Subsurface Microscopy of Multilayered Integrated Circuits

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***Abstract*—We demonstrate 325nm lateral spatial resolution while imaging metal structures located inside the interconnect layer of a multilayered integrated circuit.**

I. Introduction

The need for high resolution imaging necessitates the use of high numerical aperture (NA) optical systems. Solid immersion lens (SIL) microscopy is a diffraction limited imaging technique that provides high NAs taking advantage of the large optical index n of the immersion medium as well as the increased excitation and collection angles [1]. Numerical aperture increasing lens (NAIL) microscopy is an application of the SIL technique to integrated circuit (IC) imaging [2]. A silicon NAIL placed on the backside of a silicon substrate effectively transforms the NAIL and the planar sample into an integrated SIL. This imaging scheme allows for high resolution backside imaging through the substrate of an IC which is often necessary because opaque interconnect metal layers hinder frontside optical microscopy. NAIL technique has been employed to enhance imaging performance in widefield and confocal imaging systems [2], [3]. However, all of these efforts have focused on imaging the structures that are on the first transistor layer of the IC. Although most of the critical components are located in this layer, miniaturization of ICs made the first few metal interconnect layers extremely important for the electrical performance. Therefore, the ability to image these layers is crucial for effective failure analysis. Unlike the transistor layer, interconnect layers of an IC are surrounded by the insulation dielectric reducing the medium refractive index from 3.5 in Si to 1.5 in SiO_2 rendering the earlier studies unapplicable. In this study, for the first time, we are characterizing the limits of lateral spatial resolution for the interconnect layers of an IC in both confocal and widefield imaging schemes. In agreement with earlier studies, we observe the effect of polarization as different resolutions in different directions due to linearly polarized illumination [4], [5]. We demonstrate a lateral spatial resolution of 325nm (λ_0/4) in agreement with the values calculated theoretically.

II. Setup

The confocal microscopy part of the setup is a double-path, reflection-mode fiber-optical scanning microscope operated at λ_0=1.3μm whereas the widefield part uses LED illumination centered at 1.2μm. The widefield part has a larger field of view making on-chip-navigation easier and has the ability to acquire high resolution images using a zoom module. A sliding mirror enables us to go back and forth between the two microscopes. Additional details of the setup is explained in the caption of Fig. 1.

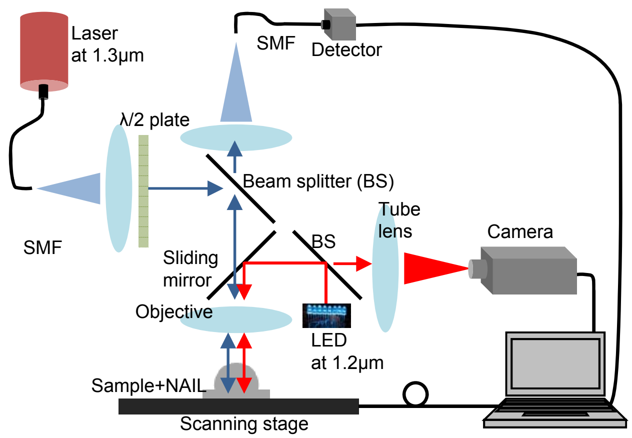

Fig. 1. Experimental setup. A sliding mirror provides switching between confocal and widefield microscopes. When the sliding mirror is out, in confocal imaging, side illumination and top detection is done with a beam splitter and the piezo stage forms a full image by scanning the sample with the NAIL. Coupling into and out of the single mode fibers (SMF) provides the confocality. λ/2 plate is used to rotate the polarization of the illumination. When the sliding mirror is in, the sample is illuminated with an LED array and the image is captured using an InGaAs camera.

