REPORT:

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WAFER INSPECTION WITH A LASER SCANNING MICROSCOPE

Introduction

The decreasing geometries and increasing die sizes of today's VLSI circuits are demanding ever more stringent controls over particle contamination on semiconductor wafers during their processing. Consequently, there is a need for objective inspection techniques to monitor defects and contaminants on the surface of semiconductor devices. The goals of such an inspection are:

- Increased die yield,
- Improved device quality,
- Statistical process control, and
- Improved characterization of device processing sequences.

A new, laser scanning microscope (LSM), developed at AT&T Technologies Engineering Research Center (ERC) in Princeton, New Jersey, automates the inspection of surfaces of patterned semiconductor wafers for particle contamination. Wafers now are most often inspected for particles by operators using conventional optical microscopes. Since this process is time-consuming, labor intensive, and requires that the wafers be handled, particle inspections are performed infrequently, usually as a process control measure after a process is found to be "particle-prone." For example, the sputter deposition of tantalum silicide ($TaSi_2$), a material used to reduce the resistivity of the polysilicon word lines on the device, can be a particle-generating process. Particle count data from the LSM have been used to implement appropriate statistical process controls (e.g., a new cleaning schedule for the sputter deposition equipment) to reduce the number of particles generated in this process.

The LSM has several advantages over commercially available wafer inspection systems. Such systems fall into two categories: (1) relatively inexpensive (less than $200,000) types designed to inspect polished wafers, and (2) more expensive ($400,000 to $900,000) systems that are capable of patterned wafer inspection, and also incorporate defect analysis by die-to-die or die-to-reticle comparison techniques. Few, if any, commercial systems are designed exclusively for particle inspections on patterned wafers. Thus, the LSM's advantages are:

- In the same price range as the inexpensive commercial systems, the LSM inspects production wafers rather than polished monitor wafers. Product quality and potential die yield, therefore, can be investigated wherever needed in the wafer processing sequence.
- In process-control applications, special equipment characterization runs are not needed and space in production runs is not taken by particle monitor wafers, as is the case with polished-wafer inspection systems.
- When particle inspection is performed on the LSM, a more objective result is obtained than is possible with optical inspection, and the inspection operator is freed to perform more demanding inspection tasks.

Optical Design

The LSM's operation is based on adaptive imaging.[2] The technique, shown in

Figure 1, employs a scanned focused laser beam to provide localized illumination of the object's surface. A number of remote detectors monitor the light scattered from the object. The signal from the detectors modulates the intensity of the scanning beam in a video monitor, which produces an image of the object.

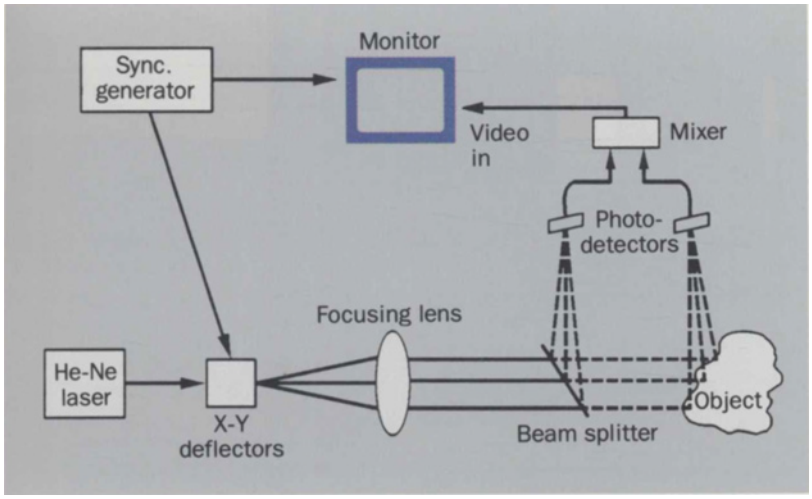


Figure 1. The operation of the new, laser scanning microscope is based on the concept of adaptive imaging.

