Technology

by Luciano Mule'Stagno and Peter Török

Scanning for Defects with Microscopes

The semiconductor industry is engaged in a huge, high-stakes experiment in scaling: whether the industry can duplicate in the future the successes of the past will depend on its ability to solve problems that emerge as its products become progressively smaller. One of these problems is contamination—particularly contamination by metals, which alter the electrical properties of silicon. Trace amounts of metals, which could be tolerated, by yesterday's micrometer-scale transistors, can cause today's smaller devices to fail.

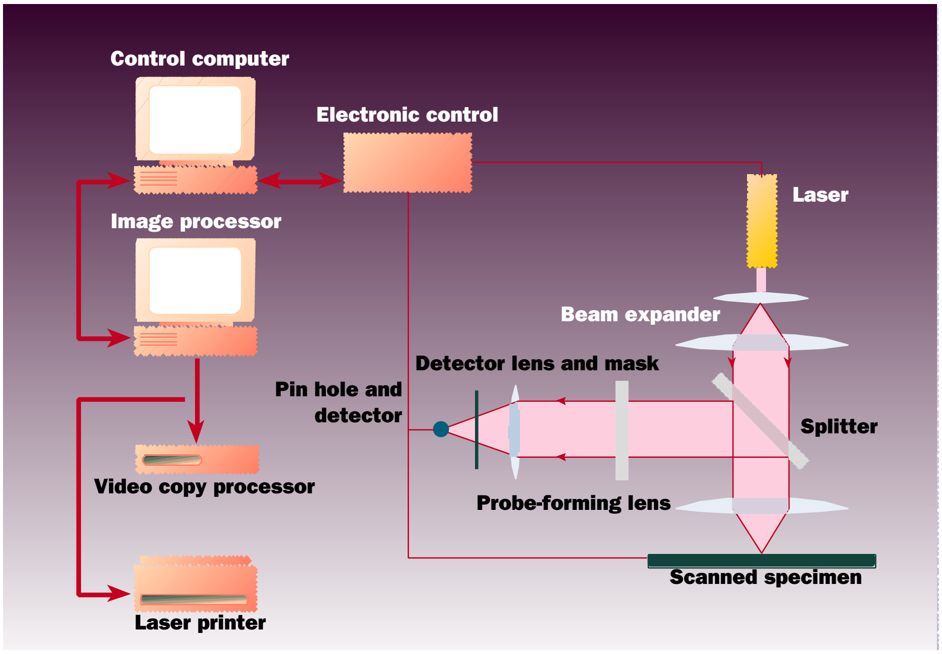

Figure 1. In SIRM, the light from an infrared laser is focused to form a probe, which penetrates the wafer. The probe is scanned laterally and vertically to form an image of the wafer defects.

The semiconductor industry has developed processes that sequester metallic contaminants in the bulk of the wafer, where they do not disturb the devices on the surface. But to optimize these processes, the industry needs a fast and accurate way of creating images of the wafer's interior. Several microscopies suitable for this purpose are being developed—among them scanning infrared microscopy (SIRM). All of the new microscopies are based on the same physical principle—namely, that silicon is transparent to electromagnetic radiation at near-infrared wavelengths.

The problem

The first line of defense against contamination is to avoid it in the first place, which is why the semiconductor industry is obsessed with cleanliness. Metals are needed, however, to make integrated circuits, and the wafer must inevitably come in contact with some surfaces during processing, so it is impossible to eliminate metals entirely. The industry therefore falls back on a second line of defense—trapping contaminants in regions other than the wafer surface, a process called gettering.

At first, most gettering was extrinsic; sinks for contaminants were formed in the back surface of the wafer by mechanical damage, diffusion of impurities, or the deposition of films. When the wafer was heated, metallic contaminants—since they are highly mobile in the silicon lattice—diffused from its front surface into the gettering sinks, where they were trapped. As devices became smaller, however, extrinsic gettering was increasingly supplemented by intrinsic gettering (IG)—where contaminants are trapped by oxygen precipitates in the bulk of the wafer.

A typical IG process consists of multistep heat treatment that takes place before the wafer is processed. All silicon wafers grown by the standard Czochralski process are supersaturated with oxygen. The wafer is first heated in the absence of oxygen to create an area of low oxygen concentration near the surface. This is called the denuded zone, and its depth is tailored to the process in question. Subsequent heat cycles nucleate and grow oxygen precipitates in the bulk of the wafer below the denuded zone.

