

G.R.R. Evaluation and Application in IC Manufacturing

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Abstract—Gauge Repeatability and Reproducibility (G.R.R.) is one part of Measurement System Analysis (MSA), which is to appraise the variability of measurement system. There are three methods to evaluate G.R.R.: Range, Average-Range and ANOVA. Range method is only to approximately evaluate measurement variability but cannot estimate the contribution of repeatability and reproducibility. So, it's not applicable in IC manufacturing. In this paper, we studied and analyzed the difference between Average-Range and ANOVA in G.R.R. evaluation by using IC manufacturing data.

Index Terms—G.R.R., average-range, ANOVA, NDC, IC manufacturing.

I. INTRODUCTION

MSA is very important to appraise the quality of a measurement system, especially for IC manufacturing with an advanced technology node, i.e. 40nm and below. The measurement error may be from appraiser, equipment, material, method or environment. The variation source analysis for the measurement system is more and more inevitable.

In MSA, G.R.R. [1], [2] as the appraisal of measurement system precision can be evaluated by the following three methods [3]: Range, Average-Range and ANOVA (Analysis of variance). Range method is only to provide a quick approximation of measurement variability and cannot calculate the repeatability and reproducibility, so Average-Range and ANOVA are more popular in IC manufacturing. Average-Range method [4], [5] is using the average and range value to appraise the measurement system, while ANOVA method [6], [7] is using the standard deviation. In this paper, we studied and analyzed the difference of Average-Range and ANOVA and the application in IC manufacturing.

II. METHODOLOGY

In this study, no manual operation was adopted and all data were collected by automatic metrology tools. And we compared G.R.R. data derived from Average-Range and ANOVA method for thick and thin films.

A. Methodology for G.R.R. Evaluation

Average-Range and ANOVA have different statistical calculation, as shown in Table I. The former uses the average range by a constant (K) to calculate the EV & AV, while the latter uses the standard deviation. In addition, to estimate

G.R.R., the process variation should be determined. According to MSA manual, there are 3 approaches [3] to have the process variation. The first one is to use specification tolerance. The resultant G.R.R. is also called Precision/ Tolerance (P/T) ratio, which is the most popular method used in IC manufacturing. The second one is to use surrogate process variation in the case of no sufficient samples to represent the process variation. That is, a long-term inline process variation taken from actual production performance is adopted. Here we use the actual standard deviation of inline or offline SPC charts which is recorded as inline TV (total variation). The last one is to use process variation taken from the parts in the G.R.R. evaluation itself by summing the square of both the repeatability variation, reproducibility variation and the part variation.

Here we also introduce NDC (Number of Distinct Categories) as another index to appraise metrology tool's capability that how many data groups could be clarified. It is the number of non-overlapping 97% confidence intervals that will span the expected product variation and should be greater than or equal to 5 [3].

TABLE I: G.R.R. DIFFERENCE CALCULATION METHODS FOR AUTOMATIC MEASUREMENT SYSTEM

G.R.R. Methodology	Average-Range	ANOVA
EV	$EV = \bar{R} * K_1$	$SS_e = TSS - [SS_A + SS_P + SS_{AP}]$ $MS_e = SS_e / (nk(m - 1))$ $EV = \sigma_e = \sqrt{MS_e}$
AV	$AV = \frac{\sqrt{(\bar{X}_{DIFF} * K_2)^2 - EV^2}}{(n * r)}$	$SS_A = \sum_{j=1}^k \left(\frac{x^2 \cdot j}{nm} \right) - \frac{x^2 \dots}{nkm}$ $MS_A = SS_A / (k - 1)$ $AV = \sigma_A = \sqrt{MS_A}$
PV (Part Variation)	$PV = [Max(\bar{x}_i) - Min(\bar{x}_i)] * K_3$	$SS_P = \sum_{i=1}^n \left(\frac{x^2 \cdot i}{km} \right) - \frac{x^2 \dots}{nkm}$ $MS_P = SS_P / (n - 1)$ $PV = \sigma_P = \sqrt{MS_P}$
G.R.R.	$G. R. R. = \sqrt{EV^2 + AV^2}$	
P/T ratio	$\%G. R. R. = \frac{6G. R. R.}{USL - LSL} 100\%$	
G.R.R./Inline TV	$\%G. R. R. = \frac{G. R. R.}{Inline TV} 100\%$	
%G.R.R.	$\%G. R. R. = \frac{G. R. R.}{\sqrt{TV^2}} 100\% = \frac{G. R. R.}{\sqrt{G. R. R.^2 + PV^2}} 100\%$	
NDC	$1.41 * PV / G.R.R.$	

