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ABSTRACT

The wafer defects influence the yield of a wafer. The integrated circuits (IC) manufacturers usually use a Poisson distribution based c-chart to monitor the lot-to-lot wafer defects. As the wafer size increases, defects on wafer tend to cluster. When the c-chart is used, the clustered defects frequently cause erroneous results. The main objective of this study is to develop a hierarchical adaptive control process to monitor the clustered defects effectively and detect the wafer-to-wafer variation and lot-to-lot variation simultaneously using data mining technique.

Keywords: wafer defects, c-chart, defect clustering, adaptive control chart, data mining.

1. INTRODUCTION

The IC fabrication has been the most popular industry in recent decades. The key competitive ability of IC products is the wafer yield. The wafer yield is defined by the percentage of the chip without defects on a wafer. To enhance the wafer yield, most IC manufacturers employ a Poisson distribution based defect control chart (c-chart) to monitor the wafer defects. The c-chart is proved to be effective when wafer size is small (e.g., four or six inches wafers). As the wafer size has been enlarged to twelve-inch, the manufacturing process becomes very complicated. Consequently, the clustering phenomenon of the defects becomes increasingly apparent. This phenomenon will affect the accuracy of the c-chart. When the conventional c-chart is used to monitor the large-size wafers, the clustered defects frequently cause erroneous results. That is, the c-chart may cause too many false alarms. This is because c-chart requires that the occurrence of a defect in any location is independent of the occurrence of defects in other locations.

The IC manufacturing process is composed of hundreds of steps. At each step, many possible factors may affect the quality of a wafer. There are three types of wafer variations: within-wafer variation, wafer-to-wafervariataion and lot–to-lot variation. The c-chart can only detect the lot-to-lot variation under the condition that the defects are scattered randomly on a wafer and there is no wafer-to-wafer variation. Besides, the cost of sampling wafers from a lot becomes expensive for large-size wafers. An adaptive control chart may be utilized to reduce the sampling cost. Therefore, the main objective of this study is to develop a complete adaptive detecting procedure of wafer defects, which concerns both multiple variations and clustering phenomenon. Using the proposed procedure, the wafer defects can be controled efficiently with low sampling cost.

2. DOCUMENTATION DISCUSSION

2.1 Clustering analysis [4]

Cluster analysis is a popular data mining technique used for combining observations into groups or clusters such that each cluster is homogeneous with respect to certain characteristics and observations of one cluster should be different from the observations of other clusters. In hierarchical cluster analysis, clusters are formed hierarchically such that the number of clusters at each step is n-1, n-2, n-3, and so on. A number of different algorithms for hierarchical clustering were developed. These algorithms differed mainly with respect to how distances between two clusters are computed. The Euclidean distance for p variables is a common formula used for computing the distance between two observations. The distance is utilized as a measure of similarity in cluster analysis.

2.2 Three-step hierarchical control process

In the IC manufacturing process, there are three types of wafer variations: within-wafer variation, wafer-to-wafer variation and lot–to-lot variation may cause the yield loss. Wells and Smith [5] claimed that the three variations must be under control to assure the quality of a wafer and they proposed a step-by-step control process as follows:

(1) Determine the uniformity of a wafer.
Calculate the non-uniformity (NU) of each wafer:

$$NU = 2V \quad \text{and} \quad V = 100\hat{s} / \overline{X} \qquad (1)$$

Where $\hat{s}$ and $\overline{X}$ represents the estimated standard deviation and mean.

(2) Draw $\overline{X}_{NU} - R_{NU}$ control chart using the values of NU to determine whether the non-uniformity of each wafer is under control.

(3) Determine the lot-to-lot variation.

(i) Calculate the average run value of every lot.

(ii) Draw $X - MR$ chart to determine whether the lot-to-lot variation is under control.

(4) Calculate the total variations of the process

$$\hat{s}_{TOTAL} = (\hat{s}_R^2 + \hat{s}_W^2 + \hat{s}_L^2)^{1/2} \quad (2)$$

The estimated within wafer variation can be calculated using the average non-uniformity of every lot. The formula is given as follows:

$$\hat{s}_L = (\overline{X}_{NU})(\overline{\overline{X}})/200 \quad (3)$$

Moreover, the wafer-to-wafer variation can also obtained using the average range of every lot. The formula is given as follows :

$$\hat{s}_W = \overline{R}/d_2 \quad (4)$$

Finally, the estimated lot-to-lot variation can be obtained using the average moving-range of every lot. The formula is given as follows :

$$\hat{s}_R = \overline{MR}/d_2 \quad (5)$$

The control process proposed by Wells and Smith has two drawbacks: it can only detect the large shift of the process, that is, it is not sensitive to the small shift; it can only be used in the quantitative quality characters.

