Advantages of Broadband Illumination for Critical Defect Capture at the 65-nm Node and Below

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As chipmakers continue innovating with new materials, structures, and processes, they face an increase in new defect types, along with new noise sources that hamper defect detection. Tunable broadband brightfield illumination technology has several advantages over a single-wavelength approach for meeting new inspection challenges and generating higher capture rates of yield-impacting defects. Modeling studies as well as fab experience show that different defect types and device layers require different inspection wavelengths for reliable defect detection. A broadband source spanning DUV through visible wavelengths can be tuned to the optimal wavelength band to create maximum contrast, considering the specific optical properties of a given layer or defect type. Its spectrum of wavelengths also can reduce color noise-interference from underlying layers that can create nuisance defects. Minimizing nuisance defects means that detected defects correlate more strongly to yield.

Signal-to-Noise Optimization

Brightfield inspection is an important part of a comprehensive patterned wafer inspection strategy that addresses a multitude of defect issues on all process layers. However, many variables impact the effectiveness of brightfield inspection on given materials and layers. The signal-to-noise ratio that underlies an inspection system's fundamental ability to provide defect capture is rooted in the contrast between the defect and its surroundings. For brightfield inspection, this contrast depends upon the optical properties of the defect and its neighborhood, and these optical properties are a function of the wavelength of the incident beam. A full-spectrum inspection system provides the broadest defect type capture, since its incident spectrum can be tuned to optimize the contrast between the defect types of interest and their surroundings. Examples of several common defect types are given below:

Bridging Defect in Photoresist Stack

The physical and optical properties of materials are based on their structure. Figure 1 shows the theoretical wavelength dependence of the brightfield gray-level signal from a bridg ing defect in two thicknesses of a photoresist/BARC stack, patterned in a line and space array. In this figure, the defect gray level signal is plotted — i.e. the difference in gray level between an image with the defect and another without the defect. One stack exhibits best defect gray level in the deep ultraviolet (DUV) range, while the other shows best defect gray level in the visible range. Because the bridging defect sig-

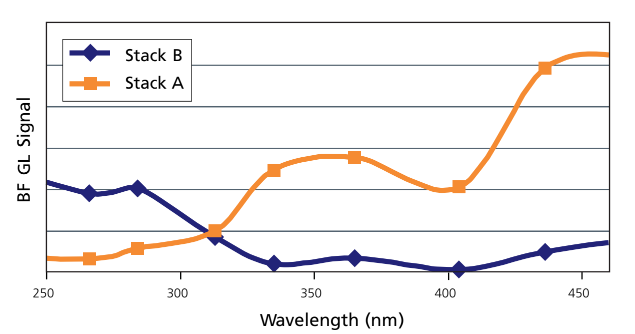

Figure 1: Modeled brightfield defect gray-level signal as a function of wavelength, for a bridging defect in two photoresist/BARC stacks patterned in a 90nm design-rule line/space array. Stack A (orange line) contains 27nm of SiON topped by 230nm of photoresist, while stack B (blue line) comprises 45 nm of SiON topped by 150nm of photoresist. In both cases the wavelength dependence is strong, which means that the ability to detect the defect in the stack depends critically on the wavelength of incident light. A bridging defect in Stack A would best be detected by visible light, in the 440 to 500 nm range, while a defect in Stack B would best be detected by DUV light, in the range of 250 to 300nm.

