Structural Optimization of Curved Image Sensor*

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Abstract

The bending strength and surface strength of thin silicon devices and structural optimization of the curved image sensor were investigated in order to achieve high quality and thin camera module with high reliability. A new surface strength test method was proposed and the effects of the stress relief treatment method, the dicing method and the thickness on the bending and surface strength were clarified through experiments. A three-dimensional large deformation finite element method (FEM) analysis was carried out to obtain the stress generated when curving the image sensor. It was made clear, judging from the measured and analyzed strength of the curved image sensor, that there were three failure modes caused by 1) bending stress at the periphery of the device, 2) surface stress at the center of the device and 3) buckling due to compressive stress at the periphery of the device. Structural optimization of the curved image sensor was carried out by the newly developed genetic algorithm and the information integration method. The optimum solution of the thickness of 51 μm , a curving radius of 20 mm, and a fracture rate of 2% was obtained for a high resolution image sensor.

Key words: Optimum Design, Structural Analysis, Computational Mechanics, Genetic Algorithms, Product Design

1. Introduction

Recently, the camera modules installed in mobile phones and digital cameras are required to be smaller and thinner as well as to have more pixels and higher quality. In order to improve the quality of an image, it is necessary to install more lenses or to increase the optical path, both of which are difficult in smaller and thinner camera modules. The development of a curved image sensor is an effective way of solving this problem, which decreases the number of lenses and shortens the optical path without the image quality deteriorating. This sensor relaxes field curvature, which is one of lens aberrations, by curving an image sensor itself. The curved image sensor provides the same function as a lens. However, when the image sensor is thinned down and is bonded on a curved base, various stresses occur in the image sensor; such as, bending stress, tensile membrane stress due to large deformation, and compressive stress at the periphery of the device. Each of these may cause an image sensor failure.

In the general process of thinning electronic devices, a wafer is ground until its thickness reaches the target value, then stress relief treatment in order to eliminate grinding scars and residual stress is conducted, and finally it is diced into the designated length. It is generally recognized that the strength of silicon devices depends on the method of wafer thinning, stress relief treatment, and dicing, and that strength has a wide scatter.¹ Further, a three-point bending is generally used as a strength test. However, silicon is susceptible

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to failures from micro cracks near the edge in a three-point bending test, which means it is an evaluation test of edge strength. On the other hand, when pressure or force is applied to the surface, the surface strength should be evaluated since the surface stress is high. However, there have been few studies concerning surface strength measurement.

Therefore, a three-point bending test and a surface strength test are reported in this paper, clarifying the effects of the stress relief treatment method, and dicing method and device thickness on silicon strength. A new test method for surface strength test is proposed, and the surface strength is clarified by using three-dimensional large deformation finite element method (FEM) analysis.

The stress in the image sensor that occurred in the process of curving was calculated by the FEM analysis. Judging from the results of FEM and the measured strength of the image sensor, the existence of multiple failure modes was clarified. Also, in order to realize both thinner thickness and higher reliability, the curving radius was made smaller and the fracture rate was decreased owing to the structural optimization using a newly developed genetic algorithm^{2, 3} and the information integration method,⁴ which are described in this paper.

2. Evaluation of Bending Strength of Thin Silicon Chip

2.1 Evaluation of Three-Point Bending Strength

Figure 1 shows a micro three-point bending test jig for a thin silicon test piece. The micro three-point bending test jig consists of a loading jig and a supporting jig. The loading jig is connected to a tensile test apparatus with 20 kN capacity, manufactured by Shimadzu Corporation (AG2000B, with a load cell of 50 N). The loading speed was 1 mm/min. The displacement of the cross head and the output from the load cell of the tensile test apparatus were interpreted as the displacement and the load of the test respectively assuming that the rigidity of the test piece was much smaller than that of the test jig.

Fig. 1 micro three-point bending test jig

The test pieces were made from the wafers of 400 μm to 600 μm thickness. The wafers were ground, and stress relief treatment was conducted (Process A or Process B). Then, they were diced into 6 mm squares by two dicing methods; (a) single cut and (b) step cut. For step cut, a half depth cut was made with a wide blade for the purpose of eliminating surface defects, and then dicing was conducted with a thin blade for the remaining portion. Figure 2 shows examples of a test piece surface after dicing. Shell type defects that were probably caused by chipping can be seen near the surface for single cut. However, for step cut they cannot be seen near the surface but only at the middle of the thickness. Thicknesses of 20 μm , 35 μm , 50 μm , 65 μm , 75 μm , and 80 μm were chosen and seven or more test pieces for each thickness were prepared for the three-point bending strength test. Chips whose thicknesses were measured with a micrometer were

not used because they may have been damaged by the measurement. Therefore, the average measurement of thickness was used as the nominal thickness of each chip.

