The International Journal of Advanced Manufacturing Technology (2018) 98:3269–3277
https://doi.org/10.1007/s00170-018-2454-3

ORIGINAL ARTICLE

Fabrication and performance evaluation for resin-bonded diamond wire saw

Mengran Ge[1] · Wenbo Bi[1] · Peiqi Ge[1,2] · Yufei Gao[1]

Received: 28 February 2018 / Accepted: 17 July 2018 / Published online: 1 August 2018

Abstract
Slicing is the initial procedure in silicon wafer manufacturing process. The cost of slicing process is about 30% of the total cost of chip fabrication. The effective approaches to decrease slicing cost are to reduce the slicing kerf loss and to decrease the thickness and breakage ratio of sliced wafer. The resin-bonded diamond wire saw has the advantages of uniform of abrasive protrusion height and the manufacturing process less impact on the core wire strength. It is expected to achieve a narrow kerf and ultra-thin wafer slicing of silicon crystal ingot with resin-bonded diamond wire saw. The aim of this paper is to develop high-performance resin-bonded diamond wire saw. Based on the analysis of fabrication process of resin bond diamond wire saw, the device for resin-bonded diamond wire saw manufacturing is developed. The mold in the fabrication device ensures the consistency of the wire saw outer diameter and the uniform of abrasive protrusion height. A test device for constant force feed slicing is developed for the slicing performance evaluation of resin-bonded diamond wire saw. The components of the coating layer materials of resin-bonded diamond wire saw are investigated via orthogonal test. Choosing the material removal rate, wire saw wear rate, coating layer binding force, and sliced surface roughness as evaluation indexes, the performance of developed resin-bonded diamond wire saw is evaluated. The optimal component ratio of the coating layer materials of resin-bonded diamond wire saw is obtained, and the verification test of the optimal component ratio of the coating layer materials is performed. The results of this paper are useful for the development of smaller-diameter diamond wire saw and high-quality slicing of optoelectronic crystal ingot.

Keywords Diamond wire saw · Resin binder · Optimization of components · Diamond wire saw fabrication · Performance evaluation

1 Introduction

The slicing of optoelectronic crystal with diamond wire saw has the advantages of low kerf loss, high slicing efficiency, high quality of sliced surface, and environmentally friendly. It is widely used in slicing process of photovoltaic silicon crystal, single-crystal SiC, and KDP crystal [1–5]. Slicing is the first machining process of single-crystal silicon ingot, and the cost of slicing process is about 30% of the total cost of chip fabrication [6]. The slicing process determines the utilization rate of crystal ingot and sliced wafer processing allowance of the following processes [7, 8]. Slicing is an important process to reduce the cost of wafer manufacturing for optoelectronics industry [9]. The effective approaches to decrease the cost of sliced wafer are to improve processing efficiency via increasing the wire speed, to decrease the kerf loss via decreasing the diameter of wire saw, and to decrease the thickness and breakage ratio of sliced wafer via improving the surface quality of sliced wafer. In the field of photovoltaic crystal silicon slicing process, the moving speed of wire saw has over 30 m/s, and the diameter of the wire saw decreased to 80 μm. However, the increasing of wire saw moving speed and decreasing of the wire saw diameter will eventually be restricted by the tensile

✉ Wenbo Bi
biwenbo@sdu.edu.cn

Mengran Ge
342445305@qq.com

Peiqi Ge
pqge@sdu.edu.cn

Yufei Gao
yfgao@sdu.edu.cn

1 School of Mechanical Engineering, Shandong University, Jinan 250061, China

2 Key Laboratory of High Efficiency and Clean Mechanical Manufacture, Ministry of Education, Jinan 250061, China

strength of the core wire. In the current of photovoltaic manufacturing industry, the minimum sliced wafer thickness of single crystal silicon is 170 μm, and the minimum sliced wafer thickness of multi-crystal silicon is 180 μm [10]. The current mainstream diameter of single-crystal silicon ingot is 300 mm, and the thickness of the sliced silicon wafer is 775 μm. The next generation of single-crystal silicon ingot diameter will be 450 mm, and the thickness of the sliced silicon wafer is expected to be 925 μm [11–13]. Thickness is an important parameter that affects the mechanical properties of the sliced wafer. To determine the sliced wafer thickness, it is necessary to consider comprehensively the wafer production technology and equipment, the bending deformation caused by the wafer's gravity, the warpage caused by the residual stress, and the breakage rate and cost of the wafer processing. The surface and sub-surface damage of sliced wafer, which decreases the strength of silicon wafer, is also an important factor restricting the thickness reduction of sliced wafer [14–16]. The uniform of abrasive protrusion height of the diamond wire saw has an important influence on the depth of surface and sub-surface damage of sliced wafer [17–20]. The uniform of abrasive protrusion height is an important parameter of high-performance diamond wire saw.