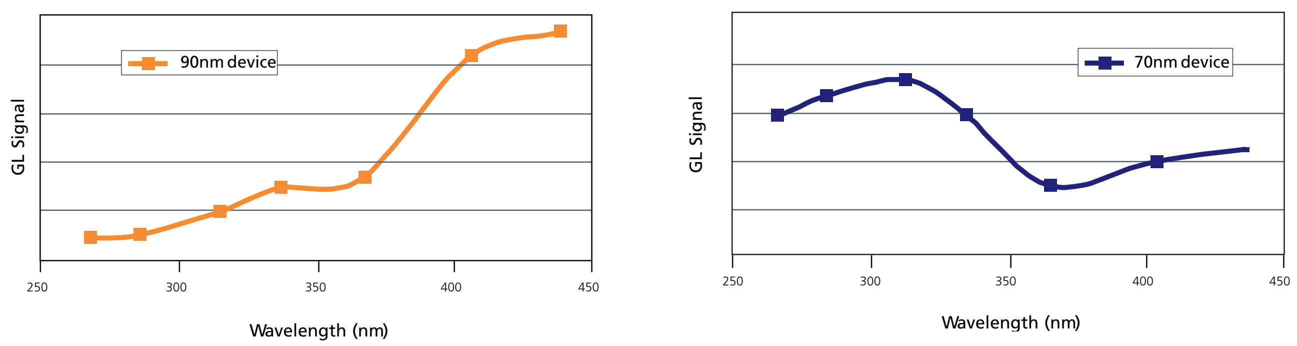

Figure 2: Modeled variation of defect gray level with wavelength for a capacitor leaning defect, detected after-etch on a DRAM device. The left graph depicts a 90nm device, where the capacitor material is polysilicon, while the right graph depicts a 70nm device, in which the capacitor material is Ti/TiN. Detection of the poly defect requires G-line illumination, i.e. 430-450nm, while detection of the Ti/TiN capacitor leaning defect requires mid-band DUV illumination, around 300-320nm.

nal changes with stack height, tunable wavelength is a critical feature in defect capture, where process changes are a necessary part of device innovation.

Capacitor Leaning

Figure 2 examines the detection of a capacitor leaning defect for a DRAM capacitor. At the 90nm node, the material of choice is polysilicon, while at the 70nm node, the material changes to Ti/TiN. Figure 2 shows that the wavelength of the defect signal changes dramatically with the new material. At 90nm (left graph), 445nm is the optimum inspection wavelength, while at 70nm (right graph), the optimum wavelength is 325nm. Once again, wavelength tuning is critical for defect detection as process parameters change.

STI Voids

Figure 3 shows how wavelength tuning affects the signal-to-noise ratio for pre-nitride-strip shallow trench isolation (STI) void detection. At 266nm the gray-level defect signal is weak. Changing the wavelength to span the range of the DUV peak can boost the image contrast by a factor of about four.

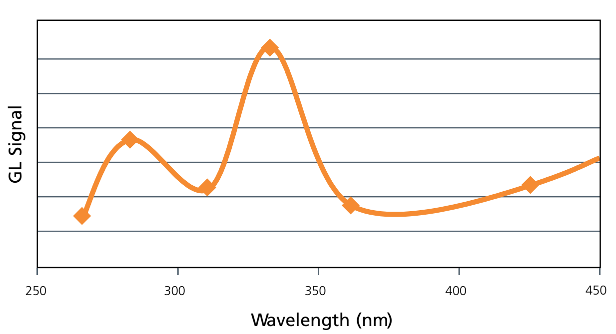

Figure 3: Simulated wavelength dependence of signal-to-noise ratio of STI void. While 266nm (first data point) provides weak contrast, selecting a wavelength that spans the DUV peak strengthens the defect's gray-level signal by a factor of about four.

Copper Bridging

Post-CMP copper (Cu) bridging at Metal 1 is another defect challenge in which wavelength flexibility offers a distinct advantage. Figure 4 shows the theoretical wavelength dependence of the defect's gray-level signal for Cu bridge on a 65nm device. In this case, DUV wavelengths provide a higher gray level signal than UV wavelengths; thus, the tunability of a broadband illumination inspection tool can translate directly into better defect capture.

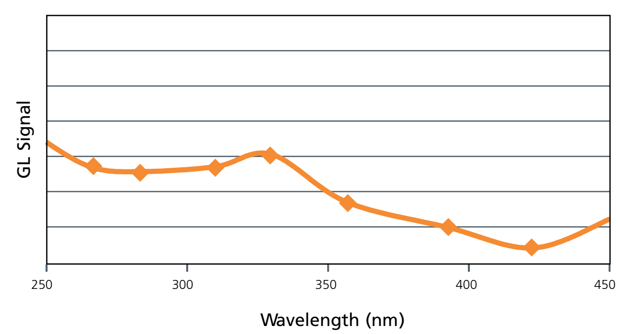

Figure 4: Simulated wavelength dependence of gray-level difference for a Cu bridging defect, detected after CMP at Metal 1 in a 65nm device. DUV wavelengths provide a stronger signal-to-noise ratio than UV wavelengths.

Etch defect on flash memory

Extending this study to the 45nm node, where intuition suggests that DUV would be preferred, we examine two defect types on a flash memory device (Figure 5). An STI etch bridging defect shows strongest gray level difference for wavelengths around 300nm. However, a gate etch microbridge exhibits the strongest gray level difference in visible wavelengths.

