

Illumination inspection technology for defect detection on advanced IC substrates

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Across the semiconductor industry, advanced integrated circuit (IC) substrate (AICS) supplies are low. The causes vary, from a limited number of suppliers who can meet performance requirements, to constrained production capacities, and increased demand resulting from the adoption of high-performance mobile devices, as well as advanced technologies like artificial intelligence (AI) and high-performance computing (HPC). And without question, the ongoing shortage of Ajinomoto build-up film (ABF), a necessary component of many AICS, plays a significant role as well. One area where this shortage of ABF and AICS is having a significant impact is in the manufacturing of flip-chip ball-grid array (FC-BGA) packages—the most advanced substrates to meet the electrical and thermal requirements for IC chips with high numbers of I/Os.

To address the substrate shortage, suppliers of FC-BGA substrates are ramping up capacity. However, that acceleration comes with high costs due to the fact that the AICS process is burdened by low yields resulting from the presence of defects that are left undetected by many macro inspection systems. Furthermore, that inability to detect certain defects is

potentially magnified as each new layer of ABF on the FC-BGA substrate is built up. In some cases, the number of layers of build-up may reach 20. With each additional layer, the potential for killer defects increases, whether the cause is ABF residue in laser-drilled vias, poor dry-film resist development, or the under- and over-etching of Cu seed.

For advanced packaging houses, addressing this issue is a matter of considerable interest. After all, few businesses are not interested in reducing waste and cost, while more efficiently utilizing an in-demand resource in short-supply, like ABF. Fortunately, optical inspection technologies are available that can discover these difficult-to-detect defects. In this article we will discuss a proven macro inspection technology that is uniquely capable of finding defects and errors in AICS.

Inspection challenges

Before we move forward, let's reexamine why ABF has become an important component in manufacturing AICS. In an AICS, specifically those made for FC-BGA, Cu is used for electrical connections and ABF is used for insulation (**Figure 1**). ABF is a compound

material of epoxy polymer matrixes and inorganic fillers. The chemical and electrical properties of epoxy polymer can be easily tailored by changing chemical components to meet various material requirements [1]. Another advantage of ABF is that it facilitates the formation of fine-pitch lines/spaces because its surface is receptive to laser processing and direct copper plating. This advantage, in part, makes ABF an ideal material for devices where miniaturization is a driving force for innovation. For pattern formation on the build-up layers of IC substrate, dry film is commonly used together with a semi-additive process to achieve copper lines down to 5µm/5µm or smaller lines/spaces in laminated substrates.

Because the main function of an IC substrate is to create an electrical connection between the IC and circuit board, the most serious process issues are shorts or open circuits, both of which require inspection tools to find defects. For example, poor dry-film development leads to bad patterning, which, in turn, leads to poor or bad signal integrity. Meanwhile, during the curing process, particles or bubbles under laminated ABF can cause pattern distortions. Left after the formation of vias through the ABF by laser ablation,