2.3 Adaptive control chart

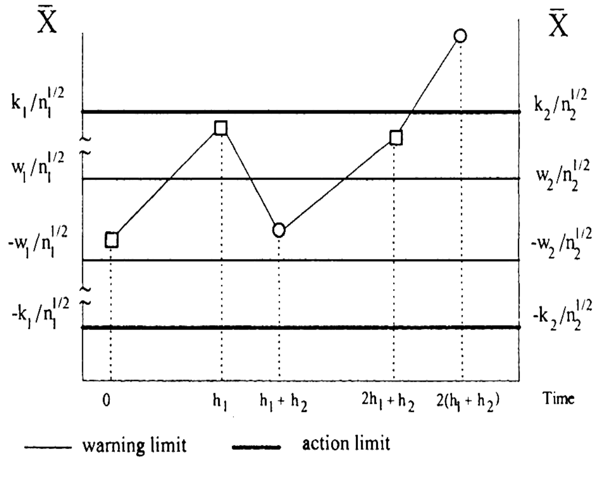
Adaptive control chart is a special kind of quality control tool in which the sample size and the sampling interval are changeable. It utilizes the previous sample data as a basis to fluctuate the sampling sizes and sampling intervals. When sample points are near out of control, a stricter sampling scheme (e.g., larger sample size and shorter sampling period) is adopted to detect the out-of control situation efficiently. When sample points are near the target value, a looser sampling scheme (e.g., smaller sample size and longer sampling period) is adopted to save the sampling cost.

In order to determine when to adopt the strict, normal or loose sampling scheme, the upper and lower warning limits must be constructed within the upper and lower control limits. If a sample point falls within the warning limits, a loose sampling scheme is utilized. If a sample point falls between the warning limits and the control limits, a strict sampling scheme should be utilized. The basic model of an adaptive control chart is depicted in Fig.1.

2.4 $\overline{X}$ adaptive control chart [3]

The assumptions and parameters of designing a $\overline{X}$ adaptive control chart can be described as follows:

(1) Assumptions



▪ => $\overline{X}$ values from samples of size n_1 (plotted on the chart using the left scale).

O => $\overline{X}$ values from samples of size n_2 (plotted on the chart using the right scale).

Figure.1 Adaptive control chart

(i) The observations follow a Normal distribution.

(ii) Suppose the sample size and the sampling interval of the traditional control chart are n_0 and t_0, respectively. A sampling scheme of n_1 (small sample size) and h_1 (long sample interval), or n_2 (large sample size) and h_2 (short sampling interval) is determined for an adaptive control chart. When the process is in control , the sample size and sampling interval of an adaptive control chart should be the same as a traditional $\overline{X}$ control chart. That is,

$$E[n(i)] = n_0 \quad (6)$$

$$E[t(i)] = t_0 \quad (7)$$

(2) Design of parameters

(i) Let I_1 be the zone within the warning limits, I_2 be the zone between the control limits and warning limits, and I_3 be the zone within the control limits. The lower and upper boundaries of I_1, I_2 and I_3 are defined as follows:

$$I_1 = [-w, w] \quad (8)$$

$$I_2 = (LCL, -w) \cup (w, UCL) \quad (9)$$

$$I_3 = (LCL, UCL) \quad (10)$$

(ii) From the assumption (ii), the following equation can be obtained:

$$n_0 \Pr(Z \in I_3) = n_1 \Pr(Z \in I_1) + n_2 \Pr(Z \in I_2) \quad (11)$$

Because Z follows a standard normal distribution, the following results can be obtained:

$$\begin{aligned} \Pr(Z \in I_3) &= 2f(w) - 1 \\ \Pr(Z \in I_2) &= 2(f(UCL) - f(w)) \quad (12) \\ \Pr(Z \in I_1) &= 2f(UCL) - 1 \end{aligned}$$

Using (11) and (12), the warning limits can be rewritten as follows:

$$w = f^{-1}\left[\frac{2f(UCL)[n_0 - n_2] + n_1 - n_0}{2(n_1 - n_2)}\right] \quad (13)$$

For a given sampling interval, a formula derived from (11) and (12) is given as follows:

$$t_0 \Pr(Z \in I_3) = t_1 \Pr(Z \in I_1) + t_2 \Pr(Z \in I_2) \quad (14)$$

w can then be rewritten as follows:

$$w = f^{-1}\left[\frac{2f(UCL)[t_0 - t_1] + t_2 - t_0}{2(t_2 - t_1)}\right] \quad (15)$$

