# The Winning Streak

## Advanced Darkfield Inspection for 65nm Design Rules and Below

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Increasingly complex technical and economic challenges continue to emerge at 65nm design rules and below, driving the need for inspection tools that provide cost- and performance-optimized defect monitoring on a broad range of layers. Conventional darkfield inspection tools based on acousto-optic deflector/photo-multiplier tubes (AOD/PMT) have reached their limit in sensitivity at throughput. This article describes an innovative new inspection technology that meets the sensitivity demands of next-generation semiconductor processing without sacrificing the high production throughput that distinguishes darkfield patterned wafer inspection.

As the semiconductor industry moves below 65nm design rules, it faces integration challenges associated with the introduction of new processes and materials as well as continued cost pressures. Shrinking design rules and process control windows require increased inspector resolution, while new substrates and device materials challenge inspectors' noise suppression capabilities. The competitive environment, shorter product life cycles and single wafer processing techniques drive the need for cost effective manufacturing, including cost effective inspectors that provide the required sensitivity at production throughputs. To date, laser-based darkfield inspection tools have filled a key role in semiconductor inspection by providing high-throughput defect monitoring capability. However, as the industry moves forward, conventional darkfield inspection technology struggles to meet manufacturers' inspection needs.

Conventional darkfield inspection tools illuminate the wafer surface with a focused laser spot. An acousto-optic deflector (AOD) sweeps the spot along one axis of the wafer surface while the stage moves perpendicular to the sweep direction in a serpentine pattern. Collectors use photodetectors, such as photo-multiplier tubes (PMTs), to detect the scattered light. Depending on optical configuration and feature implementation (i.e., polarizers, illumination angle), these systems can have excellent noise suppression, and can detect defects much smaller than the spot size. They also have high throughputs, making them ideal for patterned wafer tool-monitoring applications. As for any optical inspector, the resolution of these tools is determined by illumination wavelength ($\lambda$) and numerical aperture (NA). If the wavelength is not changed, the tool can be modified to resolve smaller features by increasing the NA. For traditional darkfield inspectors, increasing the NA corresponds to decreasing the spot size. Thus, as design rules shrink, it is necessary to shrink the spot size in

order to maintain sensitivity to critical defects. Shrinking the spot size reduces the throughput, diminishing one of the key benefits of these inspectors. In addition, single scanning spot AOD/PMT systems have a maximum possible data rate of ~300Mpps, limiting the extendibility of these platforms to future semiconductor nodes. Introducing multiple spots on an AOD-scanning tool increases the throughput linearly with the number of spots, assuming each spot maintains sufficient photon density. However, multiple spots also increase the complexity of the system significantly, leading to potential problems with reliability and matching.

A laser-based inspector has been developed that incorporates a new darkfield imaging technology. This inspector meets the sensitivity requirements of 65nm and below processing technologies without sacrificing the production throughputs distinguishing darkfield patterned wafer inspection. This article describes the fundamental features of this inspector, including the innovative darkfield imaging technology, illumination angle, polarizations, and Fourier filtering. Experimental data are presented that support the specific implementations of these features on this inspector. Additionally, several applications for this inspector are described, which highlight its capability for meeting the wafer inspection challenges beyond the 65nm processing node.

### Darkfield Imaging Technology

With true brightfield imaging inspection technology, the wafer is flood illuminated through an objective with broadband light. The reflected specular beam is imaged onto a multi-pixel detector creating a high resolution image. The imaging resolution obtained by these tools provides a clear sensitivity advantage – making these tools the sensitivity
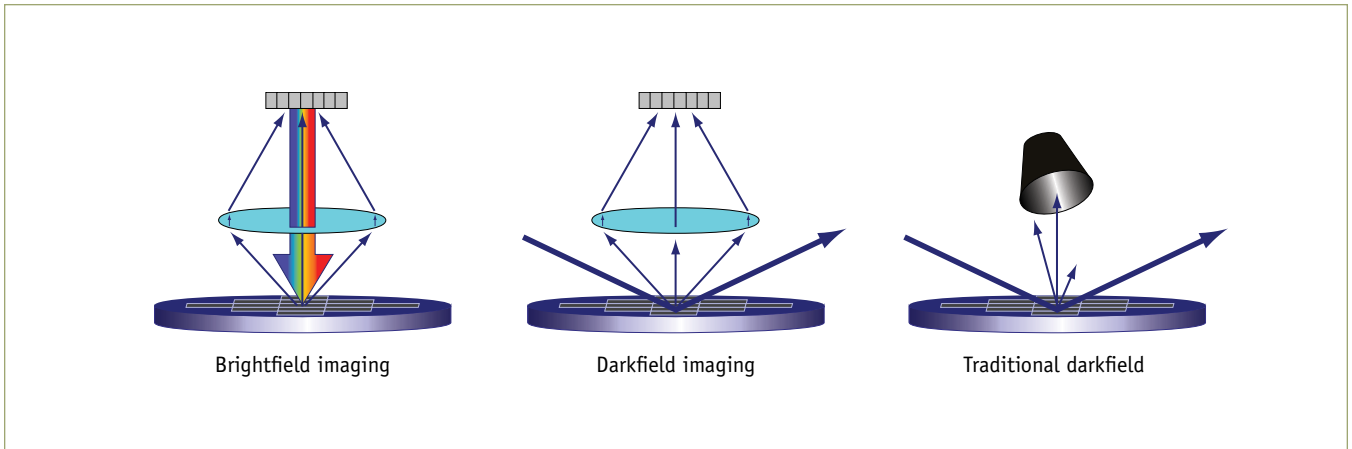
Figure 1: Depiction of true broadband brightfield imaging technology, the new darkfield imaging technology implemented in the Puma™ 9xxx inspector, and traditional laser-based darkfield technology.

