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Creation of a homogeneous temperature gradient field for the implementation of the thermomigration method in silicon

© B.M. Seredin[1], V.P. Popov[1], A.N. Zaichenko[1], A.V. Malibashev[1],
I.V. Gavrus[1], A.A. Mintsev[1], A.A. Skidanov[2]

[1] Platov State Polytechnic University,
Novocherkassk, Rostov oblast, Russia
[2] JSC „VSP-Mikron“,
Voronezh, Russia
E-mail: seredinboris@gmail.com

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Computer simulation of the temperature field of a flat resistive heater in the form of parallel strips used for thermal migration of liquid zones in silicon wafers revealed two types of local temperature gradient inhomogeneities. Monotonous radial temperature changes are associated with cooling or heating of the periphery of the plate, and periodic changes are associated with the heater bands. Both types of inhomogeneities are confirmed by the observed thermal migration trajectories of the aluminum-based zone system. The conditions for creating a homogeneous temperature gradient field for the application of thermal migration in semiconductor technology are found.

Keywords: thermomigration, temperature gradient, modeling.

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1. Introduction

The method of thermomigration (TM) of liquid inclusions (zones) under the influence of a temperature gradient provides unique opportunity to obtain through-thickness crystalline perfect epitaxial channels of a given shape in a silicon wafer [1,2]. The advantage of the method is the high rate of channel formation, by 3−4 orders of magnitude higher than the rate of solid-state diffusion. Structures with such channels are of interest for power electronics [3–7] and photovoltaics [8–10].

In the TM method a system of discrete zones of a certain shape, created on the starting surface of the wafer, migrates through the wafer in the direction of the temperature gradient. In this case, it is very important to ensure a uniform field of temperature gradient perpendicular to the wafer. Only in this case the specified zone configuration will be preserved and provide the required channel topology. Distortion of the temperature field leads to distortion of the geometry of the formed channels and makes it impossible to use subsequent operations of device structures manufacturing.

In all papers related to TM method study the temperature gradient was created in silicon wafer using a flat heating element located parallel to the wafer, in the form of a spiral of refractory wire [2] or graphite [5–7,10]. The experience is also known related heaters use for TM based on: a system of halogen lamps [3,4,8], an auxiliary wafer heated by an electron beam [11], multi-position thermal unit [12]. All heating devices made it possible to conduct experiments on TM and helped to identify its patterns and capabilities. The uniformity of the temperature gradient required for TM method industrialization is determined by the minimum value of its tangential component. The achieved value of 8 K/cm is insufficient for the effective application of the TM method on standard wafers of large diameters [10].

In this paper, we studied the possibility of creating uniform field of temperature gradient using a flat resistive heater in the form of parallel strips. For this purpose, computer modeling and precision experiments were carried out to monitor the configuration of the temperature field in silicon wafers with a diameter of 100 mm.

2. Computer modeling

The scheme of the relative arrangement of the main parts of the heating device used is shown in Figure 1. The flat graphite heater had dimensions 195 × 175 × 5 mm with strip width of 10 mm and a gap between them of 1 mm. The silicon wafer was placed parallel to the heater in the hole of the cassette 5 mm thick. The characteristic distances H, h and d (Figure 1) were specified in the ranges 2−11 mm, 0−5 mm and 0−20 mm, respectively.

The temperature field in the system under consideration is described by the known laws of electric heating, thermal conductivity and thermal radiation in a transparent medium (vacuum) [13]. Numerical modeling of these processes in the silicon wafer was carried out using the Ansys Workbench software system [14]. Based on known tabular data [15] the values of density, thermal conductivity, heat capacity, and electrical resistance were set, taking into account changes in the properties of materials depending on temperature. As a result of solving the associated problem of resistive heating and heat transfer, a stationary temperature field T in the wafer was determined. Then

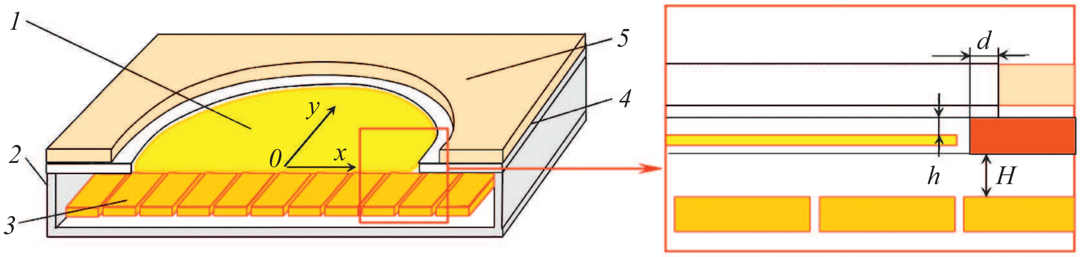

Figure 1. Scheme of the heating device used: *1* — silicon wafer; *2* — housing; *3* — heating element; *4* — cassette; *5* — front screen. The insert shows zoomed up fragment of the cross-section of the device.