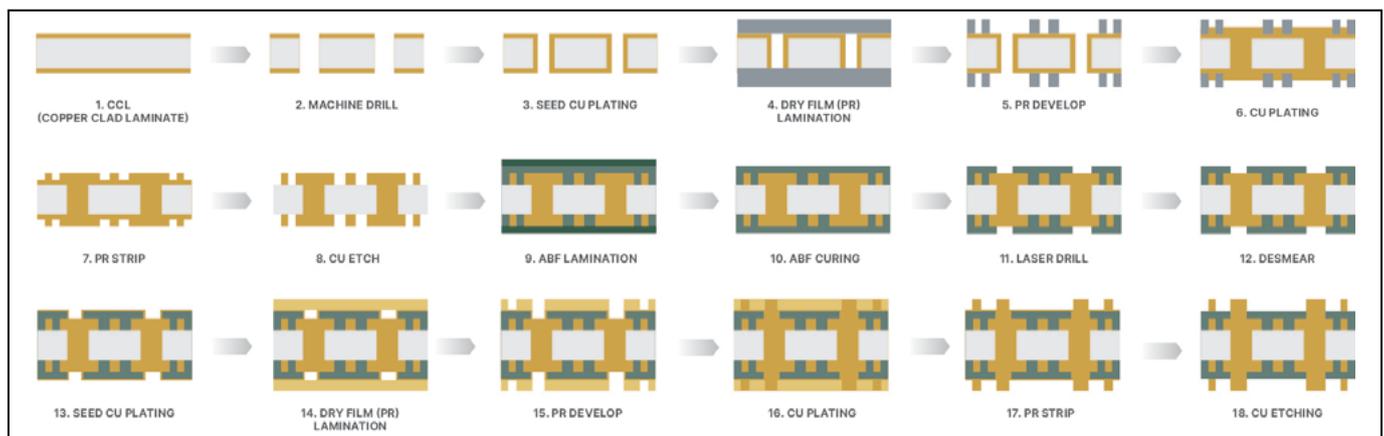


Figure 1: Typical flow of an advanced substrate process. Steps 9 through 18 are repeated for multi-layer buildup.

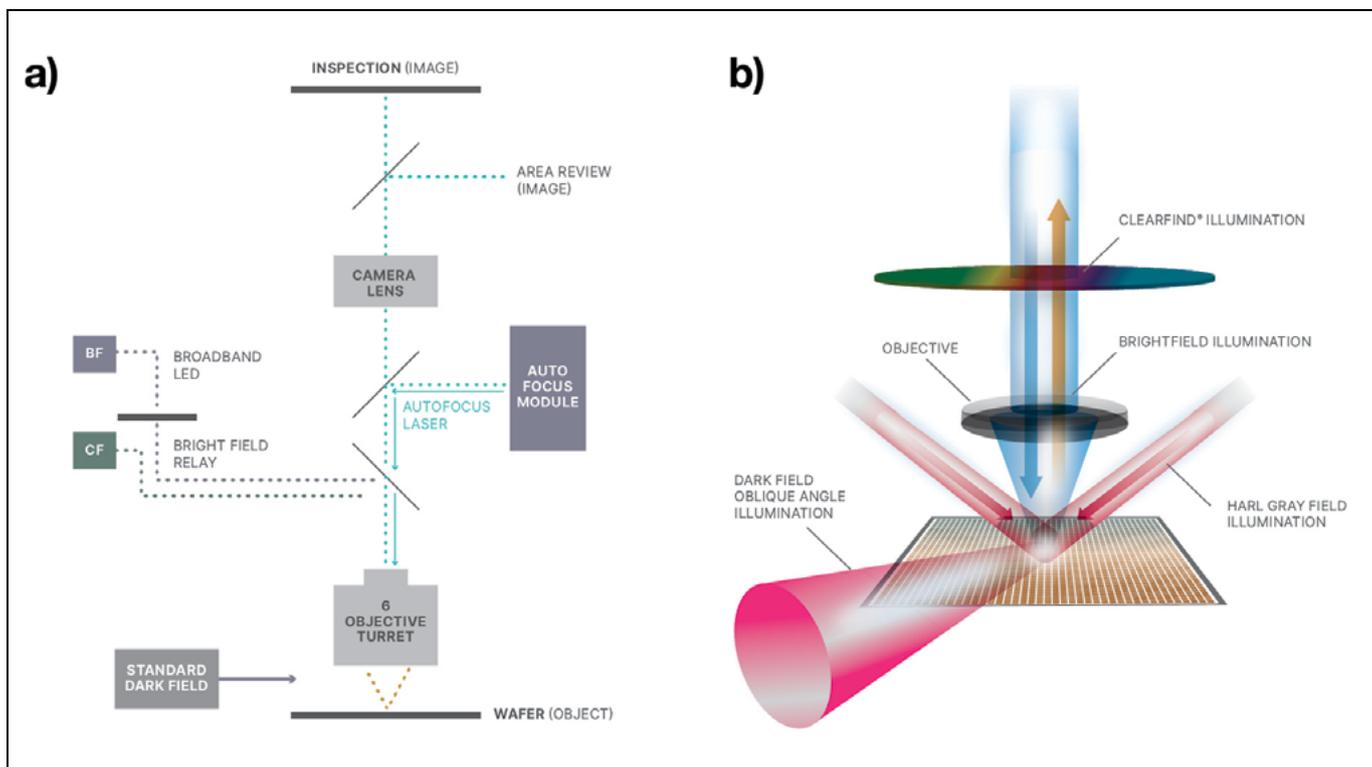


Figure 2: Schematic of inspection optics: a) Conventional macro inspection setup; and b) CF inspection setup.

