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Hole Formation in Semiconductor Materials by Laser Microprocessing

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Abstract—The process of laser formation of microholes in semiconductor substrates using an EM-4452-1 laser-processing unit with a pulse repetition frequency of a picosecond laser from 10 to 300 kHz at a radiation energy up to 10 μJ is investigated. The combination of high-speed movements of the laser beam by the galvanoscanner system and precise positioning of the processed material increases the efficiency of laser microprocessing and expands the functional capabilities of the equipment.

Keywords: laser radiation, holes, semiconductor substrates, microprocessing

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INTRODUCTION

Modern microelectronics requires microdevices based on a wide range of materials. Such materials include semiconductors (silicon, germanium, and gallium arsenide), piezoquartz, lithium niobate, lithium tantalate, langasite, langatate, leucosapphire, glass, various types of alumina ceramics, etc. Strict requirements are imposed on the technological operations required in the processing of these materials. The most common technological operations include separating substrates of the above materials into chips by cutting or scribing, dimensional processing of holes, formation of through contours, and removal of metal and oxide film coatings from the surface of substrates of these materials. Important requirements for such operations are to maintain dimensional processing accuracy parameters, minimize the disturbed layer of material on the cutting boundary, minimize the cutting width for scribing, and avoid damaging the substrate material for coating removal. Laser microprocessing is increasingly being used to meet these requirements.

A particular case of laser microprocessing is the formation of microholes in semiconductor materials. Choosing a laser source for microprocessing is a difficult problem that often requires compromises. On the one hand, criteria determining the processing quality are taken into account and, on the other hand, the productivity and the cost of the used equipment are taken into account.

LASER SYSTEM SELECTION

Selecting the laser system and the through-hole forming method depends on the technical requirements for laser processing and the physical and mechanical properties of the material to be processed. The processes occurring during interaction of laser radiation with materials and the result of this interaction depend heavily on the absorption coefficient of radiation of the peak laser power and the duration of material exposure. Regardless of the mechanism of radiation absorption, the resulting temperature increase in the exposure area leads to material destruction. The efficiency of material destruction under the influence of laser radiation depends on the power density and the duration of laser exposure. The shorter the wavelength and the smaller the real angular divergence, the more accurately the radiation can be focused and the smaller size of the exposure area can be used. The shorter the radiation pulse duration, the less thermal and deformation effect it has on the material outside the irradiated area. This effect is determined by physical processes occurring in the material during absorption of laser radiation. If the radiation pulse is sufficiently short and the energy density is sufficiently high, a small volume of material can be melted and vaporized before the heat from the irradiated area can spread to the surrounding material.

The quality of laser microprocessing is determined by the degree of roughness of the processed surface, the size of the disturbed layer in the heat-affected zone, and the deviation of the geometric dimensions

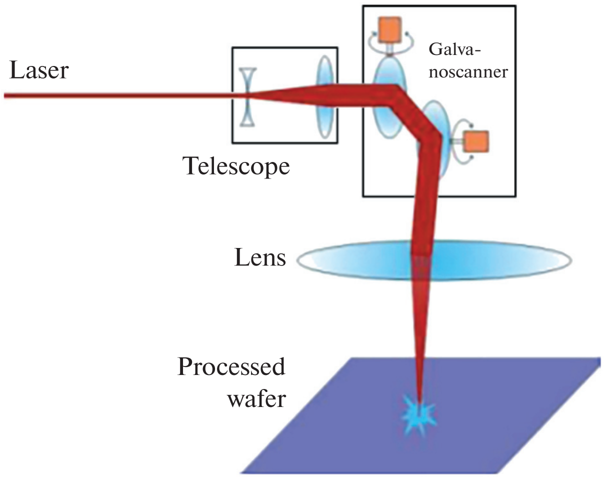

Fig. 1. Diagram of laser processing based on galvanoscanners.

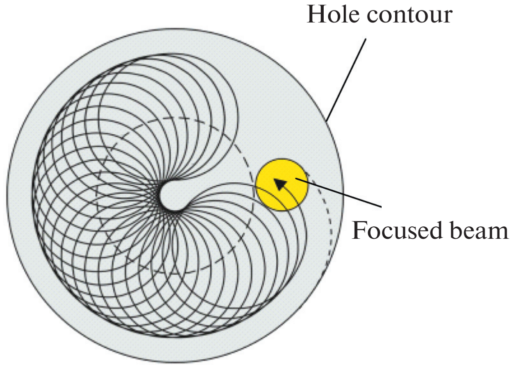

Fig. 2. Diagram of the focused laser beam movement synchronously with the movement of the processed wafer by the coordinate table in mode II.

of the resulting processing contours from the specified ones.

