Towards zero-defect manufacturing in the silicon wafer production through calibration measurement process: an Italian case

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Abstract. In electronic devices, the number of transistors and components per unit of area is still significantly increasing. In this context, the quality of the substrate of these devices is consequently increasing, making stricter and more pervasive the quality controls that a silicon wafer undergoes during its production process . This issue is extremely important to be addressed to reduce costs in quality controls in production moving towards zero-defect manufacturing. The purpose of this paper is to reduce time and costs spent in calibration procedures of the instruments needed to measure the mechanical parameters of silicon wafers, by revising and standardizing the already adopted procedures. To address this goal, the extant literature, patents, and standard about procedures employed for measuring the mechanical parameters of silicon wafers are studied. The results are elaborated and applied to an industrial case study, the Italian branch of a Taiwanese manufacturing company. In particular, the focus of the case is on the Bow/Warp machine's calibration which needs to be performed periodically to guarantee a correct measurement accuracy. Such calibration has strong implications for production efficiency and flow. The results are reported and discussed to highlight the key practical and theoretical implications.

Keywords: Silicon Wafer, Mechanical Parameters, Bow/Warp Calibration, Zero Defect Manufacturing, Waste Management.

1 Introduction

In 50 years, technology improvements in electronics drove innovation in the whole society becoming a cornerstone element in daily life. A common element for most of the electrical devices lays in the reliance on silicon, a semiconductor material used to manufacture most of the components such as transistors [1]. Transistors are key to determine the performances of the final product since device's power, efficiency and capability depends strongly on circuit density, that can be expressed as the number of transistors per chip. Over the decades, size of transistors has decreased from 20µm in 1970 to few nanometres in recent years [2]. However, the technology pace in the Semiconductor industry keeps increasing and, in such a fast-changing environment, companies must have the capabilities to quickly adapt their processes to new technological requirements. From Silicon wafer production to the final assembly of circuit, the number of quality controls on the product increases with the tightening of product's specifications. Quality control is not a value adding activity but, especially in this high value context, it can save the additional costs of transforming material that will be further processed before being scrapped [3]. Moreover, to ensure the elimination of any defect, the several quality controls needed in the industry are extremely expensive and require a huge amount of sample products wasted. To reduce avoidable quality controls limiting waste creation and costs increment, semiconductor Industry is pursuing a Zero-Defect Manufacturing (ZDM) strategy [4] which aims at producing without delivering non-conforming products to the next production step. To achieve ZDM, [5] underlined two main approaches: i) Product-oriented ZDM identifies and studies the defects on the actual parts and ii) Process-oriented ZDM studies the defects of the manufacturing equipment and based on that can evaluate whether the manufactured products are good or not. Nevertheless, at the best of authors knowledge, few contributions explored the potential benefits of introducing at process level, more specifically in the calibration phase, the ZDM principles. Therefore, in this paper the focus will be put on the application of Process-oriented ZDM approach to the measurement process of shape parameters of silicon wafers which, should be perfectly round and flat disks, through the definition of reusable test wafers. To address this goal covering the envisioned gap in terms of limited attention over the introduction of ZDM principles in calibration procedures, a case study is proposed.

Entering more in detail, the shape of the silicon wafers may deviate due to deformations and thickness variations. Indeed, one of the most important parameter to be measured is the wafer flatness, that is defined as the variation of thickness with respect to a reference plane. The reference plane can be chosen in two ways: i) Three-point method or ii) Best fit method (the one adopted in this study) [6]. In brief, the main parameters that define the variations of wafer's shape and require machine calibration are [6]: (i) Total thickness variation (TTV): the maximum variation in wafer thickness; (ii) Bow (B): the distance between the reference plane and the central point of the median surface; (iii) Warp (W) or warpage: the difference between the maximum and the minimum distance of the median surface from the reference plane. Therefore, in this contribution, the calibration process of the measurement machines located in different departments of a company is investigated considering the calibration as one of the processes where start implementing a preliminary ZDM approach. More in detail, one of the ZDM pillars is the standardisation [7], hence, to address the goal of this contribution the authors aim to evaluate the possibility to standardize the calibration procedure of the different departments, thus identifying a unique procedure putting the basis for ZDM while reducing costs and wastes.

