High Resolution Subsurface Microscopy Technique

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Standard optical microscopy is not capable of obtaining a transverse resolution with a definition better than approximately half a wavelength of light due to the diffraction limit, also termed the Rayleigh or Abbe limit. The diffraction limited spatial resolution is $\lambda/(2 \cdot \boldsymbol{NA})$ where λ is the wavelength of collected light in free space. The Numerical Aperture is defined as $\boldsymbol{NA}=\boldsymbol{n} \cdot \sin\theta_a$ where $\boldsymbol{n}$ is the refractive index of the material in the object space and θ_a is the collection angle, the half-angle of the optical collection area. In order to improve resolution of diffraction limited microscopy the ***NA*** must be increased.

One method to increase the ***NA*** is to increase ***n***, the refractive index of the material in the object space. Oil immersion and Solid Immersion Microscopy [1] techniques rely on the index of an interface material in the object space to increase the ***NA***. Subsurface imaging of planar samples by standard optical microscopy is always limited to the ***NA*** of the microscope objective lens. The ***NA*** remains the same, because the increase in index is exactly counterbalanced by the reduction of $\sin\theta_a$ from refraction at the planar boundary. This refraction also imparts spherical aberration to the collected light that increases monotonically with increasing ***NA***, thereby decreasing the resolution. We describe a subsurface imaging technique that takes full advantage of the index of the sample to increase the ***NA***.

The Numerical Aperture Increasing Lens (NAIL) [2] is a lens that is placed on the surface of a sample as illustrated in Figure 1. The NAIL is ideally made of the same material as the sample, both polished to allow an intimate contact as free of air space as possible to avoid reflection effects at the planar boundary. The convex surface of the NAIL is spherical with a radius of curvature of ***R***. The light is collected through the sample and NAIL from an object space focal plane in the sample at a vertical depth of ***X***. To obtain a spherical aberration free or stigmatic image, the vertical thickness of the lens, ***D***, is selected according to the equation $\boldsymbol{D}=\boldsymbol{R}(1+1/\boldsymbol{n})-\boldsymbol{X}$. The image is stigmatic because at that depth the points in the object plane satisfy the sine-condition [3]. This technique is similar to the Super-SIL technique where the total lens depth is $\boldsymbol{R}(1+1/\boldsymbol{n})$. Within a small range of depths in the vicinity of the focal plane the sample can be stigmatically imaged, moving away from this depth increases spherical aberration. Larger values of ***R*** should be chosen to flatten the field. For imaging a large range of depths a set of NAILs with the same ***R*** and varying ***D*** can be used to preserve stigmatic imaging over a range of sample depths. In addition to stigmatic imaging there are several other advantages of the NAIL microscopy technique. The ***NA*** of the microscope is increased by a factor of $\boldsymbol{n}^2$, a factor of ***n*** from the index and another factor of ***n*** from the increase in $\sin\theta_a$. The largest value of $\sin\theta_a$ depends on the selection of ***R*** and ***D*** but is ultimately limited to $\sin\theta_a=1$, thus the largest value of the microscope objective ***NA*** is $1/\boldsymbol{n}$. This allows for the use of smaller ***NA*** objective lenses that are less expensive without sacrificing the ***NA*** of the microscope. Thus the NAIL technique yields a resolution improvement over standard optical microscopy of at least a factor of ***n*** and up to a factor of $\boldsymbol{n}^2$. The microscope magnification and scan relaxation are also increased by a factor of $\boldsymbol{n}^2$. In summary, the NAIL technique increases the ***NA*** and subsequent resolution while preserving stigmatic imaging, and is therefore a significant improvement over standard optical microscopy for subsurface imaging at the diffraction limit. The experimental data to follow demonstrates the NAIL technique capability.

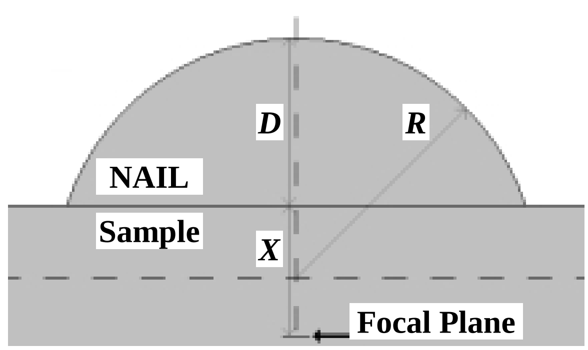

Figure 1. Schematic of NAIL and sample parameters.