leaders in optical patterned wafer inspection. With traditional darkfield technology, the wafer is illuminated with a focused laser spot, and light scattered outside of the specular beam is detected with a PMT. These tools are considered the through-put leaders in patterned wafer inspection. A new darkfield imaging inspector has been designed which incorporates the imaging technology from broadband brightfield inspectors[1]. A focused laser beam illuminates the wafer surface and scattered light is imaged onto a unique, patented multi-pixel

sensor, instead of a 'single-pixel' PMT. This darkfield imaging tool provides the high resolution needed for today's design rules without sacrificing the superior throughputs typically associated with darkfield tools. Figure 1 provides an illustration of brightfield imaging, the new darkfield imaging technology, and traditional darkfield scattering. These inspection technology illustrations depict only a subset (normal incidence brightfield and oblique incidence darkfield) of possible tool configurations.
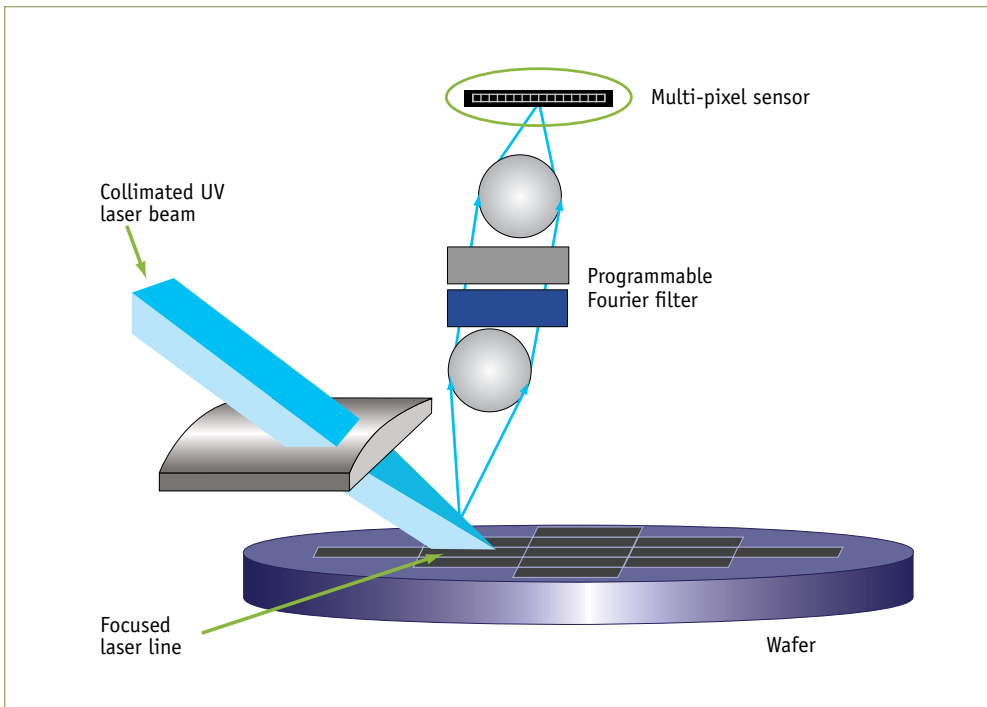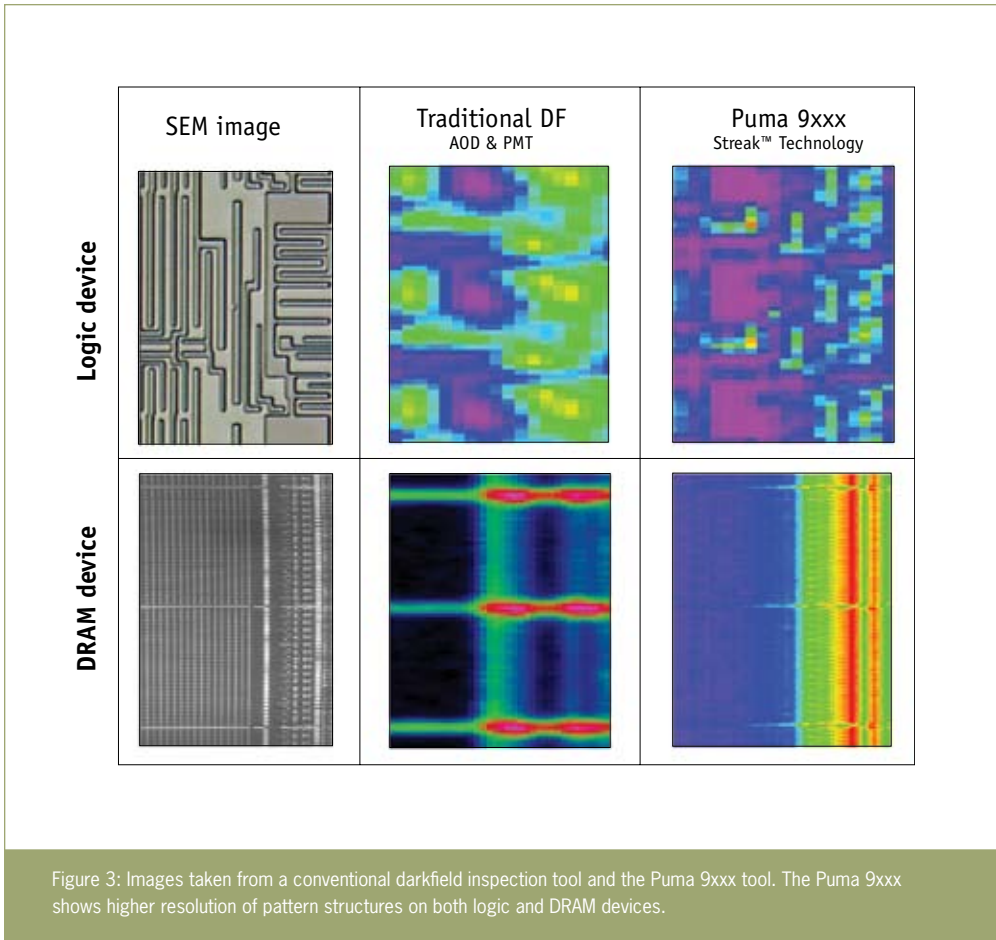


