Focusing Anomalies in the Vicinity of Dielectric Interfaces

F. Hakan Köklü, and M. Selim Ünlü
Department of Electrical and Computer Engineering, Boston University, 8 Saint Mary's Street, Boston, MA

***Abstract*—We investigate the interface effects on high numerical aperture focusing of linearly polarized illumination. Theoretical and experimental demonstration is conducted in subsurface backside microscopy of silicon integrated circuits.**

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 [2], [3], [4]. Focusing under the high NA conditions provided by the NAIL enables us to observe the effects of polarization and dielectric interfaces in the focal region. Enhanced contrast and ellipticity of the focal spot induced by the linearly polarized illumination are common results for this geometry [5], [6], [7]. In this study, we demonstrate that the longitudinal focusing parameters are also different for the directions parallel and perpendicular to the polarization direction in the vicinity of a dielectric interface. We theoretically show that the tightest spot on the interface occurs at two different focusing depths for two orthogonal directions. Experimental results validating the theoretical predictions are exhibited employing confocal microscopy of ICs.

II. Setup

The confocal microscopy setup is a double-path, reflection-mode fiber-optical scanning microscope as shown in Fig. 1. Excitation is done with a fiber coupled laser diode (λ_0=1.3μm) whose output is expanded and collimated to fill the back aperture of the focusing objective (NA=0.26). The same objective collects the reflected light and sends the detected signal through the beam splitter to a second objective which couples the signal into a single mode fiber connected to a detector. A piezo stage forms an image by scanning the sample with the NAIL. The polarization of the excitation is controlled by a half-wave plate.

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 wavelength [8]. 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.

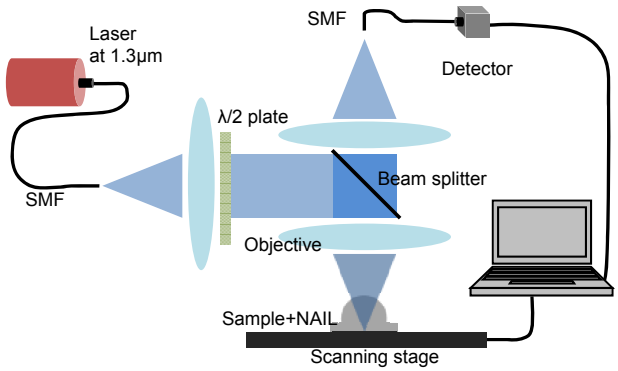

Fig. 1. Experimental setup.

III. Theory

The structures of interest are polysilicon lines that are fabricated on silicon substrate and covered with SiO_2 as insulation layer. Therefore, we calculated the focal fields at the Si-SiO_2 interface using angular spectrum representation (ASR) [9] while changing the longitudinal focus. Fig. 2 depicts the evolution of the full-width-at-half-maximum (FWHM) of the focused field at the interface in two orthogonal directions while changing the focus starting inside silicon and into the SiO_2. It is clear that the tightest focus on the interface happens at two different longitudinal focuses for two directions. This means that to be able to get the sharpest image of an edge using linearly polarized illumination, we have to adjust both the polarization direction of the illumination and the focus of the microscope. We calculated the line spread functions (LSF) for the tightest focusing conditions for comparison with the experimental results. For the tightest focus in the polarization direction, the FWHM of the LSF is 250nm. At this focus, the FWHM of the LSF in the perpendicular direction is 260nm. On the other hand, for the tightest focus in the direction perpendicular to the polarization direction, the FWHM of the LSF is 225nm whereas in the polarization direction it is 300nm.

