Digital Defect Traceability across Sapphire Processing: Case Study on Micro-LED Chain

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ABSTRACT

We present preliminary results of a case study carried out by four major market players. An automated crystal scanner recorded defects in sapphire boules as they passed through consecutive production stages: *raw crystals (boules)* ➜ *cores* ➜ *EPI-ready wafers*. In parallel, the defectiveness was assessed by experts using manual methods. The experiment design allowed tracing individual defects through all stages.

We also show how digital quality control increases wafer yield by 'intelligent wafering', i.e. by correctly positioning the sapphire core in a wafering system.

INTRODUCTION

LEDs and micro-LEDs industry highly depend on the sapphire substrate. According to IHS LED Intelligence Service, 96.7% of the global LED production in 2020 was achieved on sapphire wafers. Material defects in the substrates - such as micro-bubbles, clouds, and structures - cause rejection of finished wafers and may also disrupt large production lines for weeks.

Manufacturers mitigate this risk by imposing increasingly stringent quality requirements on their sapphire core suppliers. The latter adapt by rejecting all suspicious areas in crystals, even if they are clean but located near a defect. As a result, a considerable part of fresh-grown sapphire becomes scrap, even though it can be used if adequately evaluated.

This study is to help sapphire manufacturers to transition to digital quality control that leads to material-saving by:

- tracing how defects in raw sapphire crystals affect the quality of micro-LED wafers
- identifying critical defect features that decrease the yield for the wafer manufacturer
- coding such indicators into the raw crystal scanner software
- increasing productivity by proactively improving core and wafer processing through computer-aided optimisation.

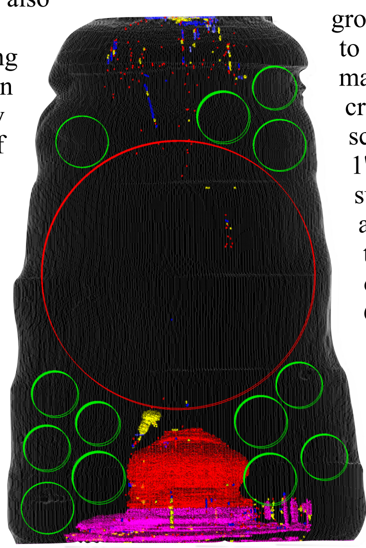


Figure 1: Scan of 90 kg raw KY-grown sapphire crystal with defect pattern and coring indications. Green shows defect-free cores; red - a defective core.

The project is led by Scientific Visual and Fametec-Ebner and involves third-party manufacturing companies and materials experts worldwide.

Scientific Visual operates the world's largest raw industrial crystal scanner, TotalScan™. Equipped with a fully automated 4-axis scanning head, it can examine crystals up to 350 kg and accurately detect internal defects down to 8 µm in sapphire, LT/LN, LBO, ZnSe, and semiconductor crystals. This service facility, located in Switzerland, was used as the analytical center for the study.

Fametec-Ebner is the market leader in heat treatment furnaces, running its own sapphire growing facility. The company meets the industry's needs for high-quality wafers by growing several 7- or 9-inch crystals in a single furnace. The crystals grown with a proprietary technique yield ultra-low bow and warp wafers that are specifically suited for micro-LED manufacturing.

The authors emphasise that this research is ongoing, and the paper shows only its interim results.

RESEARCH METHODOLOGY

1. Raw material. For this study, we used *c*-axis ∅7" HEM crystals subsequently cored to ∅6" cylinders, which is a standard size in the industry. The material was grown in several furnaces and at different times to reduce the effect of random fluctuations that may arise during the crystal growth. To select crystals suitable for the study, the authors scanned 96 raw crystals with a total weight of 1'480 kg. The crystals had to present a substantial variability of defect morphology and size. Five 7" rough crystals, representing the full range of quality from clean to very defective, were retained for processing into 6-inch cores.

The authors underline that the highly defective crystals chosen for this project do not represent the quality of Fametec-Ebner production.