Figure 2:  Streak™ technology, introduced on the Puma 9xxx, enables extendible, high sensitivity, high throughput darkfield inspection. A UV laser beam is focused onto a line on the wafer surface, and then the scattered light is imaged onto a high data rate, multi-pixel sensor.

The patented darkfield imaging technology used in the new inspector utilizes a UV laser as the illumination source. A collimated UV laser beam is focused onto a line on the wafer surface. This line is then imaged onto a linear multi-pixel sensor (figure 2). This high resolution, CCD-based sensor is capable of high data rates (>1Gpps) and enables large parallel collection. The optical elements of this darkfield imaging tool are unique to the industry and are critical enabling technologies for high resolution inspection at throughputs typically associated with traditional darkfield tools.

Traditional single scanning spot AOD/PMT systems collect only one pixel at a time, creating bandwidth requirements far in excess

| SEM image | Traditional DF<br>AOD & PMT | Puma 9xxx<br>Streak™ Technology |
|---|---|---|
| **Logic device** | | |
| **DRAM device** | | |

Figure 3: Images taken from a conventional darkfield inspection tool and the Puma 9xxx tool. The Puma 9xxx shows higher resolution of pattern structures on both logic and DRAM devices.

one normal collector. The collectors have selectable polarizers and programmable Fourier filters to minimize pattern and nuisance noise. The following sections describe low-angle oblique illumination, polarization and Fourier filtering in further detail.

## Illumination Angle

Inspection tool sensitivity can be described as directly proportional to defect signal and inversely proportional to wafer noise:

$$\text{Sensitivity} \propto \frac{\text{Defect Signal}}{\text{Noise}}$$

It is critical that an inspection tool has a strong defect signal, and equally important that the inspection tool minimizes wafer noise sources. Potential noise sources on a wafer include color variation from film thickness variations, metal grain, and prior-level defects. If these noise sources are not sufficiently suppressed, false defects due to grain or color may be reported. The illumination angle utilized in darkfield inspection is an important design element for determining sensitivity, as it influences both the scattering signal from defects and the background noise characteristics.

of those needed by the new darkfield imaging technology, which collects multiple pixels simultaneously. Single pixel data collection and AOD bandwidths limit traditional darkfield technology to maximum data rates of ~300Mpps. In contrast, the data rates of the linear multi-pixel sensor used in this darkfield imaging tool are ~1Gpps and are extendible, as there are no foreseeable limits on driving CCD-technology above 1Gpps. These data rates combine with potential upgrades in NA and $\lambda$ to create a highly extendible architecture that allows for future resolution and throughput enhancements.

Figure 3 shows two examples of the resolution obtained with this darkfield imaging technology compared to conventional darkfield inspectors. The SEM images show the areas of a logic wafer and a DRAM wafer used in this comparison. Raw scattering images were gathered using a traditional AOD/PMT darkfield system and the new darkfield imaging system. The images taken with the new inspector qualitatively demonstrate the higher resolution of the logic structures and better definition of the array/periphery interface on the DRAM device. This higher resolution translates into increased defect sensitivity and improved inspection capability on smaller design rules.