The NAIL used in this work is an undoped silicon hemisphere with radius R = 1.61mm. The optimum substrate thickness (X) for aplanatic imaging with this NAIL is $X = R/n$ = 460μm where n is the refractive index at the operating wavelengths [6]. The sample is a custom IC with 4 metal and 2 polysilicon layers fabricated at Austriamicrosystems by a 0.35μm process. The substrate thickness was reduced to 458$\pm$2μm for aplanatic imaging.

III. Experiment

The sample IC has passive parallel lines on metal1 (m1), metal2 (m2), metal3 (m3) and metal4 (m4) layers for calibration. The linewidths and spacings are 0.6, 0.8, 1 and 2μm for m2, m3 and m4 layers, whereas there is an additional set of 0.5μm lines on m1 layer as allowed by the design rules. We are presenting the images of the lines with 0.5μm width and spacing located on m1 layer and 0.6μm width and spacing located on m4 layer for two different polarization directions that are parallel and perpendicular to the lines, respectively, in Fig. 2(a) and (b). In Fig. 2(c), images taken with the widefield microscope is presented. In confocal images,the lines that are parallel to the polarization direction have sharper edges as expected from the theory. Although the image quality is not as good as in confocal imaging, widefield images also resolve the lines. Low signal-to-noise ratio prevents us from acquiring higher magnification images in widefield micropscopy. In addition, we imaged the lines with 1μm width and spacing and recorded the edge responses. Line spread functions (LSF) have been extracted to estimate the resolution. Fig. 3 illustrates sample edge responses and the corresponding LSFs for metal1 and metal4 layers in two directions. As indicated in Fig. 3, measured resolutions are 325nm and 450nm for metal1 lines in the direction perpendicular and parallel to the polarization direction, respectively. Corresponding resolutions for metal4 layer have been measured as 340nm and 460nm. Since the images and resolution data for the metal2 and metal3 layers are very similar, they are not included. Although the resolutions for metal1 layer seem to be better than metal4 layer, measurements do not show a conclusive enhancement trend from metal4 to metal1 layer. The edge responses for widefield microscopy are averaged over 50 linecuts to have an accurate measurement and the resolution is estimated to be in the range of 450-500nm for all layers. Since any single edge response would not reflect this calculation, the data for widefield images is not included in Fig. 3.

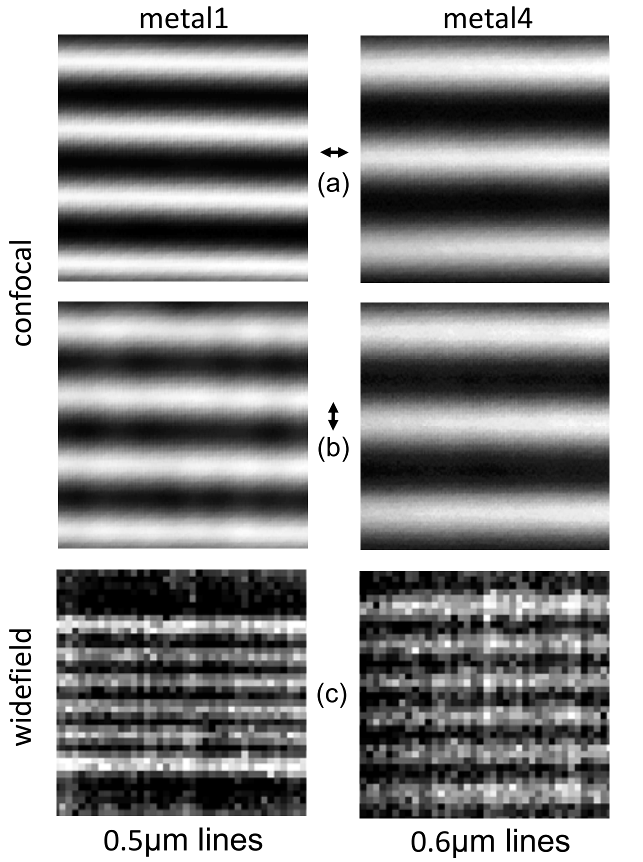

Fig. 2. (a) Confocal image of metal1 lines under horizontal polarization on the left and metal4 lines on the right. (b) Same as (a) with vertical polarization. (c) Widefield image of metal1 lines on the left and metal4 lines on the right.

