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Semiconductor inspection using the CRONUS-2P laser

In our increasingly connected and electrified society, there is a steady push to develop smaller devices operating at higher frequencies while consuming less power. Additionally, the rise of e-mobility requires compact yet high-capacity energy storage in batteries. This necessity has made the characterization and inspection of materials and devices essential in the electronics industry.

Figure 1: Schematic of the setup: Laser beams from the Light Conversion's CRONUS-2P femtosecond laser enter the MONSTR Sense Technologies' ultrafast microscope, composed of a BIGFOOT® and NESSIE® system. Within MONSTR Sense's ultrafast microscope, pump and probe pulses are generated and raster-scanned across the sample using a combination of Galvo and wafer-stage scanning.

In R&D, an accurate characterization of materials is crucial to determine their applications, validate theoretical models, and evaluate processes. As the manufacturing of these materials expands, in-line inspection tools are necessary for ensuring process consistency and identifying sources of device failures. Inspection plays a critical role in today's semiconductor manufacturing, as this industry impacts our daily lives through phones, cars, trains, data centers, and energy grids. Characterizing finished devices is also essential for ensuring the delivery of reliable and compliant products.

All-optical techniques present compelling advantages: they are non-invasive, contactless, and offer sub-micron spatial resolution. The former feature strikes a balance between high spatial resolution and the ability to conduct wafer-scale measurements. Among optical techniques, non-linear processes provide additional advantages, but require lasers producing femtosecond pulses at adjustable wavelengths.

Here, we discuss the application of Light Conversion's CRONUS-2P femtosecond laser for pump-probe imaging of wafers and devices using the ultrafast microscope developed and commercialized by MONSTR Sense Technologies. The microscope consists of two systems, named BIGFOOT® and NESSIE®, and uses nonlinear and ultrafast imaging to detect defects in raw materials and devices.

Four-wave mixing imaging - a novel inspection technique

In pump-probe imaging, as depicted in Fig. 1, a pulsed laser (typically femtosecond) is split into two or more pulses. The "pump" pulse impinges on the sample to excite a resonance. The absorption of this pump pulse, in turn, affects the material's reflectance of a second pulse, referred to as the "probe". Generally, the wavelengths of the pump and probe beams require adjustment to match the energy level configuration of the sample. If both the pump and probe beams have the same wavelength, the measurement is termed "degenerate pump-probe"; otherwise, it is referred to as "two-color" pump-probe.

MONSTR Sense Technologies' pump-probe imaging method measures background-free changes in probe reflectivity. This approach offers the advantage of detecting alterations in the band structure caused by factors like strain, doping, or a defect state, which significantly affect the probe's reflectance. Consequently, the pump-probe image serves as a sensitive tool for defect detection.

Degenerate pump-probe imaging for semiconductor nanostructures at the wafer scale

Optically active semiconductor nanostructures play a pivotal role in numerous devices. For instance, quantum dots drive innovation in many modern displays, while quantum wells are used in laser diodes due to their high emission efficiency and adaptability. Instead of altering the material, the diodes can be easily tuned by adjusting the size of the active region. These features have made quantum-well lasers indispensable in fiber optic communication, serving as a core component of the internet infrastructure.

Optical inspection of these nanostructures relies on detecting subtle changes in their band structure, which serve as critical indicators of defect states. MONSTR Sense's highly sensitive pump-probe imaging technique is optimized for capturing these changes when resonantly tuned to the electronic states within the material. Employing Light Conversion's CRONUS-2P femtosecond laser, which offers wavelength tunability, allows precise resonance with the electronic states of various semiconductor nanostructures. In this instance, we are utilizing the same wavelength for both the pump and probe beams.

Fig. 2(a) presents measurements of a 2" semiconductor wafer containing four gallium arsenide (GaAs) quantum wells with aluminum GaAs (AlGaAs) barriers. The fringes on the image stem from width changes in the quantum well and substrate thickness, leading to interference Fabry-Perot effects. Notably, many areas of the quantum well exhibit increased brightness in the overview scan. Fig. 2(b) highlights a selection of specific defects of interest on this wafer.