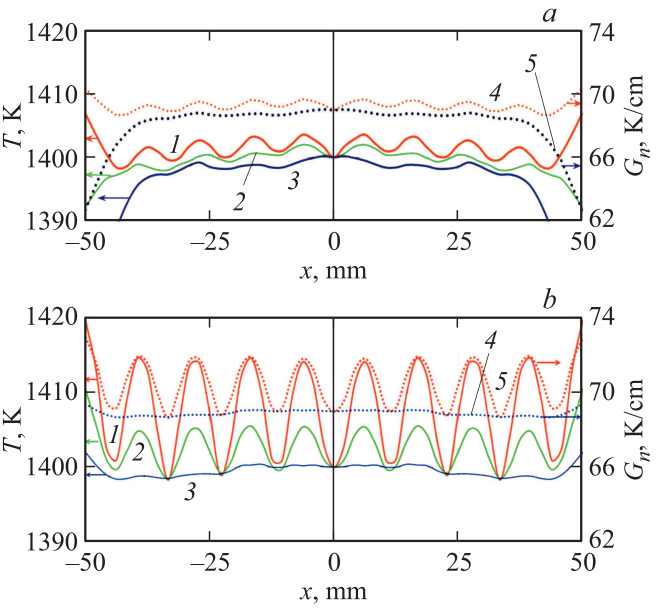

Figure 2. Dependences of the temperature distribution T (curves *1–3*) and the normal component of the temperature gradient G_n (curves *4, 5*) along the surface of the wafer along the axis $0x$ from the heater side: (*a*) curves *1* and *4*; *2*; *3* and *5* correspond to $h = 4.5$; 2.5; 0 mm at $H = 6$ mm and $d = 0$; (*b*) curves *1* and *4*; *2*; *3* and *5* correspond to $H = 2$; 4; 8 mm at $h = 4.5$ mm and $d = 0$.

the angles of deviation α of the temperature gradient from the normal to the wafer were calculated. The voltage on the heater was selected to achieve a fixed temperature T_0 in the center of the wafer in the range 1300–1500 K, corresponding to actual TM processes.

Mathematical modeling revealed two types of temperature field distortions: monotonic radial and periodic. The former were manifested in a smooth decrease or increase T in the peripheral part of the wafer, and the latter — in a periodic change T over the entire surface. Both types of field distortions are characteristic of the entire family of obtained dependences in the temperature range under study.

Monotonous deviations T from the given T_0 depended on the sizes H, h, d (see Figure 2, *a*). At the maximum distance of the cassette from the heater and the minimum depth of the wafer in the cassette, corresponding to $H = 11$ mm and $h = 0$ mm, the temperature at the edge of the wafer was lower than T_0 approximately by 25 K. Minimum H and maximum h give overheating at the edge ~ 20 K. At average values of $2 < h < 3$ mm and $8 < H < 9$ mm the temperature deviations at the edges of the wafer did not exceed several degrees. These results were obtained without the front screen. Its use, as calculations showed, led to the cassette heating around the silicon wafer. Changing the diameter of the hole d in the screen made it possible to smoothly and widely adjust T at the periphery of the wafer, and eliminated heat leakage from the periphery of the wafer even at $h = 0$. It is important for TM that the screen does not limit the heat flow passing through the wafer and, therefore, does not reduce the temperature gradient in the wafer. Periodic inhomogeneities T in the wafer had a constant increment of 11 mm along the axis 0_x. This is due to the striped shape of the heater. The amplitude of temperature inhomogeneities was determined by the values H and h and did not depend on d. The distance increasing between the wafer and the heater by more than 8 mm practically eliminated these inhomogeneities (see curve *3* in Figure 2, *b*). From the given distributions T it follows that the tangential component of the temperature gradient can reach a minimum of 1 K/cm (see Figure 2, *b*, curve *3*). The degree of heterogeneity of the normal component of the temperature gradient Gn is 0.7%.

3. Experimental results and discussion

The configuration of the temperature field in the silicon wafer was monitored by studying the thermomigration trajectories of the system of linear zones based on aluminum. To do this, a layer of aluminum was deposited onto the silicon wafer with crystallographic orientation (100) using magnetron deposition. Then, using photolithography, a system of mutually perpendicular aluminum strips $10 \times 100\,\mu$m, oriented along directions like $\langle 110 \rangle$ with a step $l = 5$ mm, was obtained. The temperature-time mode of TM process was set with a Termodat-16E high-precision regulator. Metallographic analysis of the trajectories of zones movement both in the volume of the wafer and on its surface made it possible to judge the distortions of the

