Image-sensor defects can ruin an image

Jon Titus - June 01, 2007

When you “snap” a photo with a point-and-shoot camera or a cell phone, you hope to obtain a blemish-free image. The makers of CMOS image sensors used in these and other electronic products have a similar goal: They strive to ensure that their sensors arrive at product manufacturers free of defects. Careful inspection of sensors weeds out devices that could degrade image quality.

Because a sensor provides a light-sensitive surface, small surface defects that might not affect a purely electronic device can render a sensor chip useless. Rick Bunch, fabrication manager at Micron Technology, a manufacturer of CMOS image sensors, explained that the procedures used in the production of sensor wafers are similar to those used for devices such as NAND-flash memories and DRAM. So, most inspections in the fab look only for standard wafer-processing defects. “But after we place a color-filter array and microlens on a wafer, we perform more inspections,” said Bunch. “Any physical defects that affect the lens can cause problems.”

“We look for streaks, scratches, and particulate matter,” said Keith Chin, product-development manager at Kodak, which also produces CMOS image sensors. "And we inspect to see if the color filter or microlens has separated from the top of the sensors.” Chin described inspection as a double-edged sword, because any time you handle an image-sensor wafer, you may cause problems.

“The microlens material is soft and sticky, and the more you handle it, the worse it gets,” said Chin. “If we find particulate matter on a wafer, we will send it through a spin-rincer/dryer to remove as many particles as we can. But overall, particles are difficult to remove.” Manufacturers trace over 95% of defects on a typical megapixel sensor to particles on wafers and on glass used to encapsulate individual die (Ref 1). (See Inspect glass, too)

This diagram shows a cut-away side view of a color image sensor. The Bayer color filter lets specific wavelengths reach each detector. The microlens array focuses light from a scene onto individual detectors. The curved lens surface reflects light in many directions and creates a dark background during wafer inspections.
The individual light-sensing elements (also called pixels) on CMOS image sensors range from about 4 microns down to 2.5 microns or less on a side. “Semiconductor manufacturers strive to make pixels smaller so their customers can put image-sensor die in smaller products. Smaller pixels also let chip manufacturers put more sensors on a wafer, which reduces costs,” explained Udi Efrat, strategic marketing manager at Camtek. “But smaller pixels mean smaller defects can ruin a die.”

“Inspection equipment must find particles and other defects with dimensions as small as 3 to 5 microns,” said Carl Smets, director of the R&D group at ICOS Vision Systems. “A ‘small’ scratch used to have a width of around 10 microns, but now we must detect scratches as narrow as 2 microns.”

The need to find smaller defects means inspection equipment must provide higher-resolution images, but at almost the same speed used for lower-resolution inspections. “Say you have a given area to inspect and you raise inspection resolution by a factor of two,” said Smets. “Now, inspection equipment must acquire and process four times as much image data to inspect the same area.” Equipment from ICOS uses proprietary DSP image-processing boards the company adds as needed to keep image-processing speeds high. “Our inspection algorithms and recipes remain about the same,” said Smets. “But we use oblique illumination, which better highlights scratches and particles on image-sensor wafers.”

Unfortunately, the color filter and the microlens decrease the contrast between the surface of a sensor and any defects. The curved surface of the microlenses, for example, reflects light away from a camera, so the sensor provides a dark background.

“Inspection systems find it difficult to locate dark defects on a dark surface,” said Efrat of Camtek. “To overcome that problem, we use bright-field and dark-field illumination simultaneously. Bright-field lighting emphasizes differences between bright and dark areas, while dark-field lighting lets us see three-dimensional features such as particles, scratches, protrusions, and dings. These defects effectively scatter light from a low-angle dark-field light source. Some of the scattered light reaches the camera and makes defects appear bright.”

“In image-sensor inspection, we need to look for light and dark defects,” stressed Efrat. “We let inspection-equipment operators balance the light sources so they find all the defects important to them.” In addition, Camtek applies a proprietary technique that expands the contrast information to fill the entire dynamic range available in an image.
“We also use a subpixel technique to detect defects,” explained Efrat. “Normally, a defect must cover at least two adjacent pixels in an inspection image to ensure reliable detection. But subpixel resolution lets us detect defects as small as half a pixel in an image. We can apply this technique when a wafer provides a uniform background, which CMOS sensors do at low magnification. So, we can detect small defects and still run an inspection system at about four times the scanning speed needed for a higher magnification.”

To overcome the dark background created by an image sensor’s surface, inspection systems from Rudolph Technologies illuminate wafers with 10 to 20 times the amount of light needed to inspect a wafer of purely electronic devices. “We combine the bright illumination with standard dark-field techniques that pick up surface defects,” said Rajiv Roy, marketing director in Rudolph’s Inspection Business Unit. The higher magnifications needed to find small defects increase the number of images an inspection system must acquire. But the higher-power light yields a benefit: More light decreases exposure times, so a camera can spend less time at each inspection location.

Slice, dice, and inspect

Manufacturers of CMOS image sensors often put the devices in expensive packages. To avoid assembling a damaged sensor die in a package and then discarding it after a final test, manufacturers may require inspections of sensors before and after wafer dicing. Dicing can damage die and can drop particles on their surface. “We can perform both types of inspections with little or no changeover of our inspection equipment,” noted Pieter Vandewalle, director of marketing and sales for ICOS.

During inspections, equipment must automatically classify defects by type, size, location, and other criteria. Manufacturers set up the defect characteristics and a statistical “bin” for each defect type. Bins do not hold actual sensors, just information about the location of specific types of defects.