Fig. 2 Side view of specimen (left: single cut, right: step cut)

Figure 3 shows the results of the three-point bending strength test. The strength of silicon test piece was calculated from Eq. (1), where P (N) is the load, L (mm) is the span, b (mm) is the width, and t (mm) is the thickness.

$$\sigma = \frac{M}{Z} = \frac{3PL}{2bt^2} \quad (1)$$

The average strength obtained from the three-point bending strength test was from 650 Mpa to 1320 Mpa and its 99% strength reliability was from 280 Mpa to 730 Mpa according to Fig. 3. Figure 3 shows that bending strength has minimum value in the thickness about 70μm. Also, there was no clear correlation between the stress relief treatment method and strength. The average strength of thickness of 50 μm by the single cut and Process A is 650 Mpa and its 99% strength reliability was 310 Mpa. The average strength by the step cut is 880 MPa, and 99% strength reliability is 520 Mpa. This means that a test piece by the step cut has a higher strength than that by the single cut in the same thickness and stress relief treatment. Therefore, it can be concluded that the step cut is effective in increasing the three-point bending strength.

Fig. 3 Relation between bending strength and thickness

2.2 Evaluation of Surface Strength

Figure 4 shows a micro surface strength test jig for a thin silicon test piece. The micro surface strength test jig consists of a loading jig and a supporting jig. The loading jig is connected to a tensile test apparatus with 20 kN capacity, manufactured by Shimadzu Corporation (AG2000B, with a load cell of 50 N). The supporting jig has a hole with a 5 mm diameter. The test piece was set on the supporting jig and the load was applied from a cylindrical loading jig of 1.5 mm diameter to the center of the test piece. The test conditions and test pieces were same as those of the three-point bending test that is described in the previous section.

Next, FEM analysis was conducted in order to obtain the stress of the surface strength test. Figure 5 shows the FEM analysis model (symmetric quadratic model) for the surface strength test. A shell element for test piece modeling, a rigid element for the support jig, and a contact element between the test piece and the support jig were used. Forced displacement was applied to the periphery of the 1.5 mm diameter hole. Constraint on contact elements and the symmetric condition were also applied as boundary conditions. The analysis was large deformation contact analysis. The material properties are listed in Table 1⁵. Figure 6 shows the correlation between the load and displacement by both FEM analysis and the measured results using test piece of 50 μm thickness. The measured values in the figure are load and displacement when the test piece is fractured. The analysis and measurement results in Fig. 6 agree well, indicating the appropriateness of the analysis model.

Fig. 4 Micro surface strength test jig

Fig. 5 FEM model of specimen on surface strength test

Table 1 Material properties

C11	C22	C44
166 GPa	63.9 GPa	79.6 GPa

Fig. 6 Comparison of load-displacement relation by FEM analysis and experiment

An FEM analysis to the fracture load of the surface strength test was conducted, and the maximum principal stress that occurred in the periphery of the loading jig was interpreted as the surface strength since the failure was initiated from the periphery. Figure 7 shows the surface strength of each silicon test piece with different thicknesses. The average surface strength was 1320 Mpa or higher for the test pieces whose thickness was 35 μm or more, but for test pieces of 20 μm thickness it was from 820 Mpa to 1100 Mpa, showing a strength decrease. In this study, the surface strength is higher than the point bending strength because the maximum principal stress in practical use in industrial design was adopted as the strength evaluation parameter. This is because the sizes of micro cracks on the silicon surface are smaller than those of the micro cracks on the edge. Therefore, it is considered that both agree well if the evaluation of failure mechanics takes account of the micro crack size. It was also confirmed from the failure surface observation that the failure was initiated from the dicing edge in the three-point bending test and from the surface in the surface strength test. Moreover, both the average strength and the 99% strength reliability are higher for Process A than for Process B, indicating the dependence of strength on the stress relief treatment method. It was concluded from the above results that Process A is more effective in increasing the surface strength.

Fig. 7 Relation between surface strength and thickness

2.3 Evaluation of Image Sensor Bending Strength

Fine patterns are formed on a silicon image sensor. The bending strength of the image sensor was measured in order to evaluate its effect. Image sensor wafers with thicknesses from 400 μm to 600 μm were ground to 50 μm to prepare image sensor test pieces. They were conducted by stress relief treatment of Process A and diced by step cut. Table 2 shows the dimensions of the test piece chips.

