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Note: High speed optical profiler based on a phase-shifting technique using frequency-scanning lasers

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We present a high speed optical profiler (HSOP) using frequency-scanning lasers for three-dimensional profile measurements of microscopic structures. To improve upon previous techniques for implementing the HSOP, we developed frequency-scanning lasers and a compact microscopic interferometer. The controller of the HSOP was also modified to generate proper phase-shifting steps. For measurements of step height specimens, the HSOP showed results comparable with a commercial optical profiler, even with much higher measurement speeds (up to 30 Hz). The typical repeatability of step height measurement was less than 1 nm. We also present measurements of microscopic structures to verify the HSOP's ability to perform high speed inline inspection for the semiconductor and flat-panel display industries. © *2011 American Institute of Physics*. [doi:10.1063/1.3623501]

Currently, as manufacturing tolerances decrease in the semiconductor and flat-panel display industries, three-dimensional (3D) profile measurements of microscopic structures, such as wafer bumps and column spacers, are becoming more important. Areas of inspection are also increasing. Therefore, high speed 3D profile measurements are required in these fields. Various optical techniques have been developed for 3D profile metrology, such as phase-shifting interferometry (PSI), white light scanning interferometry, and confocal microscopy.[1–3] The strengths and weaknesses of each technique have been well analyzed.[4,5] A two-wavelength PSI utilizing an injection-locking technique has been proposed to overcome the limits to measurement speed by eliminating mechanical phase shifting.[5] In this paper, a new high speed optical profiler (HSOP), which was developed by modifying and improving previous techniques, is presented.

The operating principle of the HSOP is based on two-wavelength PSI using frequency-scanning lasers.[4,5] The scanning laser enables high speed phase shifting with very high stability and small phase step error because its frequency is injection-locked to the resonant modes of a confocal Fabry–Perot cavity (CFPC). When the optical path difference (OPD) related to the profile of a specimen is measured using each laser source of the HSOP, the phase ϕ_i $(i = 1, 2)$ can be expressed as

$$\phi_i = \frac{2\pi}{\lambda_i}\mathrm{OPD}, \tag{1}$$

where $\lambda_i(\lambda_1 < \lambda_2)$ is the wavelength of each laser source. From Eq. (1), the equivalent phase $\phi_{\mathrm{eq}}(= \phi_1 - \phi_2)$ for the equivalent wavelength $\lambda_{\mathrm{eq}}(= \lambda_1\lambda_2/(\lambda_2 - \lambda_1))$ can be obtained as

$$\phi_{\mathrm{eq}} = \frac{2\pi}{\lambda_{\mathrm{eq}}}\mathrm{OPD}. \tag{2}$$

To measure a profile using the HSOP without a 2π ambiguity, the phase difference between two adjacent pixels should exist within the range of $\pm\pi$ and determines the measurable range of the HSOP. If the wavelengths of the two lasers are slightly different, the equivalent wavelength becomes much longer than the wavelength of each laser source, and the measurable range of the HSOP, which corresponds to half of the measurable OPD in the case of a single pass interferometer, can be extended to $\lambda_{\mathrm{eq}}/2$. However, when using the equivalent wavelength, the measurement error of the OPD is also amplified by a factor of $\lambda_{\mathrm{eq}}/\lambda_i$, if the same amount of phase measurement error occurs. Therefore, to increase the measurable range without sacrificing accuracy, the equivalent phase is only used for the calculation of the interference fringe order of each wavelength and its modulo-2π phase is obtained using ϕ_i.[5]

The setup of the HSOP is similar to those shown in Refs. 4 and 5, but has been modified and improved (Fig. 1). To construct the HSOP, microscopic optics and new laser sources delivered using a multi-mode fiber (MMF) were introduced. The MMF was employed to reduce ghost interference fringes formed by reflections off various optical surfaces. A rotating diffuser eliminated the speckle patterns from the MMF. When the microscopic optics were used with the laser source delivered through the MMF, the allowable length difference between the reference and the test arm of the interferometer was limited to less than 2 mm. Because the phase shift is linearly dependent on the arm length difference and the frequency-scanning range of the lasers, a wider scanning range of the laser was necessary for a sufficient overall phase-shifting range than in previous work.[4,5] Therefore, the conventional laser diodes (LDs) were replaced with distributed feedback (DFB) LDs (Eagleyard PHOTONICS GmbH). The wavelengths of the two lasers determine the measurable range without ambiguity and the amplification factor of the phase error as shown in Eqs. (1) and (2). The

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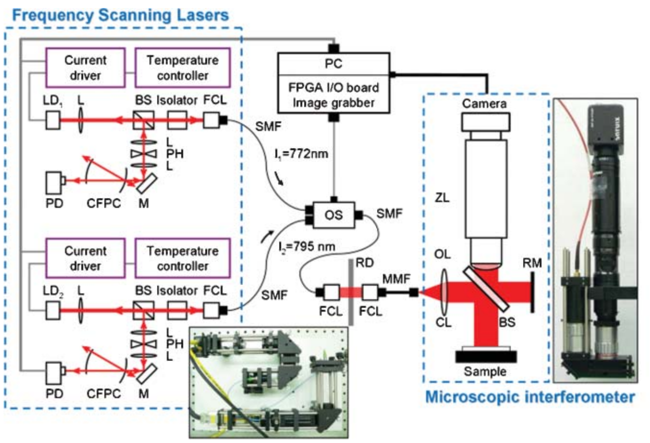