2. Crystal scanning. A Scientific Visual TotalScan™ scanner was used for defect inspection. The scanner automatically detects bubbles, structures, and clouds in raw ("as is") crystals of any shape and determines defect-free zones suitable for wafer fabrication. For illustration purposes, For illustration purposes, Fig. 1 shows an example of such defect-conscious coring on a sapphire crystal grown by Kyropolous method. The 3D defect patterns obtained at this stage served as a starting point for defect tracing.

In addition to the automated measurement, experts from the industry evaluated the crystals manually to compare the reliability of human and TotalScan™ defect identification.

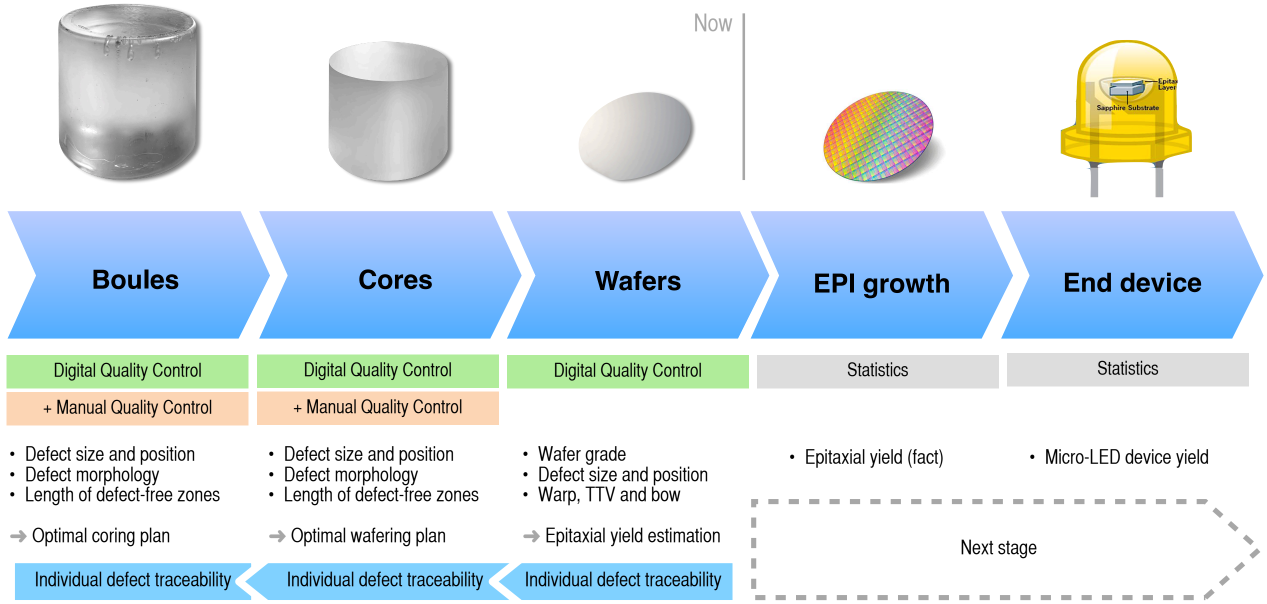


Figure 2: End-to-End study design

3. Coring. A reputable tier-one core maker processed the selected crystals into ∅6" cores. It had the references that allowed to unambiguously locate cores in the volume of the corresponding parental crystal. As in the previous stage, a fabrication expert independently evaluated the defect-free zones before passing the cores to the next wafering stage.

4. Core scanning. The five cores were (re-)scanned in TotalScan™ with the same settings as the original crystals, ensuring that their orientation was identical to one of the parent boules. The software output included defect pattern and length and position of the defect-free zones suitable for wafer processing. The 3D defect fingerprints obtained at this stage served as the second reference point in defect tracing.

