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Visible Light LVP on Ultra-Thinned Substrates

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***ABSTRACT* — Visible light laser voltage probing (LVP) for improved backside optical spatial resolution is demonstrated on ultra-thinned samples. A prototype system for data acquisition, a method to produce ultra-thinned SOI samples, and LVP signal, imaging, and waveform acquisition are described on early and advanced SOI technology nodes. Spatial resolution and signal comparison with conventional, infrared LVP analysis is discussed.**

INTRODUCTION

Laser Voltage Probing (LVP) is a key backside optical tool for modern failure analysis and real time logic debugging of signals propagating at operational speeds through integrated circuits (ICs). Conventional LVP systems rely on free carrier generation and optical absorption within the channel of CMOS transistors to modulate reflected light intensity. Infrared wavelengths are used to take advantage of silicon's relative transparency for backside probing. The incident light is reflected back, captured, detected, and amplified. The small modulations in reflected intensity resulting from free carrier density changes with electric field are used to determine local transistor logic states as a function of time. This is a powerful tool for failure analysis and device debugging/characterization [1-4] .

With the continual reduction of IC feature sizes, backside, laser-based failure analysis tools are limited in spatial resolution by the refraction limits of light and the relatively long wavelengths required for through-silicon probing. Even with state of the art Solid Immersion Lenses (SILs), modern 22 nm devices are at and past the limit of practical resolution.

To address this spatial resolution limit, we developed and demonstrate here the effectiveness of applying LVP with shorter, visible wavelengths. This is accomplished using backside ultra-thinning of Silicon on Insulator (SOI) devices. The devices are thinned sufficiently that shorter, visible wavelengths can be used for LVP analysis, thus enabling better spatial resolution and enhanced LVP signals.

SYSTEM AND SAMPLE DESCRIPTION

We demonstrate LVP using visible light (633-640 nm) on locally ultra-thinned regions within SOI devices. Creation of an improved resolution reflected light image from the backside through die thinning and shorter wavelength light has been accomplished previously [2]. Our present work goes further by using advanced deprocessing techniques to ultra-thin localized areas on SOI devices to achieve a packaged, functionality-maintained IC. These techniques include, gas-assisted Focused Ion Beam (FIB) and XeF_2 etching.

A modified LSM 310 scanning laser microscope was used to demonstrate LVP using visible light. In order to effectively probe the transistor, a high gain, low noise Avalanche Photodiode (APD) is used as the detector of the LVP signal (Figure 1).

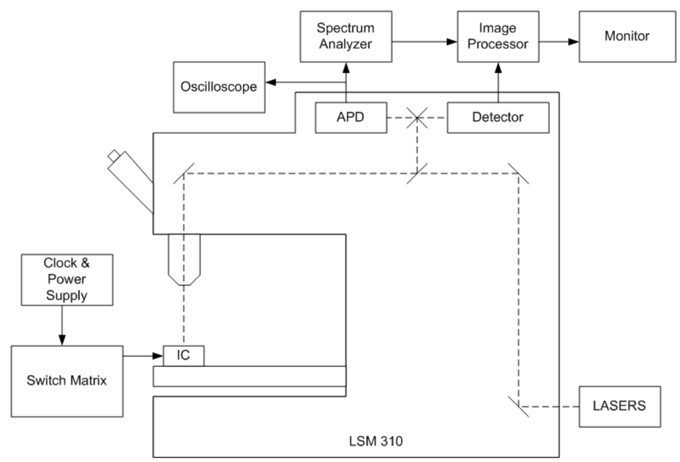

Figure 1: Schematic diagram of a modified LSM 310 with an APD detector and multiple wavelength sources for visible light LVP analysis.

MOTIVATION AND BACKGROUND

Ultra-thinning and visible light microscopy significantly enhances the resolution that can be achieved when using an air gap lens. This can be further enhanced to be roughly comparable with advanced solid immersion microscopy when oil immersion microscopy is incorporated.

$$D = \frac{0.61\lambda}{NA} \tag{1}$$

Equation 1 equates the minimum resolution limit of two points, D, to wavelength, λ, and numerical aperture, NA, of the microscope objective. As shown in Table 1 below, an oil immersion lens using visible light to image ultra-thinned silicon will render ballpark resolution performance to state of the art solid immersion lenses imaging through bulk samples using infrared light.

