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Integrated Circuit Super-Resolution Failure Analysis with Solid Immersion Lenses

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Introduction

Amazingly, Moore's law marches on. The 22 nm technology node is nearly two years in production, with 14 nm expected this summer or fall, followed by 10 nm in the next couple of years. Current commercial technology for failure analysis (FA) using backside imaging is already incapable of resolving today's smallest transistor spacing, let alone those in the very near future. Yet, backside imaging is a critical tool for testing and FA of semiconductor devices, because metallization and packaging prevent frontside access. Backside imaging is used with many FA techniques, such as photon-emission microscopy, laser voltage probing, and laser voltage imaging.[1] Greater resolution in optics is achieved through shorter wavelengths, a larger solid angle of illumination and collection, or through both approaches. In backside FA, the highest-possible numerical aperture (NA) systems are required to achieve the smallest lateral and longitudinal resolution, because backside imaging restricts the wavelength to infrared light that penetrates the silicon substrate. Using aplanatic solid immersion, the authors achieved the highest resolution through numerical apertures that approach the theoretical limit of NA = 3.5. They used advanced techniques such as adaptive optics, apodization masks, and interferometric measurements to further improve resolution and sensitivity as well as correct for aberrations.[2,3]

Solid Immersion Lens

Invented in 1990 by Mansfield,[4] solid immersion lenses (SILs) have become widely used in a variety of applications, such as high-density optical storage,[5] near-field scanning microscopy,[6] and semiconductor integrated circuit (IC) backside inspections.[7]. Solid immersion lenses take advantage of the same basic principle as oil-immersion microscopy: immersing the object and lens together in a high-index medium, thus eliminating most losses due to refraction at planar interfaces. The very high refractive indices of SIL materials silicon and gallium arsenide (GaAs), which are closely matched to the silicon IC substrate, significantly increase the effective NA of a SIL microscope system and drastically improve resolution and light collection.

Photon-based FA techniques are realized by scanning a focused laser spot over the device under test (DUT). Fault isolation resolution is fundamentally limited by the focused spot size of the scanning optical microscope. Based on the Sparrow criterion,[8] the resolution of a microscope, δ, is represented as follows:

$$\delta = 0.61 \frac{\lambda}{NA} \quad \text{(Eq 1)}$$

where λ is the laser wavelength, and NA is the numerical aperture of the system.

$$NA = n \sin\theta \quad \text{(Eq 2)}$$

Here, n is the refractive index of the medium, and θ is the maximum half cone angle of the light that can enter the objective. Using SILs to achieve the highest possible NAs is necessary to meet the challenge of resolving increasingly smaller feature sizes in ICs.[9]

A SIL is a hemisphere or hyperhemisphere lens. The spherical surface of the SIL faces the backing objective, and the planar surface is in direct contact with the backside of the DUT. Two types of SIL geometries create aberration-free imaging in a perfect, axial system. The first type is the central SIL (cSIL) configuration, where light follows the radii to focus at the center of the sphere (Fig. 1, left). The second is the aplanatic SIL (aSIL) configuration, where light refracts at the spherical surface and focuses to the aplanatic point of the lens (Fig. 1, right), a distance R/n below the center, where R is the radius of the sphere. A cSIL increases the NA of the imaging system by a factor of n over the backing objective's NA, while the aSIL increases the NA by a factor of n^2 over the backing objective's NA.[10] Both SIL types have a theoretical maximum NA equal to the index of the SIL material being used. Achieving close to the maximum NA with a cSIL requires an objective with an NA of close to 1, while achieving the maximum NA with an aSIL only requires an objective with an NA of $1/n$. For this reason, an aSIL would be preferable, if it were not for the additional challenges of aberrations.

Imaging with SILs away from the center or aplanatic points leads to aberrations. In the case of aSILs, micron-level sample thickness errors can generate significant spherical aberration because the targets of interest are no longer at the aberration-free aplanatic point of the SIL. In the case of a cSIL, the thickness error tolerance is relatively high, whereas for the aplanatic configuration the thickness error tolerance is relatively low.[11] Typical polishing tolerances on silicon devices and SILs are of the order of ±5 μm. Differences in coefficients of thermal expansion between device, package, and underfill interfaces can also introduce tens of microns of silicon warp across the DUT. In general, one cannot assume the thicknesses of SILs and DUTs will be accurate enough to avoid spherical aberrations when using an aSIL.[12]

Adaptive optics wavefront techniques are used to compensate the aberration from the DUT thickness errors and relax the thickness tolerance requirements for using aSILs. Near-diffraction-limited imaging is achieved by using adaptive optics to apply a compensating wavefront that cancels the spherical aberration introduced by DUT thickness errors.[2] An experimental demonstration of thickness mismatch correction using a deformable mirror can be seen in Fig. 2. Adaptive optics corrections of spherical aberrations mean that aSILs can achieve their full performance without requiring special sample preparation.

