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The effect of transformation of a square-shaped linear zone during its migration through a $\{100\}$ silicon wafer

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The effect of transformation of a linear zone in the form of a square with the $\langle 110 \rangle$ oriented sides during thermal migration through a $\{100\}$ silicon wafer has been revealed experimentally. The effect manifests itself in synchronous convergence of the square sides and formation of a closed pyramid-shaped epitaxial channel. Such a transformation of the zone is explained by the asymmetry of the liquid zone dissolution front with respect to the temperature gradient and by specific features of the dissolution and crystallization processes in the linear zone bends in the square corners.

Keywords: thermomigration, temperature gradient, silicon, anisotropy.

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The method of thermomigration (TM) of liquid inclusions (zones) in solids under the influence of a temperature gradient allows obtaining epitaxial channels and electrically heterogeneous structures in the silicon wafer bulk [1,2]. The zones shape during their migration through the wafer determines the shape of through channels. In view of obtaining them, of practical interest are linear zones extended in one dimension.

The laws of rectilinear zones migration in silicon have been studied in many works [2–6]. It has been established [2] that retaining the given topology of a rectilinear zones system needs a uniform temperature gradient field **G** orthogonal to the wafer and also fulfillment of certain orientation conditions accounting for the anisotropy of the silicon crystal. The effect of anisotropy manifests itself in faceting the zone dissolution front by close-packed $\{111\}$ planes. The crystallization front does not exhibit faceting. Retaining the rectilinear shape of the zone needs the $\langle 110 \rangle$ direction coincidence with the linear zone axis and perpendicularity to the temperature gradient [3,4]. In this case, the liquid zone dissolution front in the $\{100\}$ wafers is faceted by two $\{111\}$ planes symmetric about the zone axis, the angle between the planes being 70° (the angle values are rounded to the nearest degree). If this condition is not met, the zone motion during TM is unstable, and the zone takes a characteristic fragmentary shape and retains it until disintegration into separate parts. The silicon anisotropy affects not only the rectilinear zone shape but also its trajectory which may not coincide with the temperature gradient direction if the dissolution front is faceted asymmetrically with respect to the temperature gradient. A grid of orthogonal rectilinear zones migrating through a $\{100\}$ silicon wafer allows formation of a system of end-to-end closed cells which are in demand for producing power semiconductor devices [6–9]. However, reproducibility of the method is insufficient because of formation of discontinuities near intersections of the linear zones. Of interest is the use of closed intersection-free linear zones shaped e.g. as rectangles (squares), whose migration is practically unstudied.

In this work, the migration of aluminum-based linear square zones through a $\{100\}$ silicon wafer was studied experimentally. There was revealed and explained the effect of the square-shaped linear zone transformation during its migration; the effect manifests itself in the convergence of the square zone sides.

In the study, we used (100) silicon wafers *n*-type resistivity $4.5\,\Omega \cdot \text{cm}$ 100 mm in diameter, 0.55 mm in thickness, and (100) in orientation (accurately to $\pm 0.5^\circ$); densities of dislocations, stacking faults and microdefects were no more than $1 \cdot 10^2$, $5 \cdot 10^2$ and $1 \cdot 10^4\,\text{cm}^{-2}$, respectively. The starting surface was coated by magnetron deposition with an aluminum layer $10-15\,\mu$m thick. After that, a system of unconnected square-shaped closed linear zones with the square side of 2.3 mm was created by photolithography. The aluminum strips for the zones were $100\,\mu$m wide. TM was carried out in a water-cooled vacuum chamber at the temperatures of $1300-1550$ K and temperature gradients of $20-100$ K/cm. The process duration was chosen so that the zones reached the opposite (finishing) surface. The character of the zones motion was studied by the metallographic method based on the shape of epitaxial channels on sections parallel and perpendicular to the surface of the obtained structures.

The square zones migrated through the $\{100\}$ silicon wafer reproducibly, without violating the zone integrity, provided the square sides were oriented along the $\langle 110 \rangle$ directions relevant to the stable motion and symmetric

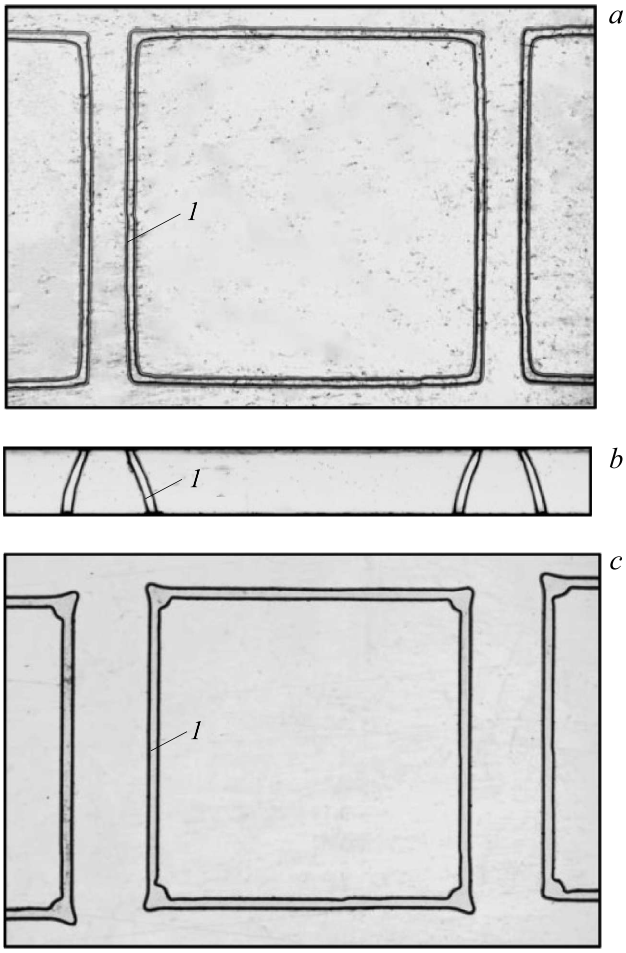

Figure 1. Photos illustrating the square zone transformations. *a* — on the start surface; *b* — cross-section of the wafer with channels *1*; *c* — at the distance of 500 μm from the start surface.

