Subsurface Microscopy of Integrated Circuits with Apodization and Polarization Control

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***Abstract*— We demonstrate a lateral spatial resolution of 160nm ($\lambda_0/8$) using apodization in subsurface backside microscopy of silicon integrated circuits - a record resolution for one-photon excitation schemes.**

I. Introduction

Development and implementation of optical methods for defect detection and imaging of silicon integrated circuits (IC) have been crucial for analysis and advancement of microelectronics [1], [2], [3]. Optical inspection through the backside of the silicon substrate is often necessary because opaque interconnect metal layers hinder frontside optical microscopy. Optical analysis of ICs is accomplished by either excitation of circuit elements or collection of emission and scattering from the circuit at wavelengths greater than 1μm, where the silicon substrate is relatively transparent, with a refractive index $\sim$3.5. Optical excitation usually employs a confocal laser scanning microscope to simultaneously acquire electrical response and confocal reflection images. The spot size of the focused excitation beam determines the lateral spatial resolution of both electrical response and confocal reflection images. It is theoretically shown that apodization of the incoming light can be used to reduce the spot size [4]. At high numerical apertures, polarization of the incoming light also affects the fields in the focal volume, resulting in an elliptical focal spot, which provides different resolutions in different directions [5]. Recently, this effect is observed at IC imaging using numerical aperture increasing lens (NAIL) microscopy [2], [6]. Here, we experimentally demonstrate that apodizing the incoming beam improves the spatial resolution significantly while preserving the effect of polarization. Using a confocal microscope with a NAIL, we achieve polarization dependent spatial resolutions of from 160nm to 200nm through apodization of the incoming beam, improved from spatial resolutions of from 210nm to 260nm when there is no apodization at λ_0=1.3μm. Our calculations show that there is more room to improve the resolution using stronger apodization without getting pronounced side lobes in the point spread function (PSF). Together with its contribution to longitudinal imaging [7], apodization seems to be a powerful and simple technique for optical inspection of ICs.

II. Experiment

The confocal microscopy setup is a single-path, reflection-mode fiber-optical scanning microscope utilizing a single mode fiber coupled laser diode (λ_0=1.3μm) and a 2x2 optical coupler instead of a beamsplitter. For coupling in and out of the single mode fiber, we use a collimating objective with matching NA and a second objective with NA = 0.26 is used for illumination and collection. A piezo stage forms an image by scanning the sample with the NAIL. The polarization is rotated by a half-wave plate located before the imaging objective. The apodization is done by blocking the center of the optical path in front of the imaging objective. The degree of apodization can be potentially changed by moving the beam block up and down.

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.

III. Results

We imaged passive structures located in the poly1 layer which are designed for microscope calibration. To characterize the effect of apodization and polarization, we took linecuts first without apodization while rotating the polarization with 10 degree increments using a half-wave plate. Fig. 1(a) and (b) shows sample linecuts taken when the incoming light polarization is parallel and perpendicular to the edge, respectively. The linecuts are fit to an error function and the PSFs are extracted. In Fig. 1(c), the spatial resolutions measured at different polarization angles are plotted. The spatial resolutions are averaged over an edge to avoid drawing conclusions due to local structural defects and error bars show the standard deviation. The solid curve in Fig. 1 is the fit to the data and the fitting function is the distance between two parallel tangentials of an ellipse. The measurements imply that the resolution changes in the range from 210nm to 260nm depending on the polarization direction.

We imaged the same structures while a circular stop is blocking the center of the beam. It blocks a circular area with an effective 3.8mm diameter of the 10.4mm wide light beam as illustrated in Fig. 2. Similar to the nonapodized case, sample linescans and resolution measurements are displayed in Fig. 2. The measurements show a resolution range from 160nm to 200nm ($\sim \lambda_0/8 - \lambda_0/6$).

