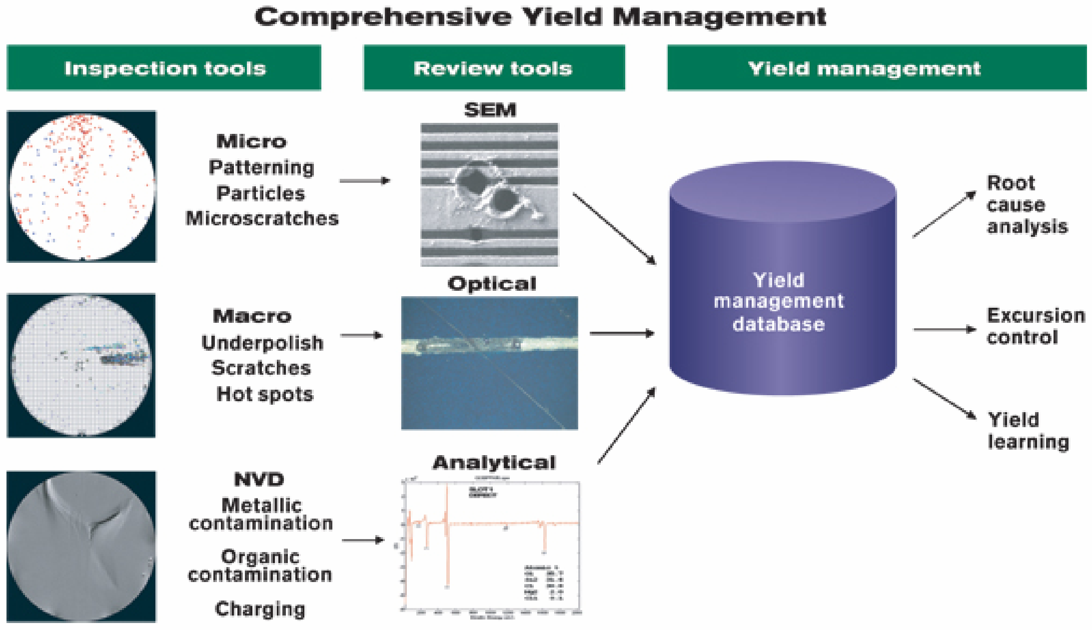
Defect Detection Drives to Greater Depths

Equipment suppliers are scrambling to develop new methods to detect particles that are smaller, visible and non-visible, while maintaining throughput.

Ruth DeJule, Contributing Editor -- Semiconductor International, 8/1/2009

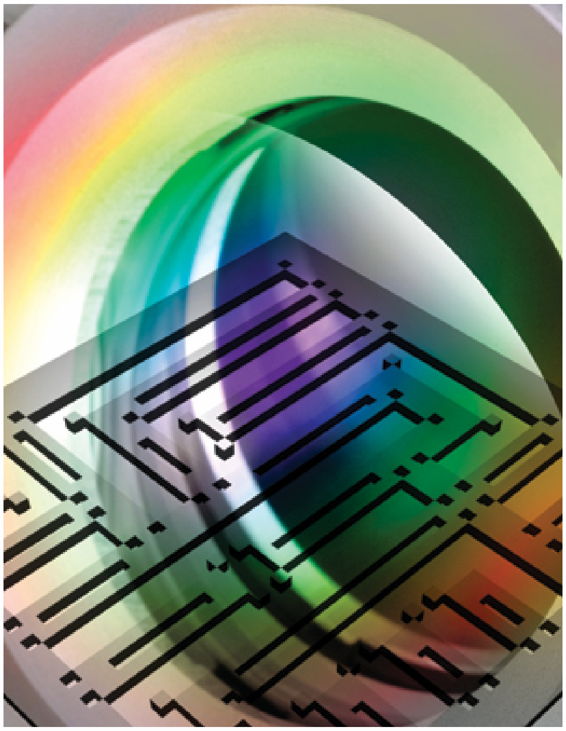
The impact of the industry's continued shrink to smaller geometries and the associated introduction of new materials and processes are hotly discussed. But unlike lithography, where new technologies have been in the press for more than a decade as the theoretical limits of optical has loomed, defect detection, the heart of yield management (**Fig. 1**), has not felt the same pressure, until recently.