Other features of this new inspector include low-angle oblique illumination with selectable incident polarizers to maximum surface selectivity and noise suppression. There are also up to three independent collectors – two low-angle collectors and

Darkfield inspection tools utilize either normal or oblique illumination. Note that what distinguishes darkfield from brightfield inspection is whether the image is formed from the specular beam (brightfield) or the light scattered outside the specular beam (darkfield), not the illumination angle. With normal illumination, the incident laser beam is oriented perpendicular to the wafer surface. With oblique illumination, the incident angle can vary from high-angle, near-normal incidence to low-angle, grazing incidence. While normal illumination can provide strong darkfield defect signal, noise sources such as color, grain and prior-level defects often limit the ultimate sensitivity. The benefits of oblique illumination depend strongly on the exact incident angle. Low-angle (grazing-angle) oblique illumination has the advantage of providing both strong signal from current layer defects and superior noise suppression capability. Low-angle oblique illumination provides significantly higher signal from the wafer surface than from underlying layers, thereby minimizing noise from grain, pattern and color variation while providing surface selectivity to limit the detection of previous layer defects.

# Applications for High Performance Darkfield Inspection

With its high sensitivity, noise suppression capability, and high throughput, the new darkfield imaging inspector is ideal for use in a broad range of semiconductor applications. Three applications are described in detail below. Additional applications include critical defect monitoring for CMP, etch and films.

*Front-end DRAM Defect Monitoring:* One semiconductor manufacturer used the new inspector for critical defect monitoring on front-end layers for 90nm DRAM production[2]. The inspector was used for baseline inspection and excursion monitoring for residue defects in high aspect ratio (HAR) structures at a buried strap etch processing step. The sensitivity of the new tool for detecting voids at STI CMP was also evaluated. While the new darkfield imaging tool captured a subset of the void defects caught by the standard broadband brightfield inspection, it did so at much higher throughput with less susceptibility to previous layer noise. The results show that the new inspector can be used as a cost-effective void monitor.

*Low Cost Photo-Cell Monitoring:* Broadband brightfield tools have traditionally been used for photo-cell monitoring (PCM) applications. The critical microlithography defects on photo layers have low topography (stains, developer spots) or are very small (CD variations, bridging, single missing or deformed contacts). The high resolution broadband brightfield

technology is ideal for detecting the widest range of these critical defects despite the slower inspection throughput.

The new inspector, with high resolution darkfield imaging capability, has demonstrated high sensitivity to critical defects on PCM wafers. Inspection results from a 70nm PCM DRAM wafer (figure A) show that the inspector surpasses the photo defect detection capability of conventional darkfield inspection and equals broadband brightfield performance at much higher throughputs. These data suggest that for design rules below 90nm, the optimum PCM strategy is a mix-and-match approach using both broadband brightfield inspection and the new darkfield imaging tool[3].

With this new PCM strategy, applications that require the highest sensitivity and capture rate of critical defects (such as resist process development or incoming resist qualification) should utilize the highest resolution broadband brightfield inspectors. However, for daily tool monitoring, where the goal is to capture critical defects at high throughput, the new darkfield imaging inspector should be used. Thus, the typical photo cell monitoring timeline in a semiconductor fab would resemble that outlined in figure B. This strategy provides the maximum sensitivity at the most critical PCM steps, while minimizing overall cost of ownership by
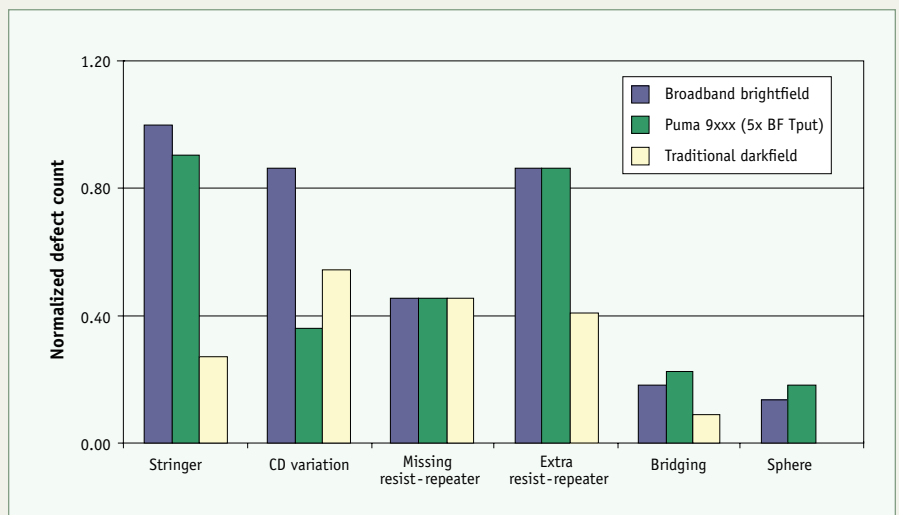
Figure A: Defect Pareto for a 70nm DRAM PCM wafer showing the inspection results for broadband brightfield, Puma 9xxx (darkfield imaging), and traditional darkfield.
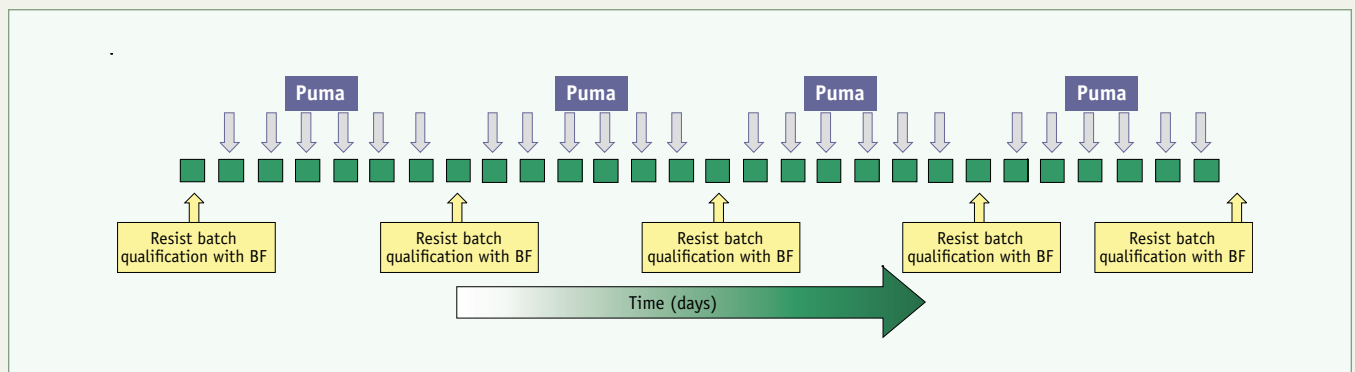