Failure Analysis Applications of aSIL Microscopy

The aSILs are used to enhance the resolution and efficiency of many different backside optical FA techniques beyond static imaging. These include photon-

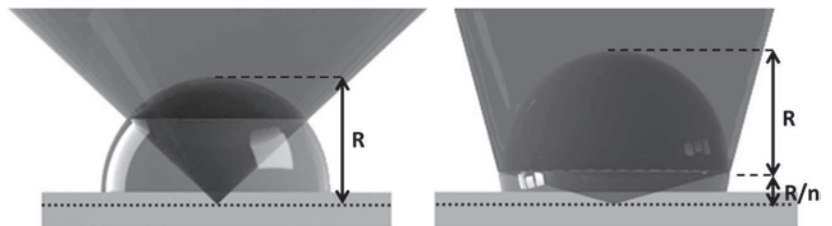

Fig. 1 SIL geometries. Left: Central SIL (cSIL). Right: Aplanatic SIL (aSIL). Both geometries are theoretically aberration-free at their respective foci, but the aSIL has a larger NA, allowing higher resolution. The diagram accurately represents the NA of the SILs, with the cSIL at an NA of 2.6 and the aSIL at an NA of 3.4. The cSIL NA is limited by the backing objective, and the aSIL NA by the refractive index of the SIL.

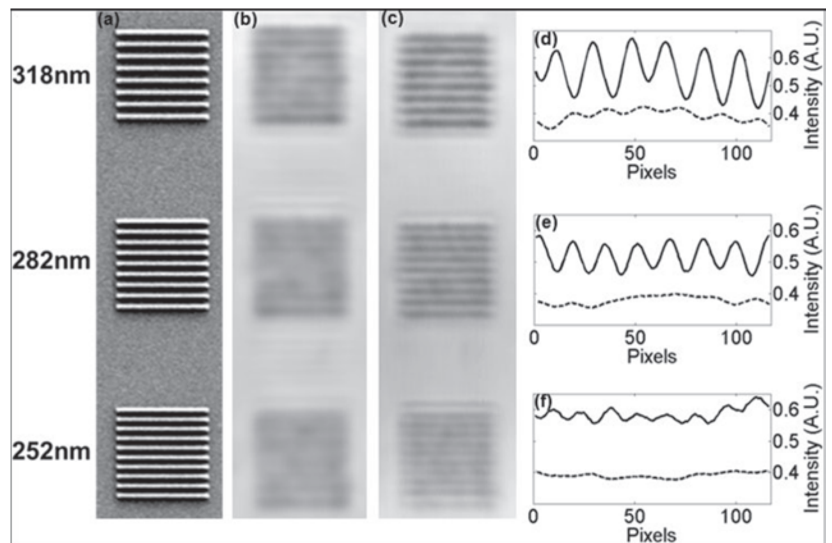

Fig. 2 Comparison before and after applying +190 nm rms first-order spherical aberration correction on a sample that is 11 μm thinner than the optimal design thickness. (a) SEM frontside image of the resolution test sample with separation of the lines marked. (b) aSIL microscope image obtained before spherical aberration correction. (c) aSIL microscope image obtained after spherical aberration correction. (d) Line cut comparison on group 318 nm. (e) Line cut comparison on group 282 nm. (f) Line cut comparison on group 252 nm

emission microscopy (PEM), laser voltage imaging (LVI), and interferometric LVI. Photon-emission microscopy is a technique for the extraction of timing information from individual transistors on ICs, which is critical in both device debug and failure analysis.[13] Smaller feature separation, reduced photon flux, and longer emission wavelengths make PEM increasingly more difficult on the 22 and 14 nm technology node devices.[14] An aSIL can maximize the collection efficiency of a PEM microscope with improvements in lateral resolution as well as enhanced collection efficiency,[7] somewhat at the expense of chromatic aberration due to dispersion of the aSIL.[15] It has been shown that chromatic aberration due to dispersion can be eliminated by the use of a corrective objective, allowing the full benefits of aSIL-enhanced PEM microscopy to be realized.[16]