The remainder of the contribution is the following: section 2 describes the research objective and the methodologies employed to address it, section 3 provides a background about the Bow and Warp (B/W) formation and calibration theory, section 4 describes the adoption of the approach to standardise the calibration procedure inside the company, section 5 discusses the results obtained through experiments and section 6 concludes the research highlighting the key contributions of the paper, limitations and future outlooks.

2 Research objective and methodology

2.1 Research objective and Research Questions

The goal of the research is to introduce the ZDM principles into the calibration measurement process considering that ZDM is usually applied to product while the application at process level, especially regarding the calibration procedures, is still limited. Indeed, from a practical point of view, the introduction of ZDM could cope with the challenges faced in the industrial environment during the calibration procedure of silicon wafer defining a standard procedure including the nominal wafer characteristics to be used. In this regard, the research aims to introduce ZDM by understanding how to standardize the B/W calibration procedures of a group of machines, which are currently located in different departments. In this way, it is expected to obtain better operational performances by reducing waste and putting the basis to embrace a ZDM approach at plant level while ensuring high measurement accuracy. To pursue the declared research objective, the following research questions (RQ)s had been formulated and addressed. RQ1): "*What are the factors and core elements affecting the quality of measurement corrections applied through B/W calibration?*" RQ2): "*How to standardize B/W calibration methodologies and practices to maintain a high measurement accuracy and improve operational efficiency?*" .

2.2 Research methodology

To answer to RQ1, both scientific literature (using Scopus) and grey literature (such as patents and standards) were reviewed based also on the suggestions from experts in the field (i.e, the person who developed one of the patents). The string of keywords used for the review was focused on specific technical topics, namely: TITLE-ABSTRACT-KEYWORD (("Silicon" or "Silicon Wafer") AND "Mechanical properties" AND "Young's Modulus" AND ("Warp" OR "Warpage") AND "Bow" AND "Manufacturing"), as also suggested by the experts. The results were scanned and selected according to their relevance to the industrial problem faced: the calibration procedure and its standardization. The selected papers, registered patents, standards, and machine's builder instructions were reviewed (RQ1). The results were discussed and applied to an industrial case, the Italian plant of a semiconductor company, to define the standard procedure to be followed by the whole plant addressing RQ2. The application case analysed was the Italian plant of MEMC Electronic Materials, controlled by GlobalWafers, a Taiwanese company producing and supplying silicon wafers for the semiconductor industry. The application case was conducted through semi-structured interviews with company's managers to investigate the AS-IS and by a 2-factors Design of Experiment (DOE) approach defining the TO-BE scenario [8].

3 Background on Bow and Warp

3.1 Mechanical parameters measurement: Bow and Warp definition

In 200mm wafers, flatness is typically measured using non-contact capacitance metrology [9]. This can be performed in different ways although one of the most widespread is prescribed by the SEMI MF1390-0218 [10]. According to it, the wafer is supported by a holding device (chuck) in its centre. The chuck has a diameter of about 3.6cm for 200mm wafers. The measurement system is composed by two probes. The distance between the probes must be accurately known and it is calibrated periodically. Wafers are rotated and scanned through the capacitance probe system to scan the selected area. The probes are capable of independent measurement of the distances between the probe itself and the nearest surface of the wafer. The result of the measurement is a set of numbers describing the thickness of the wafer in each scanned point (that result to be more than 8.000 for a 200mm wafer). Each parameter related to flatness and shape (i.e., B/W) is then computed through different algorithms from this raw data. Although the process appears to be relatively simple, it presents some issues due to the intrinsic complexity given by the low accepted tolerances. Among all, there is the gravity force effect exerted on the wafer. Since the wafer is held by a chuck whose diameter is considerably smaller than the one of the wafers themselves, the gravity force tends to pull down its edges. To not transfer this gravitational effect on the final values of the parameters, a gravitational correction algorithm must be applied as reported by the SEMI MF1390-0218 [10]. This correction is performed using data collected during the "Bow/Warp calibration" procedure, in which a representative wafer is scanned, flipped, and scanned again (see sub-section 3.2). In **Fig. 1** the effect of gravity is schematically illustrated.

