Precision Machining of Silicon Substrates

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Abstract. Brittle nonmetallic structural materials, such as quartz, glass, silicon, ceramics, ferrites and glass ceramics, are widely used in mechanical engineering, instrument making and radio electronics, as well as in optical, clock and jewelry industries. These materials have high hardness, strength, wear resistance and brittleness; therefore, their machining is a complicated problem. For production of piezoelectric resonators and filters, semiconductor devices, solid-state lasers, optoelectronic devices and other parts of electronics, plates made from monocrystals of quartz, lithium tantalate and niobate, silicon, germanium, sapphire, etc. are used. Semiconductor plates, which were obtained after cutting of a boule, have a number of defects, such as presence of a mechanically affected layer, nonflatness of sides, twisting and large variation of thickness. Therefore, after cutting it is necessary to carry out grinding and polishing. Grinding (abrasive finishing) is machining of semiconductor plates by means of hard finishing grinding discs (lapping tools) using abrasive flour grains. Finishing discs (lapping tools) are usually made from cast iron, glass, steel, copper or tin. The grain size of flour grains for grinding semiconductor plates is selected from M14 to M5. Finishing machining of silicon substrates is complicated by a number of factors, such as provision of stable sizes, and, which is more important, the required microrelief of a machined surface, and unacceptability of machining marks and micro fissure on a surface. In Perm National Research Polytechnic University, the method of abrasive finishing and polishing of surfaces of silicon substrates by means of "Rast-350" flat-finishing machine was developed. The feature of the machines is in sliding movement of a tool (lap) along a nonrecurring trajectory, which has a form of a grid of complicated configuration. At that, the speeds of movement of all points of the working face of the lapping tool are the same. The studied and proposed technological recommendations for operations of finishing and polishing of silicon substrates allowed determining the main technological regimes (time, specific pressure, and density of the grid of tool marks), as well as the required abrasive material of corresponding grain size, which allowed providing the required microrelief of substrates ($R_z$ 25 nm, $R_a$ 5 nm) and eliminating machining marks and micro fissures on a polished surface.

1. Introduction
The modern microelectronics has quite high requirements to the quality of an effective area of semiconductor materials, in particular, silicon substrates. First of all, it is necessary to provide roughness of a machined surface on the nanometer scale. In this regard, the requirements for technology and equipment for finishing of this kind of products are increasing [1-2]. By technological parameters, grinding (finishing) is divided into preliminary and final, by structural parameters – into single-sided and double-sided, by the type of used material – into grinding with unbonded and bonded abrasive [3].
Preliminary and final grinding (finishing) consists of two processes, which differ in aims, regimes and used materials. The purpose of preliminary grinding is the high-speed smoothing of a plate and the removal of the dimensional allowance. The regimes of this process have higher frequency of rotation of a grinding disc (lapping tool) and increased specific pressure of abrasive powder on the surface of a semiconductor plate. Moreover, for preliminary grinding abrasive powders with coarser grains (M28, M14, M10) are selected. The final grinding (fine finishing) has "softer" regimes of polishing and they use abrasive powders with finer grains (M7, M5). The purpose of final grinding is further improvements of the geometry and quality of surface of machined surfaces.

Grinding by means of unbonded abrasive powder is carried out using machine tools with single-sided and double-sided processing of semiconductor plates using various suspensions and pastes. During processing, grains are unbonded, i.e. not connected with each other. Abrasive suspension creates a thin layer between the instrument (lapping tool) and a processed semiconductor plate, in which abrasive grains are rolling freely. That’s why it is called unbonded abrasive material. Grinding by means of bonded abrasive material is significantly different from grinding with unbonded abrasive material, both by the physical principle of removal of a semiconductor material during polishing and by the kinematics of machining. Grinding with bonded abrasive material is carried out using machine tools with rigid axes, the feature of which is that the positions of rotation axes of a lapping tool and machined plates are constant. The main feature of this process is the structure of a grinding disc (lapping tool), which is a metal disc with applied surface diamond layer. Diamond grains are strongly attached to the surface of a grinding disc by means of special connecting binder [4].

For the improvement of the quality of machining of the surface of semiconductor materials and the decrease of the depth of mechanically affected layer, polishing is carried out. Polishing is different from grinding in the technological regime and type of an abrasive material, as well as the material of a polishing pad. The common point of these processes is the type of machining – single-sided or double-sided using unbonded abrasive material. The polishing process is carried out, generally, with soft polishing pads, which are rigid discs covered by a soft material: flannel, suède, batiste, felt, velour, cloth, silk, etc. Flour grains made from synthetic diamond, aluminum oxide, chromium oxide, silicon dioxide and zirconium dioxide (with grain size not higher than 3 μm) are used as abrasive materials. The selection of polishing cloth depends on its compatibility with the used abrasive material. Polishing cloth must be able to hold particles of abrasive material by its nap during machining of semiconductor plates. Polishing cloth must have a higher wear resistance and be inexpensive. For preliminary polishing, cloth without nap together with larger diamond grains is usually used. Cloth with nap is used for final machining using diamond grains with a size of less than 1 μm. There are several requirements for polishing pads: they must not have folds, cuts, thickened zones, ruptured threads, bulges and recesses, foreign particles and other surface defects. The wear resistance of soft polishing pads is low [5,6].

