Defect Management for 300 mm and 130 nm Technologies

Part 1: Advanced Patterned Wafer Inspection Strategies

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The transition to 300-mm wafers and the ramping of 130 nm generation devices into volume production have introduced significant economic and technical challenges for semiconductor manufacturers. In addition to the continuing trend towards using a mix of distinct inspection technologies that can be customized to fit the changing requirements of the fab, revamped defect inspection and control strategies are also required. The first in a three part series, this article explores these new methodologies that include the increasing use of e-beam inspection combined with the application of advanced optical patterned wafer inspection technologies.

Introduction

Industry Trends

In the ever-accelerating quest to remain competitive in today’s semiconductor market, manufacturers are turning towards larger wafers of higher capacity, with new process materials and architectures. For the first time in recent memory, the semiconductor industry is witnessing the simultaneous convergence of new process and materials development, shrinking design rules and an increase in wafer size. As one would expect, this places a large constraint on the effectiveness of existing inspection tools and methods that proved to be successful in earlier technology nodes.

Shrinking the feature size means less room for error, as evidenced by the requirement of emerging “zero-bias” etch processes. A defect that in previous generations was too small to cause trouble has now become yield-critical. Escalating device complexity places additional constraints on the control required for each process step, and having more process steps translates into the potential for larger accrued error.

In addition to larger wafers and smaller design rules, many leading-edge devices incorporate a new process architecture called copper dual damascene, with high aspect-ratio stacked via and metal structures. These are difficult to etch, difficult to fill, and difficult to inspect for defectivity. New insulating and conducting materials are also part of the challenge: specifically low-κ dielectrics and copper. Requiring new chemistry for deposition, electroplating, and polish, copper devices still lag behind aluminum in yield.

300 mm fabs are expected to be more profitable than 200 mm fabs, producing lower cost devices with reduced cycle times and with higher yields. However, replacing 200 mm wafers with 300 mm wafers necessitates automation advances to all process, metrology, and inspection equipment. Recipes that have been optimized for 200-mm production must be transferred smoothly to the 300-mm tools, along with a large body of accumulated knowledge and manufacturing history. With the larger wafer radius, process tolerances have to shrink so that cumulative errors still fall within acceptable limits. Because each wafer contains more die, time-to-volume is an even stronger driver than before. Each individual wafer costs more; hence, a key challenge is accelerating yield learning from development to production.
Add to these technical challenges the economic pressures that ensue with 300 mm fabs costing upwards of $2B, and investors requiring ever-shorter returns on their considerable outlay. Global economic conditions at the start of the new millennium mean that missing the market window by as much as a month may translate to a significant difference on a company's year-end balance sheet—and big differences in the pockets of their shareholders. (Table 1)

These numerous and significant challenges require risk mitigation on several fronts. In this series we focus on developing winning defect inspection and control strategies for 300 mm wafers and 130 nm design rules.

Defect Inspection Trends
For advanced design rules and 300 mm, several trends have appeared in the areas of defect reduction and control. First, time-to-market requirements have created a trend away from using one inspection methodology to detect all defect types throughout the product life cycle. Instead, a mix of brightfield, darkfield, and e-beam inspection has been emerging as the dominant approach. Because of the increasing complexity of the device fabrication processes, a combination solution must be customized to the individual characteristics of the device technology being manufactured. This solution must meet requirements for more complete defect detection, earlier in the process, at lower overall cost of ownership. This trend will be explored in more detail below.

Second, economic pressures have acted as the impetus for focusing on earlier systematic defect elimination, solving the defect problems earlier in the product life cycle. These technical challenges earlier have driven a trend towards increased use of SEM-based inspection while still relying heavily on high-sensitivity brightfield inspection in the development and ramp stages.

Further, a new trend in process development has been control of defectivity at a specified level in the early stages of technology learning cycles. The goal is to control individual process defectivity in an effort to obtain better correlation of process step-limited yield.