This technique converts two-dimensional spatial information into an electrical signal.

Past applications of adaptive imaging have successfully employed polarization detection and fluorescence (in addition to scattering-angle variations) to produce high-contrast video images of otherwise low-contrast objects. The LSM utilizes scattering-angle variations to detect particles on patterned wafers and produces three images of the semiconductor surface:

- One image contains low spatial frequencies corresponding to a conventional bright-field microscope.
- The second image has moderate spatial frequency content similar to a dark-field microscope.
- The third image contains very high spatial frequencies that would not be seen with a conventional microscope.

Since these images are available as separate video signals, they can be added and subtracted from one another to produce useful composite video images not available from conventional microscopes. Hence, image processing can be performed in real time and greatly reduces the computing time needed for image analysis.

The optical layout of the laser microscope in shown in Figure 2. The beam from a He-Ne laser is expanded and passed through an acousto-optic deflector which scans the beam at the same rate as the horizontal line scan of a video monitor. The scanned laser beam is transferred to a galvanometer scanner by means of a 2:1 telecentric lens system. The galvanometer executes a 60-Hz vertical scan, consistent with the video monitor's vertical scan rate. The laser beam, now scanned in two orthogonal directions, passes through a flat-field microscope objective and comes to a focus on the surface of the semiconductor wafer.

Light that is reflected or scattered at low angles from the object is collected by the microscope objective and then collimated. Some of this light passes through a hole in the annular mirror, is reflected by the galvanometer mirror, and is redirected to a bright-field detector by means of a beam splitter and an auxiliary mirror. The output of this detector provides a video image similar to that of a bright-field microscope. The remainder of the scattered light collected by the microscope