Short radiation pulses (τ_r) are used to ensure the minimum heat-affected zone (HAZ), short wavelength (λ) and low radiation divergence (θ) are necessary for the minimum irradiation zone (d), and high processing rate requires pulses with high radiation energy (E_r) and high pulse repetition frequency (F). Precise geometry and low surface roughness (R_z) are achieved by an optimal combination of E_r, τ_r, F, and process rate V.

The most important parameter determining the quality of laser treatment is the absorption coefficient. Semiconductor materials have the highest absorption coefficient in the visible and ultraviolet range of the spectrum. Optical absorption coefficient of radiation at a wavelength of 355 nm for monocrystalline silicon is 1.1×10^6 cm^{-1}.

The authors of [1] studied the effect of single laser pulses of nanosecond duration range on the surface of monocrystalline silicon wafers for radiation with a wavelength of 355 nm at a power density from 0.2 to 11.5 GW/cm^2. At the maximum power density, the hole depth was 60 µm. At a power density of 0.8 GW/cm^2, holes of 10 µm diameter and 10 µm depth were obtained. The pulse repetition frequency was 400 Hz at a maximum pulse energy of 0.5 mJ at a pulse duration of 44 ns. A plano-convex lens with a focal distance of 50 mm was used for focusing.

The authors of [2] studied the drilling of silicon wafers with a thickness of 200 µm by laser systems with a galvanoscanner and Nd:YVO_4 lasers (355 nm wavelength) with pulse durations in the picosecond and nanosecond ranges. The laser beam focused on the silicon wafer was moved by a galvanoscanner (Fig. 1). The laser radiation was directed through a beam expander (collimator) to the scanner, which controlled the radiation deflection in two mutually perpendicular directions, and was focused by an objective lens on the surface of the processed wafer.

The advantages of using a scanner include a high productivity of laser processing due to the use of high speeds of the laser beam movement. The disadvantages are the decrease of the beam positioning accuracy and the possibility of obtaining the minimum diameter in focus when using large processing fields.

The pulse repetition frequency of the picosecond laser during laser treatment was in the range from 100 to 500 kHz and that of the nanosecond laser was from 20 to 200 kHz. The average radiation power of the nanosecond and picosecond lasers did not exceed 460 mW. The calculated diameter of the laser spot was 10 µm. The overlap of the laser pulses ranged from 80 to 90%. The beam rotated by the scanner moved along a circular trajectory on the wafer surface (Fig. 2). The drilling time of the hole was 0.78 s. The typical size of a through hole obtained with a pulse energy of 15 µJ and a pulse repetition frequency of 30 kHz was 80 µm at the top (at the entrance to the wafer) and 30 µm at the bottom (at the exit). The speed of fast rotational motion of the beam was 115 mm/s. The velocity of the center of rotation along the circular trajectory was 20 mm/s.

According to the results of experimental studies, it can be concluded that the processes using pico- and nanosecond radiation pulses are similar in terms of laser processing quality and productivity. The difference lies in the size of the disturbed material zone. For the holes treated with picosecond laser radiation, there was hardly any such zone, while the depth of the disturbed material zone was approximately 1 µm for the holes treated with nanosecond laser radiation. Figure 3 shows images of the holes obtained using (a) nanosecond and (b) picosecond lasers. The left side shows the input section of the holes, and the right side shows the output section. The pulse energy was 15.3 µJ for the nanosecond laser and 4.6 µJ for the picosecond laser.

