

Automated Optical Inspection (AOI) For Quality Improvement

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Abstract

To improve product quality, Qorvo Fab recently implemented end-of-line automated optical inspection (AOI) to screen out die with any visual defect. This paper presents two case studies of AOI application in process trouble shooting and in evaluating contaminated wafers.

INTRODUCTION

Automated optical inspection (AOI) is a powerful quality improvement tool to screen out die with any visual defect from a processed wafer. Since AOI is a noninvasive test, it essentially can be implemented at any stage of the manufacturing process, including in-line and end-of-line inspection. In this work, we discuss end-of-line AOI application in quality improvement.

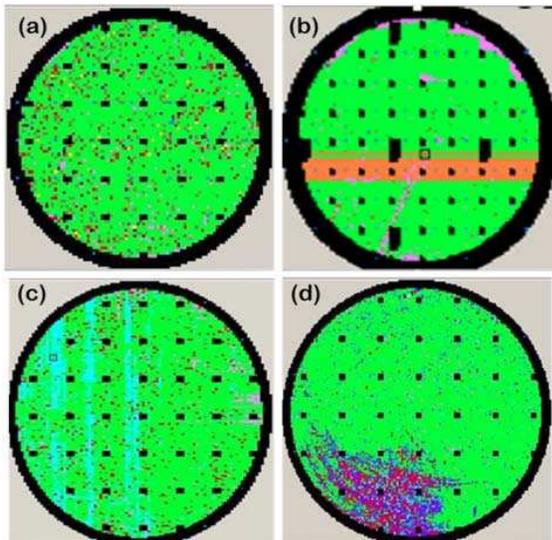


Fig. 1. AOI defect maps with distinct defect pattern. Green indicates good die, PCM colored in black, other colors represent fail die. (a) Surface debris, (b) off-set dicing, (c) electrical test probe damage, and (d) scratch.

Routine AOI defect analysis includes yield and defect Pareto summary, defect image and characteristic review, e.g., defect size, contrast, and grayscale. In addition, from defect location on a wafer we can also get some important information about potential defect root cause. For instance, Fig 1 shows four

common defect patterns due to: (a) surface debris randomly spreads on a contaminated wafer; (b) misaligned dicing forms a streak of defective region; (c) probe damage from electrical test with lines of defect die, and (d) scratch at lower left portion of a wafer. As the final step of wafer level Die Sort, end-of-line AOI can not only boost product quality, but also support upstream process trouble shooting. For instance, in-depth defect analysis of wafer with enormously low AOI yield tends to reveal root cause of dominant defect, and consequently helps to resolve process issue.

In the following sections of this paper we discuss two case studies of AOI application. In case study I, we demonstrate how AOI assists with upstream process diagnosis in combining with intensive defect analysis. In case study II, we demonstrate that besides regular end-of-line inspection, AOI can also help to recover contaminated wafer.

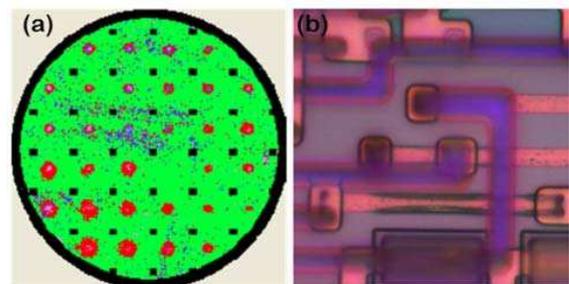


Figure 2. (a) AOI defect map shows clustered defect (red) in repetitive pattern. (b) Optical microscopic image of a defect.

CASE STUDY I:

From AOI yield review and massive defect map study, we learn that wafer with decent yield usually has randomly distributed defect, and wafer yield is inversely proportional to die size. In contrast, low yield wafer tends to have cluster defect. Cluster defect pattern sometimes gives out clue about defect root cause. For instance, AOI defect map in Fig 2 (a) shows repetitive defect region (colored in red) at the center of each reticle field. At upper left corner of each reticle field, there is a process control monitor region (PCM, in black) not being

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inspected. Reticle field defect pattern normally suggests defects are formed through pattern transfer from mask to wafer during photolithography. This hypothesis was later on verified by our defect root cause analysis.