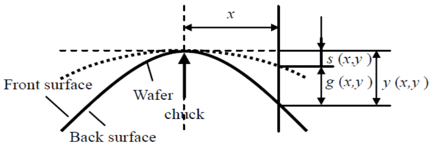

Fig. 1 Effects of gravity on a wafer under measurement

According to SEMI MF1390-0218 [10], the factors that affect the gravity induced deflection are mainly the Young's modulus (or Elastic modulus quantifying the elastic behaviour of the material), that can be affected by the crystallographic orientation (that is the orientation of the structure described by "*hkl*" Miller indices, that are the reciprocals of the coordinates of the intercepts on the XYZ axes, multiplied by the lowest common denominator) [11] [12], the nominal thickness and the nominal diameter. Moreover, also the backside conditions may influence the calibration procedure results.

This measurement method is the most adopted for measuring mechanical parameters of wafers which diameter is lower or equal than 200mm [9]. For higher diameters, different methodologies have been developed in recent years [13]. In particular, such methodologies comprise optical methods based on spectral-domain interferometer. In this measurement set-up, the wafer is unclamped and supported at the edges. For this reason, the gravitational effects do not cause deflection on the measured wafers and the measurement embodiment does not need to correct for such deflection [14].

3.2 Bow/Warp calibration procedure

B/W calibration, also defined as "Representative wafer inversion calibration" is a measurement machine set-up that needs to be performed periodically. Details about the measurements and computation behind B/W calibration can be found in [15]. The measurement apparatus is composed by a two-probe system and a chuck, on which the wafer to be measured relies. The coordinate system works as follows: the wafer's surface is identified by the angle θ and the distance from the centre X. At each measured point, identified by a couple (x, θ), corresponds a vertical distance z from the plane passing by middle of the two probes. As already mentioned, the B/W calibration is necessary to apply a correction to the measured wafer: this correction becomes necessary due to the gravitational force that is applied to the wafer (especially at the edges), when it relies on the chuck at its centre. In addition to that, as claimed in *US patent 4750141*[15], the calibration is also necessary to correct for the errors induced by the measurement apparatus itself. Overall, the B/W calibration can be subdivided into two steps: 1) X-Calibration: A first measurement M1 of the representative wafer is performed. This measure can be split into one desired wafer related component Mw and an undesired fixture and gravitational related component Mc (where M1, Mc, Mw are matrices)); 2) θ-Calibration: after the measurement is completed, the wafer is released by the chuck and the chuck alone is rotated by a predefined angle θ1, defining a second home position for the chuck. The flipped wafer is then chucked and measured again.

4 Defining the nominal standard wafer: Application case

In this section, the objective is to define the nominal wafer characteristics that the testing wafer should have. To achieve such goal the authors analysed the factors affecting the physical and metrological aspects that determine B/W calibration adjustments (emerged in section 3). This is done through an industrial use case to propose a standard procedure to be adopted homogeneously at plant level. As reported in Tab. 1, at its current state the company under analysis is adopting different calibration procedures in the different areas of the company. Moreover, a nominal wafer is often used for the test and then it is discarded. Through the analysis suggested by the findings from the extant literature and patents (see chapter 3) it is aimed to evaluate the characteristics a nominal wafer should have to be used in the different areas to reduce scraps and waste while preserving quality putting the basis to embrace ZDM.

Tab. 1 - Summary of B/W calibration procedures in the different areas

Area	Calibration frequency	Wafer used for calibration	Control Plan
A	Every lot; with a wafer taken from the production	Wafer from the lot, non-destructive process	Sampling based on position in the machine
B	Every shift	Nominal wafer, destructive process	Random sampling
C	Every change in measurement mode and every change in lot backside condition	Nominal wafer, destructive process	Random sampling
D	Every change in measurement mode and every change in lot backside condition	Wafer from the lot, destructive process	100% of wafers

As previously anticipated, the main factors affecting the gravitational deflection are the Young's modulus, the thickness and the diameter. Considering keeping stable the wafer diameter (around 200 μm), the other aspects were investigated by relying on a DOE analysis to identify a standard procedure to be applied in the whole plant.