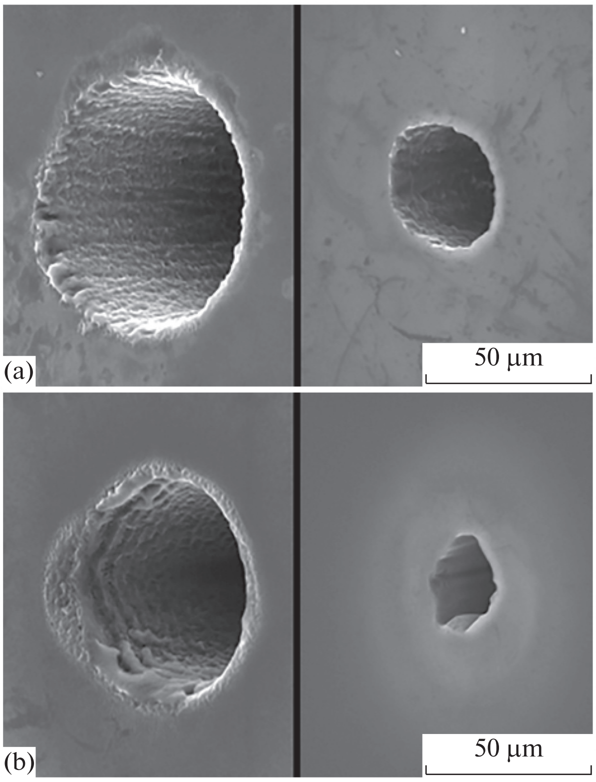

Fig. 3. Appearance of holes obtained using (a) nanosecond and (b) picosecond lasers.

Fig. 4. Integrated laser marking module based on the pulsed fiber laser ULPN-355-10-1-3-M.

In the present study, an EM-4452-1 laser-processing unit (OAO Planar-SO, Minsk), which can be used for scribing and through cutting of wafers, was used to laser microholes in semiconductor materials. Focused laser radiation makes it possible to form microholes in various materials absorbing UV laser (355 nm wavelength) [3].

The unit is controlled by means of an industrial computer. The working program is created using the menu of setting and technological parameters and the AUTOCAD editor. The image of the processed object by means of a television system is displayed on the computer screen.

Laser microprocessing is carried out by a combination of program-controlled movements of the processed wafer by coordinates *X, Y, Z* and movement of the laser beam by the galvanoscope in the *XY* plane. The cut is shaped along the path of the laser beam.

The unit is equipped with a vision system with recognition of processed wafer crystals by their topological pattern. Laser processing has no mechanical impact on the processed material, and deformations are minimal.

The laser system of the installation is based on an integrated module of laser marking on the basis of a pulsed fiber laser ULPN-355-10-1-3-M (OOO NTO IRE-Polus, Moscow). The external view of this laser system is shown in Fig. 4. The appearance of the EM-4452-1 laser-processing unit is presented in Fig. 5, and the basic parameters are presented in Table 1.

Table 1. Main parameters of the EM-4452-1 laser-processing unit

Parameter name	Measurement unit	Parameter value
Lasing wavelength	nm	355
Laser pulse energy	μJ	10
Laser pulse repetition frequency	kHz	10–300
Laser pulse duration	ns	1.5
Focus distance of the lens	mm	65
Coordinate table travel resolution	μm	1
Positioning error in coordinates *X, Y*	μm	5
Thickness of the wafer and substrates	μm	100–400
Minimum diameter of holes	μm	20

Fig. 5. EM-4452-1 laser-processing unit.

EXPERIMENTAL

The EM-4452-1 laser-processing unit can operate in two modes: without use of a galvanoscanner (mode I) and with use of a galvanoscanner (mode II).

Mode I is used for the formation of microholes when the accuracy of the galvanoscanner does not make it possible to obtain the required hole geometry. This mode makes it possible to use precise movements of the table with the wafer at low-speed relative to the stationary laser beam. However, the overlap of laser pulses approaches 100% at low drive speeds, which can lead to additional thermal load on the processed material and loss of processing quality. By reducing the repetition frequency of laser pulses, the loss of processing quality can be compensated, but the processing performance will be low. Cutting formation in this mode occurs according to the scheme of nested contours [4]. Figure 6 shows the scheme of nested contours.

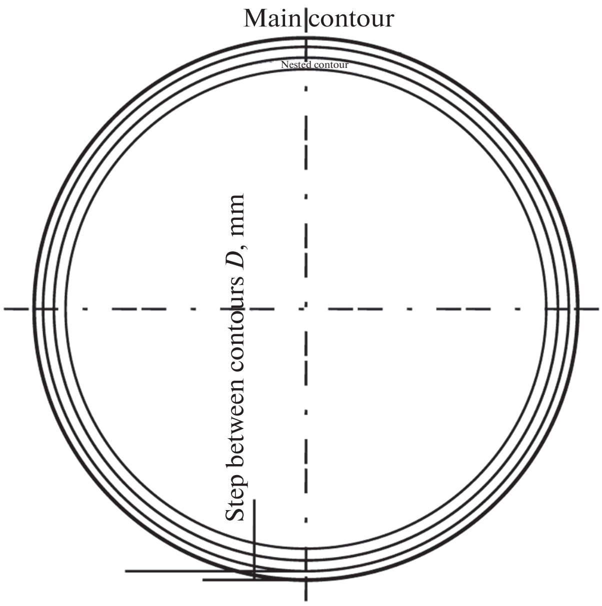

Fig. 6. Layout of nested contours in mode I.

