

High Resolution Backside Imaging and Thermography using a Numerical Aperture Increasing Lens

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As the feature size in ICs become smaller and smaller, the techniques we use to localize defects must also progress to the level that they can resolve potential errors. Additionally, because most errors cannot be identified by visual inspection alone, it is necessary to develop techniques, such as thermography, with the capability of localizing failures to the specific component or defect at fault. This paper will review the theory and application of two advanced subsurface (through the substrate) analytical techniques for IC failure analysis –solid immersion lens microscopy and thermography.

Standard non-contact optical resolution is limited by diffraction to about half the wavelength of light. This limitation is particularly problematic when topside metallization requires near-infrared (NIR) imaging through the backside or substrate of the Si IC because Si absorbs wavelengths shorter than about 1 μm . So while Si IC technology has achieved process scales of 0.13 μm , standard subsurface imaging offers only 0.5 μm of lateral spatial resolution, in the best case.

The solid immersion lens technique is based upon using 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 used are high index materials ($2.0 < n < 3.5$). 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. Recently, we have implemented such a solid immersion microscopy technique for subsurface imaging. [1,2]

A Numerical Aperture Increasing Lens (NAIL) is placed on the surface of a sample as illustrated in Fig. 1. The convex lens surface effectively transforms the NAIL and planar sample into an integrated solid immersion lens. Figure 2 shows a qualitative comparison between conventional far-field backside NIR imaging and NAIL microscopy, where both images are obtained on a Hamamatsu $\mu\text{AMOS-200}$, IC Failure Analysis System. Using an optimized confocal microscope, we have already demonstrated a lateral resolution of 0.23 μm . [1]

Thermoreflectance offers the ability to perform subsurface thermography while taking advantage of the increase in resolution that the NAIL offers. Thermoreflectance works on the basis of a change in refractive index with temperature change, allowing us to relate the change of reflected light to the change in temperature in the following manner [3]:

$$\frac{\Delta R(T(t))}{R} = \left[\frac{1}{R} \frac{\partial R}{\partial T} \right] \Delta T(t) = C_{th} \Delta T$$

Where R is the intensity of reflection, T is the temperature, and C_{th} is the thermoreflectance coefficient.

Using a confocal microscope, we have already demonstrated $0.9\ \mu\text{m}$ lateral spatial resolution using this technique [4] without a NAIL on the topside of a Si IC. A line scan of a heated polysilicon $0.6\ \mu\text{m}$ wire is shown in Fig. 3 to demonstrate resolution. For subsurface imaging, this resolution can be significantly improved by using NAIL. Additionally, the index change with temperature is enhanced at wavelengths around $1.1\ \mu\text{m}$, because of the presence of the silicon band-gap, allowing for more sensitivity in measuring temperature changes.

We have two samples to demonstrate our thermography technique. The first consists of $0.1\ \mu\text{m}$ thick Al wires of varying widths ($0.2 - 5.0\ \mu\text{m}$) on a double-side polished silicon wafer. A sample AFM image of this sample is shown in Fig. 4. By running current through the wires, we create thermal profiles for imaging. This sample will primarily be used to determine the resolution of our system. The second sample is a flip chip bonded IC with $0.13\ \mu\text{m}$ minimum features. The chip contains localized short circuits that create hot-spots for thermal imaging. The locations of these hot-spots have been verified by SQUID-based (superconducting quantum interference device) current-density measurements. Because imaging with the NAIL requires strong optical coupling between the lens and the substrate, an optical profilometer was used to insure that the NAIL could be effectively used on the sample. As shown in Fig. 5, the chip is sufficiently smooth and flat to mount the NAIL. The purpose for using this sample is to demonstrate that the subsurface thermoreflectance thermography can localize heating to a specific component that is failing.

We will present an in-depth discussion of the physics behind the NAIL imaging and thermoreflectance techniques. We will also present thermal images using the technique and compare experimental thermal and spatial resolution to theoretical limits.