Electroplated diamond wire saw is manufactured by electroplating a metal layer on metal wire surface and concreting diamond abrasives in the deposited metal. The characteristics of electroplated diamond wire saw are higher abrasive binding strength and lower production speed [21]. For electroplated diamond wire saw, the electroplating process leads to the decrease of core wire strength and poor consistency of abrasive protrusion height. Resin-bonded diamond wire saw is bonded to the diamond abrasive on the core wire surface using resin binder. The mold in the fabrication device ensures the consistency of the wire saw outer diameter and the uniform of abrasive protrusion height. The defects of resin-bonded diamond wire saw are lower abrasive binding strength and wear resistance. In order to enhance the abrasive binding strength and wear resistance, the attempts have been made to add metal powder in resin binder, to modify resin binder, and to optimal component ratio of the coating layer materials of resin-bonded diamond wire saw [22, 23].

In this paper, the manufacturing process of the resin-bonded diamond wire saw is analyzed. The device for resin-bonded diamond wire saw manufacturing is developed. A constant force feed slicing test device is developed for the slicing performance evaluation of wire saw. The optimal component ratio of the coating layer materials of resin-bonded diamond wire saw is obtained and verified. The results of this paper are useful for the development of smaller-diameter diamond wire saw and high-quality slicing of optoelectronic crystal ingot.

2 Fabrication of resin-bonded diamond wire saw

2.1 Manufacturing process of resin-bonded diamond wire saw

Resin-bonded diamond wire saw consists of the core wire and coating layer. The high-strength metal wire is used as core wire to ensure the tensile strength, torsional shear strength, and fatigue strength of the wire saw. The coating layer is formed by curing the mixture of diamond abrasive, resin

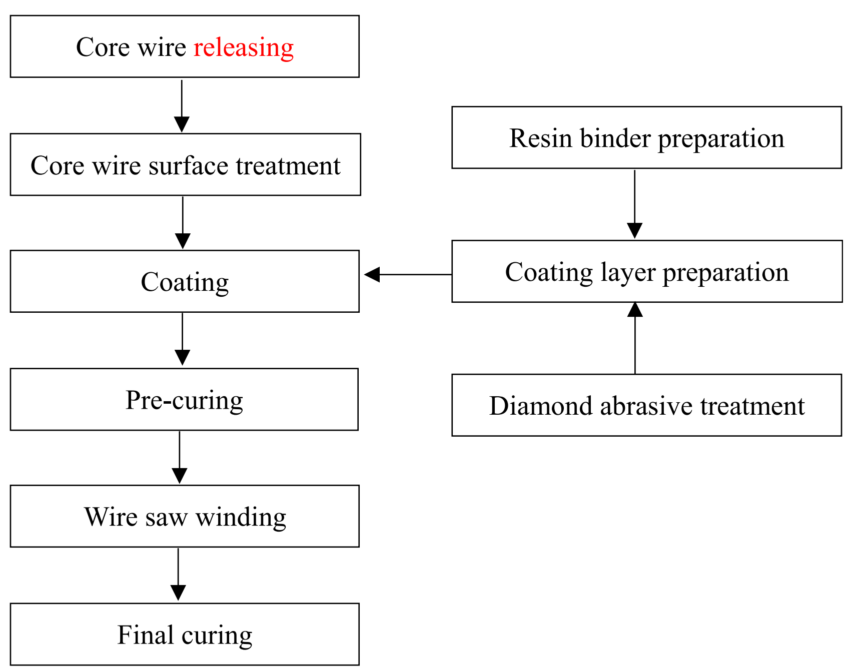


Fig. 1 The manufacturing process of resin-bonded diamond wire saw

binder, and additives on the surface of the core wire. The manufacturing process of resin-bonded diamond wire saw includes diamond abrasive surface activity treatment, resin binder preparation, coating material preparation, core wire surface activity treatment, coating and curing process of coating layer, core wire releasing, and pre-cured wire saw winding. The manufacturing process is shown in Fig. 1.

The manufacture process of resin-bonded diamond wire saw shown in Fig. 1 is described as follows:

1. The resin binder is prepared by mixing the components according to the requirements for the wire saw coating.
2. Diamond abrasive treatments include diamond abrasive surface cleaning and activation processing. The purposes of the treatment are to remove the impurity attached on the diamond abrasive surface, to improve its surface activity, and to increase the binding strength between the abrasives and the resin binder.
3. The coating layer material preparation is to mix the treated diamond abrasive with the resin binder and to stir evenly.
4. Core wire releasing and wire saw winding are releasing the core wire from the supply spool and winding the pre-cured wire saw on the take-up spool, and keeping the tension force is stable using tension force controller.
5. Core wire surface treatments include surface cleaning and activation processing. The purpose of the treatment is to remove the surface contaminants of core wire, to improve its surface activity, and to increase the binding strength between the core wire and the resin binder.
6. Coating process is important for resin-bonded diamond wire saw fabrication. The coating mold is used to ensure the consistency of the wire saw outer diameter, the thickness uniformity of the coating layer materials, and the consistency of abrasive protrusion height.
7. The curing reaction of Epoxy-phenolic resin takes a long time in the manufacturing process. The purpose of pre-curing process is to realize the partial curing reaction of resin binder on-line, and the wire saw can be wound on the take-up spool without binding together. The diamond abrasives and core wire are bonded together firmly at final curing process off-line, and the resin-bonded diamond wire saw is obtained after final curing process.

