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

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ABSTRACT

Nanoscale imaging of defects in ICs is a great current technological challenge as IC feature sizes continue to shrink. We have developed novel techniques based on a Numerical Aperture Increasing Lens (NAIL) to study semiconductors at very high spatial resolution. The NAIL is placed on the surface of a sample and its convex surface effectively transforms the NAIL and the planar sample into an integrated solid immersion lens. Addition of the NAIL to a standard microscope increases the NA by a factor of square of the index n, to a maximum of NA = n. In silicon, the NA is increased by a factor of 13, to NA = 3.6. The spatial resolution improvement laterally is about a factor of 4 while longitudinally it is a factor of 12.5 corresponding to an overall reduction of the volume of interrogation by a factor of 50.

Subsurface solid immersion microscopy can be applied to thermal imaging of blackbody radiation at IR wavelengths. We have designed, built, and demonstrated the use of a subsurface solid immersion microscope with capability for confocal imaging in 3-5µm wavelength range and demonstrated a resolution of 1.4µm, representing the highest resolution subsurface thermography to date.

Keywords: thermal imaging, high-resolution, failure analysis, solid immersion lens.

1 NUMERICAL APERTURE INCREASING LENS

The semiconductor industry has continued to advance at the rapid pace of Moore's Law through continued shrinking of the physical dimensions of the semiconductor devices, which are already at the nanoscale and will soon approach the atomic scale. New materials and devices at nanoscale herald a revolutionary age for science and technology, provided we can observe the detailed operation and discover and utilize the underlying principles. An important topic in nano-optics is optical microscopy and spectroscopy. Optical spectroscopy provides a wealth of information on structural and dynamical properties of materials, especially when combined with high-resolution microscopy because the spectral features can be spatially resolved. However, there are fundamental limitations of conventional microscopy. In case of imaging objects with optical fields propagating to the far-field, the basic constraint is the diffraction of light, which limits standard optical microscopy to a spatial resolution comparable to the wavelength of light. For imaging objects through a substrate, which is opaque for short wavelengths, this limitation becomes more stringent. Reducing the wavelength or increasing the collected solid angle can improve the spatial resolution of surface microscopy. We have recently developed novel techniques based on a Numerical Aperture Increasing Lens (NAIL) to study semiconductors at very high spatial resolution. [1,2] The NAIL is placed on the surface of a sample and its convex surface effectively transforms the NAIL and the planar sample into an integrated solid immersion lens. Addition of the NAIL to a standard microscope increases the NA by a factor of square of the index n, to a maximum of NA = n. In silicon, the NA is increased by a factor of 13, to NA = 3.6. Figure 1 shows inspection images of Si circuits fabricated by 180nm and 130nm technologies, displaying the striking improvement provided by the NAIL technique. Using an optimized confocal system we demonstrated lateral spatial resolution of approximately 200 nm. [1] The spatial resolution improvement laterally is about a factor of 4. One of the important features of NAIL microscopy is improved

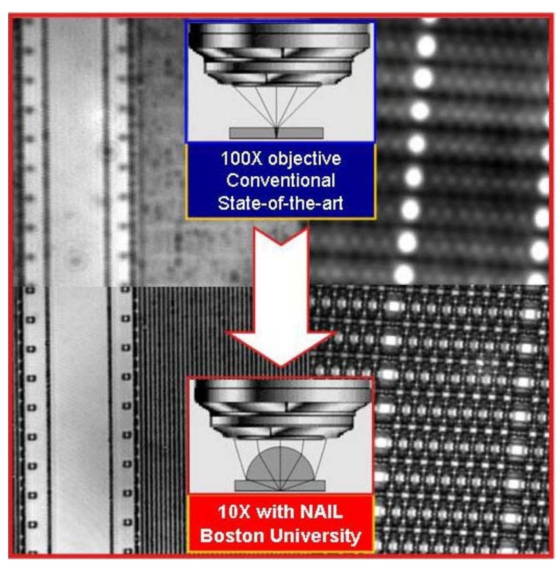

Figure 1. Qualitative comparison of the images displays the NAIL technique's striking improvement over state-of-the-art resolution.

light collection efficiency (scales with the square of NA), particularly important in the study of quantum dots as well as a variety of semiconductor failure analysis modalities including thermal imaging.