We can see from the examples above that tunable wavelength is a critical component for wafer inspection when a broad range of defect types, or a broad range of materials or material

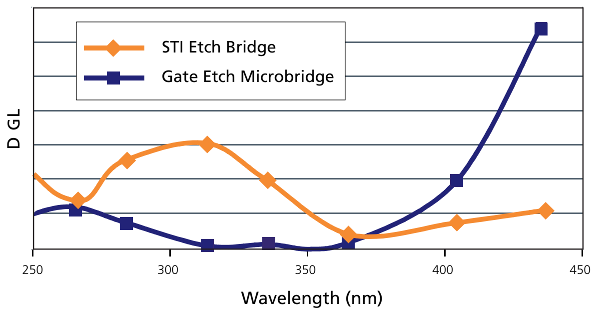

Figure 5: Simulated wavelength dependence of gray-level difference for two etch defects: an STI etch bridge and a gate etch microbridge, in a 45nm flash device. DUV wavelengths provide a stronger signal-to-noise ratio for the gate etch defect, while visible wavelengths provide stronger capture for the STI etch defect.

parameters are present. Optimal defect capture varies from the visible, for an after-etch polysilicon capacitor leaning defect in a 90nm DRAM, through the deepest DUV, for a Cu bridging defect after CMP on a Metal 1 layer. Thus, the conventional wisdom that shorter wavelengths allow capture of smaller defects is a simplification that is inaccurate in many cases. Instead, a wide spectrum of wavelengths optimized to the defect and layer is key to detecting the wide range of defect types that occur in a fab.

Noise Suppression

Typically, inline inspection algorithms compare one die to another to detect the presence of defects. In some cases, neighboring die may exhibit slight variations in dielectric film thickness which appear as different gray levels to single-wavelength brightfield systems. (Single-wavelength darkfield systems using oblique illumination angles are not as strongly affected because their grazing angle of incidence reduces the amount of light that penetrates below the surface, thus significantly decreasing the intensity of the interference fringes.) Because slight film thickness or refractive index differences do not affect performance of the device, such "color noise" defects are considered nuisance. Single-wavelength brightfield systems must resort to post-processing defect binning to minimize the reporting of color-noise false alarms. The case below demonstrates that broadband inspection systems are inherently better suited to coping with normal process variation.

Figure 6 shows a graph of the theoretical reflectance from a silicon dioxide (SiO_2) wafer surface versus changes in film thickness using an incident beam of 266nm. The blue line on the graph shows a cyclic pattern due to light interference at the thin-film interfaces at various depths in the wafer. Film thickness variation can yield different reflectivity responses from die to die, or even across a given die. If a small variation occurs near a peak or trough in the curve, the change in reflectivity will be minimal. However, a small change in film thickness where the curve has the steepest slope can result in dramatic changes in reflectivity, detected as color noise. Color noise can show up as nuisance defects, or can affect the ability to detect defects of interest, whenever neighboring-die algorithms are used.

There are two ways to minimize this effect. The first is to use high numerical aperture (NA) objectives, as demonstrated in Figure 6. For film thicker than about 200nm, using a high NA dramatically reduces the magnitude of the reflectivity change with film thickness. When a high NA is used, the light intensity is distributed over a wide range of incidence angles, which tend to cancel. The result is that the interference peaks are weaker — reducing the color-noise problem.

The second method for reducing color noise is to use a broadband light source instead of a single-wavelength source. A broadband source has a short coherence length, as defined by the equation CL = 1^2/D1. As the bandwidth, D1 increases, the coherence length decreases. Because the thin-film interference effects that underlie the reflectance variations rely on light that is coherent over the thickness of the layers, the shorter coherence length of the broadband source minimizes this variation. When broadband light is sent through high NA optics, the two effects add, and color noise is dramatically reduced, as seen in Figure 7.

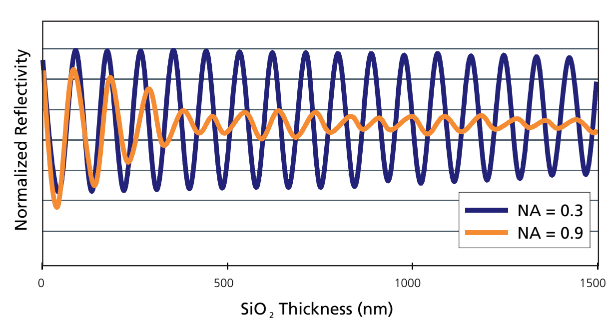

Figure 6: Simulated effect of numerical aperture (NA) on normalized reflectance as a function of SiO2 film thickness, for a wavelength of 266nm. The blue line indicates a lower NA of 0.3, while the red line indicates a higher NA of 0.9. For films greater than about 200nm, higher NA provides significant advantage in reducing color noise that arises as a result of normal process variation.