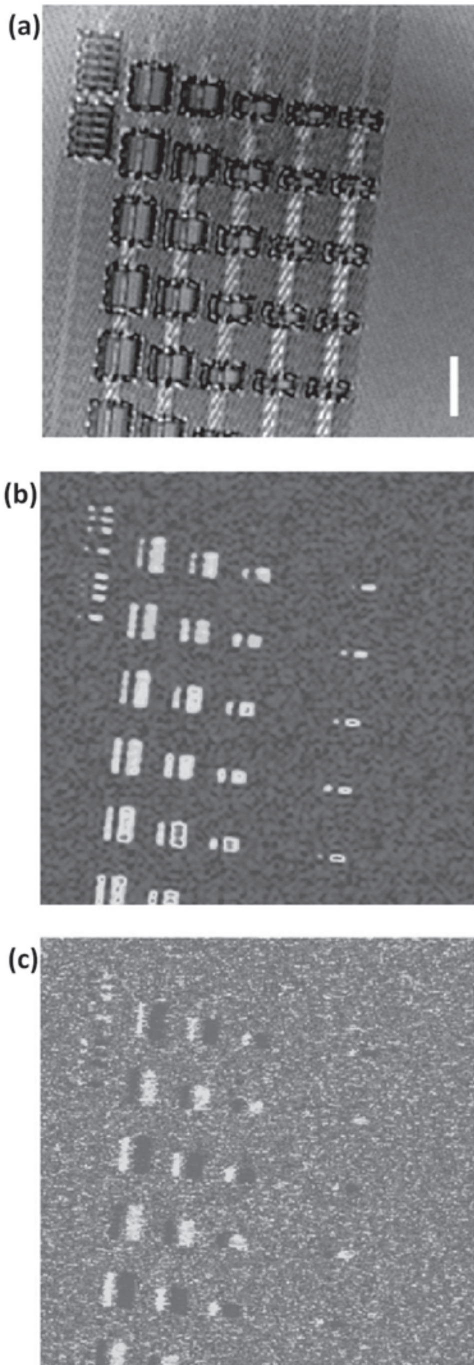

Fig. 3 Demonstration of the dual-phase interferometric LVI technique. (a) Reflectance image of a 32 nm silicon-on-insulator technology IC. (b) Carrier modulation map of the same IC at 12.5 MHz. (c) Phase map of the same IC at 12.5 MHz. Scale bar = 5 μm

Modulation mapping/LVI is an established technique for imaging the carrier activity at a given frequency.[17] The presence of free carriers in semiconductor devices alters the local refractive index and modulates the intensity of the laser beam reflected from the device. In LVI, the reflected beam intensity is detected by a fast photodetector, and the signal is then filtered at a specific frequency using a spectrum analyzer or lock-in amplifier.[18] A spatial modulation map is formed by recording the amplitude of the filtered signal while the laser beam is scanned in a region of interest. The map can then be investigated to identify the location of any unexpected activity. The amplitude of the reflectance modulation is typically on the order of parts per million of the reflected beam, making sensitive and quantitative measurements a major challenge, especially because incident laser power density must be limited in LVI to avoid device