Figure B: Optimum photo-cell monitoring timeline in a fab. This strategy uses the Puma 9xxx as a daily tool monitor while high resolution broadband brightfield tools are used for monitoring the most critical PCM processing steps.
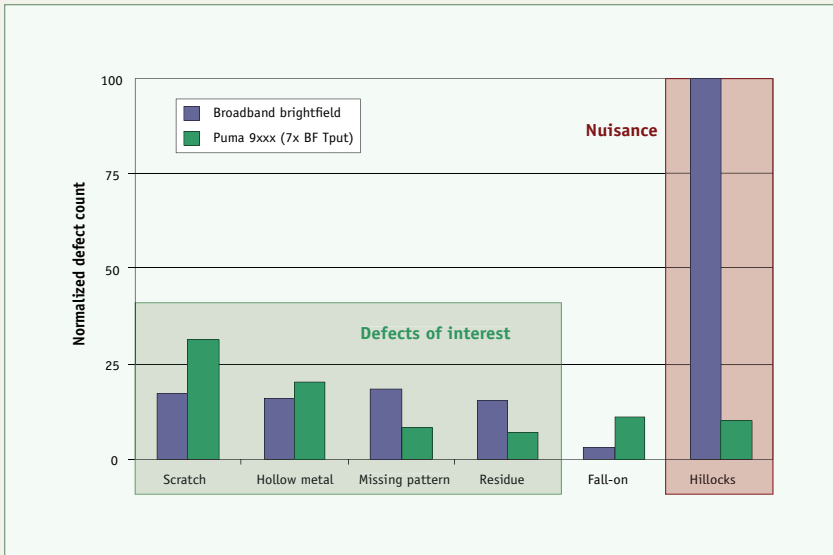
Figure C: Defect Pareto for a 90nm logic metal 4 copper CMP wafer showing the inspection results for broadband brightfield and Puma 9xxx (darkfield imaging). The Puma 9xxx provides comparable capture of defects of interest at higher throughput while significantly reducing hillock nuisance defects.
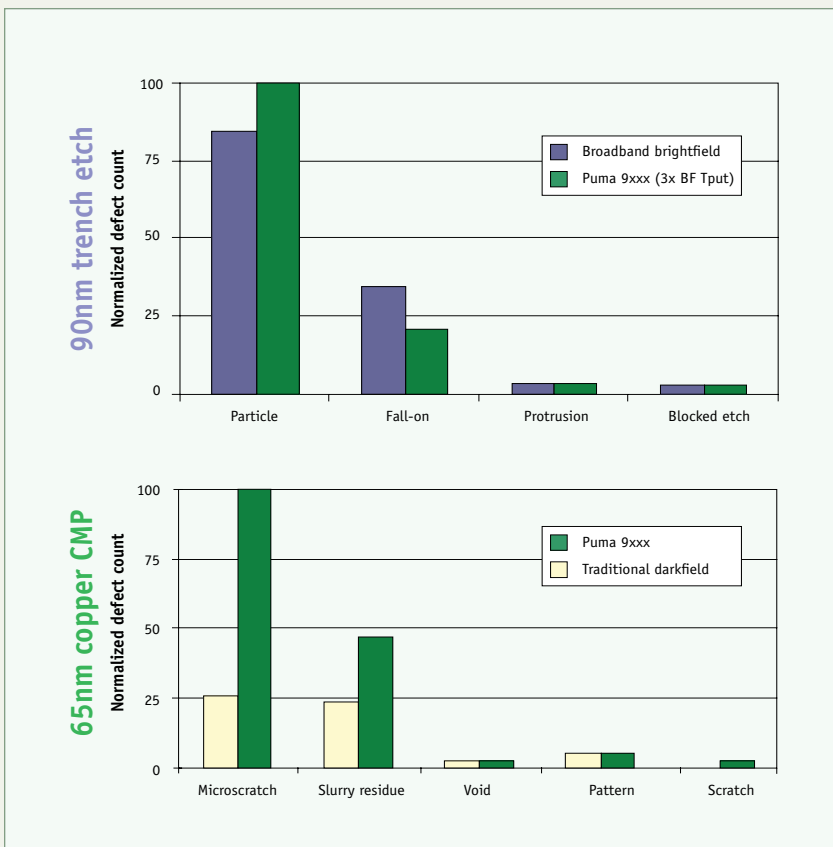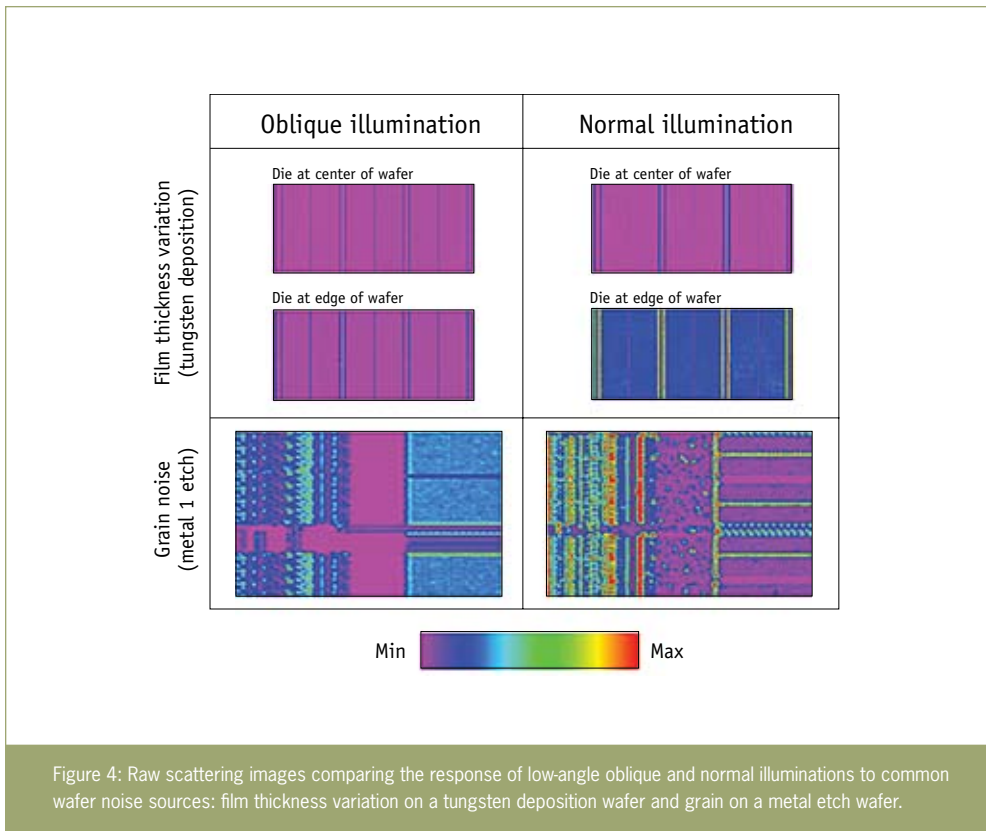