FIG. 1. (Color online) Experimental setup of the HSOP. The insets show photographs of the frequency-scanning laser and the microscopic interferometer. LD: laser diode; M: mirror; CFPC: confocal Fabry–Perot cavity; PD: photodiode; PH: pinhole; CL: collimating lens; BS: beam splitter; FCL: fiber collimation lens; SMF: single-mode fiber; MMF: multi-mode fiber; OS: optical switch; RD: rotational disc; ZL: zoom lens; OL: objective lens; RM: reference mirror; PC: personal computer; FPGA: field programmable gate array.

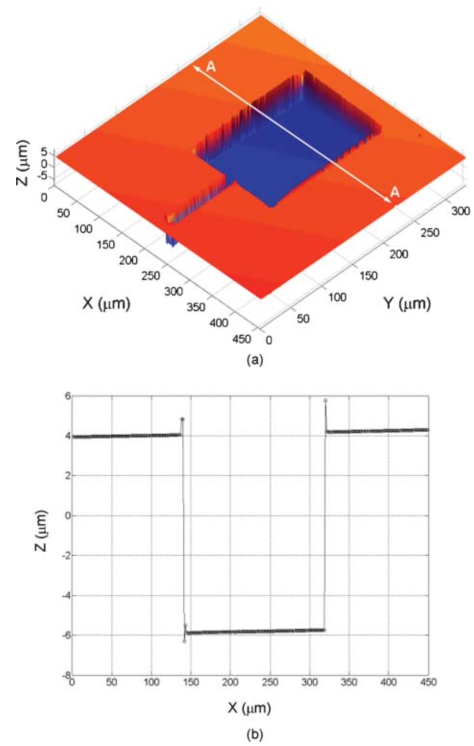

FIG. 2. (Color online) Measurement results for a step height standard (KRISS, SHS-010M). (a) 3D profile; (b) sectional profile along the line A–A′.

wavelengths were chosen based on the needs of the target applications. The DFB LDs with central wavelengths of 772 nm and 794 nm were used. This resulted in a measurable range of 13.7 μm, which corresponds to half of the equivalent wavelength. A current driver (ILX Lightwave, LDX-3220) can obtain a frequency-scanning range of 94 GHz without any mode hopping.

The CFPCs were designed to generate proper phase-shifting signals and were fabricated with two confocal mirrors attached on a hollow Zerodur® spacer. To maintain the phase step value, as in our previous work,[5,6] the free spectral range (FSR) of the CFPC can be increased by shortening the length of the CFPC proportionally because of the reduced difference in length between the reference and test arms. However, because the small cavity length makes fabrication and alignment difficult, we designed the cavity length of the CFPC to be 20 mm, which resulted in a FSR of 3.75 GHz in the TEM_{01} mode and produced trigger signals at every five resonant modes to capture interference images. With the frequency step of 18.75 GHz, phase steps of about 90° could be achieved.

The microscopic interferometer for the HSOP was configured to be a Watson interferometer,[6] which is a variation of the Michelson interferometer. A Mirau-type interferometer cannot be used because a length difference between the measurement and reference arms is required to generate phase shifting when the frequency of the laser is scanned. The interferometer was created in the objective lens of the microscope using a 10-mm cube beam splitter, a 10-mm reference mirror, and a collimation lens (Mitutoyo, M Plan APO 5×). The microscope optics consisted of a conventional zoom lens system (Navitar, Zoom 6000) and the objective lens (Mitutoyo, M Plan APO 5×). The high speed CCD camera (Pulnix, TM-6740CL) captures a 10-bit interference image (320 × 240) at every external trigger signal with a maximum frame rate of more than 400 Hz, when 2 × 2 binning is applied.

The controller of the HSOP was composed of a field programmable gate array (FPGA) reconfigurable I/O board (National Instruments, NI 7831R) and an image grabber (National Instruments, NI PCIe-1429) installed on a personal computer (PC). Because the I/O board provides high speed, multifunction data acquisition, and flexibility with onboard processing, it can execute high speed processing and generate control signals for the LD current driver and optical switch. The most critical role of the I/O board is to produce trigger signals for capturing interference images at constant phase steps. The I/O board identified the resonant modes of the CFPC by comparing the predefined threshold level with the transmission signal of the CFPC. These were acquired at a rate of more than 200 kHz, and the trigger signal was sent to the image grabber at every five resonant modes. The trigger signal was turned off after the predefined duration to equalize the intensity of every interference image by closing the gate of the camera.

To verify the performance of the HSOP, we measured two kinds of step height specimens with nominal step heights of 3 μm (KRISS, SHS-003M) and 10 μm (KRISS, SHS-010M), respectively. These samples were measured at 1 Hz and 30 Hz repetition rates, and the results were also compared with the measured values of other instruments. To calculate the phase image of each wavelength, five interference images were acquired and saved in the RAM of the controller PC. A 3D profile was obtained using these ten interference images through the calculation procedure described in Ref. 5. This process was implemented on a PC as a post-processing step, but a high speed processing module based on a FPGA is being developed for real-time processing.