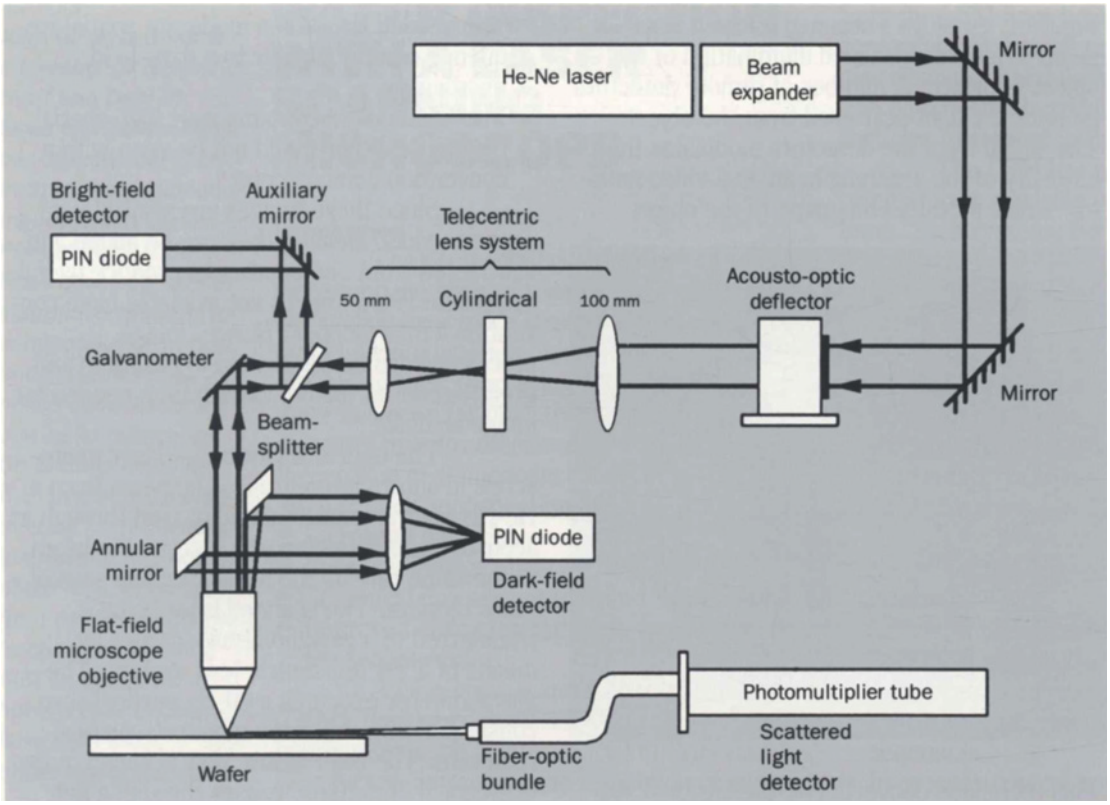


Figure 2. The optical system for the laser scanning microscope.

objective is intercepted by the edges of the annular mirror and directed to a dark-field detector. This light contains higher spatial frequency information and corresponds to a dark-field microscope image.

Some of the light scattered from the wafer will not be collected by the microscope objective due to its limited numerical aperture. This is especially true if the wafer has a pattern with sharp edges. In a conventional microscope, the image information in this high-angle scattering would be lost. Fortunately, the laser microscope utilizes this high-angle scattering to great advantage. As shown in Figure 2, a remote scattered-light detector can be positioned to collect this light to produce an additional video image, which contains information related to sharp surface discontinuities and particles on the wafer surface.

The ultimate resolution of the LSM, in the video imaging mode, is limited by the acousto-optic deflector. The resolution of the

system is the number of resolvable positions, N, that the scanner can produce. Typically, N = 500 for commercially available scanners. Although the acousto-optic deflector sets the limit on the number of resolvable spots in the field of view, the actual field size is determined by the effective focal length of the lens following the deflector. Hence the size of a resolution element is determined by the objective used. For instance, for a 16x objective, having a field size of 320 by 240 μm, the ultimate resolution is 0.6 μm. However the realized resolution depends on the spot size (2.5 μm). Using Rayleigh's criterion for resolution, the limiting resolution is 1.2 μm.

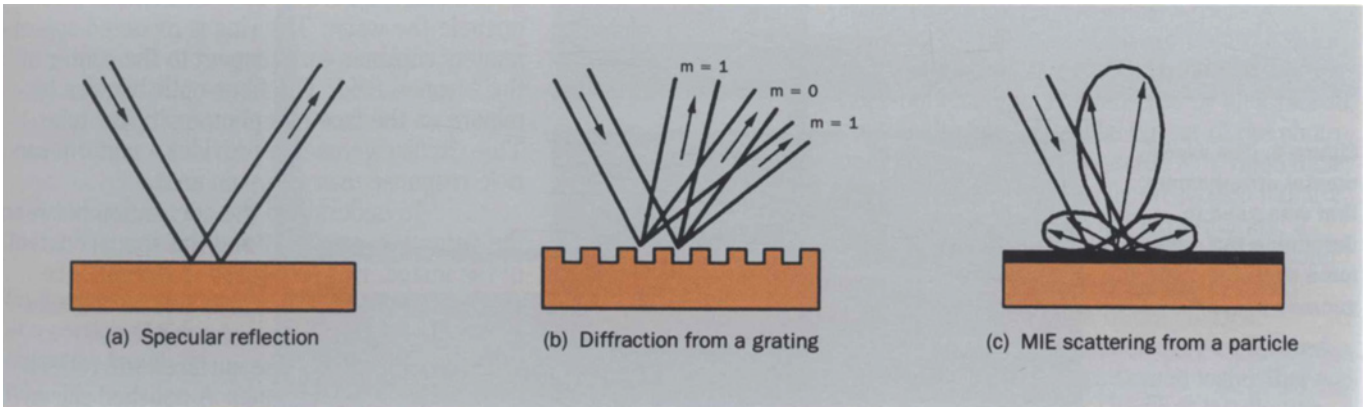


Figure 3. Scattering profiles of various surface features.

