Grey Relational Analysis for Abnormal Multi-Quality Characteristics Screening to Simplify the Quality Control in Silicon Wafer Slicing Process

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Abstract

Silicon wafer wire saw machine requires high precise to slice an ingot. When long time slicing, the machine vibration and the slicing wire knife unstable motion will cause slicing precise drift. Slicing manufacturing process involves several synchronously occurred multiple quality characteristics, such as thickness (THK), bow, warp, total indicator reading (TIR) and total thickness variation (TTV), which must be closely monitored and controlled. However, when the yield of synchronously multiple quality characteristics is unstable or the wire saw machine precise is drift, the decision maker must consider to control and monitor the machine specially. Grey relational analysis (GRA) is used to prevent a bad-condition wire saw machine produce an abnormal product that screens from the synchronously occurred multiple quality characteristics in order to provide the process quality control effectively. Finally, a case study and the exponential weighted moving average (EWMA) control chart are presented to demonstrate and verify the feasibility and effectiveness of proposed method.

Keywords: Silicon wafer manufacturing, multiple quality characteristics, grey relational analysis, EWMA control chart

1. Introduction

Silicon wafer slicing is an increasingly complex manufacturing process, such as high purity levels, crystallographic perfection and precise mechanical tolerances, complicating efforts to effectively monitor the process stability and quality control of each product type. However, when the yield of synchronously multiple quality characteristics is unstable or the wire saw machine precise is drift, the decision maker must consider to control and monitor the machine specially. Slicing is a kind of cutting that cannot easily yield the required precision. Five synchronously occurring precision quality characteristics, thickness (THK), bow, warp, total indicator reading (TIR) and total thickness variation (TTV) must be simultaneously inspected using by ADE6300 auto testing equipment. These characteristics are: (1) THK: the distance through the wafer between corresponding points on the front and back surfaces (measured at the center of the wafer) (see Fig.1) [3]; (2) bow: the maximum central point deviation above or below the reference plane, *a* or *b*, respectively; the bow can be defined as (a+b)/2 (see Fig. 2) [2]; (3) warp: the difference between the maximum, T_{max} , and minimum, T_{min} , distances of the median surface (or central plane) from a reference plane (see Fig. 3) [19]. (4) TIR: the summation of the sample surface's maximum height above and its

maximum depth below the microlithographic focal plane (see Fig. 4) [19]; (5) TTV: the difference between the maximum and minimum values of thickness of a wafer, encountered in a multipoint scan pattern (see Fig. 5) [19].

A case firm does not appropriately regard the bad-condition wire saw machine, they only use the THK quality characteristic to measure and control the quality of the entire process. Generally, the \overline{X} -R control chart is used and takes one sample–work-piece from 25 work-pieces to monitor the problems of abnormalities. Five sample-work-pieces are taken from 25 when warp, bow, TIR and TTV are inspected.



Roberts [13] introduced the EWMA control chart as a tool for detecting small shifts in the mean of a process. In the semiconductor industry, EWMA-based controllers have led to the development of EWMA feedback controllers for compensating against disturbances that affect the batch-to-batch variability in the quality characteristics of silicon wafers at a process setup [4, 7, 17]. Alejandro et al. [1] constructed control charts based on orthogonal contrasts to detect specific deviations from target for a semiconductor manufacturing operation. They investigated both Shewhart and EWMA charts. The EWMA charts were more effective in shift detection than their Shewart counterparts when the shift was small. Gan [10] proposed a two-dimensional chart; Reynolds and Stoumbos [15] considered the use of two

EWMA charts to observe Chen et. al [5] proposed an EWMA chart to monitor process mean a variability with one EWMA chart. Kenneth [12] used three-dimensional added variables and partial residual plots control chart to control simultaneously two or three quality characteristics to monitor the abnormality. Whichever the control charts are used, they generally require enough sample data to analyze process problems. However, in the slicing process, the job is often modified for small batch manufacturing. Therefore, seldom samples can be used and engineers cannot be helped to deal with abnormality quality on a product line or bad-condition wire saw machine.

In statistical methods, decision makers confront multi-variables by considering many samples and assuming that they obey some identified distribution to analyze and compare their relationships. Process capability indices (PCIs) must assume that measurements are taken form normally distributed populations. Several indices proposed for use with non-normal populations [6, 13, 14, 18, 20, 21]. Conventional, PCIs studies treat products as if they have only one critical characteristic of interest. However, slicing has five characteristics that are critical to the customer. Therefore, grey relational analysis (GRA) procedures can be appropriately used to reduce the sample size without knowing data. The main feature of the "GRA" is that it can be used with seldom data and can apply an arbitrary distribution of data to make an objective decision [8]. The bad-condition wire saw machine could be screened from the synchronously occurred multiple quality characteristics and those sampling data without reducing the quality of the entire process quality. Additionally, the EWMA control chart is used to demonstrate an on-line process that continues to monitor 100 data to verify the effectiveness of using the grey relational analysis in the wafer slicing manufacturing process.