B. Experiment Design for G.R.R. Evaluation

We designed 3 groups of experiments as listed in Table II

Manuscript received April 29, 2015; revised August 5, 2015.

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to study the effect of measurement objectives, measurement and estimation methods on G.R.R. Additionally, Precision/Tolerance (P/T) ratio is also estimated by using the data.

TABLE II: EXPERIMENTS FOR G.R.R. EVALUATION

	Wafer	Operator	Times
Average-Range	1pcs	3	3
Average-Range	5pcs	3	3
ANOVA	5pcs	3	3

III. DATA ANALYSIS AND RESULTS

Based on above design, typical thickness metrology tools are selected for data collection, covering the thick and thin film thickness of production line.

A. Different G.R.R. Methods Data Analysis

1) P/T ratio

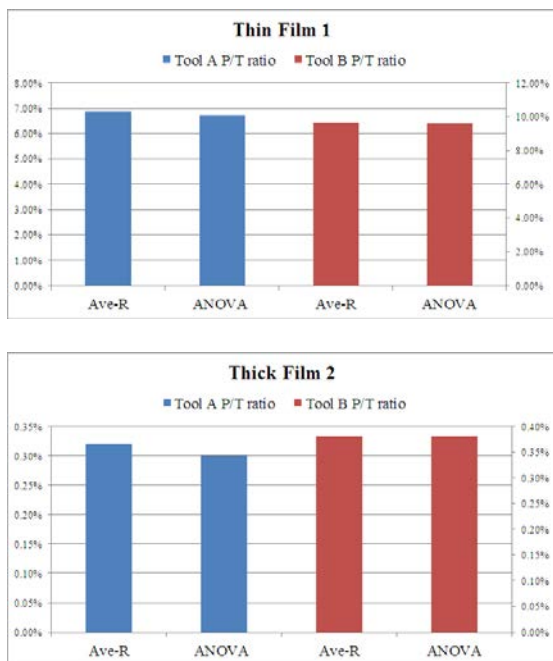


Fig. 1. P/T ratio comparison.

From Fig. 1, it can be seen, whatever thick or thin film, P/T ratio derived from Average-Range is higher than that derived from ANOVA.

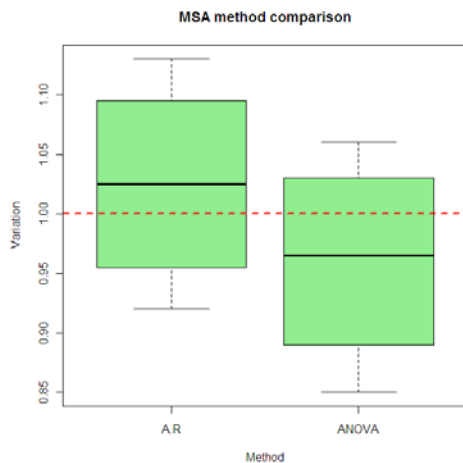


Fig. 2. Two methods calculation result comparison.

To validate the observation, we calculate the standard variation derived from Average-Range and ANOVA,

respectively, by repeated sampling from a group of normal distributed samples with standard variation of 1. It can be seen from Fig. 2, the mean value of Average-Range is higher than that of ANOVA, although t test shows no statistical significant difference with p value of 0.34 which is higher than 0.05. In this case, Average-Range is preferred considering its friendly calculation.

2) PV

Measurement system error has not only EV and AV, but also part variation.