In this mode, the speed of table movements by coordinates X, Y and the amount of table movement by coordinate Z after each series of nested contours, the number of cycles of movements on nested contours, the number of nested contours, the step between contours, and the value of the radius of each nested contour are specified. The use of nested contours makes it possible to increase the cutting width in order to compensate the shielding of laser radiation by the walls of the cut in order to maintain effective material removal in the process of laser cutting, and the number of nested contours is selected mainly based on the required depth of the cut. Laser cutting is performed by removing material layer by layer while processing a series of nested contours.

Mode II involves fast beam movement by galvanometer scanners and slow precise XYZ movements of the wafer by the table. In order to form microholes, a scheme of the focused laser beam movement is used in this mode synchronously with the wafer movement by the coordinate table. In this mode, the diameter of the circle formed by the scanner, the number of vectors on the circle, the delay on the vector, and the number of passes of the laser beam around the circle are specified (Fig. 2).

The basic parameters of the process of laser formation of holes in silicon wafers was calculated. Thermal penetration depth for silicon:

$$X = (\alpha\tau)^{1/2}, \quad (1)$$

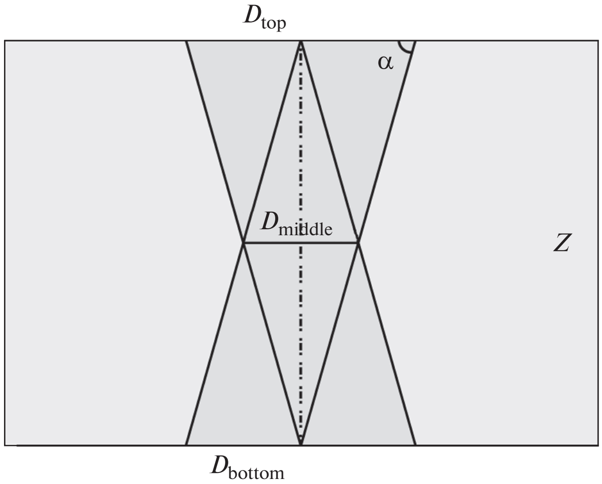

Fig. 7. Diagram of the profile (hourglass) of a hole formed by double-sided laser processing: D_{top} is the diameter of the hole on the top surface of the wafer; D_{botton} is the diameter of the hole on the bottom surface of the wafer; D_{middle} is the diameter of the hole at half the thickness of the wafer; α is the angle of the cone hole in one-sided processing (top), and Z is the thickness of the wafer.

where α is the thermal conductivity coefficient of silicon 89 × 10^{-5} m^2/s and τ is the laser pulse duration.

For the ULPN-355-10-1-3-M pulsed fiber laser, this depth was 1.15 μm.

Average laser pulse power was

$$P_{pulse} = \frac{E_{pulse}}{\tau}, \quad (2)$$

where E_{pulse} is the energy of the laser pulse, (10^{-5} J).

With a laser pulse duration of 1.5 × 10^{-9} s, its average power was 6.7 kW.

The diameter of the beam in focus was as follows:

$$d = \frac{4fM^2\lambda}{(\pi D)}, \quad (3)$$

where f is the lens focal length (65 mm); M^2 is the beam quality (1.4); D is the beam diameter at lens input (4 mm); and λ is the laser wavelength (355 nm).

At a wavelength of 355 nm, the beam diameter in focus is 10 μm. The power density in the focus reached 2 × 10^9 W/cm^2.

The speed at which the beam moved during processing was

$$V = dF(1 - O_d), \quad (4)$$

where F is the laser pulse repetition frequency and O_d is the laser pulse overlap factor.

For the coefficient O_d = 0.8, which is optimal in terms of quality/performance ratio, the beam movement speed during processing was 400 mm/s at the pulse repetition frequency of 200 kHz.

RESULTS AND DISCUSSION

In laser microprocessing of holes, the walls of the hole are usually inclined and the hole is tapered. Based on the laser microprocessing conditions, radiation parameters, lens focus, and processing speed, the inclination angle of the hole wall can be in the range of 2–10 deg.

In order to obtain holes with equal diameters on both sides of the wafer, bilateral laser processing is possible, when the holes are formed alternately on both sides of the wafer on the same axis. Figure 7 shows a schematic of the profile (hourglass) of a hole formed by the bilateral laser processing.