Table 2 Dimensions of image sensor specimen

	Si chip	X chip	Y chip
$L \times W \times t$ (mm)	$6.0 \times 6.0 \times 0.048$	$5.9 \times 5.9 \times 0.041$	$5.0 \times 4.5 \times 0.046$

Figure 8 shows the results of the three-point bending test and the surface strength test. The silicon chip has the highest bending strength, Y chip has the second highest, and X chip has the lowest according to the point bending test. Their measured results have a similar scatter.

On the other hand, there is rather big difference in the surface strength according to the chip. The surface strength has the same order of strength as the bending strength; that is Si chip > Y chip > X chip. The silicon and X chips have a similar scatter, and the Y chip has a smaller scatter. This is considered to be because of the residual stress in the chip, the dicing method, and the thinning method.

Fig. 8 Probability distributions of bending and surface strength

3. Structural Analysis of Curved Image Sensor

3.1 Analysis Model

An FEM analysis was conducted to clarify the structural strength issues when the image sensor is curved. Figure 9 is the FEM analysis model when the image sensor is mounted on a curved base. For FEM analysis, Ansys 7.1 software was used. A shell element was adopted for modeling the image sensor (element number 181), and a contact element for between the image sensor and the base (Element number 170 and 174). A pressure of 1 Mpa (10 atm) was applied in the z-direction on the image sensor. Constraint was applied to the contact elements and to the base surface, and symmetry condition was also applied as a boundary condition. The large deformation contact analysis was conducted.

The results of FEM analysis for less than 1 MPa are shown in Fig. 10. The maximum principal stress distribution at the pressure of 0.05 MPa, which makes the maximum principal stress (tensile stress) of the edge the highest, is shown in Fig. 10 (a). The minimum principal stress at the pressure of 1 Mpa, which makes the minimum principal stress (compressive stress) of edge the lowest, is shown in Fig. 10 (b). The maximum principal stress distribution at the pressure of 1 MPa, which makes the maximum principal stress on the surface the highest, is shown in Fig. 10 (c). The deformation distribution at the pressure of 1 MPa is shown in Fig. 10 (d).

It can be seen from these figures that the stress in each sensor is very high. Therefore, the evaluation of various failure modes is necessary for a curved sensor; they are (1) failures caused by tensile stress which is generated due to edge bending, (2) failures caused by tensile stress in the central part which is generated due to large deformation, and (3) buckling failures due to compressive stress in the edge.

Fig. 9 FEM model of curved image sensor

Fig. 10 Analytical results of curved image sensor

3.2 Estimation of Fracture Rate in Curving

According to the bending strength test of the image sensor and the FEM analysis, the fracture rate of the image sensor mounted on the curved base can be estimated by following equation.

$$\rho_t = 1 - (1 - \rho_e) \times (1 - \rho_s) \times (1 - \rho_z) \quad (2)$$

Where, ρ_e is the fracture rate caused by a tensile failure at the edge, ρ_s is that caused by a tensile failure at the center, and ρ_z is that caused by a buckling failure at the edge.

The theoretical solution of flat plate buckling shown by Eq. (3)⁶ was used to calculate the buckling strength. If the maximum compressive stress at the edge exceeds this

buckling stress σ_{cr} , a buckling failure occurs.

$$\sigma_{cr} = \frac{k\pi^2 E}{12(1-\nu^2)} \left(\frac{h}{b} \right)^2 \quad (3)$$

Plate width b was 0.5 mm considering the test piece that was fractured due to buckling and the length of the compressive region shown in Fig. 10 (b). The compressive buckling coefficient k is 1.3 assuming that three sides are fixed and one side is free. Here E is Young's Modulus (169Gpa), ν is Poisson's Ratio (0.2), and h is thickness. The variation factor of the buckling strength V_W was assumed to be 0.2.

Table 3 shows estimated fracture rate ρ_t calculated by Eq. (2) for each chip mounted on the curved base, assuming the variation factor of generated stress V_L , to be 0.2.

The failure modes of each curved chip can be anticipated from Table 3, and it was confirmed that these failure modes agree well with failure modes in the experiments. It can be also seen that the fracture rate becomes lower as the curvature becomes larger. The higher fracture rate for the X chip is because the bending strength and surface strength are low and because the probability of a buckling failure is high due to its thinner thickness. The lower fracture rate for the Y chip is because the bending strength and surface strength are high and because the generated stress is low due to its small size.