Based on the previous discussion, this study focuses on (1) screening the bad-condition wire saw machine from the multi-quality characteristics for inspecting and sampling tightly to control defective work-pieces in the slicing process, and (2) applying EWMA control to verify that the proposed screening method effectively monitors abnormities in the inspected work-pieces. The rest of this paper is organized as follows. Section 2 describes grey relational analysis and its algorithm. Section 3 describes case implementation. Conclusions are discussed in Sections 4.

2. Grey Relation Analysis and Its Algorithm

The grey system method, initiated by Deng [8, 9], has been widely applied to various fields including manufacturing processes. In this paper, the grey relational analysis is applied to solve the synchronously occurred multiple abnormal GRA is illustrated as following:

(1) Calculate the Grey Relation

Let X_0 be the referential series with K entries of $X_1, X_2, ..., X_i, ..., X_N$ then

$$\begin{aligned} X_0 &= \left\{ x_0(1), \, x_0(2), \, ..., \, x_0(j), \, ..., \, x_0(K) \right\}, \\ X_1 &= \left\{ x_1(1), \, x_1(2), \, ..., \, x_1(j), \, ..., \, x_1(K) \right\}, \\ &\vdots \\ X_i &= \left\{ x_i(1), \, x_i(2), \, ..., \, x_i(j), \, ..., \, x_i(K) \right\}, \\ &\vdots \\ X_N &= \left\{ x_N(1), \, x_N(2), \, ..., \, x_N(j), \, ..., \, x_N(K) \right\}. \end{aligned}$$

The grey relational coefficient between the compared series X_i and the referential series of X_0 at the *j*-th entry is defined as:

$$\gamma_{0i}(j) = \frac{\Delta \min + \Delta \max}{\Delta_{0i}(j) + \Delta \max},$$
(1)

where $\Delta_{0i}(j)$ is the absolute value of difference between X_0 and X_i at the *j*-th entry, that is

 $\Delta_{0i}(j) = |x_0(j) - x_i(j)|, \text{ and } \Delta \max = \max_i \max_j \Delta_{0i}(j), \quad \Delta \min = \min_i \min_j \Delta_{0i}(j),$

The grey relational grade (GRG) for series of X_i is given as:

$$\Gamma_{0i} = \sum_{j=1}^{K} w_j \gamma_{0i}(j) .$$
⁽²⁾

where W_j is *j*-th weight of series X_i .

(2) Normalization (or Date dimensionless)

Before calculating the grey relational coefficients, the data of series can be treated based on the following three kinds of situation and the linearity of normalization to avoid distorting the normalized data [11]. There are:

1) Upper-bound effectiveness measuring (i.e., larger-the-better)

$$x_{j}^{*}(j) = \frac{x_{i}(j) - \min_{j} x_{i}(j)}{\max_{i} x_{i}(k) - \min_{i} x_{i}(j)},$$
(3)

where $\max_{i} x_{i}(j)$ is the maximum value of entity j and $\min_{i} x_{i}(j)$ is the minimum value of entity j.

2) Lower-bound effectiveness measuring (i.e., smaller-the-better)

$$x_{i}^{*}(k) = \frac{\max_{j} x_{i}(j) - x_{i}(j)}{\max_{j} x_{i}(j) - \min_{j} x_{i}(j)},$$
(4)

3) Moderate effectiveness measuring (i.e., nominal-the-best)

$$x_{i}^{*}(k) = \frac{\left|x_{i}(j) - x_{ob}(j)\right|}{\max_{i} x_{i}(j) - \min_{i} x_{i}(j)}, \text{ if } \min_{j} x_{i}(j) \le x_{ob}(j) \le \max_{j} x_{i}(j),$$
(5)

$$x_{i}^{*}(j) = \frac{x_{i}(j) - \min_{j} x_{i}(j)}{x_{ob}(j) - \min_{j} x_{i}(j)}, \text{ if } \max_{j} x_{i}(j) \le x_{ob}(j), \text{ or }$$
(6)

$$x_{i}^{*}(j) = \frac{\max_{j} x_{i}(j) - x_{i}(j)}{\max_{i} x_{i}(j) - x_{ob}(j)}, \text{ if } x_{ob}(k) \le \min_{j} x_{i}(j).$$
(7)

where $x_{ob}(j)$ is the objective value of entity *j*.