Figure 8 shows photos of holes in silicon wafers with a thickness of 400 μm after double-sided laser treatment in mode I. The following parameters were used to form the holes in this mode:

1. Velocity (V), mm/s, 0.2;

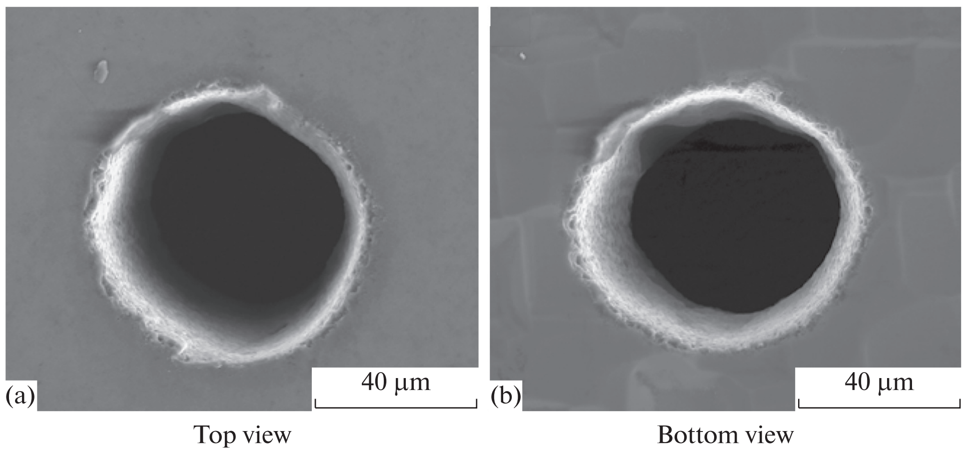

Fig. 8. Electron microscope view of the holes in a 400 μm thick silicon wafer after two-sided laser treatment in mode I.

2. Number of passes along the contour (*N*), 30;

3. Number of enclosed contours (*n*), 5;

4. Step between the contours (*D*), mm, 0,005;

5. Diameter of the main contour (*d*), mm, 0.05;

6. Energy of the laser pulse (*E*), μJ, 10;

7. Frequency of repetition of laser pulses, kHz, 10.

The time of hole formation was 100 s.

The following parameters were chosen to form holes with a diameter of 400 μm in a silicon wafer with a thickness of 400 μm during one-sided laser treatment in mode II:

1. Table movement speed, mm/s, 1.5;

2. Number of table passes along the contour, 22;

3. Number of nested contours, 1;

4. Step between contours, mm, 0;

5. Diameter of the main contour, mm, 0,3;

6. Energy of the laser pulse, μJ, 10;

7. Laser pulse repetition frequency, kHz, 250;

8. Diameter of the circle formed by the scanner, mm, 0.1;

9. Number of vectors on the circle formed by the scanner, 80;

10. Delay at the point on the circle vector (scanner), ms, 1.

The time of forming a hole was 15 s.

Therefore, the efficiency of laser microprocessing depends on the choice of laser radiation parameters, laser treatment method, and speed and accuracy of laser beam movement relative to the processed material. The shorter the wavelength and the smaller the real angular divergence, the more opportunities to focus the radiation and ensure the smallest possible size of the treatment area.

CONCLUSIONS

Short wavelength radiation is better absorbed by materials used in microelectronics; therefore, its use in laser microprocessing is preferable. The shorter the duration of the radiation pulse, the less thermal and deformation effect it has on the material outside the irradiation zone.

The quality and productivity of the formation of holes in silicon wafers using a galvanoscanner is significantly higher. This is due to the possibility of working at high speeds of the beam movement, which provides an optimal coefficient of overlap of laser pulses at the maximum pulse frequency and effective removal of slag. However, obtaining quality holes using a galvanoscanner depends on its precision and dynamic characteristics.

Obtaining holes with a diameter of less than 30 μm at a processing depth of more than 200 μm is problematic without using a galvanoscanner due to the shielding of radiation by the walls of the hole and the slag formed on them. Lack of power density in the zone of radiation makes it impossible to effectively evaporate the material and create the required vapor pressure for slag removal. In this case, the radiation energy is spent not on evaporation but on heating and melting of the material in the treatment zone.

Using a combination of high-speed movements of the laser beam by the galvanoscanner system and precise positioning of the processed material blanks in the EM-4452-1 laser-processing unit makes it possible to increase the efficiency of laser microprocessing and expand the functional capabilities of the equipment.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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