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Two-photon laser-assisted device alteration in CMOS integrated circuits using linearly, circularly and radially polarized light

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The rapidly developing semiconductor industry demands constant innovations in optoelectronic imaging of semiconductor integrated circuits to keep up with continuing device scaling. It was recently shown that two-photon laser-assisted device alteration (2pLADA) can deliver precision fault isolation. Here we describe an investigation into the influence of the incident light polarization on the 2pLADA spatial resolution. Linear polarization provides a highly confined but elliptical focal spot, while circular polarization diminishes the lateral resolution but benefits from a symmetrical focal spot. Radially polarized light potentially provides the highest lateral imaging resolution in all directions at the expense of the longitudinal resolution. By comparing 2pLADA results obtained using linear, circular and radial polarizations we show that certain polarizations have advantages in particular applications. Therefore a polarization optimized 2pLADA tool can achieve a sufficiently high performance to isolate faults of transistors separated by as little as 100 nm and maybe smaller.

1. Introduction

The progressive decrease in feature sizes of complementary metal-oxide semiconductor (CMOS) integrated circuits (ICs) means that diagnostic solutions for spatial fault localization within these devices must also be continuously refined to remain relevant for the prevailing technology node. Optical techniques – specifically the laser stimulation of semiconductor devices – encompass a wide variety of failure analysis methodologies such as optical beam-induced resistance change (OBIRCH) [1], resistive inter-connect localization (RIL) [2], soft defect localization (SDL) [3], optical beam-induced current (OBIC) imaging [4] and laser-assisted device alteration (LADA) [5]. As feature sizes diminish, these techniques face an immediate and acute challenge to their ability to provide sufficient spatial resolution, since the wavelength of light inside silicon is typically >300 nm, more than an order of magnitude larger than the current production node [6].

We concentrate here on LADA, which is a well-established imaging/analysis technique used to isolate interaction sites of timing-critical transistors [7]. In its original form, LADA employed a continuous wave (CW) laser and therefore provided no detailed temporal information [8], however we recently showed how this limitation can be overcome by using two-photon absorption (TPA) induced by an infrared femtosecond laser [9]. In this earlier work we demonstrated how TPA, which generates electron–hole pairs within the active CMOS layer, could be synchronized with the internal clock of the device to allow a race condition to reveal speed-limiting transistor-switching evolution with a timing resolution below 10 ps [8].

In this paper we now address how the polarization state of the excitation light in two-photon LADA (2pLADA) influences the outcome of the technique. Previously, it was shown that the optical-beam induced current (OBIC) lateral resolution is significantly enhanced by TPA due to the effective narrowing of the point-spread function (PSF) associated with the nonlinear character of TPA [10]. The resolution achieved in sub-surface CMOS imaging is also considerably enhanced by using a solid-immersion lens (SIL) [11] and the highest resolutions can be achieved by combining TPA with SIL imaging [12]. Under the large values of numerical aperture (NA) associated with SIL microscopy it is known that the polarization state of the incident light plays a significant role in determining the image resolution [13]. The conventionally employed linearly polarized light forms an approximately elliptical

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focal spot [14], extended along the E-field vector of the light, implying that radially-polarized (RP) illumination could be used to further reduce the PSF area, since RP light experiences no equivalent PSF distortion under high-NA focusing [15].

In the following sections we detail the outcomes of 2pLADA imaging using various polarization states. We employed linear, circular and radial polarizations to investigate how 2pLADA imaging resolution depends on the E-field distribution of the incident light. The imaging system employed a liquid-crystal radial polarization converter (RPC) [16,17] to generate a radially polarized beam with a high degree of mode purity, and in a way which allowed easy insertion and removal of the RPC to facilitate direct comparisons between different polarization states of the incident light.

2. Femtosecond laser excitation source

The 2pLADA was stimulated by 1280-nm pulses delivered from a source that used the Raman self-frequency shifting technique in a photonic crystal fiber (PCF) when pumped by a mode-locked ytterbium-doped fiber laser (YDFL), which is shown in Fig. 1 [18]. The YDFL produced 1.3-ps chirped pulses at a nominal repetition frequency of 100 MHz, which could be modified over a range of ~500 Hz by actuating a piezo-electric transducer, on which was mounted one of the intracavity fiber collimators. A fast electronic feedback loop was used to lock the repetition frequency of the laser to an external 100-MHz clock supplied by the tester, while a slow loop which actuated an intracavity motorized-translation stage was used to maintain this lock over many hours in the presence of environmental changes. The laser pulses were compressed to durations of 160 fs by using a pair of Gires–Tournois interferometer mirrors, following which their average power was 350 mW. Next, these de-chirped pulses were coupled with 75% efficiency into a highly nonlinear PCF. The resulting supercontinuum contained chirp-free Raman-soliton pulses at the desired wavelength of 1280 nm, which were then isolated by using a thin-film long-pass filter with a cut-off wavelength of 1200 nm. Finally, the filtered 1280-nm pulses were coupled into a polarization-maintaining delivery fiber, after which they were measured to have durations of 200 fs and an average power of 20 mW (200 pJ).