Another development is an increase in inspection capacity, a reversal of an earlier drive to reduce capital expenditures on inspection tools, when inspection was perceived largely as a non-value-added expense. As the opportunity cost of lost yield rises in line with the capital cost of the fab, experience has shown that more, not less, inspection is the most cost-effective approach. Thus the industry has seen an increase in inspection capacity, as shown in Table 2 and Figure 1.

Finally, increased focus on defect reduction and control in the photolithography area has driven development of new methods, including increased use of automated macro defect inspection, backside inspection, and bright field inspection based photo-cell monitors. This important trend will be explored in more detail in Part 2 of this series.

Table 1. Accelerated fault learning rates translate into enormous financial gains for the 300 mm fab.

Table 2. Recent data from ICE shows that expenditures on wafer inspection equipment has risen in the transition from 250 nm to 180 nm devices, and from 180 nm to 130 nm.
Determining Inspector Mix

Of all the variables that influence a fab’s time to yield, having the right inspection strategy is clearly one of the most important. Effective strategies, tailored to a fab’s unique requirements and applied properly throughout a product life cycle, ensure that issues concerning device yield and reliability are identified early in the process and corrected. As a result, not only can development time be reduced, but also new product and technology transfers can occur faster and at higher yields, accelerating ramp to full volume production.

The cornerstone of any inspection strategy is the inspection system itself. The three basic inspection technologies are brightfield, darkfield and e-beam (see sidebars). The objective is to combine these technologies into an overall inspection strategy that delivers the optimum sensitivity/cost of ownership combination for any given application. To sacrifice throughput for unnecessary sensitivity, or to sacrifice needed sensitivity for throughput, would be inefficient and potentially very costly, decisions. (See Figure 2).

While combinations of the three main inspection technologies provide the most flexible and cost-effective strategy across all layers in the face of changing inspection requirements, fabs do not want to proliferate more technologies than necessary, with each technology having different matching requirements, automatic defect classification capabilities, recipe set up procedures, etc; a balance must be achieved. To the extent that different technologies share common attributes—such as software for analysis, automatic defect classification (ADC), recipe management, overlay comparison, and matching, as well as diagnostic support—the negatives of multiple inspection technologies can be offset.

It is critical that the multiple inspection technologies should be complementary—each should excel in distinct applications, providing the required sensitivity at the lowest cost of ownership for their targeted applications. Multiple technologies provide the maximum range of response to changing inspection requirements.

A range of inspection capabilities also provides opportunity for synergy among the various tools, further leveraging the capabilities of each. For example, certain defect types that initially may be detected on a fab’s most sensitive tool during development can later be monitored using a less sensitive but higher throughput tool that has been specifically “trained” to detect them. This reduces the overall cost of inspection, and frees the higher resolution tool for more critical inspection steps requiring its capabilities. It must be noted that this “migration or transfer” to an alternative technology should be based on both cost and utility and not just cost alone.

Inspection strategy during development and ramp

As a product progresses through its life cycle, from development through ramp to production, the requirements for inspection also progress (Figure 3). Early in the product life cycle, most defect problems are unpredictable and systematic—particularly when new materials, new processes and/or new device architectures are involved. To move through the development cycle quickly and effectively, inspection equipment must have high sensitivity and high capture of as broad a range of defects as possible. In this phase, the inspector mix will emphasize e-beam and DUV-brightfield inspectors. The fundamental inspection need in this phase is improved “cycles of learning (COL)” to flush out the basic process inadequacies.
Later, in the transfer and ramp phase, the goal is to reach yield entitlement in the shortest amount of time. More and faster yield learning cycles are critical, and high throughput darkfield inspection tools can help accelerate yield learning in applications where they have the required sensitivity. In the transfer and ramp phase, a mix of the three technologies is typically employed, including brightfield, darkfield and e-beam inspection.

The stages of development, transfer and ramp are receiving more attention today because of more stringent requirements for return on investment and narrower market windows for the finished product. During this phase thorough defect characterization is critical, to minimize the probability of encountering unknown defect types during production.

