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Uncertainty evaluation of diameter measurement in float-zone crystal growth production

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Abstract

Float-zone crystal growth is a method for manufacturing silicon crystals with higher purity and higher resistivity due to crucible-free intrinsic. Diameter measurement of both silicon polycrystalline crystal and monocrystalline crystal using vision system technologies plays a significant role in float-zone silicon crystal growth production yield. The correct measurement evaluation is important since low measurement quality can propagate errors in the diameter control system, thus negatively affect the properties of the growing crystal. Therefore, it is essential to obtain diameter measurements with high accuracy as well as with relatively low uncertainty. Targeted to float-zone silicon crystal growth, the paper presents the uncertainty evaluation of diameter measurements from digital images following the Guide to the Expression of Uncertainty in Measurement (GUM). The uncertainty of diameter measurements of a cylindrical gauge was assessed in the test bench simulating float-zone crystal growth production. The resulting uncertainty of the measured diameter of 203.85 mm was 0.26 mm without considering the uncertainty contribution from thermal expansion.

Diameter measurement; Vision system; Measurement uncertainty; Float-zone crystal growth

1. Introduction

Silicon wafers are the backbone of the electronic industry. Wafer fabrication begins with single crystal growth process where single crystal ingot is grown from polycrystalline melt. Among all crystal growth techniques, Float-zone (FZ) has proved to be the technique allowing for manufacturing the purest crystal with high resistivity [1], and therefore FZ crystal is preferred in high power electronics and innovative devices [2]. In the FZ method, the polysilicon is melted by a contactless inductive coil and a monocrystalline seed crystal is immersed into the melt and grown into silicon ingot, as shown in Figure 1. The crystal continuously moves downwards during production while the camera measures at the fixed position, thus enabling dynamic diameter measurement by measuring the distance between two points on the circular crystal at a specific height.



Figure 1. The principle of FZ process.

In the FZ method, the crystal diameter is strictly controlled to ensure the crystal grows according to specifications. The accuracy of the measured diameter will determine the accuracy of the diameter control system [3]. Additionally, keeping the diameter under control limit can help reduce extra waste and reduce scrap. Therefore, it is desirable to measure the crystal diameter with high accuracy and efficiency.

Unlike other crystal growth techniques where only indirect measures such as weight-based method or ellipse fitting method [3] are feasible, it is easier to directly measure crystal diameter during the FZ process with optical-based method due to higher process visibility allowed by the contactless heating. With a vision system pointing at a crystal, the crystal diameter is defined as the distance between two edges of the crystal in the image, as shown in Figure 1. The diameter measurement approach normally consists of two steps. First, the camera is calibrated to obtain the correspondence between 2D image coordinates and 3D world coordinates. Then image processing techniques are utilized to extract the edge of the crystal, thus the diameter dimension can be extrapolated from the calibration routine. The diameter control system depends on reliable estimates of the measured diameter. Therefore, this paper describes an approach to estimate diamters measurement uncertainty following Guide to the Expression of Uncertainty in Measurement (GUM) [4].

2. Problem statement

The crystal diameter measurement can be simplied as a cylinder measurement where the optical axis is set to be perpendicular to the cylinder axis, as shown in Figure 1. The focus and aperture of the camera are kept unchanged during diameter measurement. The measurement in an image can be calculated through the pin-hole camera model. However, due to the property of pin-hole model, the light ray is tangent to the cylinder, as shown in Figure 2, which means that the measuring length is actually AB instead of diameter.



Figure 2. Transformation of measured length into actual diameter with trigonometric principle.

Therefore, the trigonometric principle needs to be applied to transform measured length into actual diameter, as indicated in Eq. 1 and Eq. 2.

Diameter:
$$Q_3 = Q_1 \sin \theta_1$$
 (1)

$$= Q_1 \frac{Q_2}{\sqrt{Q_2^2 + \left(\frac{Q_1}{2}\right)^2}}$$
(2)

Where: Q_1 is the distance between two edge points, measured from the image with estimated camera parameters; Q_2 is the distance between the nodal point of the lens and the origin of world coordinates.

3. Uncertainty evaluation

The thermal expansion coeffienct of silicon is around 2.56 \times $10^{-6} K^{-1}$ [5]. However, due to the complex thermal behaviour of monocrystalline silicon and the difficulty of measuring the crystal temperature at temperatures over 1400 °C, the uncertainty contribution from thermal expansion is not considered in this study. Therefore, we setup a test bench to simulate the crystal growth in a temperature-controlled room. In terms of the requirement from the industry, the target value of measurement uncertainty is set to 0.3 mm. The measurement procedure begins with the camera calibration to obtain the camera-specific parameters. Then the measuring object is loaded in front of the camera with the fixed distance of 1200 mm. Feature point detection was carried out for identifying the edge points of the measuring object and thereafter the distance between two edge points (Q_1) is computed. Finally, the diameter is corrected by Eq. 2. In this study, we selected a test cylinder with diameter of approximately 203.85 mm to be the test sample, on which we evaluate the uncertainty. The uncertainty contributors in this study were investigated as follows:

(a) Bias of the diameter output from the model (Q_3)

In order to obtain the bias of the model, we measured a multiple cylinder gauge with diameters ranging from 5 mm to 150 mm. The deviation error for each diameter of the gauge is shown in Figure 3. The bias of the model is defined as the difference of the averaged 30 measurements from 30 replicated images, against the reference diameter. The χ^2 test on the deviation errors gave a value of χ^2 = 139.8 against a confidence interval of 80% from 3.49 to 13.36, which means that the experimental distribution is too different from the normal. Therefore the presence of a systematic effect is evident and the null hypothesis must be rejected. Therefore, regression is used to deduce the pattern of the systematic factor versus the reference diameter. Here we assumed that the trend can be well described by a 3-segment function: linear line model for middlescale diameter, two parabolic model for small and large diameters, and the least square to calculate the parameters of the assumed model. The data were then corrected by the residual regression model, providing a data distribution that was validated by comparing it with the normal distribution as acceptance methodology for the chosen regression model. The bias of the test sample can thus be obtained from the regression model. Finally, considering a rectangular distribution, a bias standard uncertainty contribution of 1.3×10^{-1} mm for the test cylinder is obtained.

(b) Resolution of edge points detection of the camera (Q_1)

The feature point detection is carried out on a small Region of Interest (ROI) with a height of approximately 34 pixels. The computed distance of edge points is thus a mean distance of ROI. Therefore, resolution is tested by measuring diameter in different heights in an example image where the averaged diameter is taken as the diameter for that image. The standard deviation of these 34 pairs of points' distances of 2.7×10^{-4} mm was employed as $u_{Q_{1-res}}$.

(c) Reproducibility of edge points detection of the camera (Q_1)

Reproducibility is tested by taking 30 replicated images for the test cylinder. The standard deviation of 30 replicated Q_1 measurement of 6.5×10^{-4} mm was employed as $u_{Q_{1-res}}$.

(d) Bias of the measuring distance Q_2

The distance was obtained from the camera calibration and the uncertainty was evaluated to be 1 mm. Applying a rectangular distribution, a bias contribution was evaluated to be 5.8×10^{-1} mm.



Figure 3. Box-plot comparison for different diameters. Apparently there are systematic effects along different diameter.

Table 1 summarizes the contribution of the above uncertainty sources. A standard uncertainty of the test cylinder diameter can be evaluated based on Eq. 3. Finally, an expanded uncertainty U with k = 2 was evaluated to be 0.26 mm, less than target uncertainty (0.30 mm).

$$u_{Q3} = \sqrt{u_{Q_{3}-bias}^{2} + \left(\frac{\partial Q_{3}}{\partial Q_{1}}\right)^{2} \left(u_{Q_{1}-res}^{2} + u_{Q_{1}-repr}^{2}\right) + \left(\frac{\partial Q_{3}}{\partial Q_{2}}\right)^{2} u_{Q_{2}-bias}^{2}}$$
(3)

Table 1. Uncertainty budget of the diameter measurement.

Sources of uncertainty	Symbol	Standard uncertainty u	Sensitivity coefficient c	$c^2 u^2$
Bias of Q_3	$u_{Q_{3-bias}}$	$1.3 \times 10^{-1} \mathrm{mm}$	1	$1.7 \times 10^{-5} \text{ mm}$
Resolution of Q_1	$u_{Q_{1-res}}$	$2.7 imes 10^{-4} \mathrm{mm}$	9.9×10^{-1}	$7.3\times10^{-11}\rm{mm}$
Reproducibi lity of Q ₁	$u_{Q_{1-repr}}$	$6.5 imes10^{-4}~{ m mm}$	9.9×10^{-1}	$3.6\times10^{-10}~\text{mm}$
Bias of Q_2	$u_{Q_{2-bias}}$	$5.8 imes10^{-1}\mathrm{mm}$	1.1×10^{-3}	$4.1 \times 10^{-10} \text{ mm}$
Combined uncertainty	u _c			$1.3\times10^{-1}~\rm{mm}$
Expanded uncertainty	U(k = 2)			$2.6 \times 10^{-1} \text{ mm}$

4. Conclusion

Diameter measurements using a vision system play a significant role in the float-zone silicon crystal growth process. This paper presented the uncertainty evaluation of diameter measurements from digital images following the Guide to the Expression of Uncertainty in Measurement (GUM). The uncertainty of diameter measurements of cylindrical gauge was assessed in a test bench simulating float-zone crystal growth production with resulting uncertainty of the measured diameter equal to 0.26 mm, without considering the uncertainty contribution caused from thermal expansion.

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