Microscope Operation

Light scattering is widely used in the semiconductor industry for particle detection. However, this technique has had limited application to patterned wafer inspection because the periodic pattern acts as a diffraction grating, making it difficult to distinguish the signal produced by the pattern from that produced by the particles. Work done by Jablonowski, Truax, and Schmitt at the ERC has produced a technique employing a focused laser beam and patented detection system that is relatively insensitive to the pattern signal. The wafer travels on an x-y translation stage, while the focused laser beam is scanned over the wafer's surface perpendicular to it.

The collection optics monitor light scattered at angles near 90° to the laser illumination. The angular distribution of the light scattered from a particle on the wafer surface is similar to that predicted for spherical particles by Mie scattering (i.e., scattering in narrow angular lobes). If particles are small (less than 1/10 the wavelength of the light), the scattering can be calculated as if the particles were point dipoles. However, if the particles are larger than 1/10 the wavelength, the scatter intensity is not symmetrical in a solid angle, but greater in the forward and backward direction. The value 1/10 the wavelength of the He-Ne

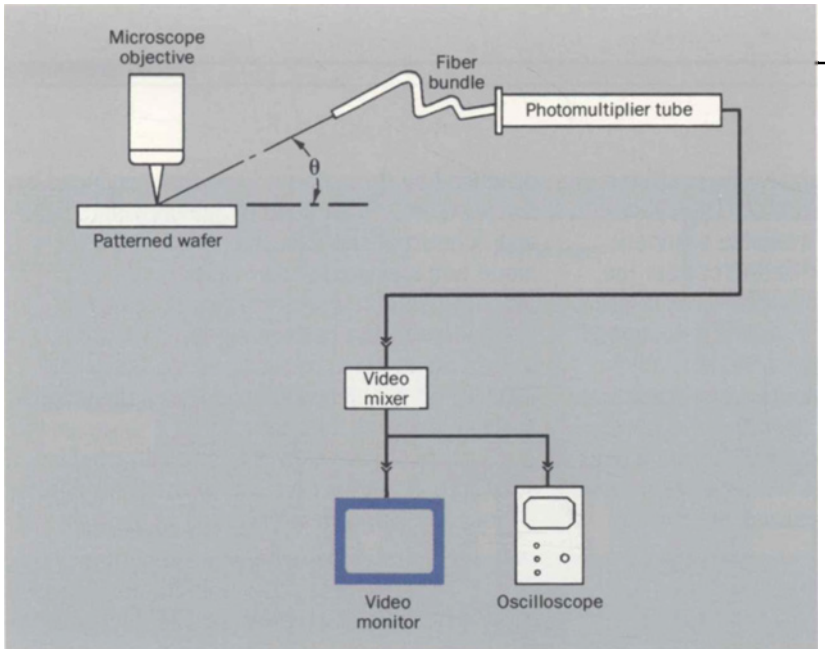


Figure 4. The experimental arrangement that was used to determine the optimum detector geometry.

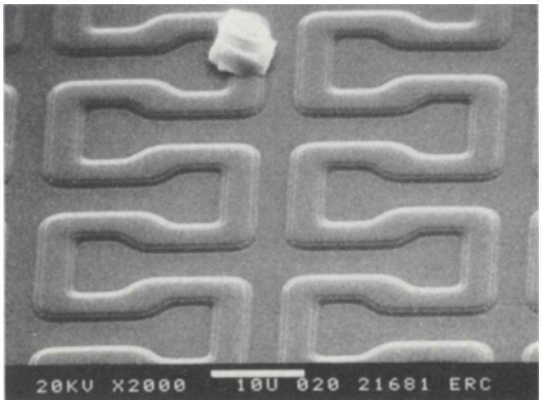


Figure 5. Scanning electron microscope photograph shows a contaminant on the surface of an MOS 16K RAM patterned wafer.

laser, 0.6328 μm, is an order of magnitude smaller than the particles to be detected, thus ensuring that the system operates in the Mie regime.