Table 1

Lens Type	λ (nm)	NA	D (nm)
3.0 SIL	1340	3.0	272
	1064	3.0	216
1.4 Oil	633	1.4	276
	532	1.4	232
Air Gap	633	0.9	429
	532	0.9	361

While these resolution enhancements do not surpass a state of the art SIL, they do provide an alternative when SILs are not an option. This technique gives significant enhancements, to those working on SOI samples with thick Buried Oxide (BOX) layers which can be ineffective for use with SILs. It also gives another option to failure analysts that are not equipped with state of the art imaging technology, but may find it plausible to ultra-thin devices. For SOI devices, this technique also appears to enhance the sensitivity of the LVP signal. This is likely accomplished in a twofold manner. First, by reducing the loss factors which occur when probing through many microns on thick samples, and second, by taking advantage of the better silicon based detectors which can be used in the visible light region [5].

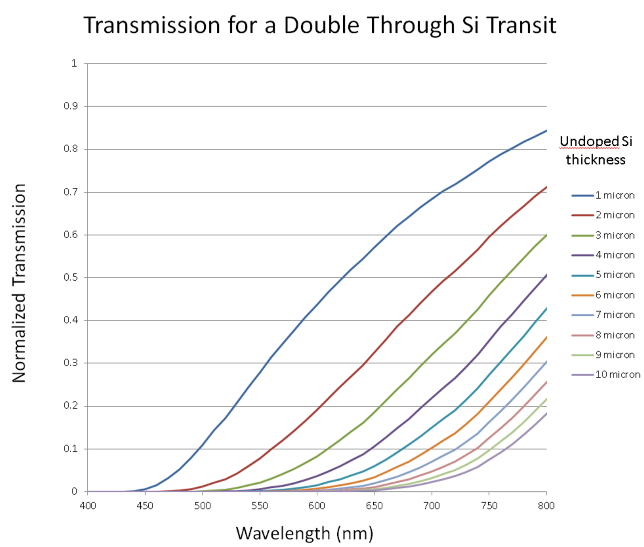

Figure 2: Round-trip transmission of visible light through different thicknesses of undoped silicon. Data to create the curves was from [6].

Visible light loss through doped silicon is high. Despite high losses, adequately thinned silicon, even at visible wavelengths, provides sufficient reflected light to create an image and capture an LVP signal. The extent to which the silicon must be thinned is shown in Figure 2. In all cases where the substrate is doped, losses will be higher. Heavily doped silicon will create substantially higher losses.

The examples shown in this paper are for SOI technologies. Demonstration of the approach on bulk silicon devices will be the subject of future work.

EXAMPLE RESULTS

Example 1: 350 nm SOI

As a proof of concept, an SOI device was prepared with a region of interest consisting of a buffer amplifier (Figure 3) on a 350 nm technology operating at 3.3 V. The deprocessing consisted of backside silicon FIB removal in the region of interest. FIB milling stopped shortly before the BOX layer. The remaining residual silicon was removed by etch gasses resulting in a clean, glass-like viewport to the areas of interest.

A conventional, backside, 1320 nm LVP system was used to show functionality of the buffer as well as derive an understanding of the overall LVP signal for a given intensity laser.

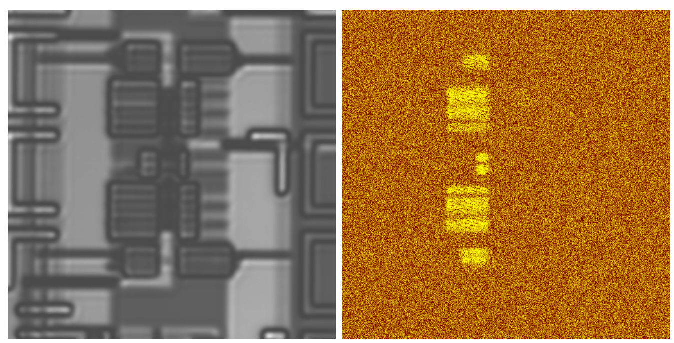

Figure 3: Reflected light image of the buffer on a traditional LVP system using 1320 nm light to create the reflected light image and the 1 MHz frequency map.

