

Application of carbon for the formation of discrete aluminum-based zones during their thermomigration in silicon

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A system of discrete linear zones in the form of an orthogonal grid of intersecting rectilinear zones, rings or squares, when they thermomigrate through a silicon wafer, forms epitaxial channels forming through-closed cells demanded by power electronics. Experimental studies have revealed specific defects in the form of spherical bumps in the zones from the starting surface. The presence of such defects violates the specified topology of the channels, making post-migration processing impossible. In this paper, the causes of these defects are established and a method is proposed for their effective elimination using a thin layer of carbon in the form of soot.

Keywords: Thermomigration, end-to-end channels, defects, carbon.

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1. Introduction

The application prospects of *n*-type silicon wafers with through *p*-type cells obtained by thermomigration (TM) of aluminum-based linear zones in electronics were established in [1–6]. Alongside with a certain progress in development of the TM method, serious problems hindering its advancement have recently been revealed. Specifically, as the diameter of the used silicon samples increased, it became hard to preserve the strict homogeneity of the temperature gradient field in a silicon wafer and the specified zone topology in the TM process. These issues were addressed in [7,8]. It became crucial at this stage of development of the TM technology to identify the causes of formation and eliminate spherical defects (bumps) on the starting surface of zones.

Defects in the form of bumps have been first discovered in [3,5,6] in TM of intersecting rectilinear zones through a silicon wafer with crystallographic orientation (100). According to the authors of these studies, the bumps consisted of aluminum oxide with silicon inclusions and reached 3 mm in size with a zone width of 0.1 mm. Only a few (less than ten) defects of this kind were typically present on a silicon wafer 125 mm in diameter. However, even a single bump disrupted the planarity of the wafer surface, and entire wafers with many cells had to be discarded during post-migration processing. The authors of [3–5] have attempted to eliminate these defects by optimizing the temperature-time TM regime, regulating the oxygen pressure in a protective nitrogen atmosphere, and varying the geometry of aluminum zones on the starting surface of a wafer. These measures helped reduce the number of bumps on a wafer, but the researchers could not get rid of them completely or determine the cause of their formation. The present study is focused on elimination of this specific defect that emerges in TM.

2. Experiment

Monocrystalline silicon wafers (100) with a diameter of 100 mm, a thickness of 0.6 mm, *n*-type conductivity with a resistivity of 4.5 Ωcm and a dislocation density of 10^2 cm^{-2} were used in experiments. TM was performed in a vacuum water-cooled chamber in a heating device [9] providing a uniform temperature gradient field of 40–90 K/cm at a temperature of 1300–1420 K. In order to form zones, a 10-μm-thick layer of aluminum was applied to the starting surface of the silicon wafer by magnetron deposition. Photolithography was then used to form a system of closed aluminum strips in the form of a grid, rings, or squares on the starting surface. The area within a cell formed by these strips was varied from 1 to 14 mm², the minimum intercell distance was 0.2 mm, and the width of aluminum strips for the zones was 0.1 mm. It should be noted that this topology of a discrete zone system provides higher integrity of zones under TM (~ 90 %) than a grid of intersecting linear zones (~ 50 %).

A layer of carbon in the form of soot applied from a hydrocarbon flame onto the starting surface of the silicon wafer with deposited aluminum for the zones was proposed as a means to eliminate bump defects. Reproducible application of soot was carried out using a setup based on a two-axis manipulator. The flame source (stearin candle, kerosene lamp, or gas burner) was positioned under the silicon wafer. The wafer was moved at a rate of ~ 1 cm/s and passed over the flame with a given step in accordance with the specified algorithm. The wafer surface heating temperature was monitored with an infrared pyrometer and did not exceed 400 °C. The type of hydrocarbon used was not a critical factor. A total of 5–6 passes were needed to apply a continuous layer of soot 0.1–1 μm in thickness.