From AOI defect images, we observe deformed metal line at a specific location of each AOI fail die. Optical microscopic inspection of defect at higher magnification also reveals narrowed metal line as shown in Fig 2 (b). Multilayer metal stack at the defective location increases the complexity of root cause analysis. From Focused Ion Beam (FIB) analysis at the cross-section of a defect, we are able to identify defective metal layer and eventually to narrow down process steps at risk. Further process tool checkup reveals defect metal was due to a malfunctioning hardware of a photolithography step prior to metal deposition. After replacement of the faulty hardware, we were able to eliminate this particular type of metal defect according to a continuous monitor of metal width before and after the tool repair (shown in Fig 3, dw2 calculated from electrical test).

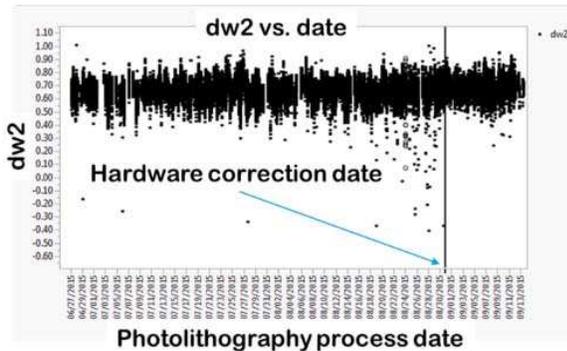


Figure 3. Continuously monitor of metal width (dw2, calculated from electrical test) before and after tool change.

Interestingly, electrical test data shows AOI fail die pass electrical test marginally with out-of-family IQICM value (an electrical test parameter, not specified in this paper). For instance, electrical test results of wafers with out-of-family IQICM are shown in Fig 4, where borderline die are highlighted in black to show similar reticle field related defect pattern. This case study demonstrates end-of-line AOI helps to trouble shoot process/tool issue and it can also screen out borderline die from electrical test to improve product quality.

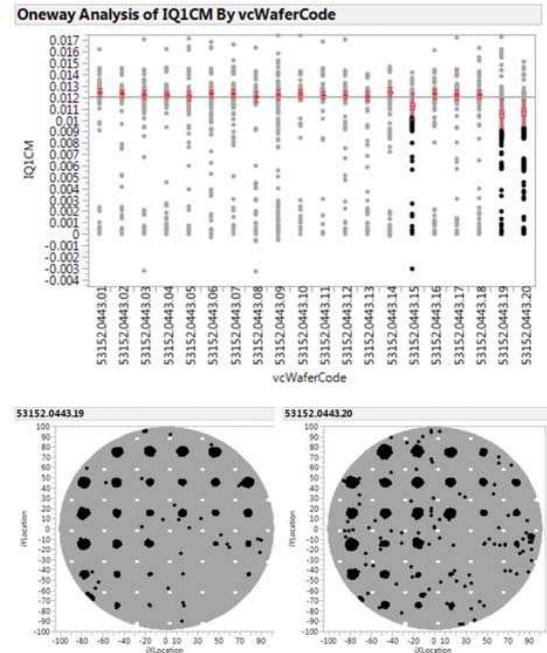


Figure 4. Electrical test result of defective wafers and control wafers. Wafers with lower mean of IQICM have metal defect. Defective die are highlighted in the corresponding electrical test maps.

CASE STUDY II:

Bond pad contamination can cause weak or non-stick on pad (NSOP) issue during unit assembly. In this case study, we demonstrate end-of-line AOI can be used for detecting bond pad contamination with a special pad inspection recipe.

Assembled unit with NSOP defect is shown in Fig 5 (a) and (b). Scanning electron microscopy (SEM) images from a return unit reveal missing wire from bond pads at lower left corner of the die. For comparison, Fig 5 (c) and (d) are SEM images taken from a control unit with normal wire bonding. To find out the root cause of NSOP, Energy Dispersive X-ray Spectroscopy (EDS) coupled with SEM was applied to analyze elemental composition of bond pad surface with missing wire. EDS spectrum (in Fig. 6) taken from undisturbed region of NSOP pad indicates gold bond pad is covered with a thin layer of chemical consisting gold, gallium, arsenic, and oxygen. These surface contaminants presumably come from GaAs substrate during wafer singulation.