3. Case Implementation

Silicon wafer processes include crystal growing, pulling, slicing, lapping, etching, polishing, and cleaning. Their measurement items of process quality and the parameters of quality control are, (1) lack of precision in measuring thickness (THK), bow, warp, total thickness variation (TTV), total indicator reading (TIR) caused by unstable motion of the wire knife and scrape mark during slicing process and (2) quality control parameters, such as, electricity, resistivity

and oxidation that relate to crystal pulling are not discussed in this paper. In lapping process, the lapped wafer will be revised those quality characteristics in item (1) by using precision lapping machines. However, the manufacturing cost of the lapping and polishing processes are much higher than that of the slicing process. Hence, quality control of slicing process mainly focuses on the bad-condition wire saw machine.

3.1 Procedure of Screening Bad-condition Wire Saw Machine

The GRA method can screen the best decision for controlling events. This method can be used to screen the bad-condition wire saw machine from the slicing process to reduce the number of defective work-pieces. This section includes three parts of the procedure. The first part is implementing a GRA method. The second part is online verifying the verification of feasibility of the model. The EWMA method is used as basis of comparison. The third part is making the final decision. Figure 6 depicts the GRA for screening bad-condition wire saw machine in slicing process.

Step 1: Sample five 6-inch wafers randomly and measure their quality characteristics.

Step 2: Decide the referential series and the compared series.

Step 3: Make data dimensionless for determine $x_i^*(j)$ (if necessary).

Step 4: Compute $\Delta_{0i}(j)$.

Step 5: Compute the relational coefficient, $\gamma_{0i}(j)$, of all compared series.

- Step 6: Compute the grey relational grade, Γ_{0i} , and determine the worst Γ_{0i} . Thus, the *i*-th series is the bad-condition wire saw machine in slicing process.
- Step 7: Perform an EWMA verifying analysis and continuously monitor the 6-inch ingot. Measure THK of 100 work-pieces from each machine.
- Step 8: Make the final decision; determine the bad-condition wire saw machine, which requires controlling and monitoring specially.



Fig. 6 Procedure of Screening Bad-Condition Wire Saw Machine

3.2 Numerical Illustration

Step1: Sample five 6-inch work-pieces, whose samples have been completely confirmed at random and measure the multiple quality characteristics at five points on work-pieces, using a measuring instrument, ADE6300. Then average the measured data of these points. (See Table 1.)

Sawing	Quality Characteristics				
Machine	THK	warp	bow	TIR	TTV
M1	746	21.8	14.0	0.493	1.657
M2	760	15.0	4.5	0.413	1.197
M3	751	22.8	2.5	0.421	1.782
M4	756	21.9	8.9	0.441	1.037
M5	765	16.7	5.7	0.503	1.622

Table 1 Measured Multiple Quality Characteristics of 6-Inch Wafer (Unit: μ)

Step 2: THK quality characteristic is a nominal-the-best response and using the customer object value is 760 μ m. Other four quality characteristics, warp, bow, TIR and TTV, are small-the-best-response. Therefore, the referential series is $X_0 = (760, 15.0, 2.5, 0.413, 1.037)$ and the quality characteristics of compared series, X_1 , X_2 , X_3 , X_4 and X_5 (i.e. M₁, M₂, M₃, M₄ and M₅ in Table 1).

Step3: From Table 1, data dimensionless for THK, warp, bow, TIR and TTV are given by Eq. (5) and (4), respectively. The results are tabulated in Table 2.

Sawing Machine	$x_i^*(j), j = 1, 2, 3, 4, 5$				
Reference series (<i>i</i> =0)	1	1	1	1	1
M1 (<i>i</i> =1)	0.737	0.005	0	0.111	0.168
M2 (<i>i</i> =2)	0	1	0.826	1	0.701
M3 (<i>i</i> =3)	0.474	0	1	0.911	0
M4 (<i>i</i> =4)	0.211	0.115	0.443	0.689	1
M5 (<i>i</i> =5)	0.263	0.782	0.721	0	0.192

Table 2 Summary of Data Dimensionless

Step 4: Compute $\Delta_{0i}(j)$. The results are tabulated in Table 3.

Table 3 The Result of $\Delta_{0i}(j)$

Quality Characteristics		Δ	$_{0i}(j), j = 1, 2, 3, 4$, 5	
M1 (<i>i</i> =1)	0.263	0.995	1	0.889	0.832
M2 (<i>i</i> =2)	1	0	0.138	0	0.299
M3 (<i>i</i> =3)	0.526	1	0	0.089	1
M4 (<i>i</i> =4)	0.789	0.885	0.557	0.311	0
M5(i=5)	0.737	0.218	0.279	1	0.808

Step 5: Compute the relational coefficient, $\gamma_{0i}(j)$ of compared series by using Eq. (1) and the results are tabulated in Table 4.

Step 6: Computer the relational rating, Γ_{oi} , by using Eq. (2) and determine the smallest grade. Thus, the bad-condition wire saw machine screened in slicing process is "M1".