Table 3 Estimate probability of failure

	Bending radius	Bending failure at edge ρ_e (%)	Buckling failure at edge ρ_s (%)	Tension failure at center ρ_z (%)	Total failure ρ_t (%)
Si chip 6.0 × 6.0 × 0.048	R18	0.1	4.6	0.5	5.2
	R20	0.1	1.5	0.5	2.0
	R25	0.0	0.1	0.3	0.4
X chip 5.9 × 5.9 × 0.041	R18	5.5	26.8	21.0	45.4
	R20	3.2	16.8	7.7	25.7
	R25	1.2	7.1	0.6	8.8
Y chip 5.0 × 4.5 × 0.046	R18	1.2	0.0	0.6	1.8
	R20	0.9	0.0	0.2	1.1
	R25	0.4	0.0	0.0	0.4

4. Structural Optimization of Curved Image Sensor

To achieve a smaller curving radius and a lower fracture rate, the structural optimization of the curved image sensor (high resolution device, Z chip) was conducted using a newly developed generic algorithm and the information integration method, which led to high quality and thin camera module with high reliability. The optimization parameters were the thickness and the curving radius of the image sensor. The maximum principal stress and minimum principal stress at the edge, maximum principal stress at the center, the clearance between the base and the image sensor at the center, and the curving radius were evaluated. The evaluation functions were based on the information integration method, and Eq. (4) was used. In Eq. (4), e_j is each evaluated value, e_t is the sum of each evaluated value, r_{j1} is the target value, and r_{j2} is the limitation value. Table 4 shows the target values and the limitation values. Figure 11 is an optimization flow chart.

The results of the optimization analysis are shown in Fig. 12 and Table 5. The optimum solution was an image sensor thickness of 51 μm , a curving radius of 20 mm, and a fracture rate of 0.02 (2%). The reliability of the maximum principal stress at the edge is not high in the chip. Therefore, dicing, which affects edge strength, should be carefully

conducted.

Table 4 Targets and restrictions

	Target, r_{j1}	Restriction, r_{j2}
Bending radius R (mm)	18	21
Gap (mm)	0	0.002
Maximum principal stress at edge (MPa)	74	277
Minimum principal at edge (MPa)	$\sigma_{cr} / 1.9$	$\sigma_{cr} / 2.9$
Maximum principal at center (MPa)	689	854

$$\begin{aligned}
 &\text{if } e_j \leq r_{j1} \quad \text{then} \quad e_j = 0 \\
 &\text{if } r_{j1} \leq e_j \leq r_{j2} \quad \text{then} \quad e_j = \log \frac{r_{j2} - r_{j1}}{r_{j2} - e_j} \\
 &\text{if } r_{j2} \leq e_j \quad \text{then} \quad e_j = 10 \\
 &e_i = \sum_{j=1}^n e_j
 \end{aligned} \tag{4}$$

Fig. 11 Optimization flow chart

Fig. 12 Results of structural optimization of curved image sensor

Table 5 Optimum solution and probability of failure of curved image sensor

	Optimum solution	Probability of failure
Thickness (μm)	51	—
Bending radius R (mm)	20.0	—
Gap (mm)	0.0004	—
Maximum principal stress at edge (MPa)	246	0.013
Minimum principal stress at edge (MPa)	-756	0.003
Maximum principal stress at center (MPa)	446	0.000
Total probability of failure		0.02

5. Conclusions

In this paper, three-point bending tests and surface strength tests of thin silicon chip for the curved image sensor were conducted, and the effects of the stress relief treatment method, the dicing method and the thickness on silicon strength were clarified. The strength of the image sensor was quantitatively evaluated and structural optimization using the genetic algorithm and the information integration method was conducted in order to make the curving radius of the image sensor smaller and to make the fracture rate in the curving process lower. The results are described below.

- (1) A new test method for surface strength evaluation was proposed, and strength tests were conducted focusing on the maximum principal stress as a main parameter. The results showed that the surface strength of silicon is higher than that of the three-point bending strength.
- (2) The bending strength has minimum value in the thickness about $70\mu\text{m}$ but there is no clear correlation between the average bending strength of a silicon chip and stress relief treatment method. A step cut dicing results in higher strength than a single cut dicing if the thickness is the same and same stress relief treatment is applied.
- (3) The surface strength of a silicon chip depends on the stress relief treatment method. That is, Process A makes the strength higher than Process B.
- (4) Three-point bending tests and surface strength tests were conducted for X and Y chips, which are image sensors, clarifying that strength depends on the image sensor.
- (5) It was clarified that three kinds of failure modes, that is bending failure at the edge, buckling failure at the edge, and tension failure at the center, exist when the image sensor was mounted on the curved base from the strength tests and the structural analysis. Moreover, these failure modes agreed well with the observation of the failure modes in the

experiments.

- (6) Multi-purpose optimization was carried out for a high resolution device (Z chip) in order to achieve a smaller radius of curving and a lower fracture rate for multiple failure modes when the image sensor was mounted on the curved base. The optimum solution of the thickness of 51 μm , a curving radius of 20 mm, and a fracture rate of 2% was obtained..

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