When devices are then built in the denuded zone—or, as is sometimes done, in an epitaxial layer deposited on the wafer's surface—these precipitates getter stray metal atoms. The mechanisms by which they do so are still the subject of debate, but it appears that the oxide particles generate dislocations, and the metallic elements then precipitate on these dislocations.

Many factors affect the IG process. The efficiency with which the precipitated particles getter contaminants depends on their size and their density, and these parameters, in turn, depend on the initial concentrations of oxygen and the exact details of thermal treatments. To optimize IG processes, the industry really needs a means to routinely monitor what are called bulk microdefects, a term that encompasses both precipitates and dislocations.

Defect density is currently measured by a cleave-and-etch technique: an operator cleaves strips from a wafer, treats them with one of a variety of etchant mixtures, and counts the etch pits under a microscope. The accuracy of the technique depends on the operator's skill, and the corrosive, toxic etchants are environmental and health hazards. Further, because the method is destructive, it can't be used to follow the evolution of precipitate populations as a wafer is subjected to the multistep IG process.

If wafer defects must be characterized more accurately, transmission electron microscopy (TEM) is used, but this technique is also destructive, and it is slow. It is practical if the failure of a device betrays the lateral position of a defect, but it is impractical if the defect density is low, the defects are

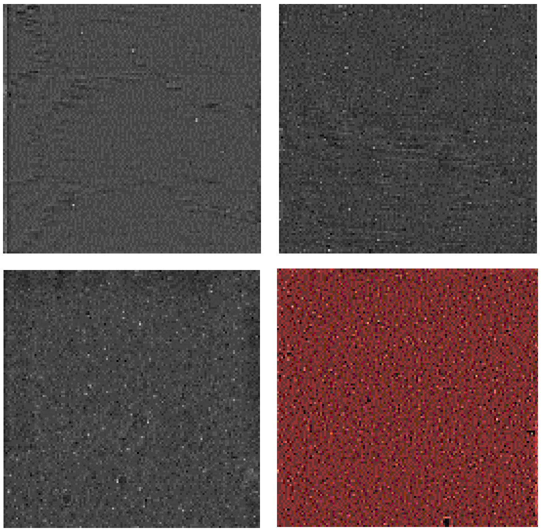

Figure 2. A typical SIRM image shows defects as bright spots if they are in focus and as dark spots if they are slightly out of focus.

in the bulk of the wafer, or a large volume must be sampled to obtained statistically significant results.

The solution

In the past decade, three light-scattering microscopes that are suited for the monitoring of bulk microdefects have been developed by scientists on three continents. In the 1980s, a group at IBM led by J. S. Batchelder and M. A. Taubernblatt developed the optical precipitate profiler (OPP), which makes use of the interference between two halves of a split beam to detect particles in silicon. A commercial version of the OPP instrument is made by High Yield Technology (Sunnyvale, CA).

The laser scattering tomograph (LST) was first demonstrated in 1981 by Kazuo Moriya and Tomoya Ogawa of Gakushuin University in Tokyo. Mitsui and Ratoc, also of Tokyo, now makes commercial versions of this instrument, which is widely used in Japan.

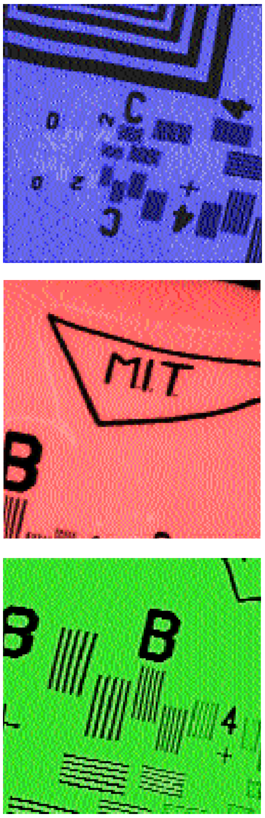

Figure 3. SIRM images a pattern that was etched into the surface of a polished silicon wafer that was bonded to another wafer. The pattern is clearly seen through 300 µm of silicon.