Particle signal intensity is highest for low and high angles, while the signal intensity for the pattern (i.e., diffraction grating) is low for high scattering angles ($\theta > 60°$). Consequently, by comparing and thresholding the signal at high angles ($\theta > 80°$), the system can discriminate between the particles and the wafer pattern. The collection optics consist of a rigid ring supporting 11 fiber bundles that encircle the wafer. The ring is mounted approximately coplanar with respect to the center of the scanned field. The fiber-optic bundles terminate on the face of a photomultiplier tube. This circular geometry provides a uniform particle response over the scan area.

To understand the correlation between the detection geometry and the spatial content of the image, it is necessary to examine the scattering profiles of various surface features. Figure 3a illustrates specular reflection. Smooth, flat, mirror-like surfaces will reflect light in this simple manner. A polished silicon wafer can be considered a specular surface and techniques for inspecting these wafers rely on detection of departures from specular behavior to locate flaws or scratches.[3] Diffraction from a grating is illustrated in Figure 3b. Here a number of diffracted beams (only three are shown) originate from the surface relief grating. A patterned semiconductor wafer can be represented as a complex two-dimensional grating. Finally, scattering from a particle is shown in Figure 3c and the scattering determined from Mie theory.[4] In general the intensity distribution is determined by the size,

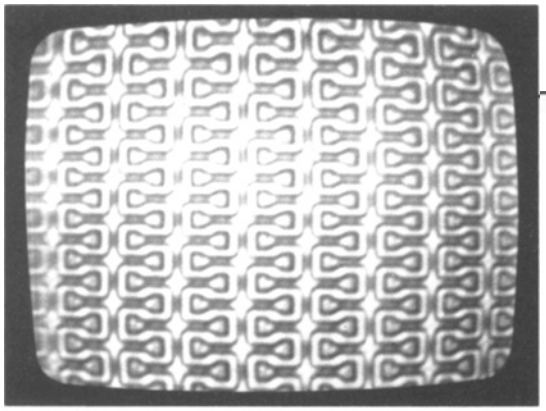
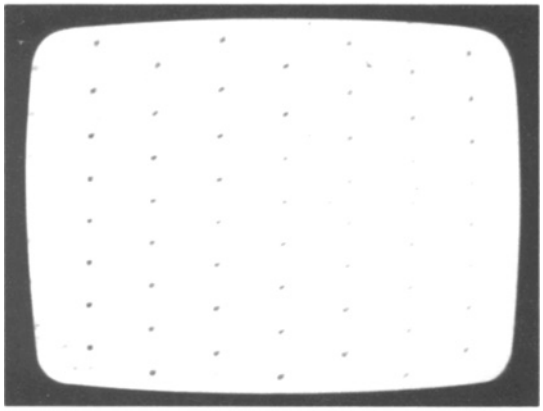
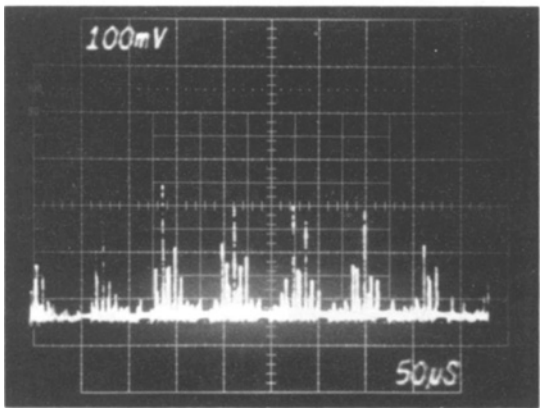


Figure 6. Video monitor and oscilloscope images of a patterned wafer without contamination. (a) Bright-field image of pattern, field-of-view free from contamination.



(b) Video image obtained through a fiber bundle, $\theta = 30°$. Same field-of-view as in (a).