1. A comprehensive yield management strategy combines data from various inspection and review tools to speed time to yield. (Source: Qcept Technologies)

Traditional inspection systems use an optical light source and detect the response of that light. Defects are then reviewed using a high magnification SEM. Further testing with energy dispersive X-ray (EDX) spectroscopy determines the nature of a material. Detection systems may be macroscopic, initially intended as a replacement for human visual inspection, or microscopic for high resolution requirements. The higher throughput macrosystems typically operate between 80–150 wph, ~30× faster than microsystems, and are designed for one resolution, between 5–10 µm for state-of-the-art tools.

However, there is now a greater need to make systems that can detect smaller particles and do it faster. And with non-visual defects (NVDs) and mask defects (**Fig. 2**) becoming more of a yield issue, traditional optical detection with SEM and EDX may not be enough. This article will discuss the innovations that will carry the industry to the 22 nm half-pitch and some defect detection technologies that could move us beyond.



2. An Aerial lens, used to inspect photomasks by emulating the imaging system of a scanner, is shown superimposed on the image. (Source: Applied Materials)

Macro vs. micro

Today's economic environment is prompting equipment manufacturers to increase versatility in these multimillion-dollar capital investments. For pioneers like Rudolph Technologies Inc. (Flanders, N.J.), five different objectives are housed in a single macroscopic system to detect defects 10, 5, 2, 1 and 0.5 μm in size. Inspecting 2 and 3 μm etch clean residue to 5 μm CMP scratches is achieved on one tool. This configuration may further eliminate obsolescence when transitioning from one technology node to another.

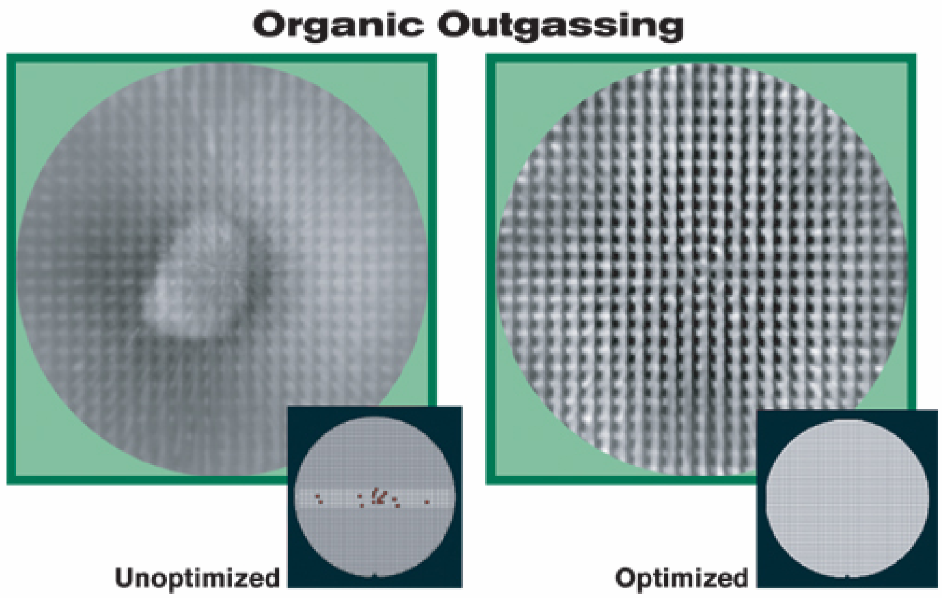
"The challenge is to find small but yield-relevant defects from a large amount of nuisance defects," said Dillip Patel, defect metrology program manager at Sematech (Austin, Texas). Brightfield systems are generally used for patterned wafer inspection. It is difficult to detect defects at the bottom of contacts or residue in vias. Currently, there are no high-speed tools available for inspection of such 3-D or high-aspect-ratio structures. Instead, voltage contrast from e-beam inspection is used, which is very slow. Fabs still use some form of destruction testing to verify the cause of device failure, which is both time-consuming and expensive.