Figure D: Defect Paretos demonstrating the sensitivity of the Puma 9xxx on advanced design rule back-end logic devices. In the top Pareto, the Puma 9xxx shows comparable sensitivity at higher throughput compared to broadband brightfield on a 90nm logic trench etch wafer. In the bottom Pareto, the Puma 9xxx shows superior sensitivity to traditional darkfield on a 65nm logic copper CMP wafer.

employing a high throughput tool that provides adequate sensitivity to critical photo-related defects.

*Back-end Logic Defect Monitoring:* Back-end logic defect monitoring presents a unique set of inspection challenges. Dense pattern structures with small design rules require high resolution inspection capability for detecting critical defects. Transparent dielectric films, rough metals and multi-layer film stacks test an inspection tool's nuisance suppression capability by creating multiple noise sources, such as prior-level defects and metal grain.

The new darkfield imaging inspector has been widely adopted for back-end logic defect monitoring. Its superior back-end noise suppression capabilities, due to low-angle oblique illumination and selectable incident and collection polarizations, are illustrated in figures 4 and 5. Figure C further illustrates the inspector's nuisance suppression by showing inspection results on a 90nm logic metal 4 copper CMP wafer relative to broadband brightfield inspection results. The inspector detects all defects of interest at higher throughput than the broadband brightfield tool while providing 10x lower capture of hillock nuisance defects. This sensitivity at higher through-put enables higher sampling, while the reduction in nuisance defects improves overall time to results.

The detection capability of the new darkfield imaging inspector on back-end logic devices is further demonstrated in figure D. The bottom Pareto illustrates how the darkfield imaging technology of this new inspector greatly enhances detection capability when compared to a traditional darkfield inspector on a 65nm copper CMP logic wafer. In the top Pareto, the new inspector demonstrates sensitivity comparable to a broadband brightfield inspector at much higher through-puts on a 90nm trench etch logic wafer. This improved sensitivity combined with superior noise suppression capabilities makes the new darkfield imaging inspector ideal for back-end logic defect monitoring applications.

Figure 4: Raw scattering images comparing the response of low-angle oblique and normal illuminations to common wafer noise sources: film thickness variation on a tungsten deposition wafer and grain on a metal etch wafer.