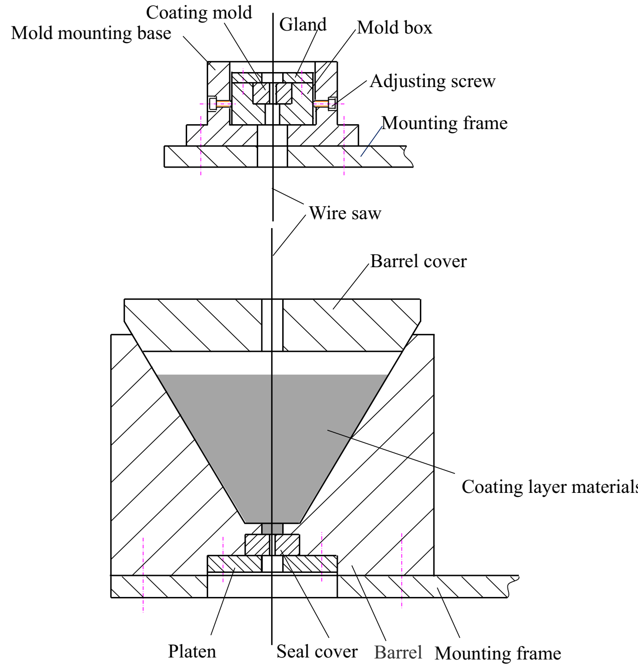


Fig. 3 Mechanical structure of the coating unit

2.2 The manufacturing device of resin-bonded diamond wire saw

In the manufacturing process of resin-bonded diamond wire saw, the processes of diamond abrasive treatment, resin binder preparation, coating layer materials preparation, and final curing seriously constrain manufacturing efficiency if on-line completion. So, these time-consuming processes are completed off-line. The processes of core wire releasing, core wire surface treatment, coating, pre-curing, and wire saw winding are integrated to the manufacturing device of resin-bonded diamond wire saw. Figure 2 is the diagram of the manufacturing device of the resin-bonded diamond wire saw developed in this study. The manufacturing device consists of four modules: core wire supply, core wire surface treatment, coating and pre-curing, and wire saw winding.

The core wire supply module releases and tensions core wire. The servo motor drives the supply spool to release the core wire, and the core wire is tensioned with tension controller. After releasing from the supply spool, the core wire is

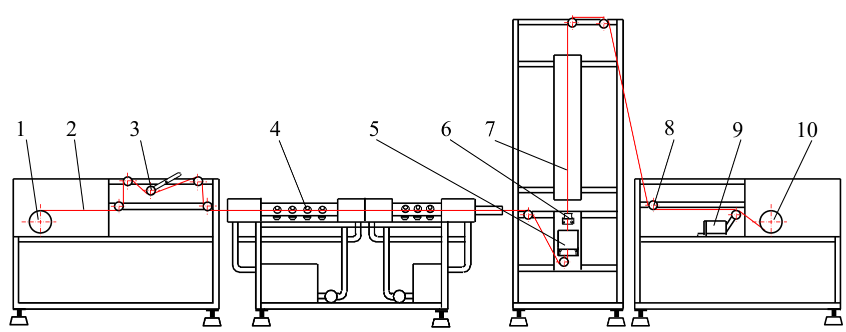


Fig. 2 Schematic diagram of the manufacturing device of resin-bonded diamond wire saw. 1 Supply spool, 2 core wire, 3 tension controller, 4 ultrasonic cleaning and rinsing, 5 coating unit, 6 coating mold, 7 pro-curing cavity,8 guide wheel, 9 wire arrangement, 10 take-up spool

Table 1 Factors and levels of the orthogonal test

(A) Epoxy/ phenolic	(B) CTBN (wt%)	(C)KH-550 (wt%)	(D) SiO_2 (wt%)	(E) Abrasive (mg/ml)
3.0:1	9	0.5	1	450
2.75:1	11	1	3	500
2.5:1	13	2	5	550
2.25:1	15	3	7	600

guided with guide wheel to pass the tension controller. The tension controller is a swinging arm with a counterweight. The swing angle of the swinging arm is monitored with the sensor and fed back to electrical controller. The swing angle of the swinging arm is controlled with the electrical controller via adjusting the rotational speed of core wire supply spool. The tension force of the core wire will be stabilized if the swing angle of the swinging arm is stable at the set point.

The core wire treatment module consists of ultrasonic cleaning part and ultrasonic rinsing part. In the ultrasonic cleaning part, the cleaning agent liquid is heated to a set temperature and maintained, and the core wire is soaked and treated in the cleaning agent liquid. In the ultrasonic rinsing part, the core wire is cleaned with pure water.