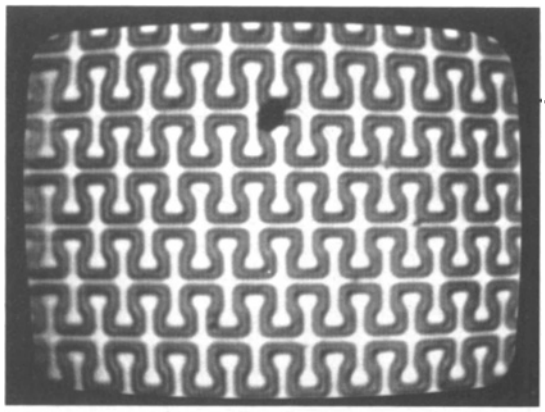


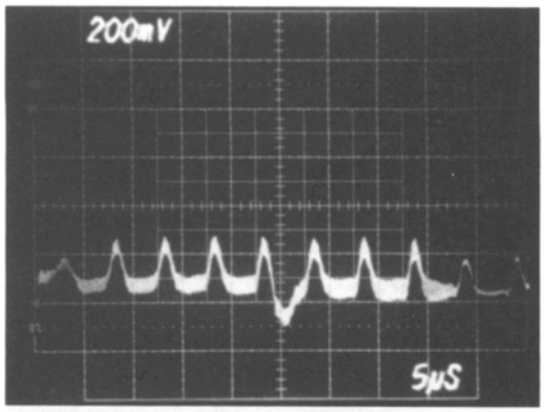
(c) Oscilloscope photo of a portion of video signal for image in (b).

shape, and composition of the particle. Typical particles appearing on the surface of semiconductor wafers are dust, chips of silicon, photoresist flakes, etc.

The goal in designing the LSM was to maximize the particle signal while minimizing the signal from the pattern. To achieve this, the field of view of the detector must be centered at a high angle with respect to the incident beam. This eliminates the more intense low-order diffracted light while detecting the particle signal. The experimental arrangement for determining the optimum detector geometry is shown in Figure 4. Scattered light from the wafer is collected by a fiber-optic bundle and detected by an attached photomultiplier tube. The output of the photomultiplier tube was connected to a video mixer and displayed continuously on a video monitor and an oscilloscope. In the experiments, a gate/source/drain-level MOS 16K RAM wafer was used. Figure 5 is a scanning-electron microscope photograph of the surface.

Initial experiments were conducted using a portion of the patterned wafer that was free of contamination. The fiber bundle was positioned at various angles with respect to the wafer surface. For example, at 30° the video display is shown in Figure 6b. The dots are the images of the corners in the pattern. In fact the sum of all the images obtained during a rotation of 360° simply outlines the edges of the pattern. Figure 6c shows a portion of the video signal. The optimum angle lies between 1° and 3° with respect to the wafer surface. In this configuration, the video monitor displays the particles on the wafer without the pattern. Figure 7a shows an image of a particle on the surface of a patterned wafer, and the video sig-





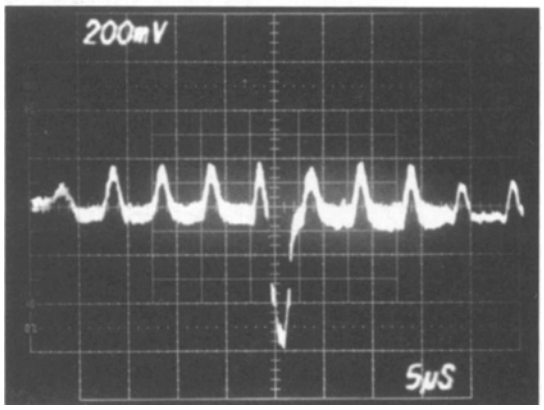


Figure 7. Video monitor and oscilloscope images of patterned wafer with a contaminant. (a) Bright-field image shows particle on wafer.

(b) Oscilloscope trace of one video line of image in (a). Note dip in signal when scan line crosses black particle.