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residual ABF can also affect the integrity of the electrical signal. Etching the Cu seed layer is the final process step of each build-up layer; this step defines the routing of Cu trace lines. Under- or over-etching the Cu seed layer can lead to shorts and open circuits. Preventing shorts and open circuits is a critical issue when addressing decreases in yield.

Conventional macro inspection is typically done using one of two techniques: bright-field (BF) and dark-field (DF) illumination (Figure 2a). Both BF and DF techniques use light-emitting diode (LED) sources that cover the visible wavelength region. In BF illumination, the camera objective and illumination source are positioned on a common axis perpendicular to the surface of the substrate so that the camera sees the specular reflection of the source illumination. Therefore, the BF image is formed by the reflected light from the sample and is therefore a strong function of light attenuation and reflection between differing materials on the sample. In DF illumination, the camera is positioned away from the direction of the specular reflection of the illumination source. On a flat, mirror-like surface, the specular reflection from the substrate is directed away from the camera, and the field becomes dark. But any particle or surface irregularity that

scatters light out of the specular beam will make the field bright. This characteristic makes DF illumination particularly good at identifying small particles and defects on a flat specular surface.

We also used another inspection illumination technology, Clearfind® (CF). The optical path of this technology is also shown in **Figure 2b**, but **Figure 3** illustrates in more detail how this technology works. The light source for this new illumination technology is a monochromatic blue laser with a stable wavelength and output power. The laser beam is collimated and expanded into a horizontal line at the sample and then scanned over the surface. Stimulated by illumination, the sample either reflects the light from the source, or emits secondary photons of lower energy, depending on the types of materials involved. Metals have continuous energy bands in the visible wavelength regions and will either absorb or reflect incident photons. Organic materials, such as polymers, exhibit distinctive optical properties that are not present in the metals or common inorganic materials used in IC substrate manufacturing. These properties tend to be unique to organic molecules displaying a high degree of conjugation, such as polycyclic aromatic hydrocarbons, and in linear or branched chain organic polymers with multiple regularly interspersed pi bonds [2]. The emission from the organic surface tends to be anisotropic and, therefore, less sensitive to surface topography that could potentially direct most ordinary BF- or DF-reflected light away from the detector. Moreover, photons of the same energy are blocked by the filter; as a result, any reflection or scattering from the metal surface cannot be collected by the imaging camera. This results in increased sensitivity to organic residue and reduced sensitivity to interference from the surrounding features.

The method described above has the additional advantage of being relatively insensitive to signal variations caused by metal grains. The new technology has been found to be very effective in detecting invisible defects on fan-out wafer-level packaging (FOWLP) and fan-out panel-level packaging (FOPLP) [3,4]. In our investigation, we employed a high-speed, near-infrared laser-triangulation autofocus system that maintains a constant distance between the imaging optics and the area being scanned to keep the image focused.

Imaging is accomplished using a high-resolution line scan camera. The image pixel size corresponds to 0.7µm at 10X, which provides the highest level of magnification for inspection.

Via inspection

ABF is a widely-used insulating dielectric in advanced IC substrates used for FC-BGA. To make electrical connections between layers, vias are formed by high-energy ultraviolet (UV) lasers. Occasionally, ABF is not completely removed from the via, which results in a poor electrical connection through the via and, in turn, negatively affects signal integrity. Therefore, inspecting the via after laser ablation is necessary to find such defects (Step 12

