Seeing inside chips and cells: High-resolution subsurface imaging of integrated circuits, quantum dots and subcellular structures

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35-word abstract: In this work we examine two general approaches to subsurface imaging, the first using solid immersion lens technology to optimize the numerical aperture and the second an interferometric spectral fluorescence technique for buried emitters.

The vast majority of scanned probe microscopy imaging modes requires the proximity of the probe to the surface objects under study, and thus the many advances in the last decade yielding nanoscale resolution largely do not apply to subsurface imaging. In this work we examine two general approaches to subsurface imaging, the first using solid immersion lens technology to optimize the numerical aperture and the second an interferometric spectral fluorescence technique for buried emitters.

Nanoscale imaging of defects in ICs is a great current technological challenge as IC feature sizes continue to shrink. We have developed and demonstrate two advanced subsurface (through the substrate) analytical techniques for IC failure analysis – solid immersion lens microscopy and solid immersion lens thermography. Standard non-contact optical resolution is limited by diffraction to about half the wavelength of light, limiting standard subsurface imaging in Si to only 0.5 μm of lateral spatial resolution, in the best case. Solid immersion technique uses a transparent (at the wavelength of interest) semi-spherical lens where the object space is either at the interface of the lens or embedded within a similar material. The solids are high index ($2.0 < n < 3.5$) and with the combination of λ/n wavelength reduction and numerical aperture increase, diffraction limited resolution increases of greater than 10 ($\sim n^2$) in the lateral direction and greater than 30 ($\sim n^3$) in the longitudinal direction have been demonstrated, together with factors of 10 increase in light gathering ability. [1,2] Figure 1 shows a qualitative comparison between conventional far-field backside NIR imaging and NAIL microscopy. Using an optimized confocal microscope, we have demonstrated a lateral resolution of 0.23 μm. [1]

Subsurface solid immersion microscopy can be applied to blackbody radiation sources at longer wavelengths as well. We have designed, built, and demonstrated the use of a subsurface solid immersion microscope with capability for confocal imaging to >5μm wavelength. We have fabricated 100nm thick Al wires of varying widths (200 – 500 nm) on double-side polished silicon wafers. By running current through the wires, we create thermal profiles for imaging. Figure 2 shows the resolution improvement from >5μm to a resolution of 1.3μm, representing the best subsurface thermography to date.

Fluorescence is the workhorse of biological imaging, currently constrained by diffraction to a resolution of a significant fraction of the wavelength. Utilizing the modification of the spontaneous emission of fluorophores located close to a mirror, we have developed a technique for high-resolution imaging of buried emitters.[3] The interference between direct and reflected emission waves of fluorophores results in spectral fringes that can be precisely described with a classical model that considers the relative intensity, polarization state, and

specific dipole orientation. This yields information about the location of the emitters (dipoles) with sub-nanometer precision. The nanometer sensitivity is demonstrated by measuring the height of a fluorescein monolayer covering a 12 nm step etched in silicon dioxide. In addition, the separation between fluorophores attached to the top or bottom layer in a lipid bilayer film is determined with sub-nanometer precision.

Recently, we have extended this technique to resolve multiple layers in three dimensions, spaced as closely as 10 nm for sparse systems. Three dimensional subsurface imaging is done by utilizing scanning standing wave excitation combined with advanced inversion techniques. Reconstruction algorithms are developed that use specific a-priori knowledge to produce higher resolution images. A-priori conditions can be applied directly; applied to a limited region of the object; applied in one dimension (for an object with a layered structure such as lipid bilayers); or applied in two dimensions (for an object with a filamentary structure such as actin fibers). A reconstruction algorithm is described and applied to both real and simulated experimental examples.

Key Words: thermal imaging, high-resolution, fluorescence imaging, spectroscopy

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