(c) Particulate image added to bright-field image. Note that particulate image is enhanced compared with (b).

nal of one scan line is shown in Figure 7c. From the figure one can see that the 3:1 signal-to-noise ratio is favorable and that structure due to the pattern is not evident in the image. This is possible because the particle scatters a significant amount of light at very high angles while the higher diffracted orders from the pattern are relatively weak.

Control Circuitry

A prototype system was developed at the ERC to inspect patterned wafers automatically, and a PDP 11/23 minicomputer handled its data and control processing. Also, a pick-and-place robot arm transports the wafers from the cassettes to the laser microscope, minimizing contamination due to handling. The system inspects predetermined sites for contaminants and records the number, size and location of each detected particle. A block diagram of the electronics is shown in Figure 8. The output from the LSM can be stored on a hard disk or fed to a line printer.

The operator loads the cassette then the computer begins a scan. The motorized x-y-z stage moves the wafer, allowing the focused beam to traverse it. A ring of fiber bundles is mounted to the face of a photomultiplier tube, which monitors the amount of light scattered at high angles the instant the laser beam hits the wafer. As a particle passes through the laser beam's illumination, light is scattered at near 90° into the fiber bundle. Particle data from the photomultiplier tube trigger the interrupt request of the computer. The computer then latches the scan position and particle count from the x-y stage controller. The frame-storage-and-display electronics control the galvanometer and acousto-optic scanner to syn-

chronize the position signal with the stages. Through the parallel input/output port, the computer controls the movement of the stages and the wafer handling system. The frame storage and display boards, interfaced through the Q-Bus,[5] along with custom software allow the system to determine the size of the particles detected by the fiber ring.

The LSM is flexible and adaptable to different types of wafers. The system is fully automatic and capable of detecting particles as small as 1 μm at a rate of 1 mm^2/sec. Position accuracy is 12.7 μm and limited only by the step size of the stage.

Performance Data and Applications

The performance of the LSM was evaluated over several months in the MOS V clean room at AT&T-Technology Systems in Allentown. The primary application for the LSM evaluation was as a process monitor for particle contamination resulting from various wafer processing operations. Four to eight wafers from a production lot awaiting processing at a particular step were inspected using the LSM before and after processing. The area of the wafers programmed for inspection was a horizontal strip across the wafer center, approximately 10 cm^2 in area. The LSM data files for each wafer before and after processing were compared to determine the number, size, and location of particles added during the process. These experiments were carried out using wafers at several processing levels to evaluate the applicability of the LSM for inspection of wafers with varying degrees of topography and various types of films on the surface (e.g., polysilicon, $TaSi_2$, aluminum). In some experiments, the wafers were also inspected using an optical microscope to verify the results of the laser microscope inspection.

Most LSM performance data were collected for 256K DRAM wafers (codes 63A and 63B) at the $TaSi_2$ deposition process. Wafers from seventeen lots (102 wafers total) were inspected before and after the deposition process using the LSM. In addition, the wafers from ten of the seventeen lots were inspected optically, confirming the LSM results. The results of these inspections showed a correlation between the number of wafers previously processed through the $TaSi_2$ sputtering equipment (i.e. the cleanliness of the machine) and the number of additional particles on the wafer after deposition. When the equipment cleaning interval is every 2000 wafers, there are 0.75 additional particles/cm^2 after deposition, while at a cleaning interval of every 1500 wafers, the number of particles added by the process is reduced to 0.46 particles/cm^2. This result prompted a change in the cleaning schedule for the MOS V $TaSi_2$ deposition equipment. Additional studies have been carried out by the MOS V engineering staff to characterize the contributions of various parts of the sputter deposition process cycle to elevated particle counts following processing. The results of these studies will be reported elsewhere.