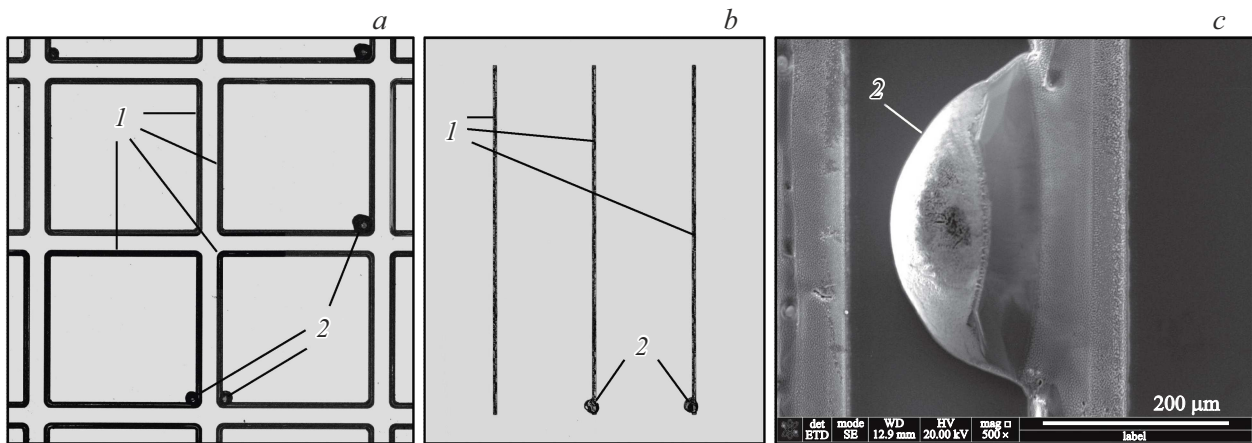


Figure 1. Photographic images of typical wafer fragments with square (a) and rectilinear (b) channels 1 on the starting surface side and with defect 2 in the form of a bump (c).

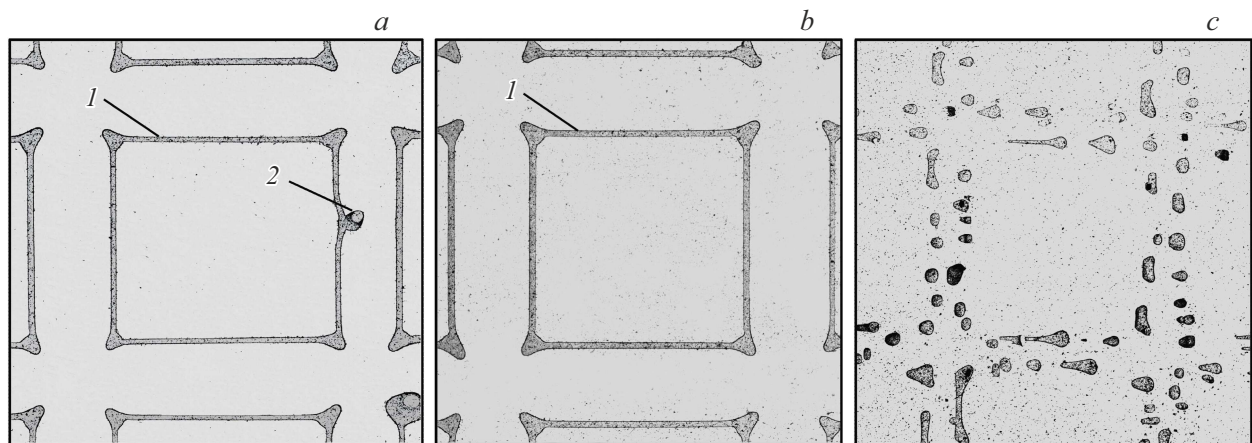


Figure 2. Photographic images of epitaxial channels 1 at a distance of $30\mu\text{m}$ from the finishing surface. a — With defect 2 in the form of a bump; b — without a defect; c — torn into separate parts as a result of „cold“ deposition of finely dispersed carbon.

3. Results and discussion

Figure 1 presents the photographic images of fragments of the silicon wafer with defects in the form of bumps on the starting surface of square and rectilinear zones after TM. It was established that bumps emerge only in a certain fraction of zones ($\sim 60\%$) and only a single bump may form per zone regardless of the TM conditions, zone orientation, and temperature gradient in the crystal. The photographic images of epitaxial channels near the finishing surface after its polishing and development by chemical etching in Dash etchant are shown in Figure 2. It can be seen that a bump defect deforms locally the channel formed by the cell (Figure 2,a). The diameter of spherical bumps was $0.2\text{--}0.3\text{ mm}$; according to energy-dispersive analysis data, they were formed from silicon doped with aluminum. Visual observations of TM of the starting surface of the wafer with zones through quartz glass of the chamber revealed that all the bumps arose at the initial stage of the process within the first 5–10 min, while the overall time of migration of the

zones through the wafer was 60–90 min (depending on the chosen temperature and the magnitude of the temperature gradient).

A layer of carbon in the form of soot applied from a hydrocarbon flame to the starting surface of the wafer with prepared aluminum for the zones eliminated completely the bump defects (Figure 2,b). The use of soot did not disrupt the integrity of migration of linear zones and did not exert any significant influence on the rate of zone motion. The width of channels obtained using soot increased by $\sim 20\%$.

We have also attempted to apply a carbon layer without a flame. A graphite paint spray or suspensions containing finely dispersed carbon (aquadag, ultra-dispersed graphite, hydrogenated fullerene, and soot in acetone) were used for this purpose. None of these substances produced a positive effect: linear zones were torn into separate parts (Figure 2,c), and the channels turned out to be completely unsuitable for fabrication of semiconductor devices.