In this experiment, limited by sample preparation, only within wafer and wafer to wafer variation are counted. As shown in Fig. 3, PV extracted from this experiment (both Average-Range and ANOVA) cannot represent inline production measurement for both thin and thick films. It's indicated lot-to-lot or tool-to-tool variation cannot be neglected for this process. Therefore, to have a relative accurate G.R.R. estimation, sample preparation should cover all possible variation sources to total part variation. However, it's not applicable in real operation in G.R.R. evaluation.

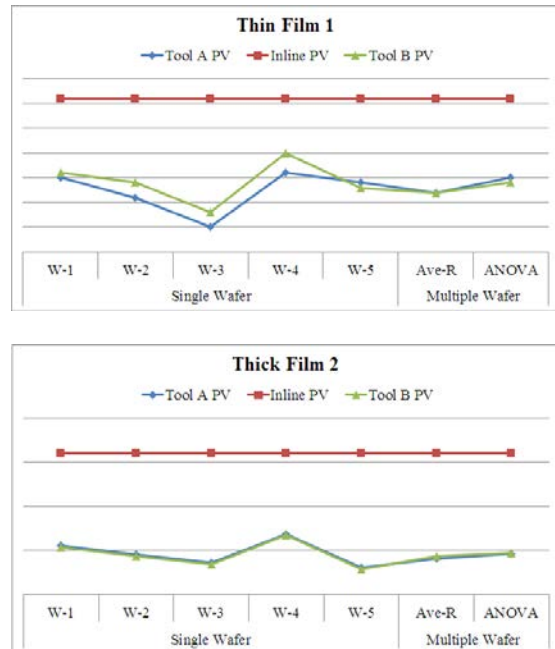


Fig. 3. PV comparison of single wafer and multiple wafers.

3) Effect of process variation on G.R.R.

Using the three approaches described in section 1, %G.R.R. is calculated as shown in Fig. 4. It can be seen G.R.R./TV is much higher than the other two approaches because of the under-estimated TV (only within wafer and wafer-to-wafer variation is covered limited by sample preparation). And P/T ratio is lower than G.R.R./inline TV. Additionally, from the comparison of inline TV derived G.R.R./inline TV and P/T ratio. The process capability can be estimated. The higher the ratio of inline G.R.R./inline TV to P/T ratio is, the better the process capability is. Obviously, the process capability of thick film is much better than that of thin film.

In addition, it's noted that thin film measurement is challenging for both tool A and B. Both P/T ratio and G.R.R./inline TV is marginal pass comparing with 10% criteria. Checked the stability monitor and production line monitor data of the same level for thin film, it's found the contribution of metrology tool induced variation is about 15% of total process variation

($\sigma(\text{metrology})/\sigma(\text{process})=0.022/0.1435=15\%$), and higher than 10% (Fig. 5 and Fig. 6). Further checked the metrology tool SPEC sheet limit, it's 0.017. It means the thickness measurement tool is not suitable for the thin film measurement due to the variation of the thin film measurement is out of the metrology tool limitation ($0.022 > 0.017$).

From the above discussion, both P/T ratio and G.R.R./inline TV can effectively evaluate metrology tool capability. To simplify G.R.R. evaluation, P/T ratio is preferred. That should be the reason for P/T ratio is so popular.

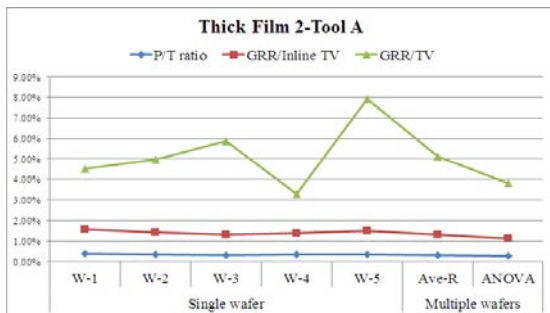
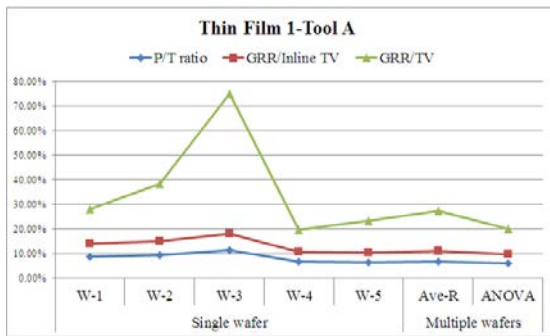


Fig. 4. P/T ratio, GRR/inline PV and GRR/TV comparison.