In addition to the extensive study of the $TaSi_2$ level, a number of wafers have also been inspected at the polysilicon, aluminum, and phosphorus-doped glass or BPSG (borophosphosilicate glass) levels. Again, wafers were inspected before and after the process of interest, and the results compared to give information on the number of particles added by each process. Although data on each of these levels are limited, experience with the

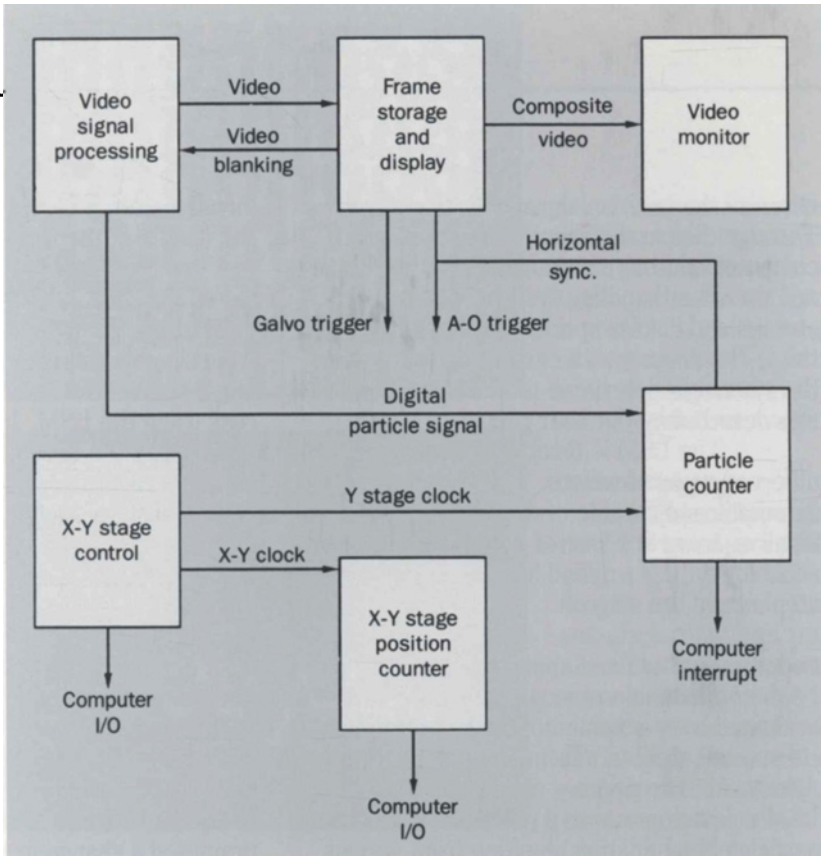


Figure 8. The electronics for the new, laser scanning microscope.

polysilicon and phosphorus-doped glass (or BPSG) levels has indicated that LSM inspection of these levels is quite similar to that of the $TaSi_2$ level and can be carried out using inspection parameters similar to those for $TaSi_2$.

In contrast, the aluminum level presents some unique problems. The ability of the prototype LSM system to distinguish between particles and the edges of the pattern on the wafer is diminished at the aluminum level due to topography and the reflectivity of the aluminum film. The distinction may be enhanced by lowering the scattered-field detector ring relative to the wafer surface. Lowering the ring on the prototype LSM system gives much improved particle detection capability with minimal edge pickup. A modified wafer load/unload scheme is being developed for use on future versions of the LSM system to allow implementation of the lowered ring configuration as a permanent feature.

Conclusions

While commercially available wafer inspection tools are of two general types: (1) inexpensive, polished-wafer inspection systems, and (2) more expensive, patterned wafer defect detection/image processing/metrology systems, the LSM falls somewhere in between, both in capabilities and in price. The detection system of the LSM is limited to particles and

does not provide linewidth or registration measurement capabilities. However, the LSM does inspect patterned, production wafers and thus offers a convenient tool for process monitoring without the need for special monitor wafers. The estimated price of the LSM is $150,000 to $175,000. In addition, the LSM inspection can be used to replace particle inspections done by operators (e.g., following processes such as $TaSi_2$ deposition), freeing the inspection operators for more demanding inspection tasks. Thus, the laser scanning microscope provides a convenient, relatively low cost method for particle inspection on patterned, in-process silicon wafers.

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