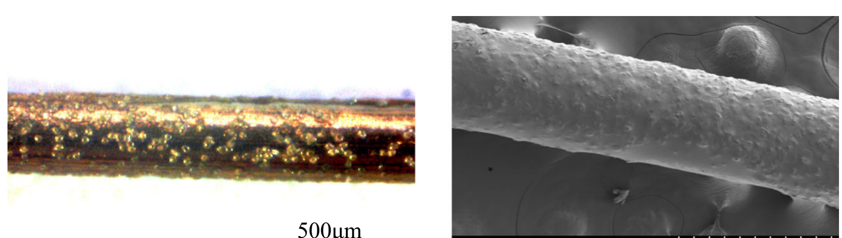
The coating and pre-curing module consists of coating unit and pre-curing cavity. The mechanical structure of coating unit shown in Fig. 3 is composed of a barrel set and a coating mold set. The barrel is used to hold the coating materials. The cleaned core wire enters from the bottom of the barrel and passes through the coating materials, and the coating materials adheres to the surface of the core wire. The coating mold is fixed in the mold box with gland, and the concentricity between the center hole of the coating mold and the core wire is adjusted by the adjusting screw. The diameter of the coating mold center hole and the concentricity between the center hole of the coating mold and the core wire ensure the consistency of the wire saw outer diameter, the uniformity of the coating layer thickness, and the uniformity of the diamond abrasive protrusion height. The pre-curing cavity is a channel with constant temperature, and the coated wire saw passes through this channel, and the coating material will undergo a curing reaction to be pre-cured.

The wire saw winding module winds the pre-cured wire saw on the take-up spool. The take-up spool is driven by a servo motor to ensure that the wire saw moves at a constant velocity. The wire saw arrangement device ensures that the wire saw is evenly arranged and wound on the take-up spool.

2.3 Orthogonal test design for component ratio optimizing of coating materials

The resin-bonded diamond wire saw is formed by binding diamond abrasives and core wire with resin binder. The resin binder needs to have well wettability with diamond abrasive and core wire. After curing, the diamond abrasive and core wire should be combined firmly, wear-resistant, and heat-resistant. In general, phenolic resin, epoxy resin, and polyurethane are used as the resin binder. The components of the coating materials are selected based on the results of previous research [23]. The components include bisphenol A-type epoxy resin E44, phenolic resin 2127, liquid rubber CTBN, coupling agent KH-550, SiO_2 nanoparticles, diamond abrasives, active diluent 669, and curing accelerator DMP-30. The bisphenol A-type epoxy resin E44 is used as a resin binder, and thermosetting phenolic resin 2127 is used as a curing agent. The role of liquid rubber CTBN and SiO_2 nanoparticles is to enhance and toughen the resin binder. The coupling agent KH-550 reinforces the interfacial adhesion between diamond abrasive, core wire surface, and the resin. The curing accelerator DMP-30 reduces the curing temperature and curing time. The active diluent 669 is used to adjust the viscosity of the coating materials in order to mix the components uniformly and achieve the appropriate diamond abrasive protrusion height of the wire saw.

The orthogonal test is used to optimize the component ratio of coating materials. The orthogonal test factors are epoxy resin and phenolic resin ratio (A), content of CTBN (B), content of coupling agent KH-550 (C), content of SiO_2 nanoparticles (D), and content of diamond abrasives (E). According to the results of previous research [23], the ratio of epoxy resin to phenolic resin is between 3:1 and 2.25:1, the content of CTBN is between 9 and 15% of the epoxy resin, the content of coupling agent KH-550 in the epoxy resin content is between 0.5 and 3%, the content of SiO_2 nanoparticles in the epoxy resin is between 1 and 7%, and the content of diamond abrasives is between 450 to 600 mg/



(a) Microphotograph (b) SEM image

Fig. 4 Surface image of resin bonded diamond wire saw ml. The optimal ratio of each component is studied by the L_{16} (4^5) orthogonal test table. The factors and levels of orthogonal test are shown in Table 1.

The resin-bonded diamond wire saw is obtained after curing of the diamond wire saw off-line in a constant temperature oven. Figure 4a shows the microphotograph (taken with ISM-PM200SB) of a typical resin-bonded diamond wire saw fabricated in this study, and the SEM image of the diamond wire saw is also shown in Fig. 4b. The diameter of the diamond abrasives is 30 to 40 μm. The diameter of the core wire is 0.3 mm. The mold core diameter is 0.38 mm. The wire saw outer diameter is $0.376^{+0.002}_{-0.003}$ mm. The wire saw outer diameter is an average of measured values of 10 points.

3 Performance evaluation of resin-bonded diamond wire saw

3.1 Test device for constant force feed slicing of wire saw

Slicing efficiency is an important index of the wire saw slicing performance. The slicing efficiency of the wire saw failed to be evaluated in wire saw slicing process with constant feed rate. That is because the wire saw with different slicing efficiency shows different bending deflections during slicing process with the same operating condition, and the different flexion deflection of the wire saw during slicing process produces different slicing feed force. In wire saw slicing process with constant force feed, the slicing efficiency of the wire saw is evaluated reasonably using slicing area per unit time at same operating condition. In order to evaluate the slicing efficiency of the wire saw, a test device for constant force feed slicing of wire saw is developed and shown in Fig. 5.

Table 2 Parameters of test device for constant force feed slicing

Parameters	Parameter value
Wire saw length (m)	1–6
Wire saw diameter (mm)	Φ0.1–0.6
Maximum travel length (mm)	600
Maximum moving speed (m/s)	0–1
Feed force	Adjustable
Workpiece diameter (mm)	Φ10–55

The test device consists of base platform, horizontal movement unit, vertical movement unit, cutting fluid supply unit, and control unit. Horizontal movement unit is mainly composed of horizontal reciprocating sliding table, wire saw bow, wire saw, and driving motor. The horizontal reciprocating sliding table is a linear mobile platform driven by a servo motor, and a wire saw bow is mounted on the platform. The wire saw is fixed and tensioned on the bow. A linear reciprocating motion of the wire saw is realized under the drive of the servo motor.