Key Words: backside, thermal imaging, high-resolution

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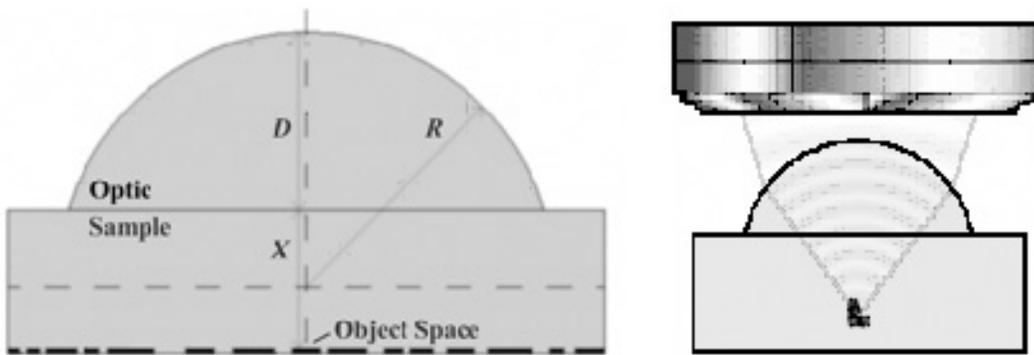
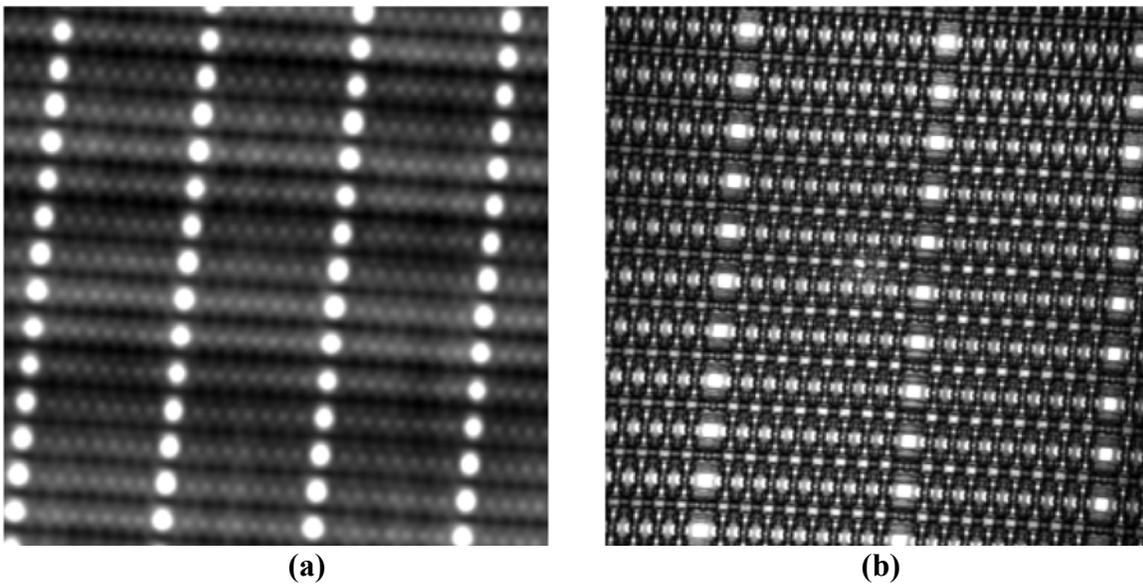


Figure 1. Use of a numerical aperture increasing lens (NAIL) to image subsurface features.



**Figure 2. Imaging using a NAIL (courtesy of Hamamatsu Corporation).
 (a) Standard imaging. (b) Imaging with NAIL.**

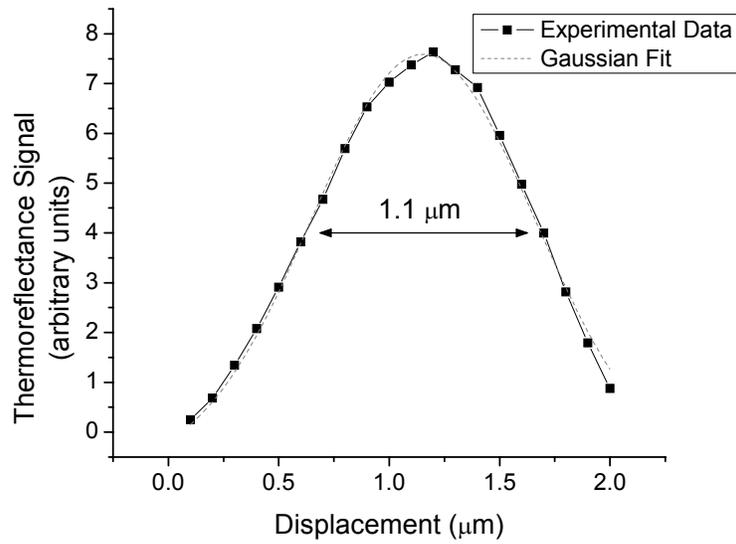


Figure 3. Thermoreflectance line-scan of a heated 0.6 μm poly-silicon line. Convolution of the spot size and the line thickness produces a resolution of 0.9 μm.