SIRM was developed at Oxford University. By 1987 Patricia Kidd, G. Roger Booker and their co-workers were using a scanning infrared microscope to investigate precipitates in semiconductors. A team including one of the authors (Török) later developed a confocal version of the instrument. The KFKI Research Institute for Material Science and the instrument company Semilab, both of Budapest, made a commercial version of this instrument.

In SIRM the light from an infrared laser is focused to form a probe, which penetrates the wafer. The probe is scanned laterally and vertically to form an image of the wafer defects. Because most of the defects are smaller than the laser light wavelength (the laser typically has a wavelength of 1.3 μm and the most of the defects are much smaller than 1 μm), they scatter the light much as the fine dust particles and water droplets in the atmosphere scatter sunlight. Depending on its mode of operation, a SIRM detects the scattered light either directly or by interferometric techniques.

SIRM has several different imaging modes; for brevity, we describe here its confocal reflection mode (Figure 1). In a conventional microscope the object is illuminated by a patch of light from an extended source through a condenser lens. An image of the object is then formed by an objective lens and viewed through an eyepiece. The resolution of the microscope is determined primarily by the objective lens.

In a confocal scanning microscope, the object is illuminated by a point source on a small volume by an objective lens. A collector lens images light from the same volume on a point detector. The point source and point detector are scanned to construct an image. The resolution of the microscope is determined by both the objective and the collector lenses. Because a confocal microscope rejects light from regions of the object other than the one currently illuminated, it provides excellent lateral and depth resolution.

A confocal SIRM can be set up to detect light transmitted through a wafer or light backscattered from the wafer. The main disadvantage of the confocal transmission mode is that variations in the wafer's thickness displace the image laterally at the detector. Because commercial semiconductor wafers are generally single-side polished, they must be polished on the back side before they are examined with this technique. The main disadvantage of the confocal reflection mode is that it cannot be used to image the area immediately below the wafer's surface. When the probe is focused at a shallow depth, reflection from the wafer surface swamps light scattered or reflected from a deeper plane.

Applications

Figure 2 is a typical SIRM image of bulk microdefects. With the current software, images 500 μm on a side can be scanned in about 5 minutes. The defects appear as bright spots if they are in focus and as dark spots if they are slightly out of focus. An image-analysis software program is used to count the number of particles.

Recent studies by one of the authors (Mule'Stagno) showed that, in wafers that had undergone oxygen precipitation, defect densities measured by SIRM agreed well with those obtained by the traditional cleave-and-etch method. And a team of scientists from MEMC, SpA (Novara, Italy), and Oxford University has employed SIRM to determine the density and size of precipitates that best gettered deliberately contaminated wafers.

SIRM can accurately measure defect densities that span the range typical of IG-processed wafers (10^7 to 10^{11} cm^{-3}). Indeed, it can measure densities an order of magnitude or two lower, which makes it a good candidate for examining grown-in and other low-density defects that can also cause device failure. (Grown-in defects are defects that are formed during the growth of the single-crystal ingot from which the wafers are cut.)

SIRM can also be used to study the particle size distribution, which depends on the initial oxygen content of the wafer and the type of heat treatment. Because the scattering intensity from a microprecipitate is proportional to the square of its volume, SIRM is extremely sensitive to size variations.

Finally, SIRM can be used to examine bonding between two silicon wafers, a technique sometimes used in the manufacture of silicon sensors. Figure 3 is a SIRM image of a pattern that was etched into the polished surface of a silicon wafer, which was then bonded to another wafer. The pattern emerges clearly, even though it was seen through about 300 μm of silicon. Using test patterns such as this one, scientists at the KFKI Research Institute for Materials Science were able to select the best bonding procedure for an application.

Other instruments

The OPP and LST offer slightly different solutions to the problem of imaging bulk microdefects. In the OPP a laser beam is passed through a prism, which splits it into two adjacent polarized beams. As they emerge from the prism, the beams are focused in the bulk of the wafer by an objective lens. If a defect passes through one of the beams, its phase is shifted with respect to the phase of the other beam. When the beams emerge from the back of the wafer, this phase change is measured, and the defect detected.

In the LST the wafer is cleaved and upended for examination. A laser beam is then focused into a wafer through the polished surface, and the light scattered at 90° to the beam by microdefects in the wafer is detected by an infrared camera. This configuration was chosen so as to enable the measurement of denuded zones. Ω

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