4.1 Young's modulus and crystallographic orientation

The first experiment performed is about the Young's modulus and the crystallographic orientations since, as previously mentioned, the Young's modulus of a thinned silicon wafer differs according to wafer crystallographic orientation as reported in Tab. 2.

Tab. 2 Young's modulus in different crystallographic orientations [16]

Crystallographic orientation	<100>	<110>	<111>
Young's modulus [MPa]	130	169	168.9

First, an experiment was executed to test the actual significance of crystallographic orientation on the goodness of gravity correction applied by the measurement instrument. Indeed, this experiment was set up to quantify the effects of crystallographic orientation of the nominal wafer on warp measurements. For this purpose, two entire lots, with different crystallographic orientation, were measured twice, each time calibrating with a sample wafer taken from the lots themselves (see Tab. 3).

Tab. 3. - Experimental design on effects of calibration wafer's crystallographic orientation

Measured Lot	Lot's orientation	Calibration Wafer	Calibration wafer's orientation

A	<100>	A	<100>
A	<100>	B	<111>
B	<111>	A	<100>
B	<111>	B	<111>

Once the data were acquired for each lot, the measurements obtained were compared wafer by wafer. To verify if the change in calibration procedure significantly affects the W measurements, the distributions of paired differences in the Warp Best Fit (WBF) numerical values are computed as $\mathrm{WarpBF_{WFRB}} - \mathrm{WarpBF_{WFRA}}$ and plotted in Fig. 2.

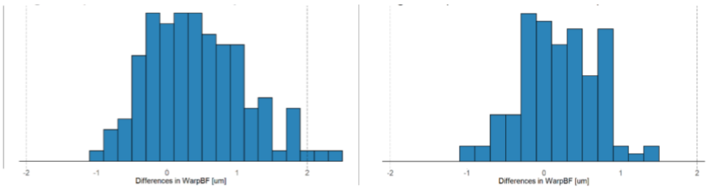

Fig. 2 Distribution of WBF differences LOT A (left) vs LOT B (right)

In the analysis performed, the most appropriate W value is the one measured when the orientation of the calibration wafer and the measured lot coincide. Nevertheless, the results show lower variability for LOT B distributions (the paired differences are always below the arbitrary ±2μm threshold and they appear to be symmetric around 0). Indeed, when measuring a <111> oriented wafer, less differences are highlighted when changing the properties of calibration wafer. In conclusion it is acceptable to measure a <111> wafer even calibrating for B/W with a <100> oriented wafer while the opposite situation introduces more variability in the results. For these reasons, and assuming that for the Bow Best Fit (BBF) would work accordingly, a crystal with <100> orientation can be used to create standard wafers to be used across the plant for B/W calibrations.

4.2 Backside conditions

The second experiment performed is about the backside condition of the standard nominal silicon wafer. Silicon wafers can be produced with different backside conditions which means that different materials can be deposited on wafer's backside, potentially causing a difference in its stiffness and elastic properties. Different materials that can be deposited on the backside are: Polycrystalline silicon, Silicon oxide and Epitaxial monocrystalline silicon. Also, different combinations of the above-mentioned materials can be deposited. To test for the significance of the backside condition on the gravitational induced deflection, 238 wafers presenting very different backside conditions were measured twice. The two measurements of the same wafer differ from each other for the representative wafer used for B/W calibration and the measurement machine used. Firstly, the B/W calibration was performed with a wafer from the lot or with a wafer with the same backside condition of the measured ones. Then, the B/W calibration was performed with one of the nominal wafers produced. Both the WBF and the BBF paired differences are centred around zero as showed in Fig. 3 and Fig. 4. Indeed, given the variety of backside conditions tested, it can be stated that there is no evidence that the wafer's backside condition affects significantly the gravitational induced deflection of a 200mm wafer supported by a 3cm diameter chuck at its centre.