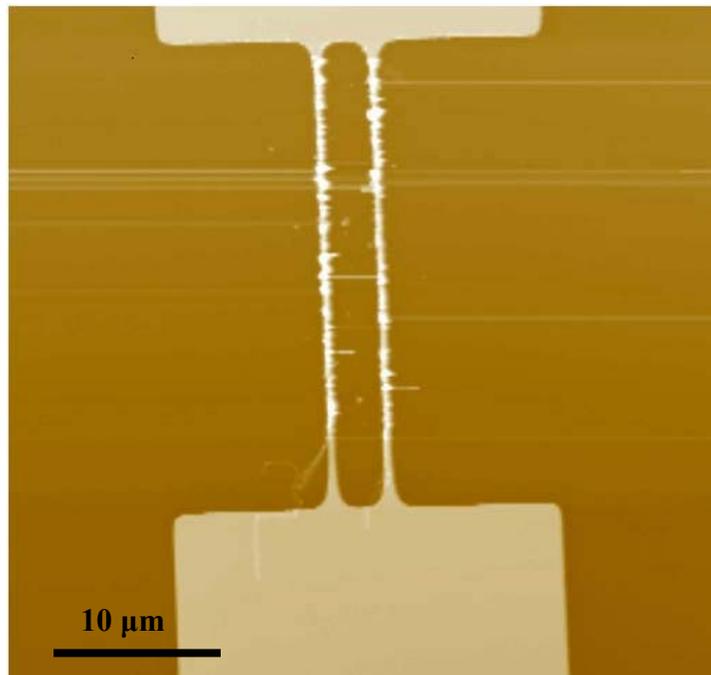


Figure 4. AFM image of double Al lines on double-side polished silicon substrate.

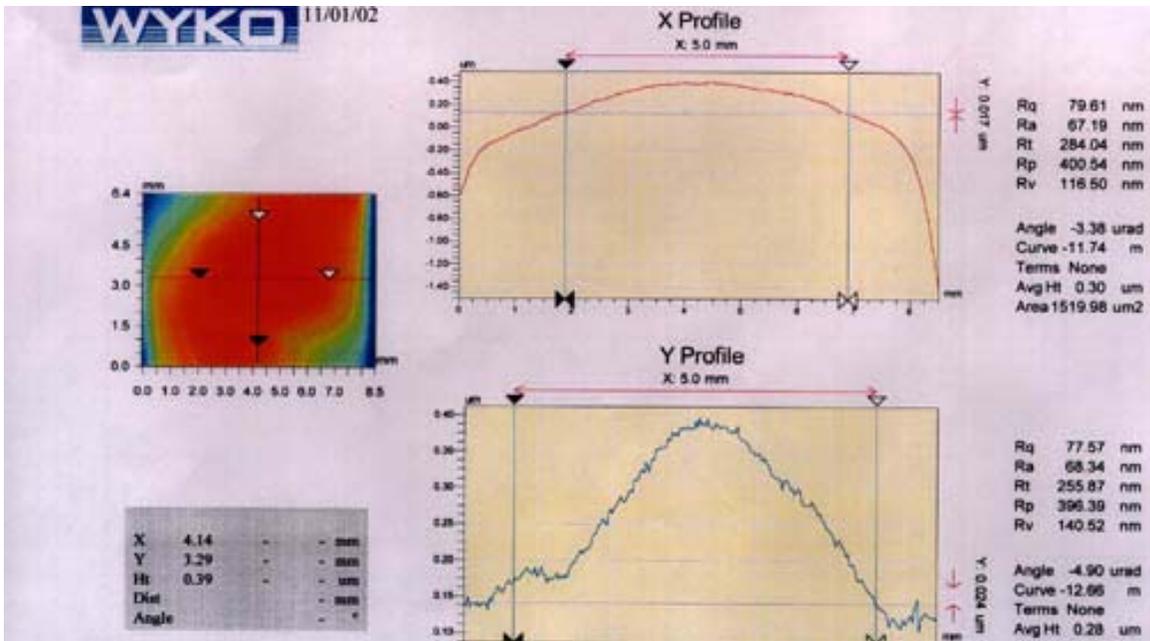


Figure 5. Optical-profilometry of IBM sample showing curvature and smoothness of thinned and polished backside surface.