The vertical movement unit includes the workpiece carrier, vertical moving sliding table, pulley, sliding guide, and load weight. The vertical moving sliding table and load weight are connected by wire ropes. The workpiece carrier is fixed on the vertical moving sliding table, and the workpiece is fixed on the workpiece carrier. The vertical movement of sliding table along the sliding guide is the feed motion of workpiece. The feed force is provided with the load weight. The parameters of the test device are shown in Table 2.

The test device shown as Fig. 5 is used to evaluate the slicing efficiency of the resin-bonded diamond wire saw developed in this research. In the slicing test of this research, the workpiece is single-crystal silicon with a rectangular cross-section, the maximum operating speed of the saw wire is 1 m/s, the feed force is 5 N, and the cutting fluid is pure water.

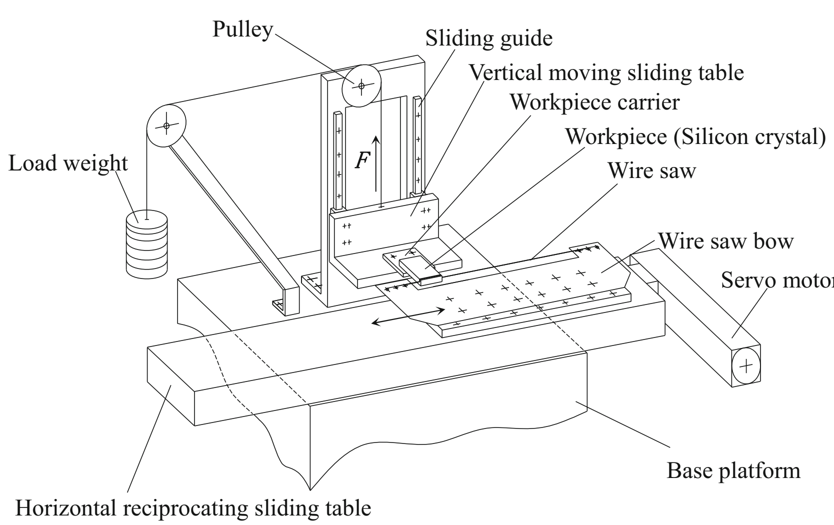


Fig. 5 Schematic diagram of test device for constant force feed slicing

Table 3 Orthogonal test arrangement and test results

No.	A	B	C	D	E	Material removal rate(mm^3/min)	Wear rate of the wire saw(mg/mm^3)	Binding force (N)	Surface roughness Ra (μm)	
									Wire saw moving direction	Workpiece feeding direction
1	1	1	1	1	1	3.491	0.155	5.98	0.34	0.88
2	1	2	2	2	2	4.579	0.129	6.07	0.28	0.63
3	1	3	3	3	3	4.655	0.137	6.11	0.28	0.46
4	1	4	4	4	4	3.863	0.224	5.59	0.30	0.68
5	2	1	2	3	4	4.398	0.113	5.68	0.30	0.35
6	2	2	1	4	3	4.791	0.137	5.95	0.27	0.56
7	2	3	4	1	2	4.163	0.161	6.06	0.22	0.48
8	2	4	3	2	1	4.534	0.213	6.03	0.21	0.37
9	3	1	3	4	2	4.492	0.146	5.96	0.23	0.52
10	3	2	4	3	1	4.136	0.121	6.05	0.22	0.31
11	3	3	1	2	4	4.803	0.140	5.94	0.24	0.34
12	3	4	2	1	3	4.396	0.179	6.26	0.24	0.63
13	4	1	4	2	3	4.411	0.154	6.01	0.23	0.32
14	4	2	3	1	4	3.838	0.144	5.78	0.34	0.69
15	4	3	2	4	1	4.471	0.157	5.92	0.32	0.51
16	4	4	1	3	2	4.433	0.123	5.99	0.27	0.53

3.2 Evaluation method of resin-bonded diamond wire saw

The performance indexes of resin-bonded diamond wire saw include slicing efficiency, wear rate, binding strength of coating materials, and sliced surface quality. The methods of evaluation testing are as follows:

1. Slicing efficiency. The slicing efficiency of wire saw is characterized by the material removal rate. The material removal rate is defined as the volume of removed material in unit time with constant force feed slicing condition. The material removal rate is obtained experimentally by measuring the volume of removed material and slicing time.
2. Wear rate of wire saw. The wear rate of the wire saw is used to characterize the wire saw service life. The wear rate of the wire saw is defined as the wire saw mass loss of removing the unit material volume of workpiece and is obtained by calculating the material removal volume and the corresponding wear mass loss of the wire saw after the slicing experiments.
3. Binding strength between the coating layer and core wire. The binding force of the coating layer indicates the binding strength between the coating layer and the core wire. While the wire saw removes the workpiece material, the tangential slicing force acting on the abrasive grain is a major factor resulting in abrasive grain shedding. The binding strength is evaluated by the corresponding frictional force when the coating material of wire saw is peeled off. The frictional force is measured using the MFT-400 multifunctional material surface performance tester.
4. Sliced surface quality. The roughness of the sliced wafer surface is an important parameter to reflect the sliced surface quality. The sliced surface quality is evaluated using the sliced wafer surface roughness. The roughness Ra is an average of measured values of five points. The roughness is measured along the direction of workpiece feeding and the direction of the wire saw moving. The roughness