NVDs

"Geometry shrinks have become much more than simply scaling," said Robert Newcomb, vice president of business development and applications at Qcept Technologies (Atlanta). Novel materials, new processes and complex structures have been impacting every aspect of IC processing, including defect detection. Traditional optically based tools cannot detect NVDs such as sub-monolayer types of residue, including scattered atoms or molecules from metallic or organic residue, and charging that may occur during a cleaning process.

NVDs may account for up to 30% of defect types, Newcomb said, with no indication of a physical defect signature from optical tools or SEM. As a result, the concept of defect detection and review has necessarily broadened to include new equipment for NVD inspection and relevant analyses such as total reflection X-ray fluorescence (TXRF) or TOF-SIMS to detect and measure metallic and organic contamination.

One NVD inspection system uses a metallic probe to detect changes in workfunction, a characteristic of chemical or material nonuniformity. A recent joint study between Semitool (Kalispell, Mont.) and Qcept identified yield loss in the center of a wafer following a cleaning process, which correlated with an organic outgassing residue. A new rinse process addressed the residue problem (**Fig. 3**).



3. An NVD inspection system detected organic outgassing in the center region of a post-via etch wafer clean, causing a corresponding yield loss pattern (left). Modifications to a single-wafer cleans tool eliminated the outgassing (right). (Sources: Qcept Technologies and Semitool)

Similarly, TOF-SIMS analysis confirmed the presence of 5×10^{11} atoms/cm^{2} of copper residue on a patterned product wafer following an RCA clean process. Ironically, there was copper on product wafers in a non-copper fab that could not be detected optically because of the low concentration.

Charge-related defects

A particular type of NVD is process-induced charge, the existence of which is well known. However, up until a few years ago it had been deemed to have little or no impact on yield loss. Fabs like Texas Instruments (TI, Dallas) began recognizing that the same charging at one design rule would become a dominant defect source at the next node. This is the current situation. Charging has become particularly problematic with the transition from batch to single-wafer cleaning tools.

Until recently, no tool could measure charge directly on solid or patterned wafers. "Because our NVD system's measurement results can also be displayed in volts (typically mV), the same physics allow for the detection of a charge signature," Newcomb said.

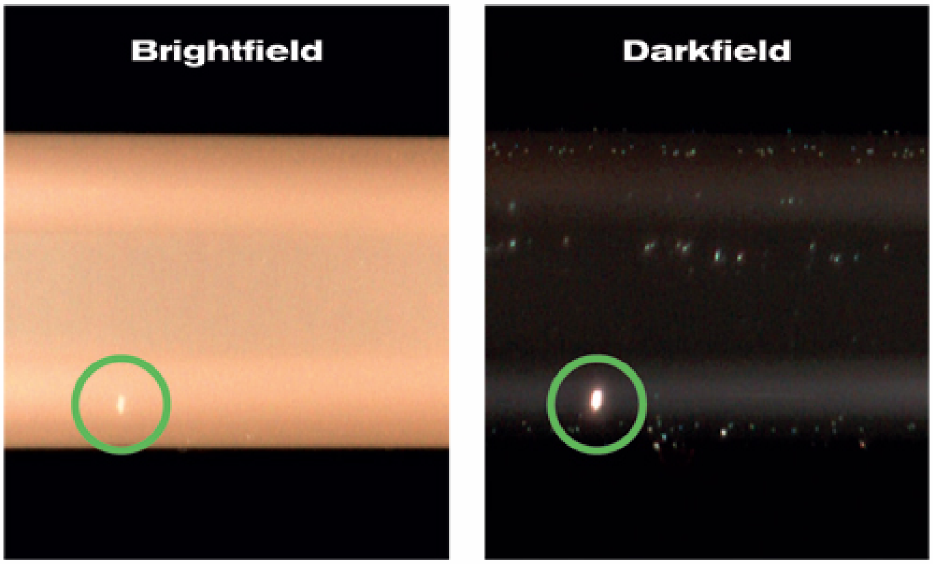
Wafer edge defects

With each new technology node beyond 90 nm, edge and backside defect detection requirements grow in significance. "The edge by far is the most difficult place to find defects," noted Scott Balak, Rudolph product manager. The edge is broken up into five different zones: Zone 1 begins 6 mm from the edge on the top surface of the wafer, Zone 2 at the upper bevel where it starts to roll off the side, Zone 3 is the apex, Zone 4 the bottom bevel, and Zone 5 is ~6 mm from the edge on the bottom of the wafer.