2 THERMAL EMISSION MICROSCOPY

Thermal emission microscopy is a non-contact optical microscopy technique that collects mid-infrared photons emitted to image the spatial distribution of temperature in a sample. The spatial distribution of temperature within a sample can be calculated, because the optical power emitted by the sample is a function of its local temperature. The optical power per unit area emitted by an object is proportional to its absolute temperature to the fourth power (Stephan Boltzmann's Law). Thermal emission microscopes are important tools in failure analysis of Si integrated circuits (ICs). Current Si IC technology has many opaque metal layers and structures fabricated above semiconductor devices, thereby hindering topside microscopy of the buried devices in their final state. Therefore, microscopy through the backside or substrate of a Si IC is often preferred. We demonstrate the improvement the NAIL yields in thermal emission microscopy of Si ICs. The theoretical lateral spatial resolution limit is 2.5 μm (~5μm for best commercial systems) for conventional thermal emission microscopes operating at wavelengths up to 5 μm. Current Si IC technology has reached submicron process size scales, well beyond the spatial resolution capability of conventional thermal emission microscopy.

The confocal scanning thermal emission microscope we built for this measurement consists of the elements shown in Fig. 2. The thermal test sample has an Al line and pads fabricated on a Si substrate. Joule heating the Al line generates a spatial distribution of temperature in one lateral direction and the longitudinal direction narrow enough to demonstrate a significant improvement in spatial resolution. However, without an accurate thermal model of the exact temperature distribution, the resulting best spatial resolution is unknown. The sample is flip chip bonded to a printed circuit board for connection and mounting on the xyz scanning stage. The computer controls the stage that scans the sample and NAIL, while acquiring the signal voltage. The sample is driven by a 900Hz sine wave from the signal genera-tor, while the lockin measures the amplitude of the second harmonic. The NAIL has a radius of curvature of 1.61 mm and a center thickness of 1.07 mm, optimized for the sample substrate thickness of 1 mm. The mid-infrared achromatic objective lens has NA = 0.25, resulting in the NAIL microscope having NA = 3.06. A cold mirror reflects the near-infrared wavelengths to an InGaAs camera for visual inspection and transmits the mid-infrared wavelengths to a cooled 50 μm diameter InSb detector, for thermal emission microscopy. [3,4]

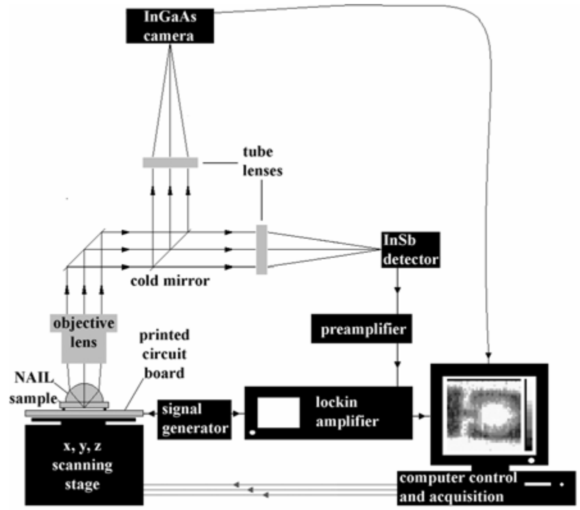

Figure 2. NAIL Confocal scanning thermal emission microscope configuration.

Figure 3 shows the resolution improvement with NAIL technique. The lower panel compares the inspection images taken by the InGaAs camera of the Al line, patterned to be 1μm wide. The thermal emission image taken by the InSb detector of the Joule heating is shown in the upper row. These images are taken at best focus. The optical power emitted due to the Joule heating follows Stephan Boltzmann's Law. Figure 4 shows a linecut in the lateral direction of the thermal emission image in Fig. 3(upper right). The full-width-at-half-maximum (FWHM) of the signal is 1.6 μm. The signal represents a convolution of the NAIL microscope line spread function and the finite spatial distribution of thermal emission in the sample. Deconvolution of the actual linewidth results in a spatial resolution of 1.4 μm representing a significant improvement over conventional thermal emission microscopy.