In many cases e-beam inspection is the best technology to detect defects in leading-edge devices during development and ramp. The physics of an electron beam provide higher resolution and greater depth of focus than any optical inspection system; thus using e-beam technology for inspection of high aspect ratio (HAR) structures is frequently the most cost-effective choice. These structures are notoriously difficult to pattern and etch, and their topology makes inspecting the bottoms of these structures challenging. Moreover, inspection of HAR structures is a critical requirement for advanced logic and DRAM devices.

E-beam inspection is the only technology that can detect electrical defects during inspection, using its unique voltage-contrast mode. (Figure 4). This makes it indispensable for detection of contact and via

1. Voltage Contrast Detection

2. e-Beam Defect Review

Figure 4. HAR defect reduction requires high resolution, material or voltage contrast, and extreme depth of focus. These attributes are commonly associated with e-beam inspection and review.

E-beam inspection

Unlike brightfield and darkfield optical technologies that measure reflected or scattered light, electron-beam — or e-beam — inspection technologies measure emitted secondary electrons. This gives these tools several key advantages.

First, electrons aren't subject to limits from diffraction, and are therefore able to detect much smaller defects, typically down to as small as 50 nm. The large depth of focus of these tools also enables them to image the bottoms of high aspect ratio trenches and vias, historically a difficult inspection problem. Finally, because electrons carry charge, they can also detect electrical defects, such as failed contacts, using a technique called voltage contrast. No other inspection technology can find electrical defects. This capability alone can make these tools a worthwhile investment. Today fabs typically rely on short-loop experiments lasting one or two weeks to determine electrical defectivity. With an e-beam system, this can be reduced to days or even hours, dramatically accelerating development of new products and technologies.
problems—which can be significant contributors to product loss, and are a growing yield concern in the manufacture of devices that incorporate copper.

A key element for effective use of e-beam inspection in these applications is having appropriate SEM review capability. To take maximum advantage of voltage-contrast inspection, a SEM review system that can employ its own voltage-contrast mode to re-detect the defect is essential. Using coordinates from the inspection, the review SEM can find the defect within a wide field of view, then zoom in for a high-resolution image automatically.

In the realm of optical inspection, brightfield systems are widely acknowledged to provide the highest sensitivity and capture of the broadest range of defect types (Figure 5). For this reason they are commonly used in the development phase, where yield issues are first identified and characterized, and control strategies are developed. Once in ramp and production, many of the brightfield inspection layers can be transferred to high-throughput darkfield tools.

Recent advances in brightfield systems include adding UV light to the broadband optical source to increase resolution, especially needed for photo and etch applications on 130 nm devices. Further advances in optical noise suppression have enhanced performance on layers with grain or color noise.

Best known methods in development and ramp
The goal during the development stage is to capture as many defect types as possible, including unknown defects and any new types that might arise from new materials and processes. Thus the inspection sampling should be dense. Typically all wafers, all levels and all lots are sampled, with a high area of inspection per wafer. Often full-wafer inspections are performed on some wafers in each lot. High-sensitivity inspections are the rule, with e-beam inspection and brightfield inspection carrying most of the load. Their recipes are generally set to small pixels for maximum capture. During development and ramp, defect review is very thorough.

The strategy will be modified as the product moves into the ramp phase of its life cycle, and defect problems are largely characterized. Instead of sampling all wafers at high sensitivity, the overall sampling scheme is less dense, with heavy sampling reserved for the critical levels. High sensitivity is still the mode of operation, and review is comprehensive and systematic. The goal is to move through ramp quickly, identifying any remaining problems and solving them before the transition to volume production.