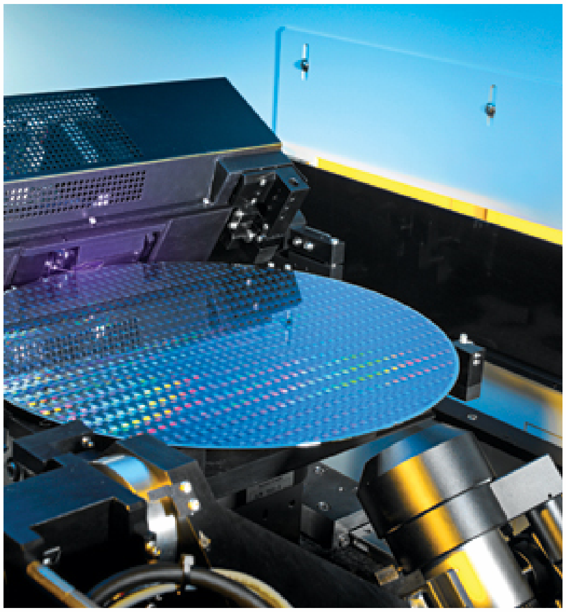
The adoption of immersion lithography has further increased the importance of edge defectivity control and metrology due to the mechanical coupling of the scanner head to the wafer surface through the immersion fluid. At 32 nm, for example, small particles (≥2–5 µm) in Zone 5 can potentially lift the wafer, thus defocusing regions during exposure.

Unlike frontside inspection tools, which have set patterns to reference, normal process backgrounds at the edge appear random, making it difficult to design algorithms that anticipate what to expect. The real challenge is determining whether an anomaly is an actual defect.

One solution is applying the strengths of brightfield and darkfield technologies. Defects that stick out from the wafer surface such as particulates and films that delaminate near the edge will generally have enough contour to scatter darkfield light (**Fig. 4**). The increased use of immersion lithography for some of the more critical steps, Balak noted, is heightening awareness of potential delamination problems on the edge that could physically cause problems on the front side of the wafer.



4. This defect image of particulates captured in both brightfield and darkfield modes demonstrates the extra sensitivity of darkfield on defects with contour. (Source: Rudolph Technologies)



5. Edge inspection solutions can help process engineers ramp immersion processes and monitor costly scanner optics' and stage contamination issues. (Source: KLA-Tencor)

In contrast, brightfield inspection can monitor edge bead removal (EBR) processes and take advantage of full-color processing to determine, for example, the defining edge of film boundaries around the circumference of the wafer of very large chips and cracks later in the processing. An algorithm of this combination can perform "dynamic modeling" for each image that it inspects and then look for statistically different — brighter or darker — pixels within that dynamic model. Edge inspection solutions include KLA-Tencor's VisEdge CV300R (**Fig. 5**) and Rudolph's E30.

Systematic defects

Defects created by the interactions among the mask, scanner and process variation cause systematic defects on the wafer. Systematic defects are particularly insidious because when they are related to the photomask, they appear on many wafers and die. To address this, KLA-Tencor (Milpitas, Calif.) has introduced a new image processing technique that brings general design specifications (GDS) information into the detection and classification (binning) algorithms of the 281X and 282X broadband brightfield inspection systems. Since GDS specifications are contained in the same instruction file that mask shops use to produce the mask, defects that occupy specific design locations can be monitored. The system matches the GDS clip of each detected defect in real time during the inspection such that the defects can be sorted according to the GDS design clip pattern type to identify systematic pattern issues. "This design-aware operation may reduce the qualification of a new mask from months to days," said Mark Shirey, senior director of marketing, KLA-Tencor.

