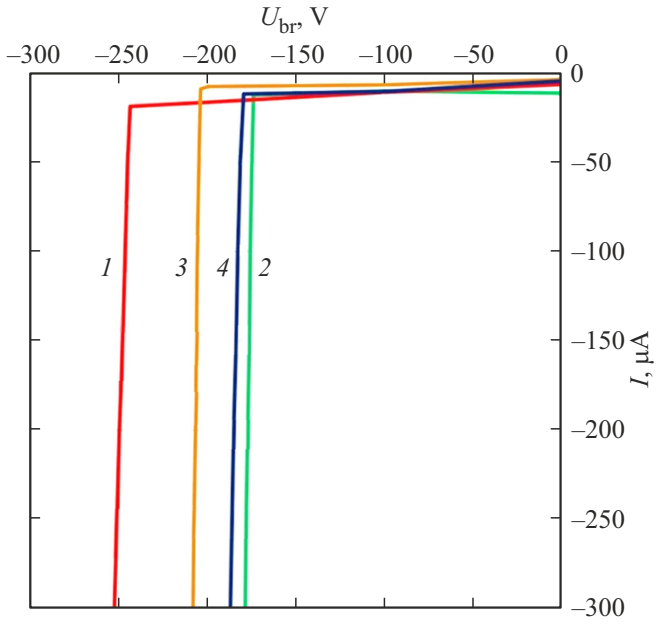


Figure 3. Typical reverse-bias $I-V$ characteristics of the inner (*1, 3*) and outer (*2, 4*) $p-n$ junctions formed by TM of small (*1, 2*) and large (*3, 4*) square zones.

Increasing $p-n$ junction breakdown voltage is important for devices using controlled avalanche processes, such as voltage-limiting diodes, Zener diodes, and avalanche photodiodes. The ability to control the depth of the inner $p-n$ junction allows the reverse-bias $I-V$ characteristic to be optimized. An array of goblet-shaped channels operating in parallel, with separate vertical interconnections, could provide the basis for a power device that dissipates heat uniformly throughout the wafer volume.

Thus, thermomigration of small square zones through a {100} silicon wafer enables the formation of curved $p-n$ junctions with negative curvature and increased breakdown voltage.

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Conflict of interest

The authors declare that they have no conflict of interest.

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