Table 4 Material removal rate analysis (mm^3/min)

Mean of *i* level	A	B	C	D	E
m_1	4.147	4.198	4.380	3.972	4.158
m_2	*4.472*	4.336	*4.461*	*4.582*	4.417
m_3	4.457	*4.523*	4.380	4.406	*4.563*
m_4	4.288	4.307	4.143	4.404	4.226
R	0.325	0.325	0.317	0.610	0.405
Optimal results	A2	B3	C2	D2	E3

The maximum value (italics entries) of m_i for each factor corresponds to the optimal level of the factor

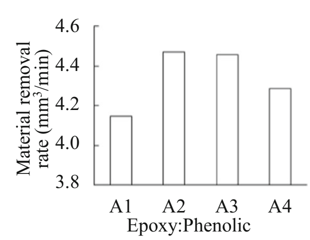


Fig. 6 Effect of epoxy and phenolic resin ratio on material removal rate

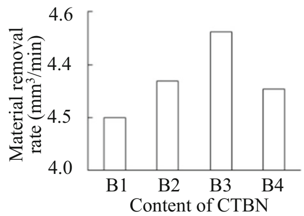


Fig. 7 Effect of CTBN content on material removal rate

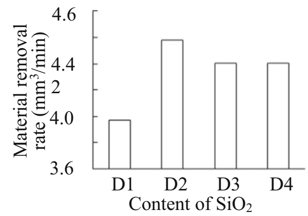


Fig. 9 Effect of SiO_2 content on material removal rate

tester is Mitutoyo SJ-201. The sampling length is 0.25 mm, and the sampling number is 5. The filtering type is 2CR, PC75, and Gauss.

4 Results and analysis

4.1 Orthogonal test results

According to the orthogonal test design of Table 1, the resin-bonded diamond wire saw with 16 different component ratios of coating materials are fabricated using the manufacturing device of Fig. 2. The performance indexes of resin-bonded diamond wire saw are measured according to the introduction in Section 3.2. The orthogonal test arrangement and the measuring results of the performance indexes are shown in Table 3.

4.2 Orthogonal test result analysis

The measuring results of the performance indexes shown in Table 3 are analyzed according to the orthogonal test analysis method. Taking the material removal rate as an example, the orthogonal test analysis of the experimental results is carried out. The analysis results of material removal rate are shown in Table 4. Where m_i ($i = 1, 2, 3, 4$) is the average of the corresponding results for each factor at *i* level. The variation trends of the material removal rate with the five factors are shown as in Figs. 6, 7, 8, 9, and 10. The value of the material removal rate for each factor shown in Figs. 6, 7, 8, 9, and 10 increases first and then decreases. This indicates that the range of level for each factor is chosen properly. The range of samples R = max (m_i) − min (m_i). The greater the value of R, the higher the level of its corresponding factor affects the performance index. The analysis results show that the content of nano-SiO_2 particles in the coating materials has the greatest effect on the material removal rate, and the effect of the content of coupling agent KH-550 is the least. The order of influence degree of each factor is D > E > B > A > C. The value of m_i for each factor shown in Table 4 increases first and then decreases. This indicates that the range of level for each factor is chosen properly, and the maximum value of m_i for each factor corresponds to the optimal level of the factor. So, the optimal component ratio of coating materials is D2E3B3A2C2 while the material removal rate as the evaluation index.

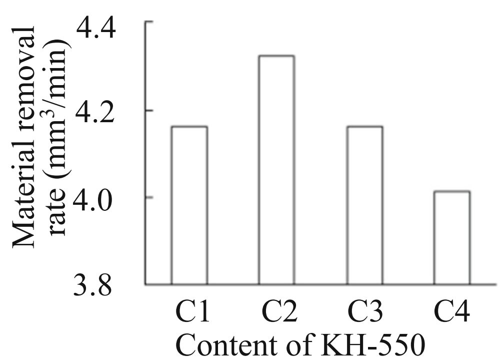


Fig. 8 Effect of KH-550 content on material removal rate

Using the same analysis method, the following conclusions can be obtained. The optimal component ratio of coating materials is B2D3C1E2A4 while the wear rate of wire saw is the evaluation index. The optimal component ratio of coating materials is E3D1A3B3C2 while the binding force of the coating layer is the evaluation index. The optimal component ratio of coating materials is A3D2E2C4B4 while the sliced wafer surface roughness along the direction of the wire saw moving is the evaluation index. The optimal component ratio of coating materials is D3A2C4B3E3 while the sliced wafer surface roughness along the direction of workpiece feeding is the evaluation index.