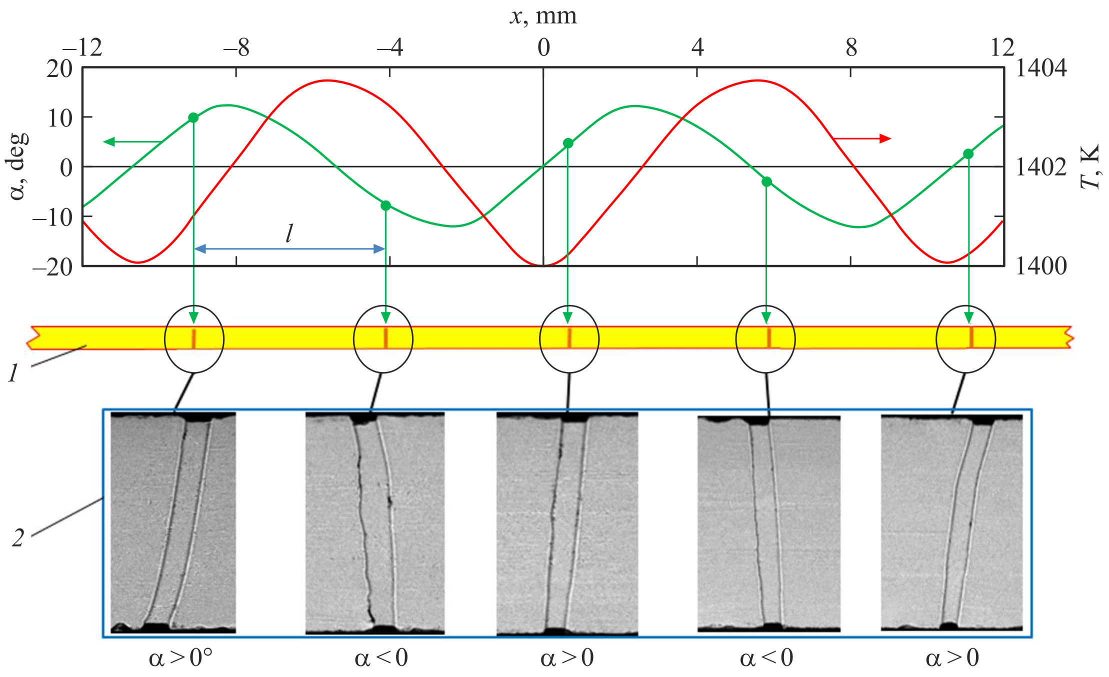

Figure 3. Distribution of temperature T and deviation angle α of temperature gradient from the normal and wafer fragment with identified trajectories of linear zones: *1* — wafer; *2* — microphotographs of sections; $h = 4.5$ mm, $H = 6$ mm, wafer thickness 550 μm; direction of zones thermomigration from bottom to top.

temperature gradient field with an accuracy of 0.1 K/cm. The trajectories of zones movement along the surface turned out to be especially sensitive to the tangential components of the temperature gradient, since the distance traveled by the zone can be set large by increasing the time of holding after the zones exit to the surface.

Both monotonic radial deviations of the movement trajectories of linear zones from the normal, directed towards the periphery or towards the center, and periodic multidirectional deviations of the trajectories of zones located along the axis $0y$ were established experimentally. The dependences of the angle of deviation of the temperature gradient from the normal along the axis $0x$ correspond to the trajectories of movement of the linear zones system (Figure 3). The experimental results are in quantitative agreement with the inhomogeneities of the temperature gradient field identified by modeling.

The influence of the cassette on the radial distortions of the temperature field, established by modeling, is physically explained by the features of radiant heat transfer between the end of the wafer and the hole walls in the cassette. To achieve thermal equilibrium, the temperature of the cassette at the wafer location must be by 10% lower than the temperature of the wafer, due to the difference in radiation absorption coefficients. The normal temperature gradient in the cassette near the central hole is approximately by three times less (due to higher thermal conductivity) than in the wafer, and the thickness of the cassette is by nine times greater. Therefore, there is an optimal value of h for suppressing radial temperature inhomogeneities.

TM method was used to form in silicon wafers with a resistivity $4.5\,\Omega\cdot$cm about 1000 end-to-end closed cells p-type of the square for diodes and thyristors for currents below 100 A. At $T = 1400$ K, $h = 2$ mm, $H = 8$ mm and $d = 10$ mm obtained $p{-}n$ transitions had a breakdown voltage of at least 300 V.

4. Conclusion

Using computer modeling the local inhomogeneities in the temperature gradient in the silicon wafer were identified. These results were confirmed experimentally using the thermomigration trajectories of the zones system. The role of the cassette holding the wafer and of the front screen with the central hole to eliminate distortions in the temperature field were established. Conditions were found for creating the reasonably uniform temperature gradient field and applying TM method on silicon wafer with diameter of 100 mm to obtain power electronic structures, determined by the values of the tangential component of the temperature gradient and the degree of inhomogeneity of the normal component of the temperature gradient, less than 1 K/cm and 0.7% respectively.

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Conflict of interest

The authors declare that they have no conflict of interest.

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