Further improvement and advancement of polishing methods for semiconductors are related to new ways of increasing the productivity, creation of polishing materials, which can provide both high quality of surface machining and good geometry of plates.

2. Problem statement

The machining of substrates before electropolishing is carried out by means of the method of abrasive finishing. "Rastr" flat-finishing machine tools (Fig. 1) are used in small-scale and large-scale production, in which it is required to frequently change small batches of parts and have wide product mix. The feature of the machines is the sliding movement of a tool (lap) along a nonrecurring trajectory, which has a form of a grid of complicated configuration. At that, the speeds of movement of all points of the working face of the lapping tool are the same [7].
Figure 1. Flat-finishing machine tools: a) Rastr-220; b) Rastr-350.

The complicity and uniqueness of relative movement trajectories of a tool (Fig. 2) and machined surfaces of parts together with capability to adjust its parameters make it possible to effectively control machining and create a surface with the designated properties of macro- and microrelief [8].

Figure 2. A trajectory of working movement of a tool (a single abrasive grain) for equipment with raster kinematics.

The capability of the selection of the shape and density of trajectory of working movement of a tool (Fig.2) allows forming the microrelief of the machined surface with optimal statistical parameters for certain properties of products. At that, the value of roughness using the parameter $R_z$ can be achieved on the nanometer scale 35-10, $Ra = 6$-2 nm.

3. Discussion
In Perm National Research Polytechnic University, the trial test of the processes of finishing and polishing of silicon substrates was conducted, the results of which are presented below.
Single-sided finishing of silicon substrates was carried out using Rastr 350 machine tool using two operations. Plates with the following dimensions were used: 30 × 45 mm, 40 × 75 mm, thickness 0.7 mm. Specimens were attached by means of glue. The parameters of initial roughness of specimens are presented in Fig. 3.

At the first stage, finishing (grinding) was carried out using a glass lapping tool and synthetic diamond powder ASM 3/2 with addition of special liquid coolant. The specific pressure on a machined part was 10-20 kPa. The time of machining was 1.5-2 min. According to the developed recommendations, finishing was carried out using a wide grid, which allowed increasing productivity. At that, isotropic roughness by the parameter $R_z 0.25-0.32$ (Ra 0.05-0.06) was provided.

At the second stage (polishing), a composite cellulose-based lapping tool was used. Polishing was carried out using ASM 1/0 diamond paste with addition of small amount of special liquid coolant. The machining regime (pressure and time) didn't change. During polishing, a denser grid of marks of raster trajectory corresponding to misalignment of frequencies of initial oscillations of instrument of 0.5-1% was used. The results of the measurement of parameters of roughness after polishing are presented in Fig. 4. The roughness by $R_z$ didn't exceed 25 nm and by Ra didn't exceed 5 nm. The overview of finished and polished substrates is presented in Fig. 5.
4. Conclusion

Thus, during the operations of finishing and polishing of silicon substrates, the main technological regimes were established (time, specific pressure, density of grid of machining marks), as well as the required abrasive material with the required grain size. The proposed operation of finishing machining
allowed providing the required microrelief of substrates of $R_z$ 25 nm and $Ra$ 5 nm and eliminating machining marks and micro fissures on the polished surface.

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**References**

[1] Heydemann V D, Everson W J, Gamble R D, Snyder D and Skowronski M 2003 Chemi-Mechanical Polishing of On-Axis Semi-Insulating SiC Substrates Mater. Sci. Forum pp 457-460, 805-808

[2] Kato T, Wada K, Hozomi E, Taniguchi H, Miura T, Nishizawa S I and Arai K 2006 High Throughput SiC Wafer Polishing with Good Surface Morphology Mater. Sci. Forum pp 556-557, 753-756

[3] Skryabin V A, Ribakov Yu V and Igonina T I 2005 Mashinostroitel 7 19-21

[4] Tam H Y, Cheng H B and Wang Y W 2007 J. Mater. Process. Technol. 192 pp 276-280

[5] Kang J, Hadfield M 2005 Original Res. Article 258 pp 2-12

[6] Kim J D, Choi M S 1995, J. of Mater. Process. Technol. 52 pp. 368–385

[7] Khanov A M, Muratov K R and Gashev E A 2016 Investigation of the Abrasive Lapping Process of oxide Ceramics Oriental Journal of Chemistry 32(1) 391-398

[8] Hanov A M, Muratov R A, Muratov K R and Gashev E A 2010 Stanki. Instrument 2 34-35