The grain noise images are from the same location on a metal etch wafer. The low-angle oblique illumination image shows little sensitivity to grain noise, while the normal illumination image shows strong signal from both current- and prior-level grain noise. These data qualitatively show that low-angle oblique illumination is better than normal illumination for suppressing common noise sources found on wafers, yielding better signal-to-noise characteristics and ultimately higher inspection tool sensitivity. The new inspector uses low-angle oblique illumination to take advantage of the wider range of conditions under which low-angle oblique illumination provides benefit. Its surface selectivity and noise suppression capabilities maximize overall defect sensitivity on the broadest range of applications.

Oblique illumination also enables the use of selectable illumination polarizations, discussed in more detail in the following section.

Figure 4 presents experimental data demonstrating the noise suppression capabilities of low-angle oblique illumination. It shows raw scattering images from experimental test benches – one using low-angle oblique illumination and one using normal illumination. The top images are from a tungsten deposition DRAM wafer that exhibited significant film

## Polarizations

Every process level can have different defects of interest (DOI) and distinct sources of noise. Different illumination and collection polarizations on an inspection tool will provide varying levels of sensitivity to DOI and to noise sources. Without selectable polarizations, first introduced in the early 1990s on the Tencor wafer inspectors, the inspector may miss key DOI or capture false counts related to wafer-to-wafer process variation. Therefore, it is critical that a

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thickness variations. Images were acquired from a specific die location for two separate die – one near the center of the wafer, and one near the edge of the wafer. The images collected with low-angle oblique illumination show little sensitivity to the film-thickness variation of the wafer, while the normal illumination images show strong sensitivity to the film-thickness variations.

darkfield inspection tool has the flexibility of using different polarizations in order to maximize DOI capture.

One of the advantages of oblique illumination is that it enables the use of selectable incident polarizations. The incident laser beam can be filtered to generate S, P or C polarized light. With normal illumination there is no
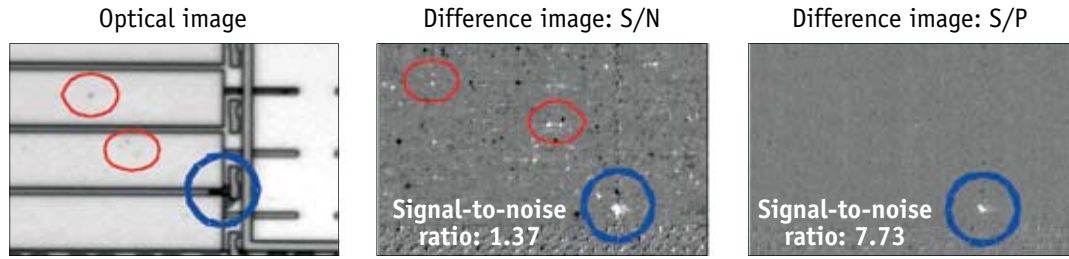
Figure 5: Optical and difference images from a metal 4 copper deposition wafer. Blue circles on the images indicate the location of the defect while the red circles highlight examples of hillocks.

distinction between S and P polarized light, and thus, there are fewer polarization options for this configuration. Polarization filters can also be included in the collectors such that scattered light of only one polarization reaches the detectors. Typical collection polarizations include S, P or none.

The new inspector has three possible illumination polarizations (S, P, C) and three collection polarizations (S, P, None) for each channel. This gives nine possible polarization combinations per inspection channel. A fully integrated software feature helps the user to accurately and quickly determine the appropriate polarization combination to use for a particular process level. These polarization selections provide the flexibility needed to inspect all critical layers with maximum sensitivity. The benefit of selectable polarizations is illustrated in the following experimental data collected from the new inspector.

Figure 5 shows images taken using the new inspector on a metal 4 copper deposition layer. The primary noise source on this layer is copper hillocks. The image on the left is an optical microscope image of an area of the wafer. The middle and right images are difference images. A difference image highlights the signal and noise characteristics of a wafer and is the image that results from subtracting the scattering image of a reference die from the scattering image of a defective die. The signal-to-noise ratio (SNR) of the defect is calculated from the difference image by measuring the intensity of the defect and calculating the noise of the surrounding pattern area. The blue circles on the images indicate the location of the defect while the red circles highlight examples of hillocks.

Scattering images were taken using S incident polarization and two collection polarizations – P and None. The difference image for S/None polarization combination is shown in the middle. Using this polarization combination, there is significant pattern and hillock noise in the image and the resulting SNR is only 1.37. The difference image for S/P polarization combination is shown on the right. This polarization combination is very effective at suppressing hillock and pattern noise and results in an SNR of 7.73. For this wafer, the use of cross polarizations is the most effective for maximizing signal on the defects of interest and minimizing the noise from copper hillocks.