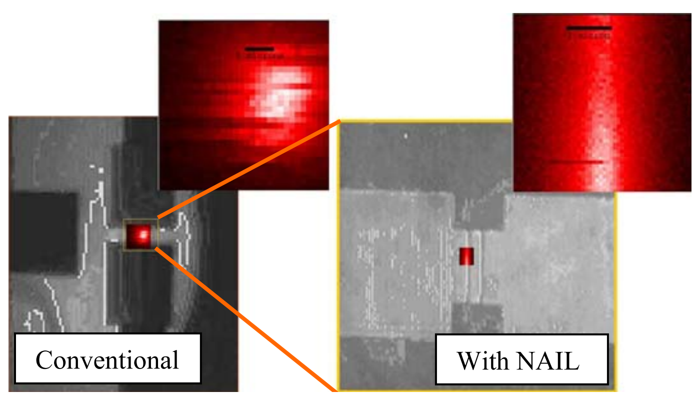

Figure 3. Solid immersion lens blackbody thermography. Left is a standard backside visual image (bottom), with blackbody image (top) showing >5μm resolution. On right, visual NAIL image clearly showing 200nm wires separated by 4μm. Red image in NAIL blackbody, showing 1.3μm resolution. The greater heating toward the center is due to electromigration and reduced thermal conductance away from the contacts

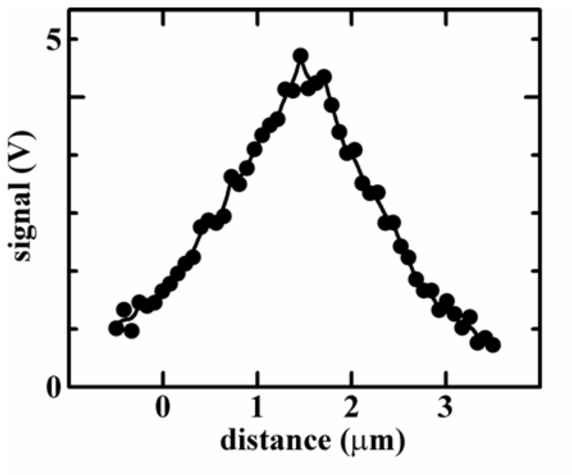

Figure 4. Lateral linecut of image in Fig. 3. The FWHM of the signal is 1.6 μm.

To evaluate the longitudinal spatial resolution we take successive images at different defocus distances in the longitudinal direction (z) and obtained a longitudinal spatial resolution of ~7μm. In comparison, the ultimate limit of longitudinal spatial resolution in conventional thermal emission microscopy is 18μm.

3 CONCLUSIONS AND FUTURE WORK

In summary, we have demonstrated drastic resolution improvements utilizing Numerical Aperture Increasing Lens technique. The application of the NAIL technique to subsurface thermal emission microscopy of Si integrated circuits demonstrates improvements in the amount of light collected and in both the lateral and longitudinal spatial resolutions, well beyond the limits of conventional thermal emission microscopy. The spatial resolution improvement laterally is about a factor of 4. Theoretically, overall reduction of the volume of interrogation is a factor of 50. We have designed, built, and demonstrated the use of a subsurface solid immersion microscope with capability for confocal imaging in 3-5μm wavelength range and demonstrated a lateral resolution of 1.4μm along with a focal depth of ~7μm. To the best of our knowledge, both of these values correspond to the best resolution in subsurface thermography to date.

Currently, we are building upon these experimental results and exploring the ultimate limitations of NAIL microscopy in thermal imaging. The diffraction of light theoretically limits the lateral spatial resolution to 0.73 μm and the longitudinal spatial resolution to 1.5 μm, for thermal emission microscopes with a NAIL, operating at free space wavelengths up to 5 μm. To eliminate the experimental limitations due to large thermal sample, we are building a system where a UV laser is focused on the front surface of the substrate (double-side polished Si wafer) to form a thermal image smaller than 500 nm in diameter.

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