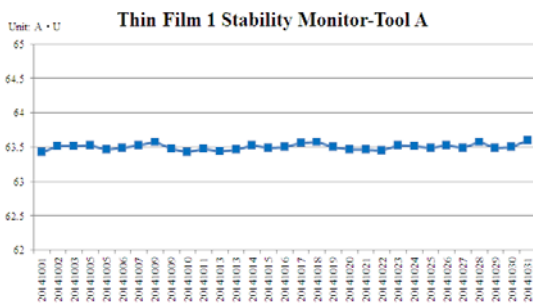


Fig. 5. Tool a thin film 1 stability monitor performance.

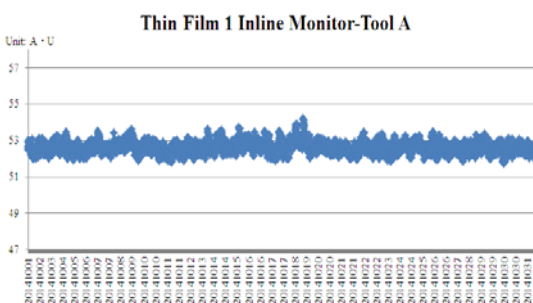


Fig. 6. Tool a thin film 1 production line monitor performance.

4) Number of Distinct Categories (NDC)

To further evaluate the capability of measurement system relative to the parts variation, NDC is calculated, as shown in

Fig. 7. It can be seen, the thinner the film is, the lower NDC is, and even lower than 5. It's reasonable, as discussed previously. Thin film has a relative high G.R.R. but low PV, comparing with thick film, as shown in Fig. 1 and Fig. 2. Especially in the case of NDC lower than 5, it's challenging to measure thin film using the same metrology tools as thick film.

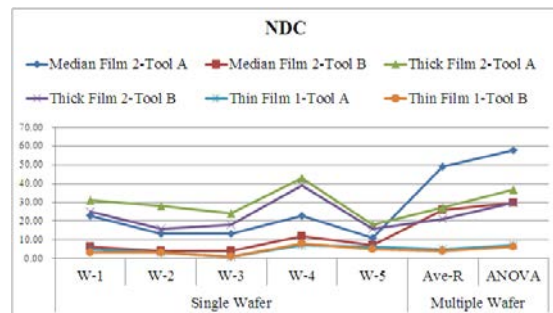


Fig. 7. NDC comparison.

IV. CONCLUSION

In this paper, we studied the effect of statistical analysis methods (average-range and ANOVA) on G.R.R. estimation by using the data measured by the typical thickness metrology tools. No statistical significant difference is found in G.R.R. by Average-Range and ANOVA methods.

As for %G.R.R. characterization, we applied 3 approaches to determine process variation, that is, surrogate process variation by long-term inline or offline production monitor, specification tolerance and the variation from G.R.R. test. Owing to the complex IC manufacturing process, the sample preparation in G.R.R. test is limited and the derived variation could hardly represent that of production line and is under-estimated comparing with long-term production line variation. So this approach is not preferred. However, from the demonstration result of thin, median and thick film data, SPEC tolerance derived from P/T ratio has the same sensibility to metrology tool capability as surrogate process variation derived from G.R.R./inline TV, and P/T ratio is directly linking to customer requirement besides its operation friendly (SPEC tolerance kept unchanged, but inline monitor derived from surrogate process variation is dynamic). Therefore, P/T ratio is preferred and popular in IC manufacturing.

Additionally, from the comparison of inline variation derived from G.R.R./inline TV and P/T ratio, the process capability can also be estimated. The higher the ratio of G.R.R./inline TV to P/T ratio is, the better the process capability is.

As for the metrology tool with P/T ratio closing to 10% criteria, the measurement is very challenging for the measurement target. The risk can be further accessed using the stability monitor data of the target measured by the metrology system. So the routine measurement tool stability monitor is also important.

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