During these two phases, killer defect Paretos are under construction; these will comprise the reference Paretos during production.
Inspection Strategy During Production

When the product moves into production, the major defect problems have been characterized and yield is acceptably high. In this phase, the goal of the inspection strategy is to sustain yields by controlling excursions of known types. To increase productivity, inspection steps are moved to higher throughput tools wherever possible. As a result, the inspection tool mix shifts towards darkfield systems, reserving brightfield and e-beam systems for situations where their unique detection capabilities are absolutely essential. Applications where brightfield still provides the best performance/cost of ownership combination typically include critical etch and lithography applications. In the production phase the e-beam inspector is employed as an auditor, checking for known problems that require its unique capabilities in either sensitivity or voltage contrast.

Darkfield inspection has been the dominant technology for many years for monitoring in the film deposition and CMP areas. Recently advances in optics and algorithms have extended darkfield capability, increasing its performance into etch and photo as well (Figure 6). The key to successful transfer of an inspection step to a higher throughput darkfield system lies in characterizing its ability to capture the yield-limiting defect types detected on the other systems. In many cases today’s darkfield systems can be configured to capture these defect types.

Best known methods for production

In the production phase, cost control is paramount. This means adjusting the sampling strategy significantly: the number of levels and percent of lots sampled are reduced, as is the wafer area inspected. For the inspection recipes, the highest sensitivity settings make way for highest throughput, while preserving sensitivity requirements. The lower limit for the sampling frequency is set by the requirement to detect excursions quickly.

A mistake that was sometimes made in the past was to underestimate the number of inspection systems required in production. A good estimate for inspection capacity should be refined to account for not only business-as-usual conditions, but also excursions, problem solving and baseline reduction. Managing an excursion includes...
process experiments, split lots and increased sampling. These require additional inspection capacity on reserve.

While the dominant yield loss mechanism during production is process tool excursions, systematic auditing for known process integration defects (also known as “line monitoring”) complements excursion monitoring to provide the best known method of production defect control. The defect Paretos that were created during development and ramp now form an important reference.

The dominant factor in determining an optimal production inspection strategy is to account for the very important interaction between process tool excursion monitoring and process integration (line) monitoring. The technology used for excursion monitoring must be able to incorporate the learning obtained from line monitoring (Figure 7—Optimal Production Planning). It is essential for tool monitoring inspectors to have the sensitivity and flexibility to take advantage of this learning.) This is one reason why integrated inspection techniques have not been implemented to date. The candidate technologies for integration to process tools have not shown the capability to capture more than very gross excursions, making the necessary interaction with line monitoring impossible. Integration will become viable when the integrated inspection technology has the sensitivity and flexibility to support this interaction at the 130 nm node.

### Summary and Conclusions

In reviewing the inspection strategies of several leading logic, memory and foundry IC manufacturers, an internal study by KLA-Tencor found that all have adopted a combination of brightfield, darkfield and e-beam inspection systems. The exact mix and match strategy varies from fab to fab depending on its unique requirements. Table 3 shows the inspection strategy of these leading IC manufacturers in the initial development phase.
Economic and technical challenges are significant in the transition to production of 130 nm devices on 300 mm wafers. New materials, new architectures and more stringent process tolerances have combined with tighter market windows and more demand for faster return on investment. Defect reduction and control trends have emerged to address these challenges. These include:

- Revising the deliverables of process development goals during early technology learning to include reduced defectivity

- More focus on early, systematic defect reduction leveraging a mix of distinct brightfield, darkfield and e-beam inspection technologies that can respond to the changing requirements of the fab

- Increasing use of e-beam inspection to address requirements for additional sensitivity and inspection of high aspect ratio structures

- Increasing fractional expenditure on wafer inspection technologies

- More focus on defectivity in the photolithography area

The current review is the first in a series of articles that will be published to comprehensively discuss defect control strategies. An optimized strategy needs to include the right technology choice, detection best practice and the subsequent analysis of the data to derive their benefits. This article has focused on utilizing a mix of inspection technologies to meet economic and technical demands. In a subsequent article, we will discuss the analysis methodology that enhances the effectiveness of this defect inspection strategy.