5. Wafering. The cores were wafered with 1.75 mm pitch and consequently polished to 0.9 ± 0.025 mm thickness by a leading LED wafer manufacturer. They were marked with reference lines and points so that their orientation and position within the parental core could be unambiguously reconstructed. Thus, the authors obtained a mutual orientation of wafers, cores, and the original raw crystals. By now, we have received the complete end-to-end dataset for the first crystal; the others are in progress.

6. Wafer inspection. Each wafer was analysed using an automated KLA-Tencor Candela® system, which gave the indication of whether it complains to micro-LED specification and, if not, the reason for it: material defects, polishing/lapping defect, or AFM.

Warp, TTV, and bow values were also measured at this stage. Fametec-Ebner wafers exhibited average values that are 2 to 15 times ahead of the industry standards (shown in brackets): average bow 12.55um (0±20 um), average TTV 2.53 (≤40 um), and average warp 13.52 (≤31 um). This high structural quality directly impacts the uniformity of the LED wavelength, maximising the output of LED devices and increasing the price of specification-compliant devices.

7. Integration of results. 3D defect patterns collected at various stages were integrated using software *Yield Pro v4.4* by Scientific Visual for sapphire quality analysis. The integration took into account their initial orientation inside each other through reference points. It allows to trace the evolution of each defect individually and draw conclusions about its specific impact on the wafer yield.

RESULTS AND CONCLUSIONS

1. Eye control largely overestimates defectiveness in raw crystals

Fig 3 shows an example of waferable area identified by the scanner and a human expert in raw crystals and in the same volume after coring.

The scanning was set to a zero-tolerance profile: any defect within the scanner's detection range (down to 8 um) rejects the corresponding wafer.

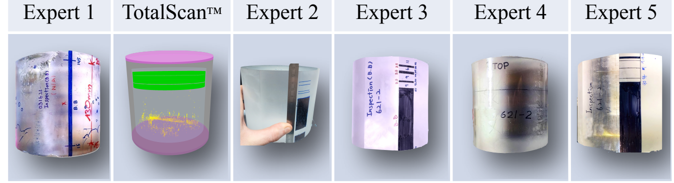
Raw boule		**Core *'as is'***			**Core *polished***
Expert 1	TotalScan™	Expert 2	Expert 3	Expert 4	Expert 5
					
0 mm	37.0 mm	48.0 mm	34.0 mm	41.0 mm	30.8 mm

Figure 3: Example of crystal evolution: sample 1621-2 (h165 mm, ∅170 mm). The bottom raw shows waferable areas identified by five human experts and TotalScan™ at various stages.

Fig. 4 shows how such evaluation correlates with the crystal defectiveness.

It can be clearly seen that:

a) visual inspectors repeatedly underestimate waferable length. It is due to objective obstacles to visualising defects in raw crystals and the psychological tendency to overestimate defects in order to mitigate risks of defective material entering the production chain.

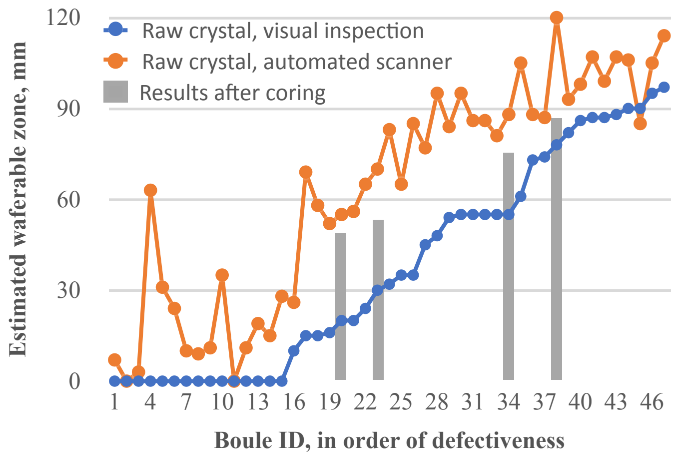


Figure 4: Waferable areas identified by a human expert and TotalScan™ in 47 raw crystals before coring. Grey bars indicate results after coring.