The visible light used to do LVP probing was a 5 mW, 633 nm HeNe laser, with approximately 100 µW of power on the sample. The buffer amplifier was clocked with a square wave, the output of the detector amplified, and the signal observed using a spectrum analyzer (Agilent EXA N9010A). When spotting the laser on the probe site, the primary harmonic from the amplifier is seen in the spectrum analyzer at roughly 15 dBm above the noise floor (Figure 4).

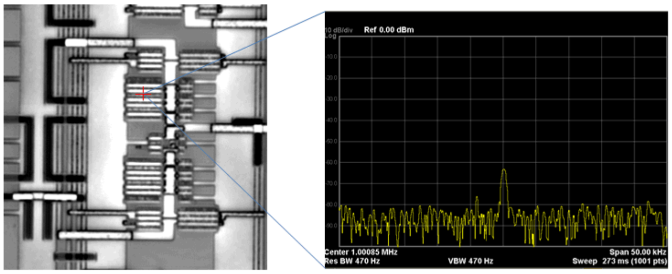

Figure 4: (Left image) Backside, 633 nm, reflected light image of a buffer amplifier clocked at roughly 1 MHz. When a 633 nm laser is pointed at the transistor (red cross) and the reflected light captured by the APD, the LVP signal is indicated by a spectral peak at the clocked frequency (right image).

Figure 5 illustrates Laser Voltage Imaging (LVI) [3] of the clocked buffer amplifier. This is done by setting the spectrum analyzer to a zero span at the frequency of the observed peak (1MHz). The analyzer's video output is used to modulate the image contrast as the 633 nm laser is scanned across the device. In this example the frequency map is slightly offset due to the scan speed and latencies within the spectrum analyzer. This is similar to conventional LVI, but shown here to work at a visible wavelength.

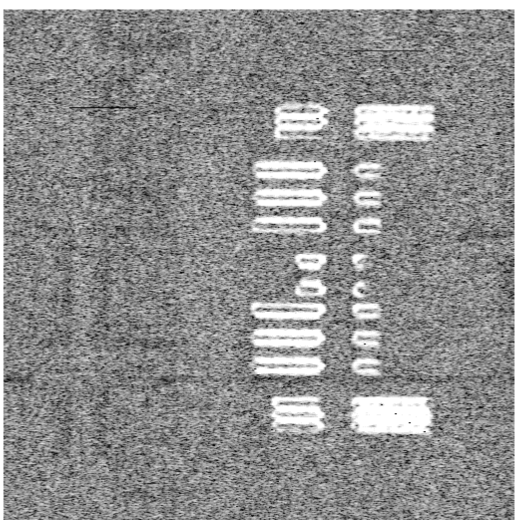

Figure 5: When the buffer amplifier is scanned with the 633 nm laser, the reflected light is collected by the APD and the resulting signal fed into the spectrum analyzer zero spanned at the clock frequency. The video out option from the spectrum analyzer can then be used to create a frequency map or LVI image of the buffer, highlighting operation at the clock frequency.

Figure 6 demonstrates that by spotting the laser at the clocked buffer amplifer, a waveform of the amplifier's logic state with time can be acquired. For this example the output of the amplifed APD signal is displayed directly with averaging on an oscilloscope.