GDS is also being used to input the most valuable areas of the die needing inspection. It defines tens of thousands of areas within the die most critical to the customer. By grouping these by functional blocks, a customized recipe can be created for specific areas, thus aiding the defect engineer in easily pinpointing and setting up an area to be inspected.

Systematic defects can occur in certain locations of the die, such as the array edge or die edge. The small ~20 μm region at the transition from a memory block to a logic/periphery region is riddled with potential defect sites. "Customers tell us that it is this region that most likely goes out of control first," Shirey noted. Newly designed mechanical and algorithm improvement to the 28XX broadband brightfield defect inspection systems called Enhanced Edge Cell Detection increases inspected area and detects defects right up to edge of the memory cell to identify process drifts.

Photomask inspection

For the past few technology nodes, printing progressively smaller device geometries on the wafer has required advanced optical proximity correction (OPC) and extreme resolution enhancement techniques (RET). Now, ultralow-k_1 lithography, especially with source-mask optimization (SMO) and inverse lithography technology (ILT) illuminations and patterns, creates a complete breakdown of the connection between mask and wafer patterns. The dual challenge of detecting printing defects on the mask without reporting excessive nuisance and false alarms becomes even tougher. In addition, critical dimension uniformity (CDU) deteriorates during the fab lifetime of a photomask with cumulative exposure in the scanner and successive cleaning. Monitoring and correcting CDU degradation either by mask or wafer inspection is essential but costly and time-consuming. The solution is to identify the problem as soon as possible — at the mask level.

For equipment manufacturers like Applied Materials (Santa Clara, Calif.), the approach to this problem has been to remain true to lithography scanner image transfer. When advanced technologies such as OPC, RET or SMO are used, what is seen on the mask is different from what is printed on the wafer. The Applied Aera2 mask inspection system eliminates the guesswork by emulating the imaging system of a scanner, including the wavelength and illumination optics, and generates an aerial image of the mask that is similar to the final printed image on the wafer.

Mask inspection is traditionally performed only in the mask shop at the time of acceptance, but mask performance evolves during use in the fab, noted Ehud Tzuri, chief marketing officer of Applied's Process Diagnostics and Control (PDC) Business Group. "We see a need to bring mask inspection into the fab, online, working together with the scanner and the rest of the lithography cell in wafer fabrication." This can be achieved with a fab-based aerial imaging mask inspection system.