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To test the NAIL microscopy technique we prepared a sample by standard silicon processing. All of the images are of this *500*-µm thick silicon chip we designed as a resolution test. The NAIL has ***R****=1.61*-mm and a ***D****=1.5*-mm. Figure 2 illustrates the infinity corrected microscope configuration with NAIL and sample. The lead sulfide IR Hamamatsu camera has a wavelength range out to *1.8*-µm. The objective lens has a ***NA*** of *0.25* and is designed for IR light. In Figure 3(a) we show an image using the standard optical microscopy technique, without the NAIL in place. The diffraction-limited resolution is *3.6*-µm. The next two images and line cut were taken using the NAIL microscopy technique, which adds a factor of *11.6* to the microscope magnification. The location of the images relative to the image of the whole chip is shown schematically. In Figure 3(b) we show a NAIL image of vertical poly-silicon lines of width and spacing *0.6*-µm. These *320*-nm thick poly-silicon lines were fabricated over a *30*-nm oxide layer on the silicon substrate, and were buried in a *2*-µm oxide layer. This image demonstrates the resolution capability for a relatively high optical contrast structure. It is often desired to image subtle variations such as those due to impurity concentration. In Figure 3(c) we show a NAIL image of vertical n-diffusion lines of width and spacing *1.2*–µm. The n-diffusion lines are lines of n^+-type diffusion doping into a shallow depth of the p-type substrate. The difference in absorption levels from the doping provides the contrast in this image. In Figure 3(d) we show a line cut of the last image, displaying the resolution capability. The NAIL microscopy technique adds a factor of *11.6* to the microscope ***NA***, which increases the microscope ***NA*** to *3* and improves the diffraction-limited resolution to *0.3*-µm as demonstrated by the data shown. Ultimately, the NAIL technique can improve this resolution down to a diffraction-limit of *0.14*-µm.

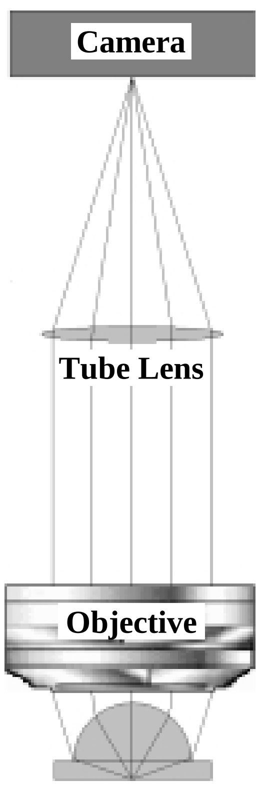

Figure 2. NAIL microscope configuration.

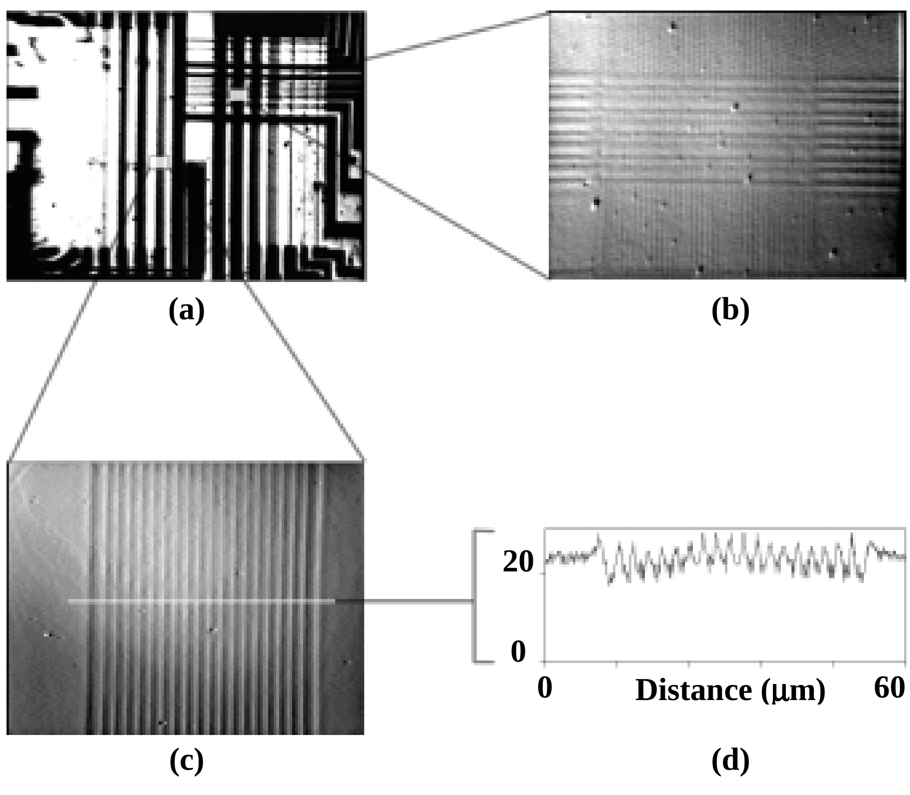

Figure 3. (a) Standard Optical Microscopy (b) NAIL microscopy of vertical poly-silicon lines (c) NAIL microscopy of vertical n-diffusion lines (b) Line cut of data from last image.

AKNOWLEDGEMENTS

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REFERENCES

1. S. M. Mansfield, G. S. Kino, "Solid Immersion Microscope," *Appl. Phys. Lett.*, vol. 57, no. 24, pp. 2615-2616, 1990.
2. S. B. Ippolito, B. B. Goldberg, M. S. Ünlü, "Numerical Aperture Increasing Lens (NAIL) techniques for high-resolution sub-surface imaging," patent pending.
3. M. Born and E. Wolf, *Principles of optics*, Cambridge University Press, New York, 1999.