4.3 Optimization of component ratio of coating materials and wire saw evaluation

The optimized components of coating materials are D2E3B3A2C2, B2D3C1E2A4, E3D1A3B3C2, and A3D2E2C4B4 (D3A2C4B3E3) when the evaluation indexes are slicing efficiency, wear rate, binding strength of coating materials, and sliced surface quality respectively. According to the principle of comprehensive balance, the material

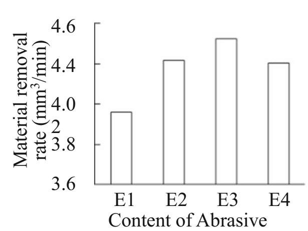


Fig. 10 Effect of Abrasive content on material removal rate

Table 5 Surface roughness of sliced wafer with wire saw of A3B3C2D2E2

Direction	1	2	3	4	5	Average
Wire saw moving Ra (μm)	0.23	0.3	0.19	0.25	0.18	0.23
Workpiece feeding Ra (μm)	0.36	0.42	0.35	0.37	0.29	0.36

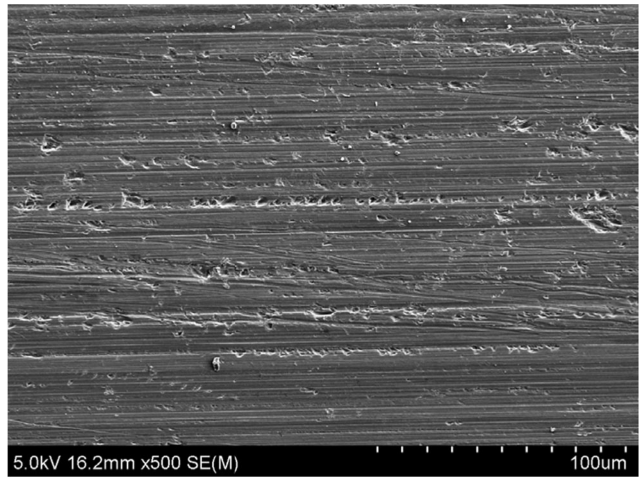


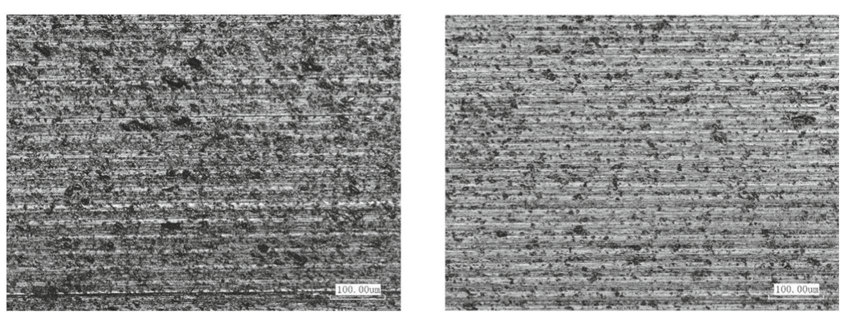
Fig. 12 Surface morphology of the sliced wafer with electroplated diamond wire saw

removal rate and wear rate of the wire saw are taken as the main evaluation indexes, and the binding force of the coating layer and the surface roughness of the sliced wafer are given appropriate consideration. A3B3C2D2E2 is selected as the optimization of component ratio of coating materials. The resin-bonded diamond wire saw with the optimization coating materials A3B3C2D2E2 is fabricated, and the tests of performance evaluation are carried out. The performance evaluation indexes of wire saw are obtained. The material removal rate is 4.926 mm^3/min, the wear rate of the wire saw is 0.129 mg/mm^3, and the measuring results of surface roughness of sliced wafer are shown in Table 5. The average value of surface roughness along the direction of the wire saw moving is Ra0.23 μm, and along the workpiece, feeding direction is Ra 0.36 μm. The binding force of the coating layer is 6.23 N which is measured with MFT-4000 material surface performance tester. The results of Table 3 show that the wire saw performance fabricated with No.11 coating materials is obviously better than others. The performance of the wire saw fabricated with the optimization coating material A3B3C2D2E2 is obviously better than the wire saw performance fabricated with No.11 coating materials.

The surface morphology of sliced single crystal silicon wafer with resin-bonded diamond wire saw is shown in Fig. 11. As shown in Fig. 6, the wafer surface sliced by the wire saw fabricated with the optimization coating material A3B3C2D2E2 is smoother than the wafer surface sliced by the wire saw fabricated with No.11 coating materials. So, the coating material A3B3C2D2E2 is optimal component ratio of coating materials for resin-bonded diamond wire saw based on the above comprehensive analysis. The electroplated diamond wire saw is common used in the semiconductor slicing industry. It is difficult to control the uniform of abrasive protrusion height of electroplated diamond wire saw by manufacturing process. Figure 12 is a surface morphology of the sliced single crystal silicon wafer with electroplated diamond wire saw. As shown in Fig. 12, there are a lot of deep scratches on the sliced surface. The deep scratches caused by high-protrusion abrasives are difficult to remove during polishing process.