After obtaining w, fix any three of the four parameters n_1, n_2, t_1 and t_2, the last parameter can be calculated using (13) and (15). For example, fixing the values of n_1, n_2, and t_1, t_2, b and c can be obtained by setting (13)=(15):

$$t_2 = \frac{t_0(n_1 - n_2) - b - t_1 c}{n_1 - n_2 - c},$$
$$b = 2(t_0 - t_1)(n_1 - n_2) f(UCL),$$
$$c = 2(n_0 - n_2) f(UCL) + (n_1 - n_0).$$

3. CONSTRUCT A HIERARCHICAL CONTROL PROCESS FOR CLUSTERED DEFECTS

This study utilizes the clustering analysis to adjust the number of defects on a wafer when the cluster phenomenon is detected. By doing so, the defect clusters are distributed randomly on a wafer and the type I error of the c-chart can then be reduced. The uniformity of a wafer is calculated and the adaptive control chart is employed to detect the wafer-to-wafer and lot-to-lot variations. The proposed procedure for detecting the clustered defect is described in the following:

Step 1: Obtain the wafer map using KLA 2110 wafer inspection system.

Cluster analysis is utilized to combine the clustered defects. Treat all defects in a cluster as one defect and the location of this defect is the location of the cluster's center. Recalculate the number of defects on each wafer

Use a goodness of fit test to check whether the adjusted (reduced) number of defects satisfies the assumption of a Poisson distribution. If it does, go to Step 2; otherwise, repeat Step 1.

Step 2 Determine whether the wafer-to-wafer variation is in control.

Calculate the value of NU using the adjusted number of defects on a wafer. Transfer the values of NU to satisfy the normality assumption. The $\overline{X}_{NU} - R_{NU}$ chart and $X - MR$ chart are constructed to detect the wafer-to-wafer variation.

Step3: Determine whether the lot-to-lot variation is in control.

The proposed adaptive U control chart is developed based on the $\overline{X}$ control chart. In monitoring IC manufacturing process, the wafers are usually sampled from every lot. The sampling interval is treated as a fixed constant (e.g., a lot). Therefore, only the sample size needs to be changed according to the previous sampling result. The process of using U control chart to monitor the lot-to-lot variation is described as follows:

1. Standardize the sample data. Because m and s are unknown, they are estimated using the historical data.. The transformation formula is :

$$Z_i = \frac{u_i - m}{\sqrt{s^2/n_i}} \cong \frac{u_i - \bar{u}}{\sqrt{\bar{u}/n_i}} \quad (16)$$

where $\bar{u}$ is the mean number of defects on each wafer and the variance is the same as the mean since the number of adjusted defects on a wafer follows a Poisson distribution.

2. Contract different sampling schemes (strict and loose) for different sample size n_1 and n_2.

3. Determine the control limits and the warning limits of the U control chart. The control limits are ± 3 since the sample data is standardized. The warning limits can be obtained using the following formula:

$$w = f^{-1}\left[\frac{2f(UCL)[n_0 - n_2] + n_1 - n_0}{2(n_1 - n_2)}\right] \quad (17)$$

4. Plot the sample points on the U control chart. If a sample point falls outside of the control limits, the process is said to be out of control.. If a sample point falls between the control limits and the warning limits, n_2 is adopted as the next sample size. If a sample point falls within the warning limits, n_1 will be used as the next sample size.

5. Return to Step2 to perform the next sampling.

4. CASE STUDY

This section presents a case study to demonstrate the effectiveness of the proposed approach. The required data in this case study are obtained from an IC manufacturing company in Taiwan. When the wafer goes through the process of ":Metal 2 Etch," the coordinates of the wafer's defects are collected using a KLA 2110 wafer inspection system which is a standard inspection tool utilizing the laser scan technique. Follow the steps described in Section 3, the result of each step is given as follows.

Step 1： There are forty lots of wafers and each lot has twenty-five wafers. Two wafers, the fifth and the twenty-fifth wafers, of every lot were selected. The coordinates of defects and the number of defects are obtained for each wafer.