Quality Characteristics	$\gamma_{oi}(j), j = 1, 2, 3, 4, 5$					Γ _{0i}
M1 (<i>i</i> =1)	0.792	0.501	0.5	0.529	0.546	0.574
M2 (<i>i</i> =2)	0.5	1	0.879	1	0.814	0.839
M3 (<i>i</i> =3)	0.655	0.5	1	0.918	0.5	0.715
M4 (<i>i</i> =4)	0.559	0.631	0.642	0.763	1	0.719
M5 (<i>i</i> =5)	0.576	0.821	0.782	0.5	0.553	0.646

Table 4 Summary of the Relational Coefficients, $\gamma_{0i}(j)$ and Relational Grade Γ_{0i}

Step 7: EWMA verifying analysis of THK

Currently, the firm applies the THK quality characteristic to monitor the slicing quality, thereby to verify our view is precise. Five wire saw machines of the effective measured value of THK is plotted on an EWMA chart. A univariate EWMA chart is modeled as

$$Z_{t} = \omega \bar{X}_{t} + (1 - \omega) Z_{t-1}, \quad t = 1, 2, ..., n,$$
(8)

Where ω is the weighting factor (defined by the decision maker) and typical values for ω are between 0.05 and 0.3 in the application of statistics process control; \overline{X}_t is the subgroup average for the current subgroup at time *t* (or the current observation if the subgroup size is one (*n* = 1)); the value of *Z* at time zero, Z_0 , is either a target value or the overall average of the selected subgroups (also defined by the decision maker).

The upper and lower control limits for the EWMA statistics are as follows [1, 5, 7, 10, 17].

$$UCL = Z_0 + \frac{3S}{\sqrt{n}} \sqrt{\left(\frac{\omega}{1-\omega}\right) \left(1 - \left(1-\omega\right)^{2i}\right)} , \text{ and}$$
(9)

$$LCL = Z_0 - \frac{3S}{\sqrt{n}} \sqrt{\left(\frac{\omega}{1-\omega}\right) \left(1 - \left(1-\omega\right)^{2i}\right)}.$$
(10)

Where Z_0 is the starting value (defined by the decision maker as either the target value or the process mean value), and *n* is the size of the subgroup.

The process standard deviation, S, is estimated using the \overline{X} chart and setting $\omega = 0.3$ and n = 2 to monitor and inspect THK. In this chart, 100 samples are generated while the process is controlled.

The measured data for THK (customer object, $760\pm15 \ \mu$) is inspected at five points on each work-piece by the measuring instrument, ADE6300 and averaging these points.

Figure 8 illustrates "M1" wire saw machines slicing and the EWMA chart of THK by \overline{X} counts. Similarly, M2 ~ M5 machines' results show in Appendix 1. In Fig. 8, machine 1 has five alarms, and the out-of-control conditions appear at the 9th, 17th, 37th, 41st and 45th signals. As result, five alarms in machine 1 are more than other machines' alarms. Furthermore, in bad-condition detected by EWMA control chart of M1 is the same as the bad grade ranking by GRA is M1.



Fig. 8 THK's EWMA Chart of M1 by \overline{X} Count

Step 8: Final decision making

Table 5 combines the result of GRA in Table 4 and EWMA control chart shown in Figure 8 and Appendix Figs A1~A4. In Table 5, M2's GRG is higher than other machines. In EWMA control chart, it is only an alarm. These two results inform that the process quality in machine 2 is stable. Nevertheless, machine 1 shows unstable. Decision makers should make much effort on prevention and maintenance of "M1" wire saw machine.

Wire Saw Machine	Decision Method		
	GRG	EWMA Control Chart Alarms	
M1	0.574	5	
M2	0.839	1	
M3	0.715	2	
M4	0.719	3	
M5	0.646	3	

Table 5 Compare GRA Decision Method and EWMA Control Chart

4. Conclusion

In the slicing process, wire saw precise and multiple quality characteristic problems arise from uncertain and imprecise data. The method of GRA method is adequate to deal with these problems. This paper presents a synthetic effective means of measurement by GRA, to screen the bad-condition wire saw machine wire saw machine from the synchronously occurring abnormalities multiple quality characteristics. The main contribution of this paper is that using seldom samples to screen out the bad-condition wire saw machine from the quality characteristics in the slicing process.

The computed results yield the following conclusions. (1) M1 is bad-condition wire saw machine in the slicing. Therefore, the case firm should monitor and inspect sample tightly on this machine. (2) The EWMA control chart is used to monitor - THK quality characteristics, by taking 100 observations during slicing to confirm the results using the GRA. The effectiveness of monitoring using the EWMA control chart is the same as that obtained using the GRA

method. (3) The case firm should use the proposed technique to improve their control of the quality of wafers. (4) GRA method allows engineers to rapidly adjust a manufacturing system to eliminate bad-condition and enhance slicing quality and process capability.

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Appendix 1: M2~M4 THK's EWMA Chart