We have calculated the focal field distributions using angular spectrum representation (ASR) [7] for the light that is focused at 0.65μm and 3.65μm beyond the interface as specified by the manufacturer specifications for the depth of metal1 and metal4 layers, respectively. ASR method enables us to take into account the polarization of the incoming light in high NA conditions as well as the polarization dependent refraction and reflection at the dielectric interface. Confocal LSFs were computed from the field calculations for comparison with the experimental results. For metal1 layer, calculated results are 310nm and 520nm in the directions perpendicular and parallel to the polarization direction, respectively. The fact that experimental value in the direction parallel to polarization is better than the theoretical value can be due to imperfect polarization. For metal4 layer, calculated results are 360nm and 450nm in the directions perpendicular and parallel to the polarization direction, respectively, virtually identical to the experimental values.

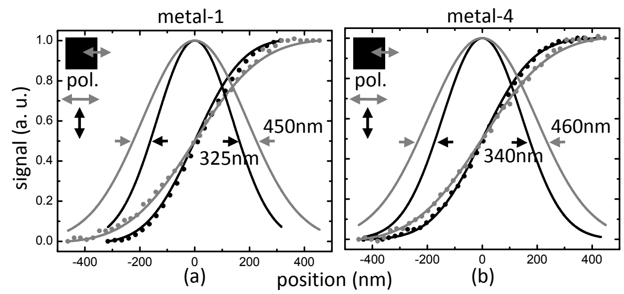

Fig. 3. Edge response data and corresponding LSFs for confocal imaging of metal1 and metal4 layers. Gray lines correspond to the linecut direction parallel to the polarization direction whereas black lines correspond to the perpendicular direction.

IV. Conclusions

In this study, we conducted the first experimental demonstration of resolution characterization for upper metal layers of an integrated circuit in subsurface optical microscopy. We have shown a lateral spatial resolution of 325nm ($\lambda_0/4$)for the first metal layer. In addition, we have calculated focal fields for the corresponding focus depths and found a high degree of agreement with the experimental results.

References

[1] S. M. Mansfield and G. S. Kino, "Solid immersion microscope," *Appl. Phys. Lett.*, vol. 57, no. 24, p. 2615, 1990.

[2] S. B. Ippolito, B. B. Goldberg, and M. S. Ünlü, "High spatial resolution subsurface microscopy," *Appl. Phys. Lett.*, vol. 78, p. 4071, June 2001.

[3] F. H. Koklu, J. I. Quesnel, A. N. Vamivakas, S. B. Ippolito, B. B. Goldberg, and M. S. Ünlü, "Widefield subsurface microscopy of integrated circuits," *Opt. Exp.*, vol. 16, p. 9501, June 2008.

[4] K. A. Serrels, E. Ramsay, R. J. Warburton, and D. T. Reid, "Nanoscale optical microscopy in the vectorial focusing regime," *Nature Pho.*, vol. 2, p. 311, May 2008.

[5] F. H. Koklu, S. B. Ippolito, B. B. Goldberg, and M. S. Ünlü, "Subsurface microscopy of integrated circuits with angular spectrum and polarization control," *Opt. Lett.*, vol. 34, p. 1261, April 2009.

[6] S. B. Ippolito, B. B. Goldberg, and M. S. Ünlü, "Theoretical analysis of numerical aperture increasing lens microscopy," *J. of Appl. Phys.*, vol. 97, p. 053105, 2005.

[7] B. Richards and E. Wolf, "Electromagnetic diffraction in optical systems. ii. structure of the image field in an aplanatic system," *Proc. R. Soc. London A*, vol. 253, p. 358, December 1959.