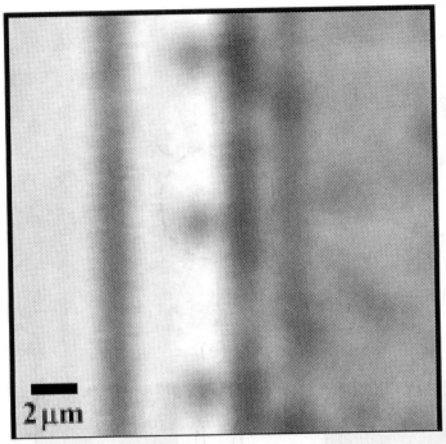
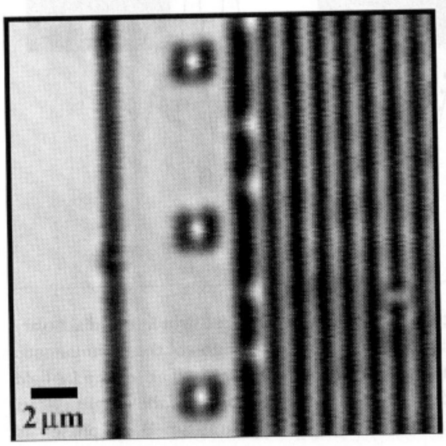


(a)



(b)

Figure 1. Images taken by the Hamamatsu µAMOS-200, IC failure analysis system, which demonstrate how a NAIL improves resolution well beyond the state of the art through substrate imaging of Si circuits: (a) image obtained with a 100x objective having a NA of 0.5 and (b) image obtained with a 10x objective having a NA of 0.25 showing that the NAIL increased the NA to 3.3.

MICROSCOPY

High-Resolution Subsurface Imaging of Silicon-Integrated Circuits

M. Selim Ünlü, Stephen B. Ippolito, and Bennett B. Goldberg

We developed a novel high-resolution subsurface microscopy technique that significantly increases the numerical aperture without introducing spherical aberration and consequently improves the diffraction-limited resolution beyond the limit of standard subsurface microscopy. The numerical aperture increasing lens (NAIL) technique improves the theoretical resolution limit from 0.5 to 0.14 µm in the near-infrared inspection of Si integrated circuits. Experimentally, by realizing a numerical aperture of 3.4, we demonstrated a resolution of approximately 0.2 µm,[1,2] which represents a fivefold improvement over the current state of the art. The figure shows images of a SRAM chip fabricated by an 0.18-µm process, which displays the striking improvement provided by the NAIL technique.

Diffraction limits standard optical microscopy to a spatial resolution of approximately half of the wavelength of light. Current Si integrated circuit (IC) technology includes many opaque metal layers and structures above semiconductor devices, thereby hindering topside inspection of devices in their final state. Hence, inspection through the backside or substrate of a Si IC is often preferred.[3] However, optical absorption in Si limits inspection through the substrate to $\lambda_0 \geq 1$ µm, yielding a theoretical lateral spatial resolution limit for standard subsurface microscopy of ~0.5 µm. Typical lateral spatial resolution values for commercial systems are inferior at approximately 1 µm. In contrast, modern Si IC technology has reached process-sized scales of 0.13 µm, which is clearly beyond the capability of standard subsurface microscopy.

By reducing the wavelength or increasing the collected solid angle we can improve the spatial resolution of surface microscopy. This has been achieved by both oil immersion and solid immersion lens (SIL) microscopy techniques,[4,5] which reduce the wavelength by immersion of the object space in a material with a high refractive index. However, in subsurface microscopy the only method to improve the spatial resolution is to increase the collected solid angle, i.e., the numerical aperture (NA) must be increased. The NA is $n \times \sin\theta$, where n is the refractive index in the object space and θ is the half-angle subtended. The large n in the object space in standard subsurface microscopy of planar samples does not increase the NA because of refraction at the planar boundary. Placing a NAIL on the backside of the substrate introduces a convex surface and effectively transforms the planar sample into an integrated SIL, allowing for a very large NA.

Ideally the NAIL is made of the same material as the sample, in this case Si, polished to allow intimate contact and to avoid reflections at the planar interface. For optimized dimensions, the object space coincides with the aplanatic points of the NAIL's spherical surface, yielding spherical aberration-free or stigmatic imaging. This configuration is similar to that of a SIL in which the aplanatic points defined by the spherical surface coincide with an object space on the planar surface of the lens.

Addition of a NAIL to a standard microscope increases the NA by a factor of n^2, to as much as a NA of n. For Si at $\lambda_0 =$ 1 µm, we increased the NA by a factor of 13 to a NA of 3.6, which corresponds to a lateral spatial resolution limit of 0.14 µm, with an initial experimental demonstration of approximately 0.2 µm.

In addition to the first implementation in Si IC imaging, we foresee other subsurface microscopy applications for the NAIL technique, including visible, biological, and thermal imaging as well as other semiconductor applications.

References

1. S. B. Ippolito, B. B. Goldberg, and M. S. Ünlü, Appl. Phys. Lett. **78**, 4071–3 (2001).
2. S. B. Ippolito, A. K. Swan, B. B. Goldberg, and M. S. Ünlü, SPIE Photonics West, San Jose, CA, January 2001.
3. Hamamatsu Corporation, 360 Foothill Rd., Bridgewater, N.J. 08807, http://www.hamamatsu.com.
4. B. D. Terris, H. J. Mamin, D. Rugar, W. R. Studenmund, and G. S. Kino, Appl. Phys. Lett. **65**, 388 (1994).
5. K. Karrai, X. Lorenz, and L. Novotny, Appl. Phys. Lett. **77**, 3459 (2000).

M. Selim Ünlü, Stephen B. Ippolito, and Bennett B. Goldberg, Boston University, Department of Electrical and Computer Engineering, Photonics Center, Boston, MA.