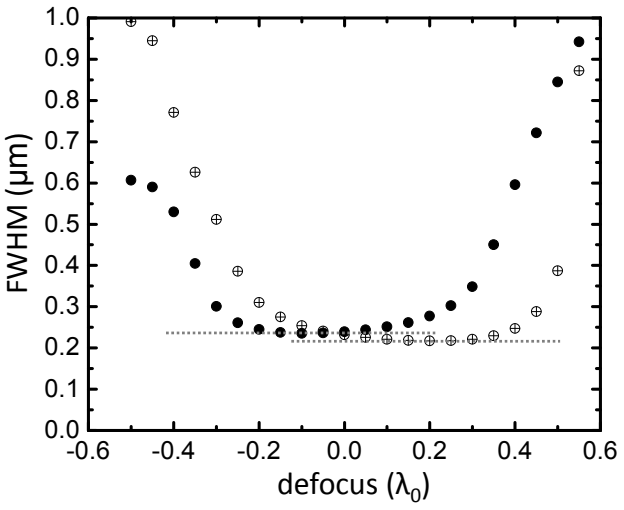

Fig. 2. FWHM calculations under changing focus. Solid dots correspond to the FWHM values of the focused field at the interface in the direction parallel to the polarization. Crossed dots correspond to the FWHM values in the direction perpendicular to the polarization.

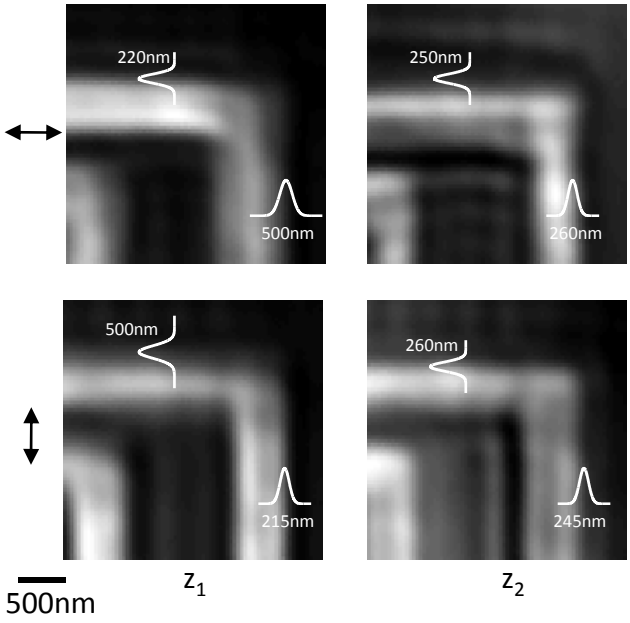

Fig. 3. Images recorded for the two longitudinal focus values of z1 and z2 which gives the best edge responses in directions perpendicular and parallel to the polarization direction, respectively. Arrows indicate the direction of polarization.

IV. Experiment

The imaging is conducted on the L-shaped polysilicon structures located at the Si-SiO_2 interface in the first layer of the IC. The L-shape allowed us to characterize the imaging performance in two directions at the same time. The 600nm width of the structures is small enough to interpret the images visually and big enough to record edge responses and extract the LSFs. We took a series of images of the same area for two orthogonal polarization directions changing the focus of the microscope using the stage. Fig. 3 shows the images that have the best vertical and horizontal edge responses for two polarizations. Upper images are taken with horizontal polarization and lower images with vertical polarization. The FWHM of the measured LSFs are indicated on the images for the corresponding edges. Similar results for both polarization directions show that we were able to avoid local structural variations. For the best edge responses in the direction perpendicular to the polarization, we recorded FWHMs of 220nm and 215nm which are very close to the calculated value of 225nm. At this focus, measured FWHMs in the other direction are 500nm. This is relatively far from the calculated value of 300nm. However, in the best edge responses in the direction parallel to the polarization, we recorded a FWHM of 260nm and the calculated value is 250nm. In the other direction, recorded values are 245nm and 250nm whereas the calculated value is 260nm. This is not a large error considering the relatively small contrast of these edges as shown in the lower right image in Fig. 3.

V. Conclusions

In this study, we are showing that under high NA linearly polarized illumination, there is not a single longitudinal focus that results in the sharpest image in every direction in a layered sample. Depending on the layout of the structures of interest with respect to the polarization direction, best edge responses are acquired at different focus parameters. The dielectric interface redistributes the illumination so that the point spread function no longer has a set narrow width in all direction at one longitudinal focus as it is for a homogeneous medium. These findings should be considered interpreting the imaging of integrated circuits.

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