3. Implementation of the 2pLADA microscope

The experimental arrangement of the 2pLADA microscope is shown in Fig. 2. Femtosecond pulses of 10 pJ energy and 195 GW/cm^2 focal intensity at 1280 nm were delivered from the laser through a 4-m polarization maintaining fiber to a collimation module which presented a beam of diameter 4 mm into the telescope system used before the RPC. The collimation module also contained a beamsplitting cube used for the deflection of the returning laser beam to the detector. Lenses L1 and L2 formed a telescope used to increase the diameter of the beam before the RPC device, whose 20-mm aperture made it necessary to use an expanded beam. A second telescope formed by lenses L3 and L4 then reduced the beam to a diameter matching the aperture of the galvanometer mirrors of the laser-scanning microscope (LSM) module. The LSM employed an integrated silicon SIL objective which provided 350× magnification and NA = 2.45. A scalar calculation of the PSF full-width-half-maximum diameter using the Sparrow criterion for the 2pLADA microscope with 1280 nm incident wavelength and NA = 2.45 provides a resolution of 260 nm, however this value takes no account of the resolution improvement due to the effect of nonlinear absorption.

The device under test (DUT) was a proprietary 28-nm-feature-size bulk silicon test device (V_{DD} = 0.8 V, clock frequency = 50 MHz). The device was engineered to perform a logic operation, which was previously described in [8]. By controlling the supply voltage the fail rate was set to 50% and typically several hundred 2pLADA images of a region of PMOS and NMOS transistors were recorded using a pixel dwell time of 32 µs and an image size of 512 × 512.

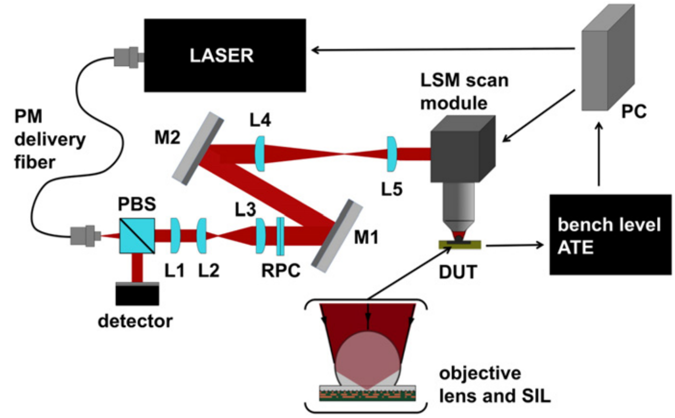

Fig. 2. 2pLADA microscope layout. The beam to the module is delivered using a polarization maintaining fiber, where it enters through a polarizing beam splitter (PBS). The PBS and its associated detector are used for confocal imaging to navigate to the area of interest in the DUT. After this, the beam is collimated using lens L1 and is expanded using lenses L2 and L3 and guided through the RPC device. Mirrors M1 and M2 are used to fold the layout and to deflect the beam into the reducing telescope (L4–L5), which images it onto the galvanometer mirrors of the LSM scan module. The beam is then guided to the 350× silicon SIL microscope objective (NA = 2.45). A half-wave plate (HWP) and a quarter-wave plate (QWP) were used just before the microscope objective to prepare the incident polarization for the imaging experiments.

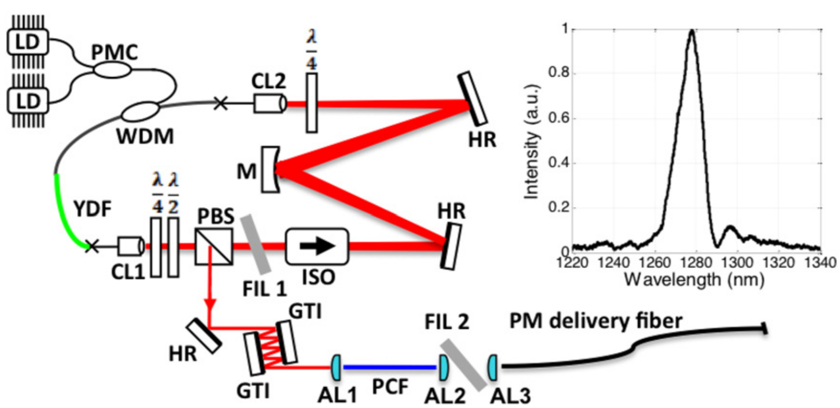

Fig. 1. Schematic of the Raman-soliton laser source. WDM, wavelength-division multiplexer; YDF, ytterbium-doped fiber; CL, collimator; λ/2, half-wave plate; λ/4, quarter-wave plate; ISO, isolator; PBS, polarizing beam splitter; FIL, interference filter; HR, high reflector; M, curved mirror; LD, laser diode; PMC, polarization combiner; GTI, Gires–Tournois interferometer; PCF, photonic crystal fiber; AL1–AL3, aspheric lenses. The laser generated 1280-nm pulses with an average power of 20 mW. Inset: laser spectrum, showing a center wavelength of 1278 nm and a bandwidth of 13 nm.