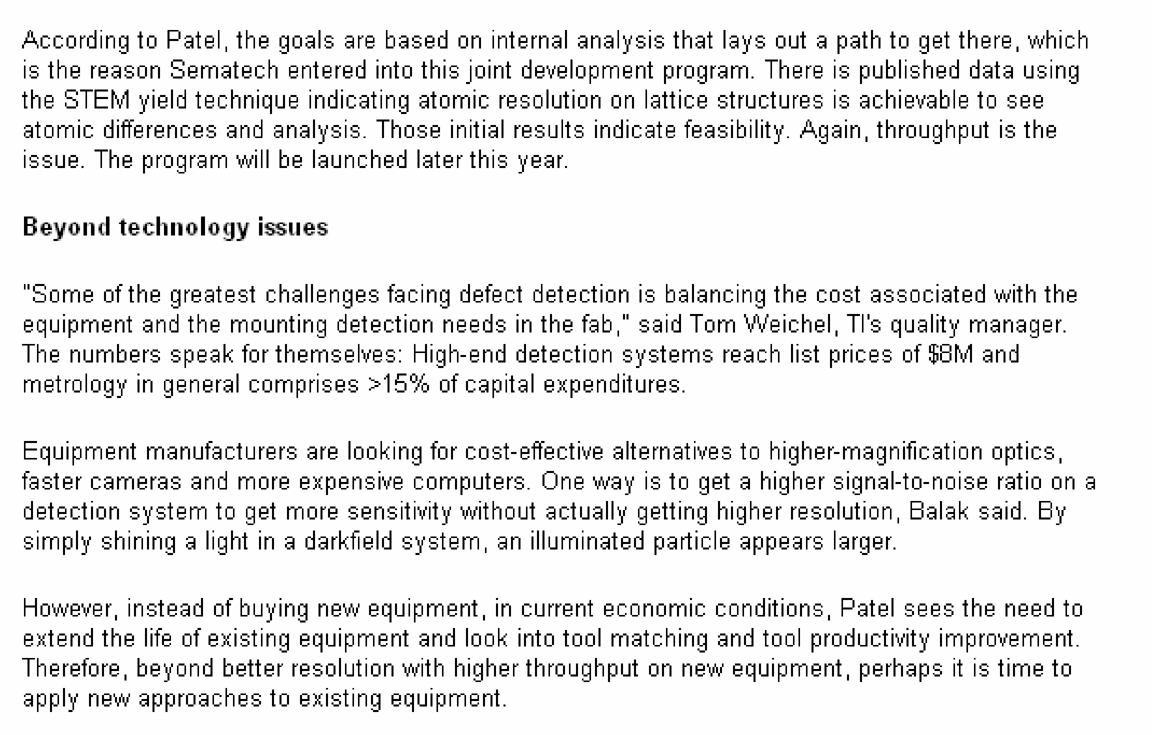
With aerial imaging mask inspection, it becomes clear which defects have been transferred to the wafer. Those printed can be identified as defects of interest and investigated. Furthermore, aerial-image-based mask CDU information, in the form of an IntenCD map, can then be fed-forward to the scanner to correct for any CD nonuniformity, rather than having to print wafers and perform wafer inspection and metrology. An overall improvement in yield and reduction in cost has been demonstrated at customer sites.

Characterization analysis

At the 22 nm node and beyond, in-line defect characterization analysis will be critical, Sematech's Patel said. Systems will be required to detect defects ≤11 nm. Current EDX equipment is limited to 50 nm. Smaller particles produce inadequate signals due to the sample volume, requiring more energy from the EDX system to penetrate and analyze the material.

According to John Allgair, metrology program manager at Sematech, electron probes with smaller interaction volumes are needed to analyze these defects. One candidate is scanning transmission electron microscopy (STEM), which has a small probe, combined with electron energy loss spectroscopy (EELS). EELS looks at the energy loss from the electrons that interact with the particle, which is a function of atomic number and thus identifies the composition of the defect.

A joint development program between Sematech and FEI Co. (Hillsboro, Ore.) will investigate the production-worthiness of STEM and EELS with throughput as a key element. Unlike EDX spectroscopy where a SEM passes a beam over the wafer and X-ray emission is collected, TEM is very labor-intensive, requiring cutting a sample from the wafer. The goal is to do this within minutes while in-line. In addition, Patel said, the system must also be easy to operate by a well-trained engineering technician rather than a Ph.D.



According to Patel, the goals are based on internal analysis that lays out a path to get there, which is the reason Sematech entered into this joint development program. There is published data using the STEM yield technique indicating atomic resolution on lattice structures is achievable to see atomic differences and analysis. Those initial results indicate feasibility. Again, throughput is the issue. The program will be launched later this year.

Beyond technology issues

"Some of the greatest challenges facing defect detection is balancing the cost associated with the equipment and the mounting detection needs in the fab," said Tom Weichel, TI's quality manager. The numbers speak for themselves: High-end detection systems reach list prices of $8M and metrology in general comprises >15% of capital expenditures.

Equipment manufacturers are looking for cost-effective alternatives to higher-magnification optics, faster cameras and more expensive computers. One way is to get a higher signal-to-noise ratio on a detection system to get more sensitivity without actually getting higher resolution, Balak said. By simply shining a light in a darkfield system, an illuminated particle appears larger.

However, instead of buying new equipment, in current economic conditions, Patel sees the need to extend the life of existing equipment and look into tool matching and tool productivity improvement. Therefore, beyond better resolution with higher throughput on new equipment, perhaps it is time to apply new approaches to existing equipment.