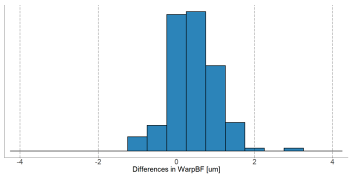

Fig. 3 Histogram of WBF paired differences

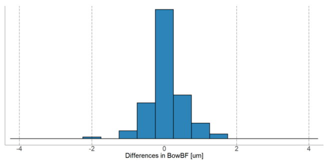

Fig. 4 Histogram of BBF paired differences

4.3 Nominal thickness

Last, the thickness of the standard nominal wafer is studied. Thanks to the empirical formula to determine the deflection induced by gravity at the edge of a wafer reported in the SEMI MF1390-0218, it is possible to estimate the gravity-induced deflection at the edge for different nominal thicknesses. Considering that the highest request by the customers in terms of thickness is 725 μm, the standard nominal wafer thickness to be used for calibration will be 725 μm

4.4 Empirical results from the application

In light of the research conducted about articles, registered patents and standards and the experiments performed, it was possible to update the B/W calibration procedure uniformizing it in all the different areas of the plant. A set of wafers from the same ingot have been produced to act as nominal samples to be used for B/W calibration. Considering that the previous procedure required to use wafers from production for the calibration (with consequent scrap due to contamination), this led to a decrease in yield losses leading the company to get closer to the ZDM approach. Indeed, thanks to this evidence it is possible to reduce the number of B/W calibrations performed across the plant as well as the number of wafers scrapped for this practice (e.g., area C passed from 35 calibrations daily to 17,2 on average every day). The first benefit is the reduction of the number of machine set-ups performed every day by increasing the capacity of the measurement gates. The second benefit is the reduction of scraps that directly impacts the plant overall output volumes leading towards ZDM. A detailed description of the results achieved is summarized in **Tab. 4**.

Tab. 4 TO-BE control plan proposal

Area	TO-BE
A	the number of calibrations is reduced, from a required frequency of one calibration per lot, to one calibration per day, unless the nominal thickness of the measured lot is significantly different from the nominal one (±25µm). Actually, most of the products requires a standard nominal thickness, thus the expected number of calibrations due to higher or lower thickness is low.
B	the number of calibrations is slightly increased: this is due to the new calibration needed when the thickness is outside the ±25µm range from the nominal one; the proposed procedure considers the effects of thickness on the gravity induced deflection, improving measurement accuracy
C	the amount of B/W calibrations performed is halved, increasing measurement machine capacity by more than 13.000 wafers/month
D	the amount of B/W calibrations performed is reduced, and the wafers used for calibrating the machines are not extracted from production wafers, but, as in all other areas, are nominal wafers purposefully created. Thus, yield losses are reduced since no wafer from production is scrapped to perform B/W calibration

5 Conclusions and Future Research Opportunities

The present contribution aims at putting the basis to embrace ZDM approach in semiconductor industry by acting on the calibration process of silicon wafer through the introduction of a standard procedure. A review was conducted on the existing literature, patents, and standards pertaining to calibration methods. The purpose was to identify the critical factors influencing the calibration procedure and to establish a standardized approach that would lead to ZDM. The identified approach was applied to an industrial case to test its validity and to identify the characteristics needed for a nominal wafer in this specific case. Based on this result, it was possible to reduce both waste and costs ensuring high quality too leading towards a preliminary embracement of ZDM. The present research has both practical and theoretical implications. Regarding the practical implications, this research supported the company in reducing the yield losses and related costs by introducing a standard calibration procedure. This standardised procedure represents for the company the initial step towards ZDM approach which is nowadays required to be competitive on the market. In addition, the selected sector may have positive impacts on the whole society considering how diffused these components are. Also, theoretical implications are worth being mentioned, since the ZDM has been explored in several sectors, but not yet investigated in the calibration procedures area within the metrology field of research. Indeed, most of the previous ZDM-related research were focused either on product or manufacturing process and never considered the opportunities in specific stage of the asset lifecycle management, like the calibration of industrial assets. Last, in addition to the opening of this research field, other future research opportunities might be mentioned based on some research limitations. A comparison with similar industrial entities might be performed to evaluate the best calibration procedure according to their past experience. This can be complemented by an extensive literature review to evaluate whether additional tests might be performed.

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