faceting of the rectilinear zone dissolution fronts. Such rectilinear zones are to move in the direction of the temperature gradient. However, the square zones motion through the wafer was found out to be accompanied by synchronous inward displacement of the square sides at an angle of $\sim 25^\circ$ to the normal. The square shape of the linear zone was retained throughout the entire motion trajectory. The area of the closed cell inside the square zone decreased monotonically with migration, and the epitaxial channel became pyramidal. In addition, protrusions with smooth contours got formed at the epitaxial channel corners and were extended along the $\langle 100\rangle$ directions (Fig. 1).

To clarify the role of angles in the square zone transformation, special experiments were performed in TM of linear zones bent on the starting surface at right angle with the 2.3 mm length of rectilinear sections oriented along the $\langle 110\rangle$ directions. In this case there were also observed deviations of the rectilinear section trajectories at the same angle to the normal. Reference sets of the rectilinear zones migrated in the wafer without deviation from the temperature gradient.

Shapes of cross-sections of the square zone sides in the wafer deep bulk differed from those of separate rectilinear zones (Fig. 2). The figure shows that the dissolution front of the square zone side is faceted by one $\{111\}$ plane on the outer side of the square, while that of a separate rectilinear zone is faceted by two symmetric $\{111\}$ planes. The zone thickness in the direction of the square zone side motion becomes significantly greater than its width (Fig. 2).

Experiments have established that variation in the linear zone shape during TM is associated with the asymmetry of the dissolution front faceting. The fact of faceting of the dissolution or crystallization front evidences for the layer-by-layer atomic-kinetic mechanism of the process [10]. The faceted front displacement requires a source of atomic steps on the vicinal plane. The rectilinear zone has a convex dissolution front and concave crystallization front; therefore, the latter always has steps helping the crystal growth, and faceting does not occur. The convex zone dissolution front excludes the existence of natural steps and gets faceted in silicon by close-packed $\{111\}$ planes. Dissolution of such a plane proceeds via the dislocation or nucleation mechanism [10].

The observed effect of displacement of the square zone sides oriented along the $\langle 110\rangle$ directions inward the square is defined by peculiar features of the processes of dissolution and crystallization in the square corners. The angle on the zonés outer contour hampers the dissolution, while the angle on the inner contour facilitates the crystal dissolution due to concavity (negative curvature). Atomic steps located in the corner on the zone inner contour propagate along the boundary and prevent formation of a faceting plane on the adjacent rectilinear section of the zone inner contour with retaining facet $\{111\}$ on the outer contour. Therefore, an asymmetric faceting occurs at the dissolution front, square zone sides deviate from the temperature gradient, corners lag behind the sides, and a closed pyramidal channel with characteristic distortions of the corners gets formed in the silicon wafer (Fig. 1). Smoothness of corners is caused by surface tension forces.

Let us notice high reproducibility of end-to-end closed cells formation with the aid of non-intersecting square linear zones: no more than five of 868 formed cells (0.6%) exhibited violations of the channel integrity.

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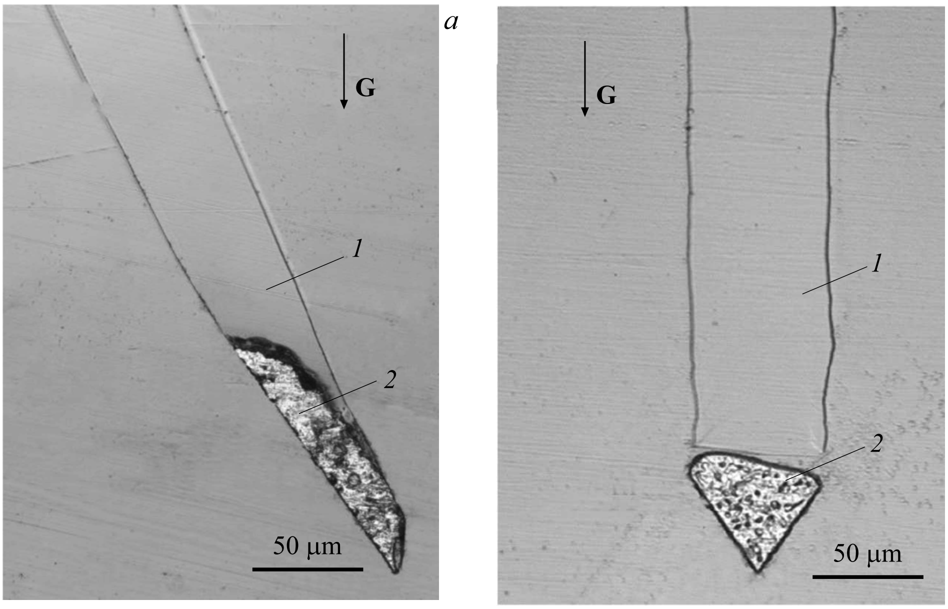

Figure 2. Cross-sections of the silicon wafer with a channel *1* and with a zone *2*. *a* — for the square zone, *b* — for the rectilinear zone.

Conflict of interests

The authors declare that they have no conflict of interests.

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