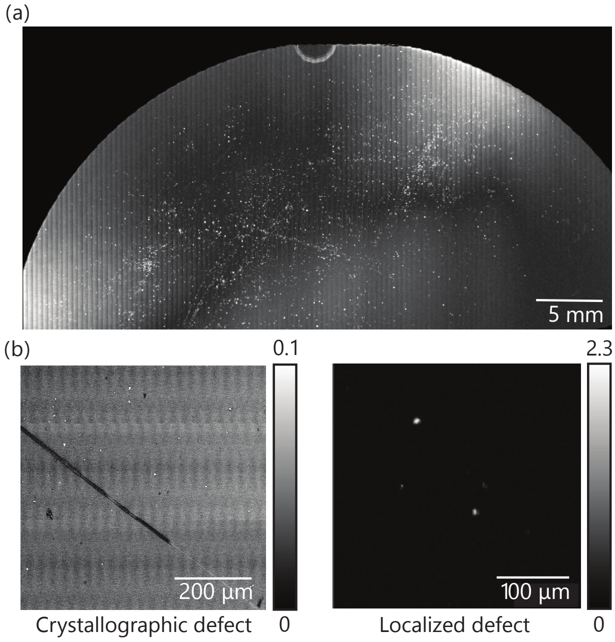

Figure 2: (a) Pump-probe image of a 2" GaAs multiple quantum well wafer. (b) Highlighted defects across the wafer.

Due to the background-free approach of MONSTR Sense's pump-probe imaging, these defects stand out better in the pump-probe image compared to linear reflectance measurements. Crystallographic defects may appear as dark and bright lines, depending on their effects on the band structure. The localized defects are particularly intriguing to observe as the localized states generate a significantly brighter nonlinear signal than the rest of the wafer.

Two-color pump-probe imaging for micro-OLED characterization

The two-color pump-probe technique proves beneficial in several areas, including stimulated Raman spectroscopy (SRS), probing energetic transitions, and examining coupling between different energetic transitions. The broad appeal of two-color pump-probe stems from its background-free detection, leading to

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diverse applications like melanoma detection and analyzing pigments in historical art. With its two independently tunable outputs, the CRONUS-2P femtosecond laser offers a broad range of pump and probe wavelength combinations across the ultra-violet, visible, and near-infrared ranges. MONSTR Sense tools are designed to function with either a two-color pump and probe pulse or a degenerate pump and probe pulse.

New potential in inspection of 2D materials

Two-dimensional materials, particularly transition metal dichalcogenides (TMDs), have gathered substantial interest due to their strong absorption and emission properties, promising various device applications. While developers aim for more scalable

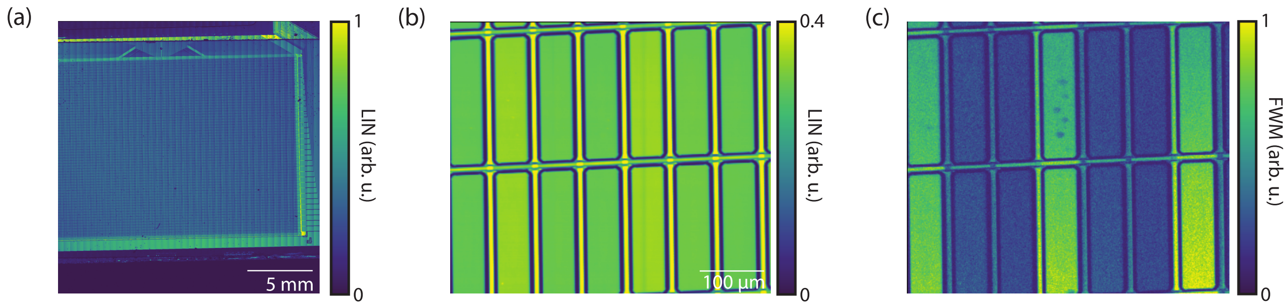

Figure 3: (a) Overview of the micro organic-LED display using linear reflectance at 850 nm. (b) Linear reflectance at 850 nm, zoomed in on a few pixels (c) Pump-probe imaging using a pump wavelength at 580 nm and probe wavelength at 850 nm.

By doubling the near-infrared output of the CRONUS-2P femtosecond laser to a visible wavelength (580 nm) for the pump beam and probing at 850 nm, we successfully captured images of defect states in micro-organic LED (micro-OLED) displays, as shown in Fig. 3. The swift spread of micro-LED displays, particularly in augmented and virtual reality applications, has demanded higher pixel densities. This poses a challenge for conventional physical probing methods assessing pixel functionality as LED pixels decrease in size. Pump-probe imaging, however, achieves sub-micron resolutions without the need for physical probes.