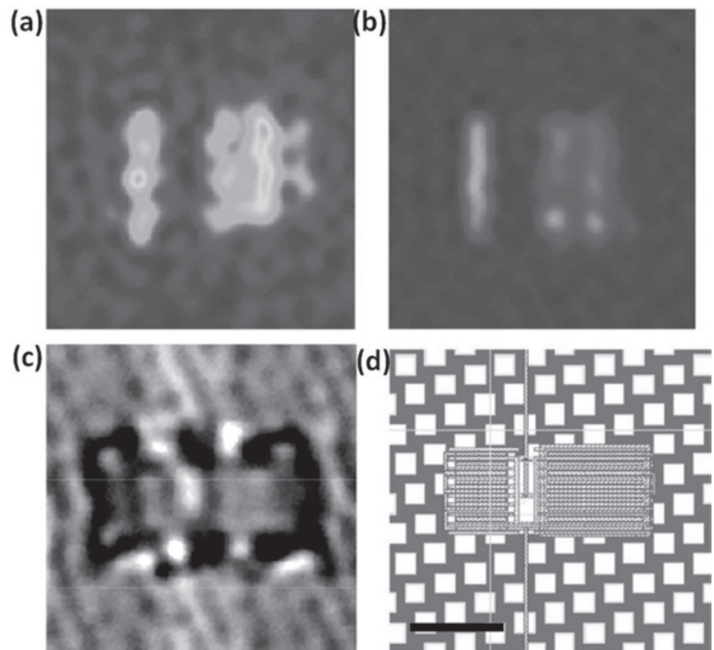

Fig. 4 Increase of SNR with interferometric removal of common mode. Modulation map images of the first inverter in the I3 chain from Fig. 3 shown (a) with and (b) without interferometric method. (c) Reflectance image of device. (d) Computer layout of device showing metal-3 filling materials in the vicinity of the transistors. Scale bar = 1 μm

alterations.[19] The speed and quality of LVI scans can be improved by using an aSIL's high collection efficiency and high resolution, but advanced technology nodes make detection of the already small reflectance modulation more difficult.

The challenge of low signal-to-noise ratio (SNR) levels in LVI signals can be overcome by using a differential dual-phase interferometric imaging method combined with an aSIL (Fig. 3, 4). In interferometric LVI, the reflected probe beam, modulated weakly by the charge carriers, is mixed separately with two reference beams with a known phase shift between them. Performing a balanced detection scheme on these two channels significantly reduces the common-mode noise associated with strong dc background and its noise. Interferometric LVI has been shown to provide sensitivity of 50 to 100 times better than conventional reflectance mapping.[3]

Super-Resolution aSIL Microscopy

High-resolution backside optical FA of current and next-generation ICs requires fault localization in the sub-100 nm regime. Even using SILs, fault isolation at this scale cannot be achieved with standard diffraction-limited microscopy. This has led researchers to investigate so-called "super-resolution methods," referring to far-field microscopy techniques to obtain object information at length scales smaller than the diffraction limit.

The study of super-resolution methods originates with Lord Rayleigh.[20] Here, the potential of super-resolution methods for semiconductor FA applications is briefly discussed. Such methods can be classified into two distinct classes:

- Vectorial tailoring methods based on focused spot size reduction through engineering the laser beam properties, such as spatial phase and polarization
- Image-reconstruction methods based on prior information about the objects under investigation when assumptions about the DUT or optical system can be made

Focused spot characteristics depend strongly on the vector properties of tightly focused beams. Linear polarization leads to elliptical focused spots distorted in the direction of the polarization vector of the beam. Dependence of the focused spot on the beam vector has spurred interest in so-called vortex beams with complex polarization properties to obtain subdiffraction focused spots.[21] In a recent experiment, a subdiffraction focus spot was achieved in an aSIL-based laser scanning microscope. The focus spot size in the experiment was reduced by approximately 20% by using a radially polarized vortex and a spin-orbit antialigned phase beam with an annular pupil mask, taking advantage of the strongly confined longitudinal focal field of the beam (Fig. 5a).[22]

Another approach to super-resolution is to process optical data with image-reconstruction techniques, employing prior information about the optical sys-