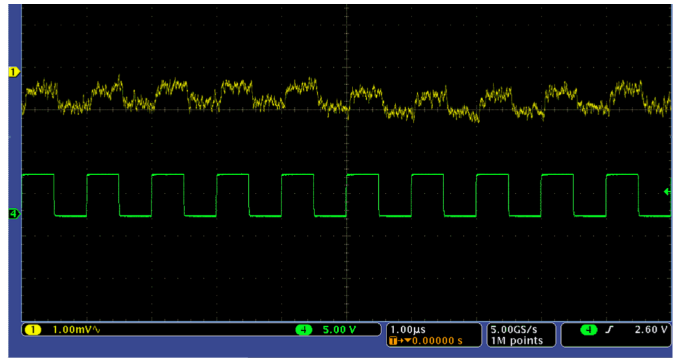

Figure 6: By spotting the laser on the buffer (red cross in Figure 4), the output of the APD can be averaged to show the clocked waveform. The yellow waveform is the averaged, clocked APD signal. The green waveform is the trigger from the clock.

In subsequent examples we demonstrate the possibility of visible light LVP on advanced SOI technology nodes.

Example 2: 45 nm SOI

To further show the extent to which this technique is useful, we demonstrate ultra-thinned LVP on a more recent, 45 nm SOI technology. In this case, the region of interest, a simple test inverter, was thinned using a XeF_2 etch that stopped on the BOX layer. Once this occurred, the region of interest was viewable through the glass-like BOX region with visible wavelengths. This test inverter was clocked using an external function generator at 1 MHz. The inverter LVI and LVP signals were then tested on a conventional 1320 nm LVP system with a 50x objective and 5 mW probe power. The reflected light image and corresponding LVI image is shown in

Figure 7.

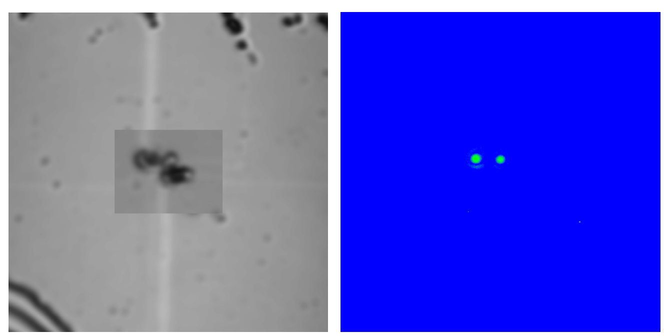

Figure 7: Reflected light image and corresponding LVI image of a 45 nm inverter using a 1320 nm conventional LVP and 50x objective.

This sample was then tested on the visible light LVP system with a 50x objective (

Figure 8) and a 63x 1.4 NA oil immersion lens (

Figure **9**). The laser probe power though the 50x lens was 100 µW and 150 µW for the immersion lens.

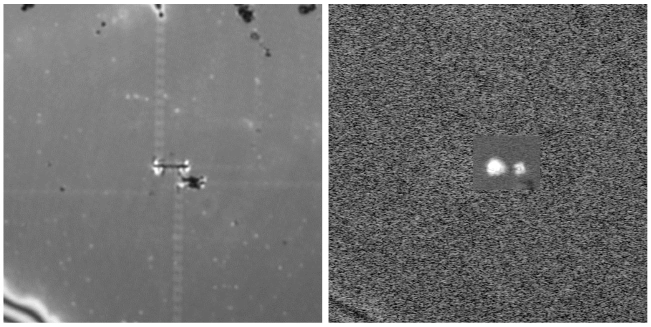

Figure 8: Reflected light image and corresponding LVI image of a 45 nm inverter using a 633 nm laser and 50x objective on a visible light system.

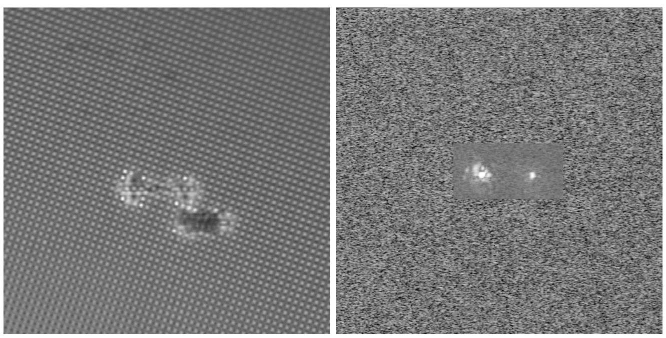

Figure 9: Enhanced resolution of the reflected light image and corresponding LVI map using a 63x 1.4 NA oil immersion lens.