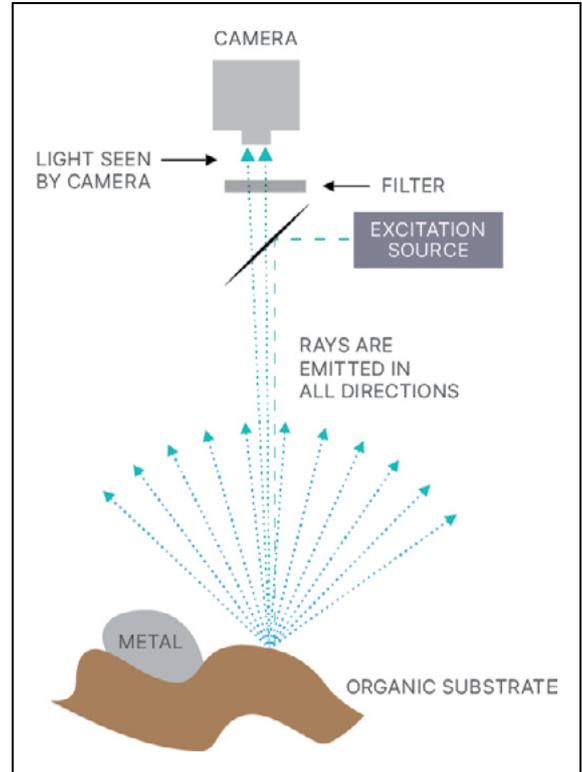


Figure 3: Illustration of CF technology.

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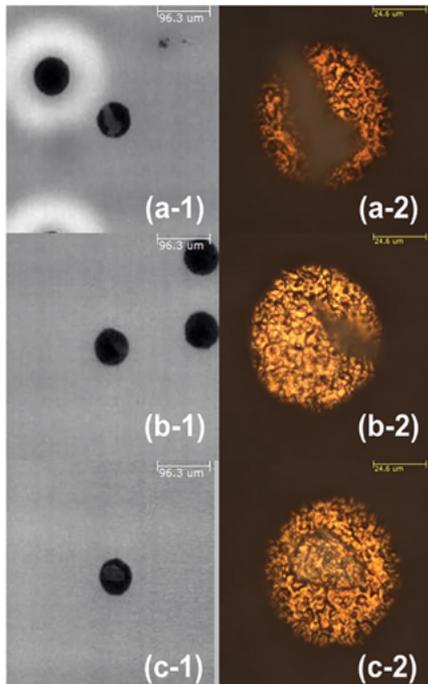


Figure 4: Images of vias with ABF residue. The left three images are those using CF illumination, while the right three images are corresponding images, but with BF color illuminations at higher magnification.

in **Figure 1**). **Figure 4** shows example images of vias with ABF residue. The left three images are those using Clearfind® illumination, while the right three images are corresponding images but with BF color illuminations at higher magnification.

For examples (a-1) and (a-2) shown in **Figure 4**, the residue is detectable using either CF or BF technology. For the CF image examples of (b-1) and (c-1), residual ABF inside the vias is easily detectable because secondary photons from the residual ABF are brighter than the rest of the Cu, which does not emit secondary photons. However, in the case of the corresponding BF images of (b-2) and (c-2), the area of residue in the image can be easily confused with the via bottom. This is because the surface of the bottom of the via is rough Cu—and because of the grainy structure of the Cu, this image is very similar to images of ABF residue. These example images clearly demonstrate that the new illumination technology is more robust for leftover ABF residue in vias.

After-development inspection: dry resist film

To create circuit patterns on each build-up layer of the IC substrate, a dry-film resist is laminated and developed on a Cu seed layer, as shown in process steps 14 and 15 in **Figure 1**. Any process excursion during development will lead to poor circuit patterning. **Figure 5** shows an image of an organic defect after dry-film resist development. All four images show defects at the same site but with different illuminations. The BF image does not show any defects, while the DF and Clearfind® images do. It should be noted that not all the defects found with DF are seen in the CF image. This is because DF illumination is sensitive to scattering from various particles, while CF illumination is sensitive to organic defects only. The DF image shows vias because of a difference in scattered light intensity, while CF cannot identify the difference between vias and the Cu seed layer because neither of these emits secondary photons, causing both regions to appear dark. Therefore, the best illumination technique to find defects after dry-film resist development is to use both DF and CF illumination simultaneously, as shown on the bottom right of **Figure 5**.

Figure 6 shows another defect example after dry-film resist development. All four images show defects at the same site but with different illuminations. In this case, Clearfind® technology images do not indicate defects. This is an indication that these defects are either metallic or inorganic dielectrics. Considering the stage in the process flow in which these defects are identified, it is very likely that these are metallic defects. The BF image indicates some defects, but with relatively low contrast, while the DF image clearly shows all defects. As we have seen, CF illumination is very effective in finding organic defects, and we believe a combination of it and DF illumination together offers the best illumination tool for the inspection of dry-film resist after development.