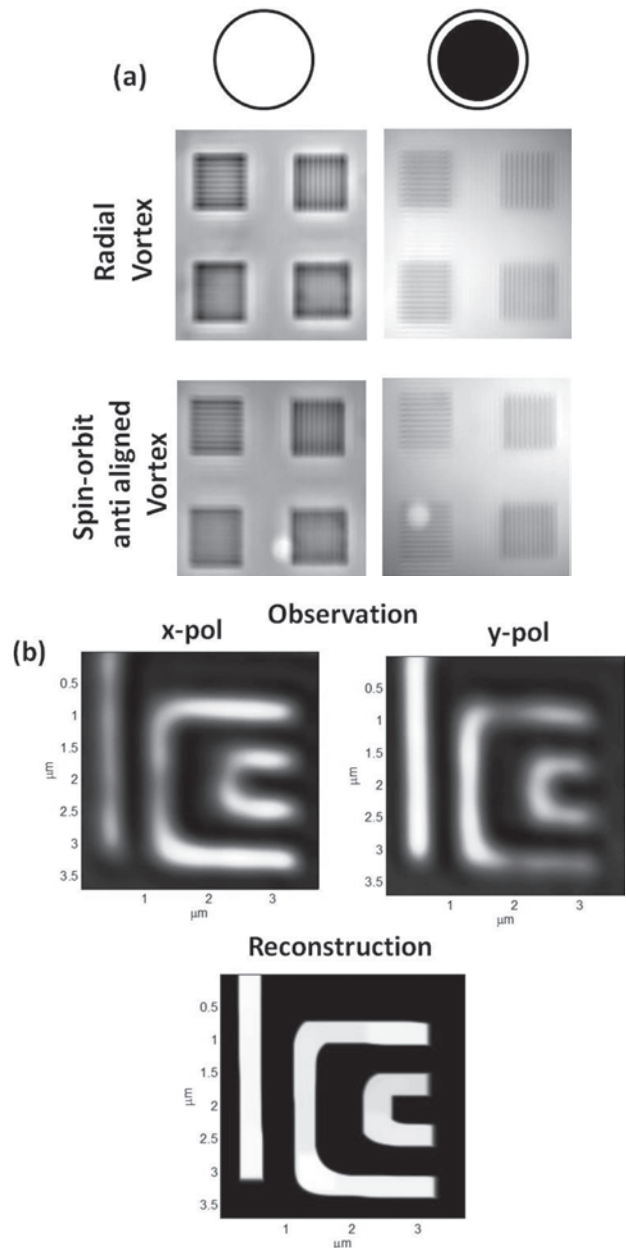

Fig. 5 *Use of vortex beams for super-resolution imaging at $\lambda_0 = 1310$ nm. (a) Left panel shows clear pupil images; right panel shows obstructed pupil images. The line pitch is 252 and 224 nm for the upper and lower rows in each image. (b) Use of nonlinear image reconstruction for super-resolution. The two observation images are of the same device taken with orthogonal linear polarizations. The reconstructed image is derived from the two observation images.*

tem model and the DUTs. Recovering subdiffraction information for different optical systems through nonlinear image-reconstruction techniques has already been demonstrated.[23] These nonlinear image reconstructions use the prior information that the underlying object is sparse and consists of piecewise continuous regions with sharp edges. A nonlinear image-reconstruction framework combining information from multiple images taken by using different polarizations can enhance FA image quality and resolution in high-NA systems (Fig. 5b).[24] Another approach for benefiting from prior information is to incorporate an overcomplete dictionary into an image-reconstruction framework. An overcomplete dictionary is particularly suited for image reconstruction in the FA domain because ICs are highly structured, and their building blocks can be predicted from the computer-aided design layouts. The authors formulated a resolution-enhancement framework that incorporates overcomplete dictionaries into image reconstruction for high-NA confocal microscopy systems for backside optical IC defect imaging and have shown 30% improvement in resolving subdiffraction-limited objects.[25]

Summary

Current backside imaging FA methods are unable to image the smallest technology-node devices already available. Next-generation backside FA will need to rely on SIL imaging, aberration correction with deformable mirrors, and LVI signal enhancement through interferometry. These resolution-enhancing, signal-enhancing, and aberration-reducing techniques can make backside FA a viable technology for current and future ICs.

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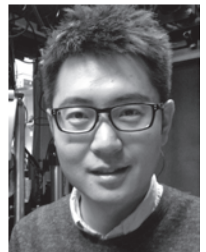

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Noteworthy Item

ESREF 2014

The 25th anniversary of the European Symposium on Reliability of Electron Devices (ESREF '14) will take place **September 30 to October 2, 2014,** in Berlin, Germany. This international symposium continues to focus on recent developments and future directions in quality and reliability management of materials, devices, and circuits for micro-, nano-, and optoelectronics. In addition to classic topics such as failure analysis and general reliability aspects, the conference will focus on such emerging themes as organic semiconductors and wide-bandgap devices. Invited experts will provide numerous tutorials.

For the first time, two user-oriented workshops will be fully integrated within the frame of the conference: the European FIB User Group (EFUG) and the European Failure Analysis Network (EUFANET) meeting. As usual, a profound equipment exhibition, placed in the conference area, will be part of the event.

"Expect the Unexpected!" is the guiding theme of the event. Hosted by the Technical University Berlin with the support of VDE (the Association for Electrical, Electronic, and Information Technologies), ESREF is the premier event in Europe for reliability and failure analysis topics and provides plenty of opportunities to share experiences, benchmark your work, and network with peers.

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