Not only does the oil immersion lens improve the resolution, it drastically improves the locality of the frequency map and consequently enhances the intensity of the LVP signal. This is most easily seen by examining the plot in Figure 10 which shows LVP spectral signals for a 50x, 633 nm laser and the 63x oil immersion, 633 nm LVP signal. The difference in laser irradiance delivered to the inverter is difficult to determine when oil is used as a coupling medium. However, as shown in
Figure **10**, the difference in LVP signal from the same region of interest increases by more than10 dBm.

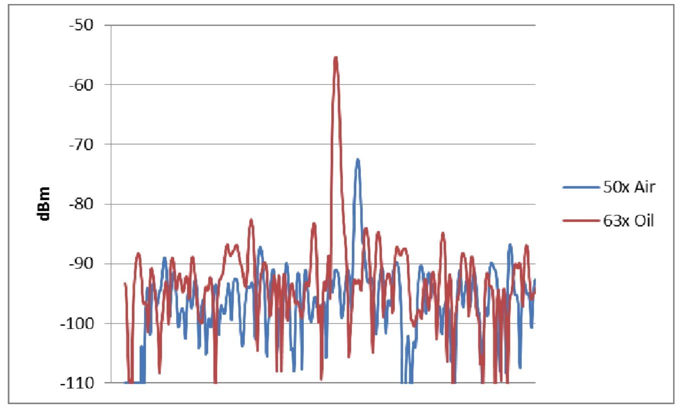

Figure 10: Two spectral peaks that represent the LVP signal from Figure 8 and Figure 9 in the frequency domain. The peaks are offset from their true frequency to illustrate the difference in signal strength between a 50x 0.5 NA air gap objective and a 63x 1.4 NA oil immersion objective. In each case, the 633 nm probe laser was pointed in the same region of LVP signal activity.

Using the 63x oil immersion objective, the frequency map from Figure 9 was used as an aide in probing the inverter. The output of the inverter, LVP waveform, and clock sync are shown in Figure 11.

Of note is the degraded waveform from the inverter. In this case it is to be expected due to the excessive loading placed on the small inverter as it drives the scope at 1 MHz.

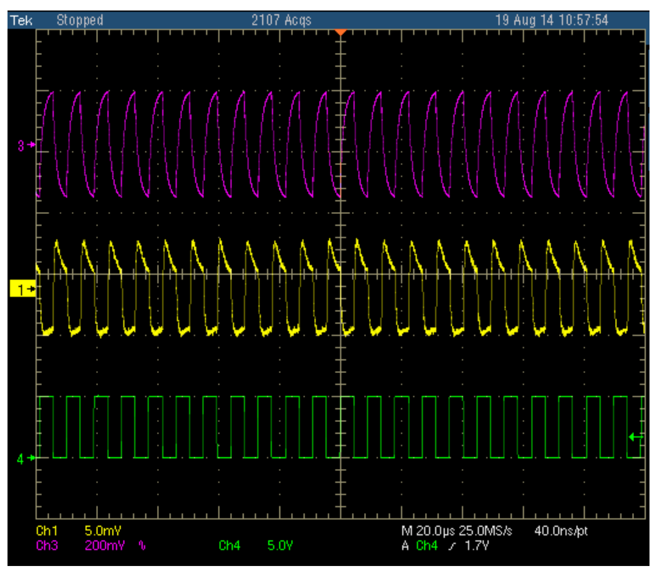

Figure 11: A waveform capture from probing an active area shown in Figure 9. The top (magenta) waveform is the output of the inverter. The middle waveform (yellow) is the from the LVP signal. The bottom waveform is from the clock sync driving the inverter.

SUMMARY

The motivation for improved spatial resolution of LVP analyses, a means to achieve improvement by the use of shorter wavelength illumination on ultra-thinned samples, a prototype system to analyze such devices, and examples of using the visible light LVP system on SOI have been described. We demonstrate this method on advanced technology node SOI devices, comparing the spatial resolution and LVP signals achieved at visible wavelength with a conventional, infrared LVP system.

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