After-etch inspection: Cu seed

After the dry-film resist is developed, the substrate goes through Cu plating to form Cu trace lines for the circuit, and then the dry-film resist is removed by stripping. At this stage, all Cu trace lines are connected by a Cu seed layer that needs to be etched to complete circuits as designed. During the process, under-etching may cause shorts, while over-etching may cause open circuits.

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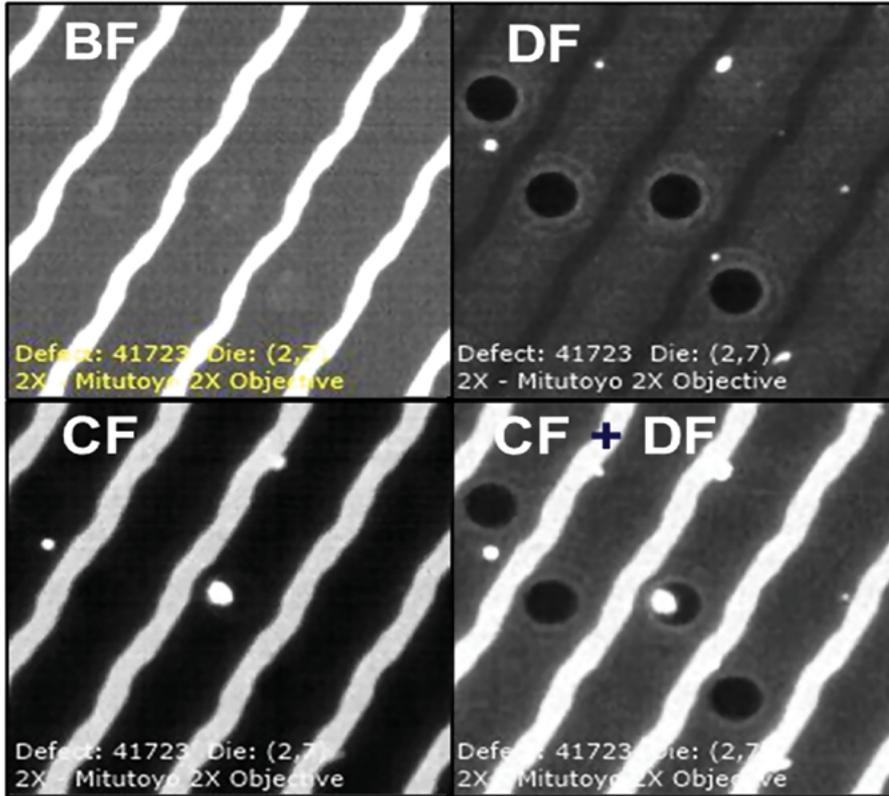


Figure 5: Organic defects after dry-film resist development inspection. All four images show defects at the same site but with different illuminations, as indicated in the panels.