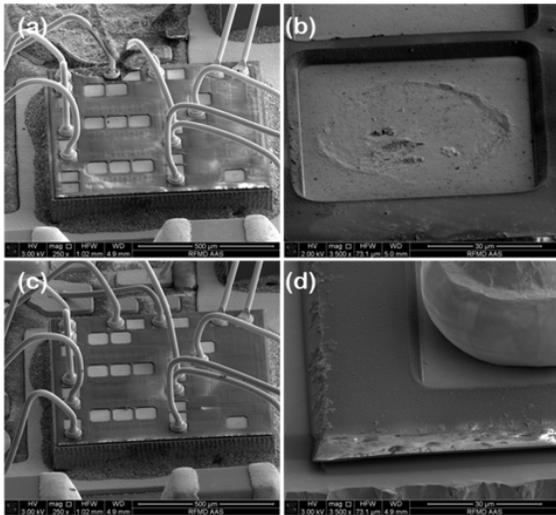


Figure 5. (a) and (b) show die with missing wire bond at lower left corner; (c) and (d) are from a control die.

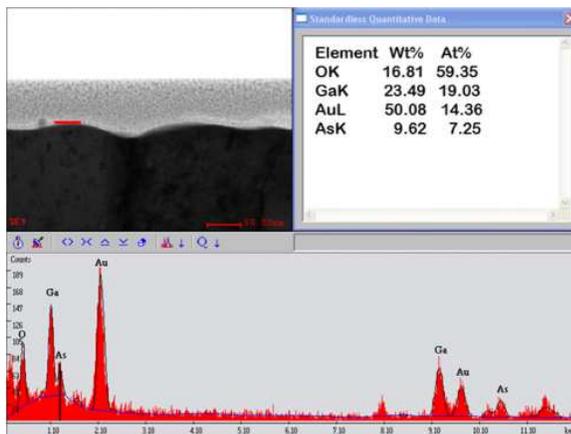


Figure 6. EDX spectrum of NSOP pad shows surface layer contains gold, gallium, arsenic, and oxygen.

In addition, optical microscopic inspection of NSOP pad discloses visual defects: NSOP pad always has discolored edges (in light orange) and it is also more or less covered with small particles as shown in Fig 7 (b). In contrast, a normal bond pad has a uniform gold color and is particle free [Fig 7(a)]. Please note that dark brown mark at the center of a bond pad is probe mark from earlier electrical test, it is irrelevant to pad contamination and does not affect wire bonding in assembly. In principle, all visible defects can be detected with AOI unless defect size is smaller than the tool detection limit. To inspect bond pad contamination, we collaborated with AOI tool manufacturer and developed a special AOI pad inspection recipe. With an optimized illumination setup, we are able to improve detection sensitivity to screen out pad with discoloration or with small particle.

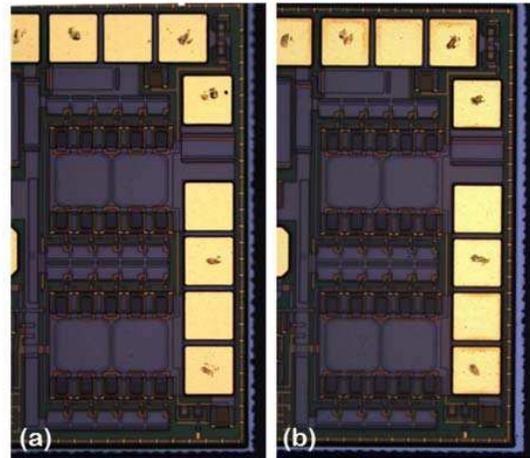


Figure 7. (a) Normal pad with only probe marks. (b) Contaminated pad with discolored regions at edges.

Figure 8 (a) is an AOI wafer map generated from pad inspection recipe. A typical pad defect captured by AOI is shown in Fig 8 (b), where defect region is marked in red. Optical microscopic inspection at higher magnification confirms the presence of discolored region on selected pads. Wafer pad yield is calculated from pad inspection map, it is the ratio of the number of pass die to the number of inspected die. Therefore wafer pad yield can be used as a metrics to quantitatively evaluate bond pad surface contamination. **Please note that wafer pad yield of NSOP wafer does not reflect Qorvo Fab production wafer AOI yield.**

To recover contaminated wafer, we need to develop a wafer clean procedure that can effectively remove surface contaminant from bond pad. The following section focuses on the evaluation of wafer clean methods by comparing wafer pad yield change before and after clean.

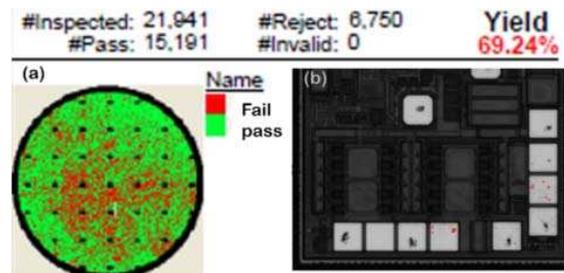


Figure 8 (a) AOI map and pad yield generated from pad inspection recipe. (b) AOI captured pad defect image.