The measurement results, which were measured at a repetition rate of 30 Hz, are shown in Fig. 2. The step height values were obtained by applying the step height calculation

TABLE I. Comparison of step height measurement results obtained using the HSOP and a commercial white light scanning interferometer (WLSI). Each specimen has reference values of (3.065 ± 0.024) μm and (9.948 ± 0.074) μm, which were measured using a calibrated stylus profiler (Taylor Hobson, Form Talysurf).

	Instrument	HSOP		WLSI
	Rate	1 Hz	30 Hz	>0.5 Hz
Specimen I (SHS-003M)	Mean	3.0627 μm	3.0628 μm	3.0689 μm
	Standard deviation	0.3 nm	0.2 nm	1.7 nm
Specimen II (SHS-010M)	Mean	9.9298 μm	9.9296 μm	9.9469 μm
	Standard deviation	0.1 nm	0.2 nm	2.6 nm

method given in ISO 5436—1 (Ref. 7) to the sectional profiles of 3D images such as those shown in Fig. 2(b). Table I summarizes the comparison results of the step height values, which were measured by the HSOP and a commercial white light scanning interferometer (WLSI). Each step height value was obtained by averaging the step heights of 70 sectional profiles. The mean and standard deviation shown in the table were calculated using 20 step height values obtained in this manner. The HSOP shows consistent measurement results regardless of the repetition rate and even better repeatability with higher measurement speed than the commercial optical profiler. The reference values of step height specimens are (3.065 ± 0.024) μm and (9.948 ± 0.074) μm, which were measured using a calibrated stylus profiler (Taylor Hobson, Form Talysurf). The last term of each reference value represents the expanded uncertainty ($k = 2$, level of confidence ~95%).[8] The measured step height values of the HSOP agreed well with the reference values within their expanded uncertainties. As an application of the HSOP, some parts of a thin-film transistor liquid-crystal display (TFT LCD) panel were measured with a repetition rate of 30 Hz (Fig. 3). Using these 3D profiles, we can efficiently inspect the shape and height of the microscopic structures composing the LCD panel, such as color filters and column spacers.

As mentioned in previous work,[5,9] multiple-wavelength PSI has the inherent disadvantage of phase noise amplification. However, because the phase for the equivalent wavelength including amplified phase noise is only used to determine the order numbers for each wavelength, the final measurement value will not suffer from phase error amplification provided the phase noise is reduced enough not to change the order numbers. The measurable discontinuity range of the HSOP was extended by a factor of about 35 compared with that of a single-wavelength PSI, and the phase noise for the equivalent wavelength was also amplified proportionally. Therefore, based on a rough calculation, the phase noise should be limited to less than $\pi/35(\approx 5.1^\circ)$ not to change the order numbers. The allowed phase error for each wavelength becomes smaller (e.g., $\pi/35 \times 1/\sqrt{2} \approx 3.6^\circ$). The phase error can be caused by various sources, such as the noise of the detector, speckle noise, phase step error, intensity variation, and vibration. Among these error sources, the noise of the detector and the laser source, because of speckle and intensity fluctuation, mainly contribute to the total phase error. The total phase error of the HSOP is usually less than the allowable phase error, but the noise amplification might generate a profiling error around the edges surrounding the features with large height discontinuities. This is shown in Figs. 2 and 3. This is an innate problem in most PSIs and can be solved with image post-processing such as removing the big discontinuity near detected edge lines. The performance of the HSOP was verified through experiments and comparison of the results. Our HSOP has the potential to be an effective tool for high speed inline inspection where microscopic 3D profiles are required.

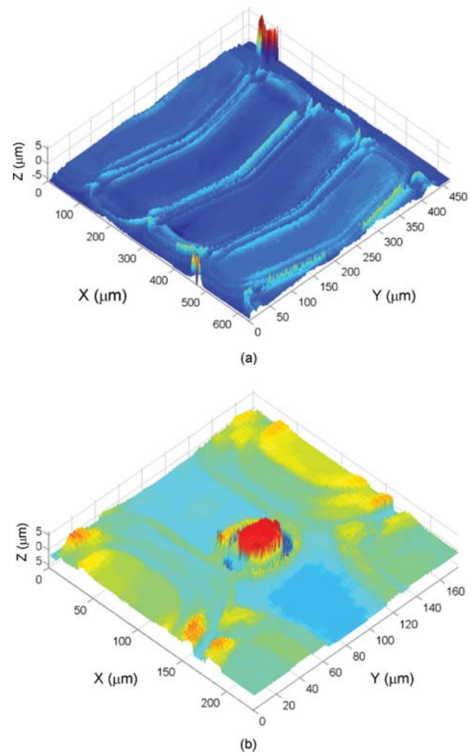

FIG. 3. (Color online) Measurement results for parts of a TFT LCD panel with a repetition rate of 30 Hz. (a) color filter; (b) column spacer.

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