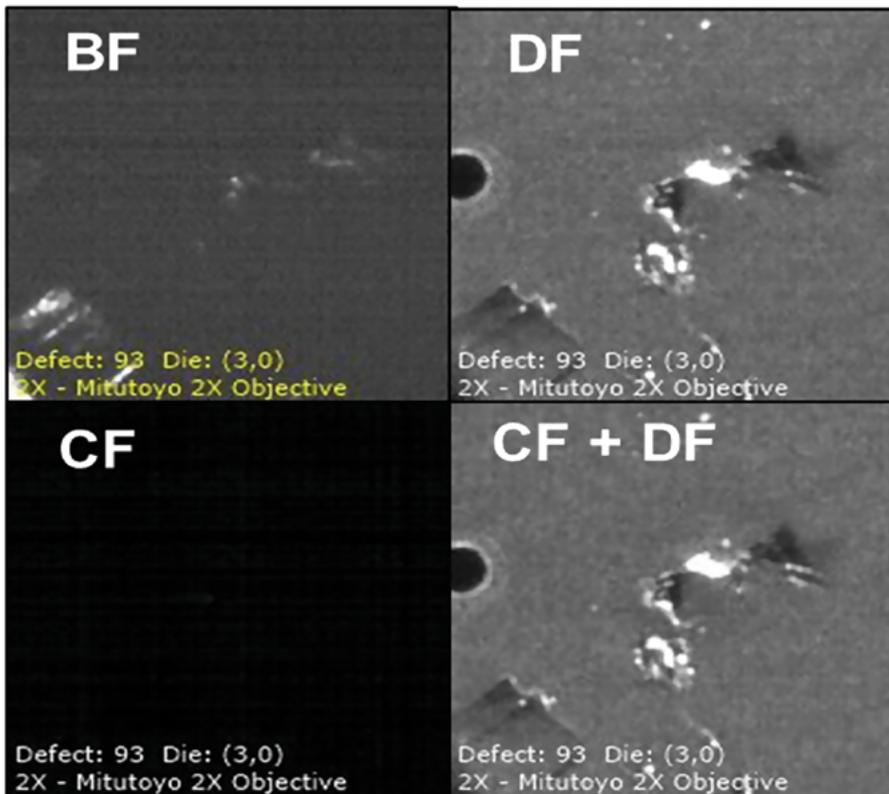


Figure 6: Inorganic defects after dry-film resist development inspection. All four images show defects at the same site but with different illuminations, as indicated in the panels.

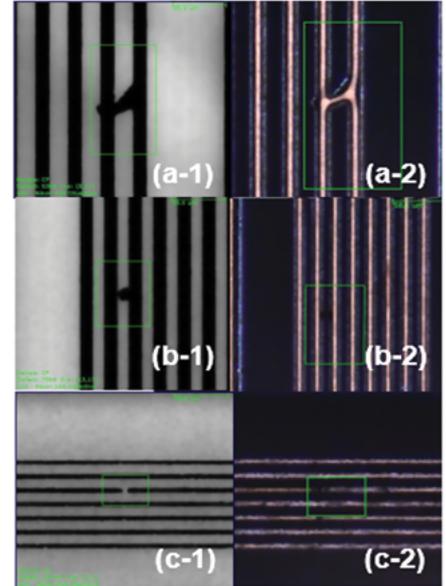


Figure 7: Three different defects for after-etch inspection of the Cu seed layer. The three images on the left are from using CF inspection, while the three images on the right are corresponding images captured with a BF color camera at higher magnification.

For residual Cu seed, if the residual Cu seed extends to 30% or more into the space between the Cu trace lines, it is considered to be a critical defect.

Figure 7 shows three different defects for after-etch inspection of the Cu seed layer. The three images on the left are from using CF inspection, while the three images on the right are corresponding images captured with a BF color camera at higher magnification. The two top images, (a-1) and (a-2), show a short circuit defect that could be easily detected with either CF or BF illumination. For the two images in the middle, (b-1) and (b-2), the defect was very clear in CF, but was not seen in BF. This is because the top flat surface of the Cu trace line only reflects light to the detector, making the area bright, while the reflection is very weak from Cu in the sloped area or from the thin and rough surface of the Cu residue. The CF technology image (c-1) clearly shows an open circuit, while an open circuit is not obvious in the corresponding BF color image (c-2). This is because the surface of Cu trace lines tend to become very rough and grainy after the etching process, making any brightness variation of the Cu line significant. In addition, any dark regions of the Cu lines can be easily mistaken for open circuits. Because the CF image is insensitive to the rough or grainy surface of metal, it is the most robust inspection technology for the after-etch inspection of Cu.



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Summary

In this article, we have compared inspection images with various illumination techniques for the inspection of ABF via residue, dry-film resist after development, and Cu seed after etching. For the inspection of via residue following the laser ablation of ABF, Clearfind[®] technology was found to be the most effective tool for identifying residue. For the inspection of dry-film resist after development, the simultaneous use of CF and DF illumination was the best choice because the former technology could easily find under-developed dry-film resist or residue inside the via, and DF could find metallic defects in the Cu area. Regarding inspection after the Cu seed etching process, CF illumination was the most efficient inspection technology because it clearly shows open or short defects without showing false defects that may come from rough and grainy surfaces when inspected by BF or DF.

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Biography

Dr. Cheolkyu Kim is a Senior Director of Applications at Onto Innovation, Wilmington, MA USA. Prior to joining Onto, Kim was a postdoctoral research associate in the Physics Department of Brown U. He received a PhD in Physics from the U. of Rhode Island and a Master's degree in Physics Education from Seoul National U., Seoul, Korea. His research has been published in various scientific journals. Email Cheolkyu.Kim@ontoinnovation.com