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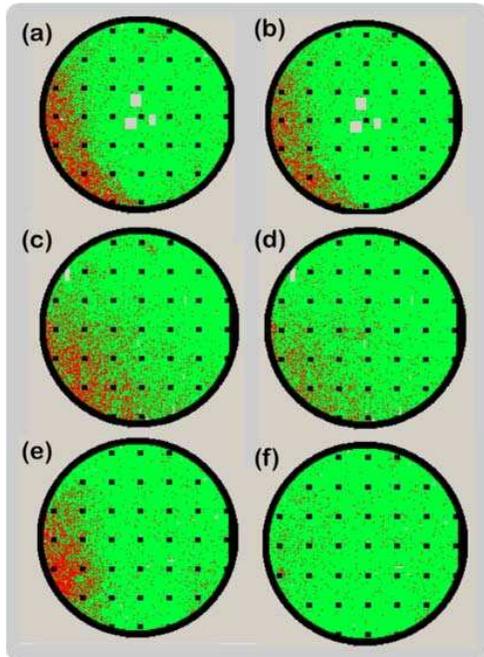


Figure 9 (a), (c), and (e) are as-received wafer maps. (b), (d), and (f) are wafer maps after clean in QDR, in high pressure DI water, or in $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$ solution, respectively.

In this experiment, three NSOP wafers were inspected with AOI using pad inspection recipe. As-received wafer maps were shown in Fig 9 (a), (c), and (e). Apparently contaminated die (> 10% of a wafer) mostly locate on the lower left side of the surface. After initial AOI inspection, wafers were cleaned with DI water in a quick-dump-rinse (QDR) tank, or with high pressure DI water, or with a solution of NH_4OH and H_2O_2 , respectively. Cleaned wafers were then retested with AOI using the same inspection recipe. Cleaned wafer maps are displayed in Fig 8 (b), (d), and (f). Wafer pad yield before and after clean is listed in Table 1. Clearly $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$ etch is the most effective clean method for removing bond pad contamination. High pressure DI water spray can recover about half of the contaminated die while QDR rinse cannot remove any pad contamination, suggesting surface contaminant is wafer insoluble but it can dissolve in $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$ solution. More likely, the water insoluble contaminant physically absorbs on gold pad and can be partially removed by high pressure water spray. To further evaluate bond pad clean with $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$ solution, a large set of NSOP wafers with different die design were tested with AOI pad recipe before and after clean. Figure 10 shows a consistent pad yield improvement after 30 seconds etch in $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$.

Table 1: Summary of wafer pad yield before and after clean.

Wafer ID	Yield as-receive	Clean method	Yield after clean
#1	0.872	DI water rinse	0.895
#2	0.840	High pressure DI water spray	0.919
#3	0.882	30 sec etch in $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$	0.971

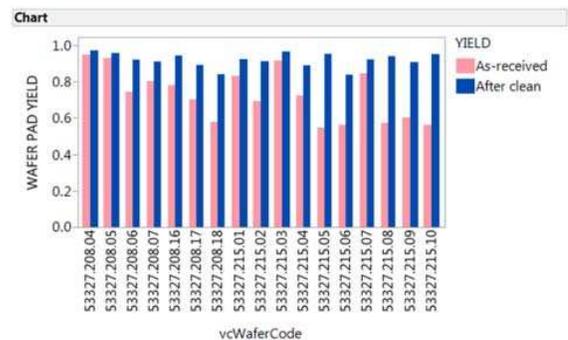


Figure 10. Wafer pad yield of NSOP wafers before and after 30 sec $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$ clean.

CONCLUSIONS:

Implementation of end-of-line AOI improves wafer quality by screening out die with visual defect. Besides its common role in quality improvement, AOI can also support process troubleshooting and evaluation. In-depth AOI defect pattern and data analysis helps to reveal defect root cause. In addition, AOI is also used for recovering contaminated wafer.

Massive AOI yield analysis from wafers with varied die size also reveals AOI yield increases linearly with reduced die area. This supports random defect theory for yield model [1]. With a constant defect density, AOI yield chart can then be used to estimate Fab new product AOI yield with known die area.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] C. Neil *et al.*, IEEE Transactions on Semiconductor manufacturing, Vol. 9, No. 3, August 1996.

ACRONYM

AOI: Automated optical inspection