Figure 3(a) presents a linear reflectance overview of a micro-OLED display with 96x64 pixels at 850 nm. Upon closer examination, differences in contrast between linear reflectance and pump-probe imaging (Fig. 3(b) and (c)) become apparent. While linear reflectance shows subtle contrast between two adjacent pixels and a third one, pump-probe imaging depicts a much stronger signal in every third pixel, indicating increased absorption near the 580 nm pump wavelength. Additionally, light-induced defects that appear as dark spots in the pump-probe image, are undetectable in linear reflectance.

growth, ongoing fundamental research focuses on smaller exfoliated samples. Techniques like spontaneous Raman and PL spectroscopy, effective for smaller samples, encounter scaling challenges with larger samples. In Fig. 4, we present a pump-probe (Fig. 4(a)) image of a few-layer $MoSe_2$ sample on a sapphire substrate. Although the sample is roughly a million times smaller than the substrate, numerous flakes of $MoSe_2$ with varying layer-number are present in the vicinity. MONSTR Sense's pump-probe imaging aids researchers in quickly locating the sample via an overview scan and enables scalability according to the sample's size. The CRONUS-2P femtosecond laser's robust power and beam-pointing stability facilitate larger, reproducible overview scans, while its tunability caters to researchers' material preferences.

Upon identifying the flakes, an in-depth analysis of their physical properties becomes feasible through MONSTR Sense's ultrafast microscope [1,2]. An example of such detailed characterization is presented in Fig. 4(b), displaying a decay time map of the sample encompassing monolayer, bilayer, and quad-layer regions. The distinctive regions are identifiable based on their decay times. Furthermore,

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aside from distinguishing the number of material layers, differences in decay times within a fixed layer region can indicate material degradation due to strain, doping, or defects.

Summary

This paper provides an overview of the robust capabilities offered by MONSTR Sense Technologies' ultrafast pump-probe microscope combined with Light Conversion's highly tunable CRONUS-2P femtosecond laser. The three highlighted samples - GaAs quantum well wafer, micro-OLED display, and TMDs – merely represent a fraction of the samples suitable for analysis using this tool. The method's high sensitivity to defect states and strain, its sub-micron spatial resolution, and increased signal strength compared to alternative inspection techniques (PL, Raman) position it as an indispensable method for the mentioned and other emerging applications.

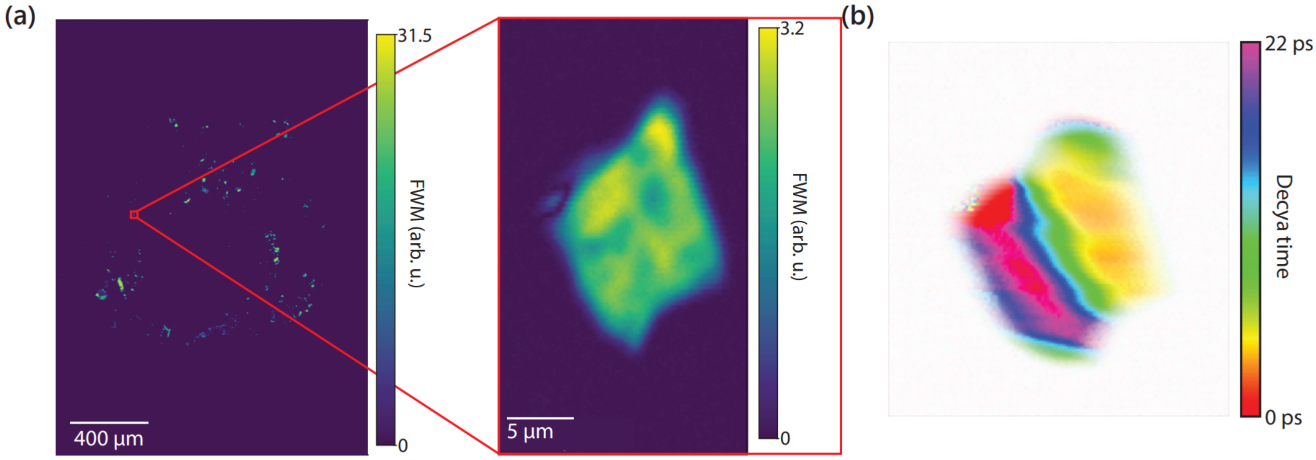

Figure 4: (a) Pump-probe image of a $MoSe_2$ mono to quad-layer on a sapphire substrate. The zoomed-in image highlights the combination of large field-of-view and high spatial resolution of MONSTR Sense's ultrafast microscope. (b) Decay time map of the multilayer sample.

References

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[2] Torben L. Purz, Blake T. Hipsley, Eric W. Martin, Ronald Ulbricht, and Steven T. Cundiff. "Rapid multiplex ultrafast nonlinear microscopy for material characterization." Opt. Express 30. (25), 45008–45019 (Dec. 2022). DOI:10.1364/OE.472054.