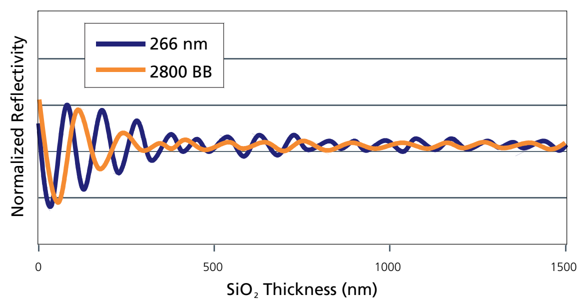

Figure 7: Comparison of single-wavelength with broadband illumination, using high NA optics, for normalized reflectance as a function of SiO_2 film thickness. In this simulation, a 266nm single-wavelength source is compared with the spectrum of a broadband DUV/UV/visible lamp, such as that used in KLA-Tencor's 2800 inspector. NA is set to 0.9 in both cases. Note that the 2800 BB illumination curve smoothes out more quickly than the 266nm curve, resulting in less sensitivity to color noise. The combination of broadband illumination with high NA optics significantly reduces color noise, especially for film thicknesses greater than 200nm.

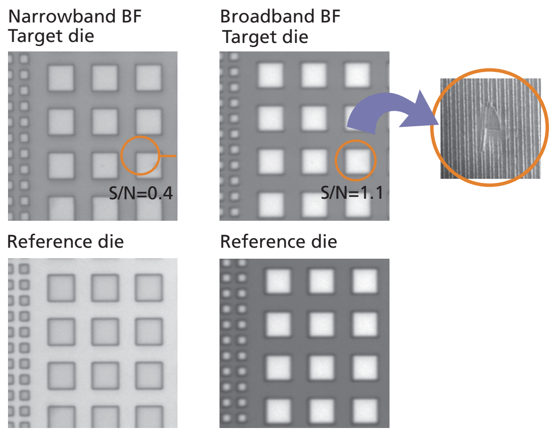

Figure 8: A broken line defect (inset) as depicted under narrow-band brightfield and broadband brightfield illumination. Under narrowband illumination, the target die (top left) and reference die (bottom left) show very different gray levels. Though the signal from the defect is strong, color noise dominates, and the defect is undetectable, with a S:N of 0.4. With broadband illumination, the target die (top right) and reference die (bottom right) show similar gray levels. Even though the signal from the defect is difficult for the eye to pick out in the image, the noise level is low enough that S:N is 1.1, well above the detectability limit.

To demonstrate this experimentally, images of an actual broken-line defect on a wafer are shown in Figure 8. Using narrow-band illumination, the target die (top left) and the reference die (bottom left) show very different gray levels, and the defect (in yellow circle) cannot be detected, with a signal-to-noise ratio of 0.4. Color noise interferes with automatic defect detection, even though the signal is high, and the eye can pick out the defect on the image fairly easily. When broadband illumination is used, the target die (top right) and reference die (bottom right) have similar gray levels, and detecting the defect is easier, with a signal-to-noise ratio of 1.1 (even though the defect is more difficult to see on the image).

A third method for reducing color noise is to use algorithms to reduce color noise after the data are collected. While this is the only method available to single-wavelength inspectors, it typically results in 3 to 5 times higher noise at time of pixelation.

Summary

For defect detection in patterned wafers, brightfield technology with tunable broadband illumination and a high numerical aperture is superior to single-wavelength DUV technology in capturing the broadest range of defect types in the presence of normal process variation. Broadband DUV/UV/visible inspection systems allow tuning of the incident wavelength to enhance detection of such defects as STI voids, capacitor leaning, and copper bridging. The ability to span a full spectrum from DUV through visible provides full coverage on all process layers by allowing immediate tuning to the optimum wavelength for a given layer or defect type for real-time inline inspection with best signal-to-noise ratio. Broadband systems are also superior to single-wavelength brightfield inspectors when normal process variation causes "color noise" defects.