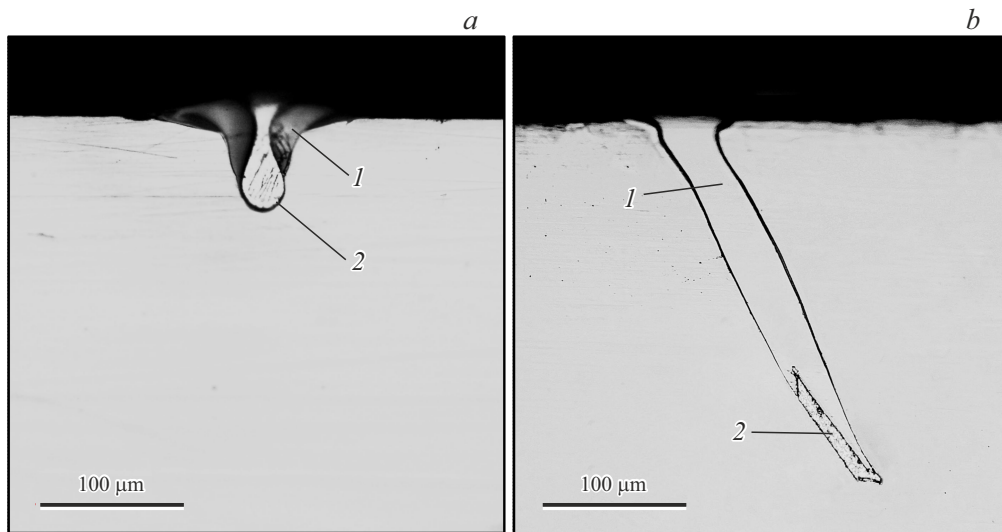


Figure 3. Photographic images of cross sections of the zone and the channel at the sinking stage (*a*) and in the stationary regime of TM of the square zone (*b*); 1 — epitaxial channel, 2 — „frozen“ zone.

To unveil the causes and mechanism of formation of defects in the form of bumps, one needs to take into account the fact that they emerge at the start of TM and are associated with the specifics of zone sinking into the crystal. The main feature of sinking is the presence of a boundary between the liquid zone and vacuum. This boundary has the minimum temperature in the zone, but crystallization at it is made difficult by the lack of nuclei. Crystallization is possible only at its edges, where a contact with silicon is established and from where the zone is overgrown as it sinks. There are no such restrictions at the dissolution front of the zone. As a result, the „hot“ boundary of the zone gets ahead of the „cold“ one, the zone is stretched in the direction of the temperature gradient, and the rate of motion of the zone as a whole decreases. This is evidenced by the lack of faceting of the dissolution front of the zone by type {111} planes (Figure 3, *a*), which is characteristic of a moving dissolution front [8].

With the zone overgrown with silicon at the „cold“ boundary, the sinking stage ends, the restrictions on crystallization are lifted, and new coordinated rates of dissolution, diffusion, and crystallization processes needed for stationary motion of the zone are established. A stationary form of the liquid zone within the crystal is established due to the fact that the atomic-kinetic processes of dissolution are impeded to a greater degree than the processes of crystallization; this leads to compression of the zone in the direction of its motion and faceting of the dissolution front by singular planes {111} (Figure 3, *b*). The difference in the forces of resistance to dissolution and crystallization is balanced by the force of surface tension of the deformed zone [10]. Excess pressure in the zone may destroy a thin layer of silicon near the overgrown starting surface of the zone and force a droplet of the solution-melt onto the surface. This droplet is what that causes the formation of a bump defect:

migrating after the zone, the droplet forms a spherical protrusion on the starting surface, induces local deformation of the channel, and establishes irregularities on the finishing surface of the wafer. The presented mechanism of formation of the defect in question is consistent both with our results for individual zones and with the data reported in [3–5] for a system of intersecting (connected) linear zones.

The elimination of defects in the form of bumps by a layer of soot is probably attributable to the fact that soot forms nuclei at the boundary of the liquid zone with vacuum, facilitating the process of zone sinking. The zone does not get stretched, and, owing to faceting of the dissolution front, the deformation of the zone ends before it sinks completely. Excess pressure is not produced in the zone. Soot has a finely crystalline structure and provides fine adhesion to the aluminum surface in „hot“ application. The size of soot particles is 0.5–1 nm, which is consistent with known data [11]. Other carbon-containing substances used had significantly larger crystallites (0.5–100 μm) and initiated uneven crystallization and zone ruptures.

4. Conclusion

The application of a carbon layer in the form of soot from a hydrocarbon flame onto the aluminum zone surface proved to be an effective means of eliminating bump defects formed in the process of thermomigration of linear zones. Defects emerged when a solution-melt droplet was forced out of the zone by excess pressure at the stage of zone sinking. Excess pressure is attributable to the difference in the forces of resistance to the atomic-kinetic processes of dissolution and crystallization at the boundaries of the discrete zone and the specifics of its sinking into the crystal. A layer of soot on the surface of the liquid zone facilitates

heterogeneous crystallization, which leads to transformation of the zone at the sinking stage without any excess pressure (the cause of emergence of the examined defects).

Conflict of interest

The authors declare that they have no conflict of interest.

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