Because the typical defect that image-sensor manufacturers want to find has about the same dimensions as dust, wafer-inspection equipment often includes a dust removal system. “An operator can remove loose particles from a wafer prior to inspecting it,” said Vandewalle. “This operation maximizes the yield of good die from each wafer.”

“Sensor manufacturers want to classify defects by zones, such as the pixel array or the interconnect pads,” said Amir Gilead, Camtek’s VP of semiconductor inspection systems. “Zone information tells operators where defects occurred, what types of defects occurred, and the algorithm that found them. Equipment operators can adjust sensitivities so an inspection system reports only defects that meet specific criteria and exist in specific zones.”

A defect or a nuisance?

Most inspections that examine the optical characteristics of CMOS image sensors take place at the back end of wafer fabrication. Compared to the rest of the fab, that area does not always provide a clean environment. So, back-end inspection will detect real defects, such as embedded particles or scratches, as well as nuisance (or false) defects, such as loose surface particles or fibers. Images taken at higher magnifications reveal smaller defects, but they also reveal more nuisance defects.
Bright-field light reflects from all surfaces, so dark defects on a dark background lack contrast. Dark-field light reflects from a wafer surface but never reaches the camera. Irregular defects do reflect this light, which reaches the camera. Defects appear as bright spots on the dark wafer.

“Algorithms now better distinguish between real and false defects on CMOS image sensors,” noted Roy of Rudolph Technologies. “And we have augmented our inspection tools so they better classify nuisance defects automatically and ensure high wafer-processing rates.” The company has recently developed a defect-classification scheme that reduces inspection costs and maintains acceptable throughput of wafers without unnecessary reclassification of nuisance defects.

Roy said, “In a clean environment, it takes less work to distinguish between true defects and nuisance defects. And much depends on the types of nuisance defects a customer has. Those ‘defects’ might include metal particles, organic material, fibers, and dust.”

Sophisticated customers realize the value of investing in a clean environment. Others eventually learn the benefits of cleanliness. “But until they do, they tell us, ‘You must make your algorithms smarter so they eliminate nuisance defects,’” explained Roy. “We put a lot of time, effort, and money into improving algorithms, but at some point we have to tell customers they might find it less expensive to invest in cleaner environments.”

**Reconstruct a wafer**

Wafer reconstruction involves placing known-good die from several diced wafers on an adhesive material in a frame that holds the material rigid and flat. The reconstructed wafer looks similar to a whole wafer, but it lacks the round edge and unused silicon around its perimeter. In theory, a reconstructed wafer should contain only good devices. But slicing the wafer and moving die to the adhesive material could damage die or allow particles to settle on them. Thus, reconstructed wafers undergo a final inspection that creates a map that accompanies each wafer and identifies defective die.
Adhesive tape holds CMOS image sensors in a format called a reconstructed wafer. A tape frame stretches the material to keep it rigid. Courtesy of Camtek.

Slight inaccuracies in pick-and-place equipment may shift or rotate die slightly when the equipment places them on an adhesive film. So, the positions of die on a reconstructed wafer may differ slightly in position and orientation from die on diced wafers. (Although the diced die are separated or “singulated,” they remain in their original fixed positions.)

Camtek uses software to align an image of a die on a reconstructed wafer with a reference image stored in the company’s inspection system. The software handles small differences in the locations of die on a reconstructed wafer and the orientation of the reference image. “This type of inspection becomes particularly important as CMOS image-sensor manufacturers produce bigger die and misalignments become larger,” said Gilead.

Inspection-equipment vendors have a vested interest in inspection results. Not only does their livelihood depend on producing good inspection results to CMOS image-sensor manufacturers, but their own equipment depends on a steady supply of high-quality cameras that use the very types of sensors they must inspect.

Reference

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<th>Inspect glass, too</th>
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<td>Some image-sensor manufacturers that place sensor die in packages with a glass top use inspection equipment to examine the glass for defects. “Even if you have a perfect sensor, defects on or in the glass can cause problems,” explained Rajiv Roy, marketing director at Rudolph Technologies. (The glass above a sensor provides protection and does not substitute for the microlens materials some manufacturers apply to sensors.)</td>
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<td>“A glass supplier inspects the glass it sells,” said Roy. &quot;A CMOS sensor manufacturer inspects the glass after it goes on and gets bonded to a complete sensor package.&quot; Although glass looks transparent, it may have defects such as discoloration, striations, and scratches.</td>
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<td>“Some defects cause more problems than others,” noted Roy. A manufacturer might decide to use glass with a slight discoloration but reject glass with tiny surface scratches. Inspection-equipment operators fine-tune inspection equipment to establish which minor glass defects to accept and which to reject.</td>
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<td>Sensor manufacturers or sensor packagers may use different package types that depend on the end use for a device. According to Roy, some packages use a single layer of glass and others use two layers separated by a vacuum. “A couple of layers of glass put particles that settle on the outer surface of the glass farther from the sensor’s focal plane. They do not affect an image as much as particles that settle close to the sensor or its focal plane.”</td>
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<td>A high-quality sensor with an extra layer of glass costs more, but it provides a better image. “Some manufacturers that employ two layers of glass have asked us to inspect all four surfaces of the glass and to distinguish between defects on each surface,” said Roy. “In general, though, most manufacturers simply want to inspect the top surface.”—Jon Titus</td>
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