5 Conclusions

Based on the analysis of the resin-bonded diamond wire saw manufacturing process, the device for the resin bond diamond wire saw manufacturing is developed. Orthogonal tests are used to optimize the component ratio of coating materials for resin-bonded diamond wire saw. A test device for constant force feed slicing is developed for evaluating slicing efficiency of the wire saw. The slicing efficiency of wire saw is evaluated by measuring the volume of removed material in unit time. Choosing the material removal rate, wire saw wear rate, coating layer binding force, and sliced surface roughness as evaluation indexes, the performance of resin-bonded diamond wire saw is evaluated. The optimum component ratio of coating materials of resin-bonded diamond wire saw is obtained via orthogonal test. The optimum components are epoxy resin



a) Sliced wafer surface by No.11 wire saw b) Sliced wafer surface by optimization wire saw

Fig. 11 Surface morphology of the sliced wafer with resin-bonded diamond wire saw and phenolic resin ratio 2.5:1, content of CTBN 13 wt%, content of coupling agent KH-550 1 wt%, content of SiO_2 nanoparticles 3 wt%, and content of diamond abrasives 500 mg/ml.

Funding information This work is supported by the National Natural Science Foundation of China (51775317) and the Key Research and Development Program of Shandong Province (2017GGX30142).

References

1. Hardin CW, Qu J, Shih AJ (2004) Fixed abrasive diamond wire saw slicing of single-crystal silicon carbide wafers. Adv Manuf Proc 19: 355–367
2. Watanabe N, Kondo Y, Ide D, Matsuki T, Takato H, Sakata I (2010) Characterization of polycrystalline silicon wafers for solar cells sliced with novel fixed-abrasive wire. Prog Photovolt Res Appl 18(7):485–490
3. Yu X, Wang P, Li X, Yang (2012) Thin Czochralski silicon solar cells based on diamond wire sawing technology. Sol Energy Mater Sol Cells 98:337–342
4. Ge M, Bi W, Ge P, Bi Y (2016) Experimental research on KDP crystal slicing with resin bonded diamond abrasive wire saw. Int J Adv Manuf Technol 87(5):1671–1676
5. Ge M, Gao Y, Ge P, Jiao Y, Bi W (2017) A finite element analysis of sawing stress in fixed-abrasive wire saw slicing KDP crystal. Int J Adv Manuf Technol 91:2049–2057
6. Ge M, Zhu H, Huang C, Liu A, Bi W (2018) Investigation on critical crack-free cutting depth for single crystal silicon slicing with fixed abrasive wire saw based on the scratching machining experiments. Mat Sci Semicon Proc 74:261–266
7. Li Z, Ge P, Bi W, Liu T, Wang P, Gao Y (2018) Coupling stress caused by thermal and slicing force in KDP crystal slicing with fixed abrasive wire saw. Int J Adv Manuf Technol 96:4333–4343
8. Chung C, Nhat LV (2015) Depth of cut per abrasive in fixed diamond wire sawing. Int J Adv Manuf Technol 80:1337–1346
9. He Z, Huang H, Yin F, Xu X (2017) Development of a brazed diamond wire for slicing single-crystal SiC ingots. Int J Adv Manuf Technol 91:189–199
10. ITRPV (2017) International Technology Roadmap for Photovoltaic (ITRPV) Results 2016. ITRPV Eighth Edn, www.itrpv.net/Reports/Downloads/2017/
11. Dhere NG (2007) Toward GW/year production of CIGS within the next decade. Sol Energy Mater Sol Cells 91:1376–1382
12. Goldstein M, Watanabe M (2008) 450 mm silicon wafers challenges-wafer thickness scaling. ECS Trans 16:3–13
13. Watanabe M, Kramer S (2006) 450 mm silicon: an opportunity and wafer scaling. Electrochem Soc Interface 15:28–31
14. Wu H, Melkote SN, Danyluk S (2012) Mechanical strength of silicon wafers cut by loose abrasive slurry and fixed abrasive diamond wire sawing. Adv Eng Mater 14:342–348
15. Brun XF, Melkote SN (2009) Analysis of stresses and breakage of crystalline silicon wafers during handling and transport. Sol Energy Mater Sol Cells 93:1238–1247
16. Wu H, Yang C, Melkote S (2016) Modeling and analysis of the grit level interaction in diamond wire sawing of silicon. Int J Adv Manuf Technol 84:907–913
17. Liu T, Ge P, Gao Y (2015) Research on the factors limiting to reduce the thickness of silicon wafers. J Synth Cryst 44:1719–1724
18. Liu T, Ge P, Bi W (2017) Subsurface crack damage in silicon wafers induced by resin bonded diamond wire sawing. Mat Sci Semicon Proc 57:147–156
19. Wang P, Ge P, Gao Y (2017) Prediction of sawing force for single-crystal silicon carbide with fixed abrasive diamond wire saw. Mat Sci Semicon Proc 63:25–32
20. Agarwal S, Rao PV (2008) Experimental investigation of surface/subsurface damage formation and material removal mechanisms in SiC grinding. Int J Mach Tools Manuf 48:698–710
21. Wu H (2016) Wire sawing technology: a state-of-the-art review. Precis Eng 43:1–9
22. Enomoto T, Shimazaki Y, Tani Y (1999) Development of a resinoid diamond wire containing metal powder for slicing a slicing ingot. CIRP Ann Manuf Technol 481:273–276
23. Bi W, Ge P (2016) Orthogonal experiment on coating material of resin bonded abrasive wire saw. Diam Abras Eng 36:11–14