(b) the human error is higher in crystals with high defectiveness. It might be related to "bias trap": when finding significant defective areas, the human expert tends to consider the whole crystal defective, despite the presence of commercially significant waferable zones.

The overall statistics show that human expert underestimates waferable areas by ~32% in raw crystals and ~27% in cores. With manual quality control, most of these erroneously defective zones would be sent to scrap.

2. Defect-conscious wafering enables up to 7% more wafers

When there are few defects in the core, their positioning to the cutting planes matters. Knowing the precise defect coordinates allows calculating a core offset to position more defects into sawing gaps and out of future wafers.

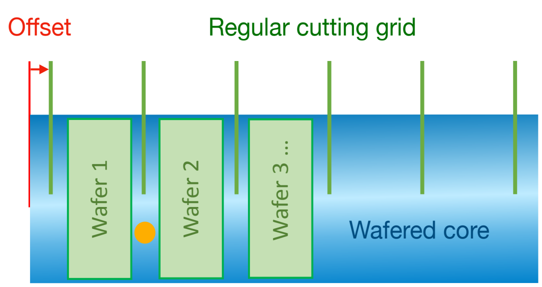


Figure 5: The principle of Intelligent Wafering: pre-computed offset of cutting grid increases the number of good wafers (patent pending).

Table 1 shows an example of such gain. The only parameter to control is the offset of the first cutting plane to the edge of the core.

Out of all possible offset values, the table shows the theoretical worst and the theoretical best, yielding 44 or 49 good wafers out of 57, respectively. That makes 7% yield difference. In practice, the cutting wire or blade is positioned with imprecision of ±0.25mm, so that the first cut is unlikely to be exactly at the best offset (1.4 mm in this case). The correction for the imprecision reduces number of good wafers to 48, therefore ensuring a gain of 4.5% over uncontrolled "blind" core positioning, which averages at 46 quality wafers.

Table 1. Intelligent wafering: wafer yield as function of core offset, as sketched in Figure 5.

	Offset, mm	Good wafers	Bad wafers
Worst cut	0.6	44	13
Best cut (theory)	1.4	49	8
Best cut (practice)	1.4 ± 0.25	48	9

3. The study allows to calibrate yield-impacting defect threshold for LED wafers

The cores chosen for the end-to-end test have typically a conical distribution of defects in the seed area. In other words, the defect density in wafers decreases from the bottom upwards and was zeroed at a certain height.

As the scanner has a higher defect sensitivity than required by LED standards, it raises the question where to set the threshold separating yield-impacting defects from tolerable ones. Combining data from TotalScan™ and Candela® let us derive the cut-off: defects below it are not diagnosed at wafer quality control and, thus, can pass into production. Fig. 6 shows the distribution of defects and the wafers' status.

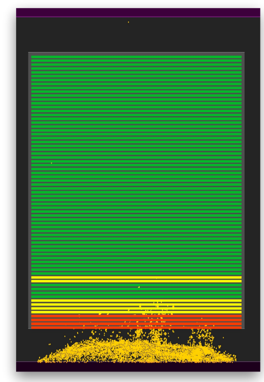


Figure 6: Wafer compliance in the crystal 3121-4. Green - good wafers, yellow - defects detected by TotalScan™ in raw crystal, red - defects detected by TotalScan™ in raw crystal and Candela® in wafers.

Disclaimer: This article presents first available data, which is not statistically valid. The information will be refined with the oncoming end-to-end statistics. For example, the compliance of an individual defect-containing wafer may be influenced by the defect location depth (on the surface or in the volume). This random fluctuation will be averaged out with the statistically valid dataset.

SUMMARY

Thanks to end-to-end defect tracing, the authors correlated defects yield-impacting defects in polished wafers with the ones identified by TotalScan™ in the raw crystals.

The consortium will continue to gather more statistics. The complete dataset and metrics are available to project participants.

The obtained correlations confirm that digitalisation of crystal quality control offers tangible opportunities to improve profitability. Processing companies could extract from 5 to 20% more quality wafers with intelligent processing.

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