High spatial resolution subsurface thermal emission microscopy

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Thermal emission microscopy measures the spatial distribution of temperature in a sample. Thermal emission microscopy is a non-contact optical microscopy technique that collects mid-infrared photons emitted by the 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. However, the reflection and refraction of light at the planar interface between the substrate and the air, limits the amount of light and spatial resolution a microscope can obtain. We previously demonstrated the improvement a Numerical Aperture Increasing Lens (NAIL), a Si plano-convex optic, yields in visual inspection microscopy of Si ICs.[1] In this paper, we demonstrate the improvement the NAIL yields in thermal emission microscopy of Si ICs. The theoretical lateral spatial resolution limit is 2.5 μm for conventional thermal emission microscopes operating at wavelengths up to 5 μm. Typical lateral spatial resolution values for the best commercial systems are about 5 μm. Current Si IC technology has reached submicron process size scales, well beyond the spatial resolution capability of conventional thermal emission microscopy. The large refractive index of Si (n = 3.5), offers the potential for significant improvement in spatial resolution. We experimentally demonstrate a lateral spatial resolution of better than 1.6 μm and a longitudinal spatial resolution of better than 5.2 μm.

The confocal scanning thermal emission microscope we built for this measurement consists of the elements shown in Fig. 1. The thermal test sample has an Al line and pads fabricated on a Si substrate. The width of the Al line was patterned to be 1μm. 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.[2] 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 generator, 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 Indium Antimonide detector, for thermal emission microscopy.

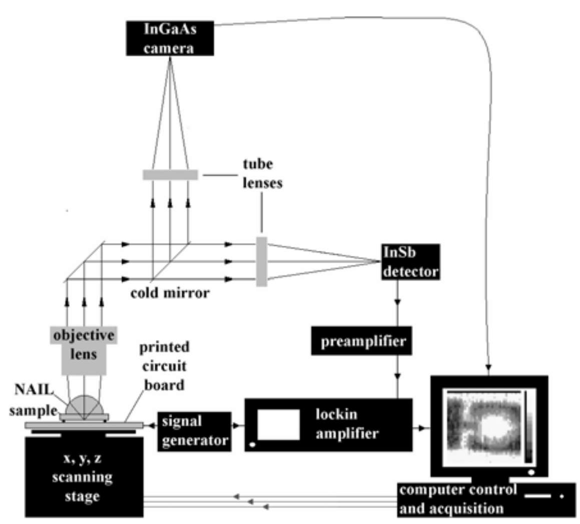

FIG. 1. NAIL Confocal scanning thermal emission microscope configuration.

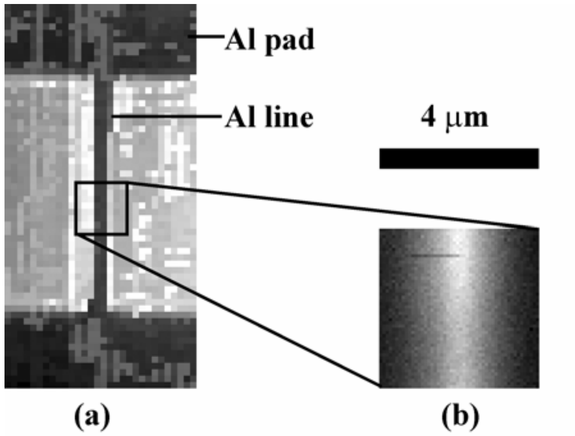

FIG. 2. Images of Al line patterned to be 1μm wide (a) inspection image taken by InGaAs camera and (b) thermal emission image of the Joule heating taken by InSb detector.

The inspection image taken by the InGaAs camera of the Al line, patterned to be 1μm wide, is shown in Fig. 2(a). The thermal emission image taken by the InSb detector of the Joule heating is shown in Fig. 2(b). These images are taken at best focus. The optical power emitted due to the Joule heating follows Stephan Boltzmann's Law. Figure 3 shows a linecut in the lateral direction of the thermal emission image in Fig. 2(b). 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. According to the Houston criterion we demonstrate a lateral spatial resolution of better than 1.6 μm. This represents a significant improvement of the lateral spatial resolution over conventional thermal emission microscopy.

To evaluate the longitudinal spatial resolution we take successive images at different defocus distances in the longitudinal direction (z). The peak values of each image are plotted in Fig. 4. For positive defocus values the collection focus is in the silicon. For negative defocus values, the collection focus is below the silicon/metal/air interface, where the signal values are a result of the complicated near-field problem of reflection from the interface. The FWHM of the signal from the positive defocus values indicates a longitudinal spatial resolution of 5.2μm. This represents a significant improvement of the longitudinal spatial resolution over conventional thermal emission microscopy, where the ultimate limit is 18μm.

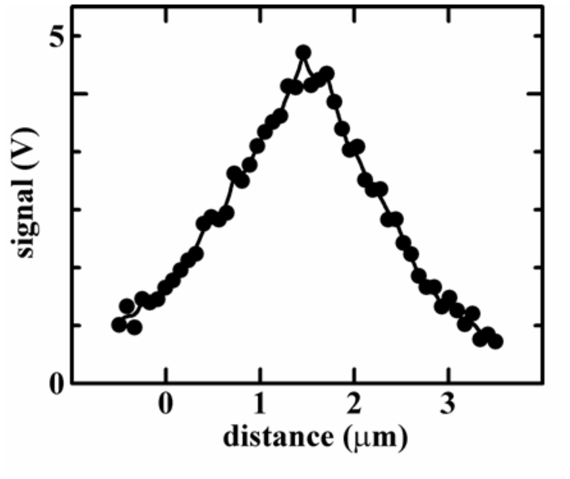

FIG. 3. Lateral linecut of image in Fig. 2(b). The FWHM of the signal is 1.6um.

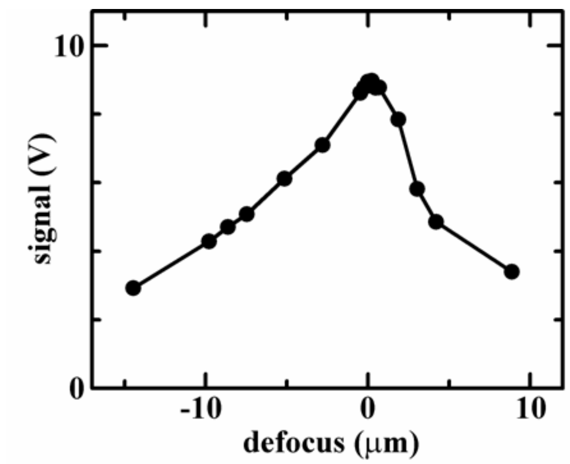

FIG. 4. Peak values of images at varying defocus. From positive defocus values the FWHM of the signal is 5.2um.

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[1] S. B. Ippolito, B. B. Goldberg, M. S. Ünlü, "High spatial resolution subsurface microscopy," *Applied Physics Letters* 78 (2001): 4071.

[2] David G. Cahill, Wayne K. Ford, Kenneth E. Goodson, Gerald D. Mahan, Arun Majumdar, Humphrey J. Maris, Roberto Merlin, Simon R. Phillpot, "Nanoscale thermal transport," *Journal of Applied Physics* 93 (2003): 793.