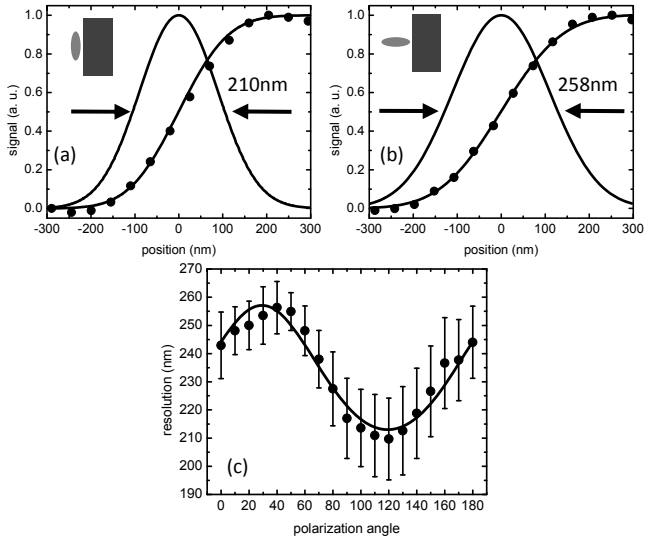

Fig. 1. Resolution measurements without apodization. (a) Linecut data, error function fit and PSF are shown for parallel polarization direction. (b) Same as (a) when the polarization direction is 90° rotated. (c) Resolution is measured while rotating the polarization direction from 0 to 180°.

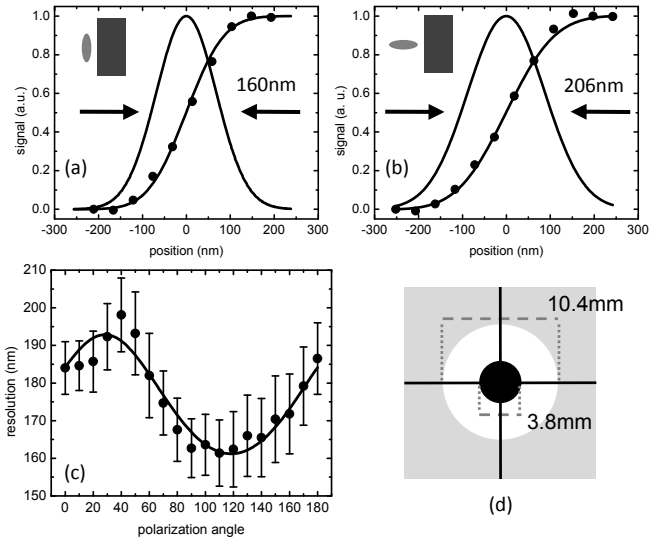

Fig. 2. Resolution measurements with apodization. (a) Linecut data, error function fit and PSF are shown for parallel polarization direction. (b) Same as (a) when the polarization direction is 90° rotated. (c) Resolution is measured while rotating the polarization direction from 0 to 180°. (d) Apodization geometry.

We imaged the smallest calibration structure in order to observe the effect of apodization and polarization on the image quality. Fig. 3(a) shows an image taken without apodization. The linewidths of this structure are 350nm. The polarization direction is horizontal as indicated by the arrow. Fig. 3(b) and (c) show images of the same structure with apodization at different polarization directions. Horizontal lines are much clearer in Fig. 3 as expected. The effect of polarization is not as pronounced in the vertical lines due to drift problems of horizontal scanning direction.

We conducted theoretical calculations of focal fields using angular spectrum representation [5]. Our calculations show

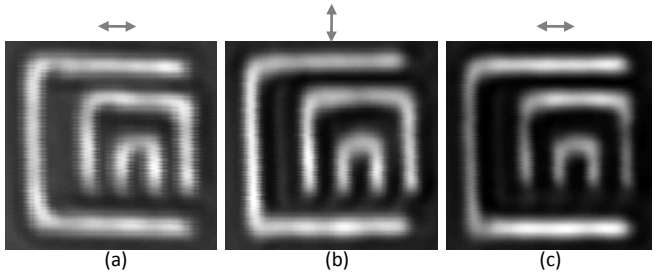

Fig. 3. Arrows show the polarization direction. Linewidths are 350nm. (a) Image taken without using apodization. (b)(c) Images taken using apodization.

that full width half maximum (FWHM) value of PSF changes depending on polarization from 210nm to 230nm for the case without apodization. For apodized setup, we calculated FWHM values in the range of from 160nm to 210nm. The calculations for the apodized case agree well with our experimental measurements of from 160nm to 200nm. There is a slight disagreement for the nonapodized case which can be attributed to NAIL - substrate contact problems since in this case light is passing thorough a larger contact area than apodized case. For stronger apodizations, we have calculated that the FWHM of PSF can be improved down to 120nm in the direction perpendicular to polarization direction. The FWHM in the polarization direction increases for stronger apodizations due to longitudinal component of the focal field.

IV. Conclusions

We demonstrated a record lateral spatial resolution for one-photon excitation schemes by apodizing the excitation and collection path. We achieved a lateral spatial resolution of 160nm ($\sim \lambda_0/8$) in the perpendicular direction to the polarization direction of the incoming light. Our calculations show that resolutions down to 120nm are achievable with stronger apodization. The technique presented here is expected to make significant improvements in other optical inspection methods employing optical excitation.

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