Another example of the use of selectable polarizations is demonstrated with the following data collected on the new inspector on a metal 3 after develop inspect (ADI) wafer. The primary DOI on this wafer is broken resist lines. The primary nuisance source is prior-level, copper filled scratches. Table 1 shows SNRs calculated from images gathered at all nine polarization combinations for a DOI and a nuisance defect. The ideal polarization combination for inspection would be one that maximizes the SNR on the DOI while minimizing the SNR on the nuisance. From this table, it is easily seen that S/P provides the highest SNR (8.33) for the broken line defects and the lowest SNR (1.18) for the prior-level scratches. These results show that S/P is the best polarization combination for meeting the inspection goal of detecting broken resist lines while suppressing prior-level nuisance defects.

| Polarization | DOI signal-to-noise | Nuisance signal-to-noise |
|---|---|---|
| S/P | 8.33 | 1.18 |
| S/S | 1.0 | 1.53 |
| S/None | 3.75 | 1.5 |
| P/S | 2.2 | 1.54 |
| P/P | 3.0 | 1.41 |
| P/None | 2.6 | 1.5 |
| C/S | 1.4 | 2.4 |
| C/P | 5.0 | 1.43 |
| C/None | 4.6 | 1.55 |

Table 1: Signal-to-noise ratios for a DOI (broken resist) and nuisance (prior-level scratch). Data were collected on a metal 3 ADI wafer with the Puma 9xxx at all nine polarizations and demonstrates the power of selectable polarizations in maximizing signal on DOI while suppressing nuisance and pattern noise.

## Fourier Filtering

Certain semiconductor devices, such as the array regions of DRAM, SRAM and Flash devices, have areas of repetitive pattern structure. When illuminated with a coherent laser source having a wavelength on the order of the cell spacing of the pattern, this periodic structure gets imaged to discrete lines in the Fourier plane. A simple method of decreasing pattern noise and enhancing the defect signal in these array areas is to use an adaptable Fourier filter – a filter located at the Fourier plane that blocks the diffraction lines resulting from repetitive pattern areas. Using such a filter can significantly increase sensitivity in the array by reducing pattern noise.

Experimental data from the array region of a defect standard wafer – where programmed defects are arranged in a grid by type and size – illustrate the use of a Fourier filter using raw scattering images (figure 6). The image on the left shows an area of the defect standard wafer without Fourier filtering applied. The image is very bright with pattern noise, and it is difficult to distinguish the defects from the background pattern scatter. In the image on the right, the same wafer is shown with Fourier filtering applied. The diffraction pattern noise has been suppressed, and the defects are clearly distinguished from the background. These data clearly illustrate the pattern suppression and defect signal enhancement benefits of using a Fourier filter when inspecting array regions of a wafer.

The new inspector includes programmable, flexible Fourier filters. These are not fixed filters or pre-set masks. Rather, these filters are truly programmable based upon the unique scattering characteristics of each device. The Fourier filters automatically learn the exact location of the diffraction lines in the Fourier plane and then apply a filter to each individual diffraction line. This methodology effectively filters the repetitive pattern noise while minimizing the amount of detection area lost to filtering. Thus, defect signal is maximized while pattern noise is minimized, providing increased sensitivity in array areas.

## Conclusions

As the semiconductor industry moves to 65nm design rules and below, semiconductor manufacturers face multiple challenges associated with new materials and tighter geometries. Cost pressures have escalated due to increased competition, shorter product life cycles and the move to single-wafer processing. These technical and economic challenges drive the need for inspection tools that provide cost- and performance-optimized defect monitoring on the broadest range of process layers.

A new laser-based darkfield inspection tool has been developed which utilizes unique, patented darkfield imaging technology to meet these inspection challenges. This technology employs line scanning and a multi-pixel sensor that provides both high resolution to detect critical DOI, and high data rates (>1Gpps) to meet required production throughputs. The tool also draws on a multitude of experimental data to maximize its sensitivity and noise suppression capabilities. As a result of these data, the tool incorporates low-angle oblique illumination for surface selectivity and noise suppression; selectable incident and collection polarizations for maximizing sensitivity to DOI while minimizing noise due to nuisance and film thickness variations; and true programmable Fourier filters to provide superior pattern suppression and sensitivity on memory devices.

Applications for the new darkfield imaging tool include front-end memory defect monitoring, back-end logic defect monitoring and low cost daily photo-cell monitoring, complementing higher sensitivity broadband brightfield inspections at critical photo steps. With its high sensitivity, high throughput and noise suppression capability, the new inspector meets the cost and performance requirements for defect monitoring on a broad range of semiconductor applications at 65nm and beyond.
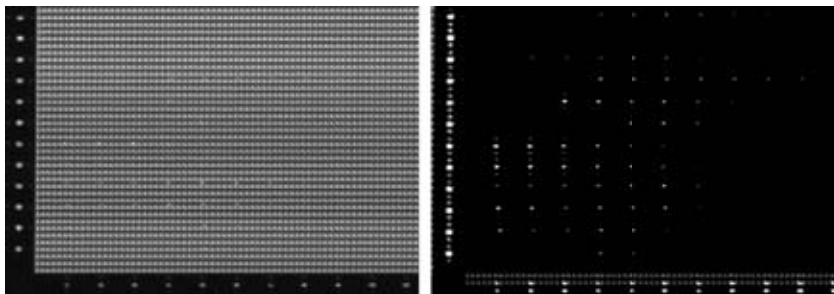
## Acknowledgements

Figure 6: Array area of a programmed defect wafer with and without Fourier filtering applied.

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