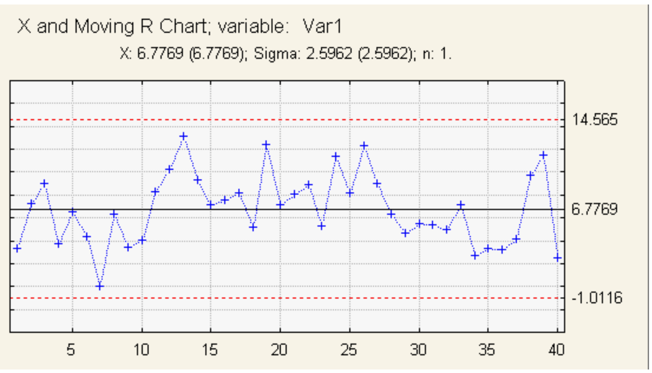


Fig. 1. The revised X control chart

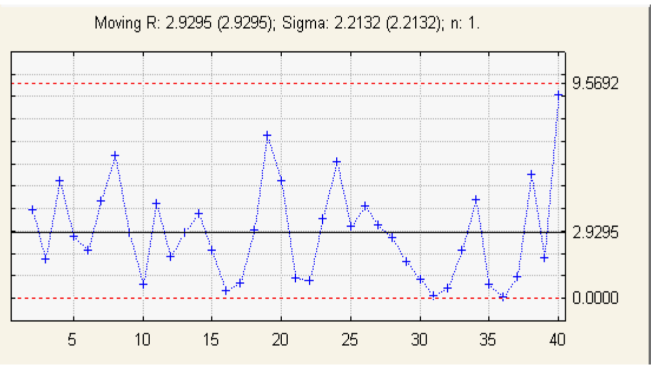


Fig.2. The revised MR control chart

Step2： The $\overline{X}_{NU}-R_{NU}$ chart and $X-MR$ chart are constructed to detect the wafer-to-wafer variation. The results are shown in Fig, 1 and 2. No wafer-to-wafer variations are observed in these two charts.

Step3：

$$w = f^{-1}\left[\frac{2f(3)[1.5-2]+1-1.5}{2(1-2)}\right]$$
$$= f^{-1}[0.74935]$$
$$= 0.675$$

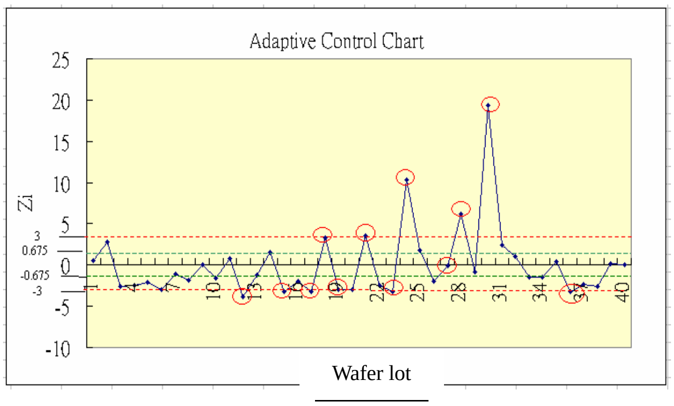


Fig 3. The proposed U adaptive control chart

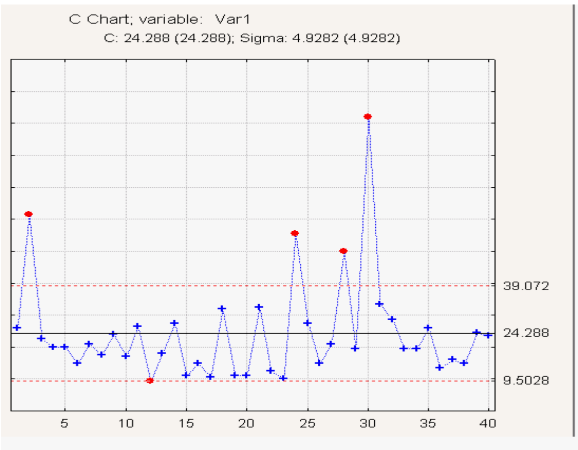


Fig..4. The traditional c-chart

The U adaptive control chart can detect 11 out-of control lots; while the traditional c-chart only detect 5 out-of–control points. Consequently, the proposed control process can detect small shift and determine the source of variation coming from the wafer-to-wafer variation or the lot-to-lot variation.

5. CONCLUSION

As the wafer size increases, a wafer's defects are no longer randomly distributed. They tend to cluster. In this study, a procedure is proposed to monitor the wafer defects in IC manufacturing. The Clustering Analysis is employed to adjust the number of wafer defects, thereby allowing not only the adjusted number of defects to satisfy the assumption of Poisson distribution but the conventional c-chart to still be used as well. The adaptive control chart is utilized to reduce the sampling cost. The proposed approach can reduce the false alarms caused by the clustered defects. The effectiveness of the proposed approach is demonstrated through a case study.

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