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Galvo-scanning chromatic confocal microscopy for high-speed 3-D surface measurement

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The article presents high-speed chromatic confocal microscopy for 3-D surface profilometry. Extremely high accuracy and efficiency of surface profilometry on microstructures are critically demanded in various manufacturing processes, such as semiconductors fabrication. A Galvo-scanning confocal measuring system is proposed to achieve high efficient area-scan chromatic confocal microscopy. The proposed optical system is designed to be fully telecentric through all the light illumination and imaging sections to satisfy full-field measurement without optical aberration. Optical line-scan illumination and imaging modules are designed to fit with an electrical-driven galvanometer for high-speed line scanning optically. A large measuring FOV with high chromatic measuring accuracy can be expected. To verify the developed probe's measuring precision and accuracy, pre-calibrated step-height gauges were tested to show that the measurement bias can be kept below 239 nm with a standard deviation of 126 nm. The measuring speed of the system can reach more than 8000 line/s when the galvanometer reaches its design specification. The measuring efficiency would be credited with a high level of scanning performance in the current state of the art in 3-D confocal microscopy.

1. Introduction

Many commercial chromatic confocal technologies [1] have been developed with ultra-high-speed measurement specifications for automated optical inspection (AOI). However, for most of the existing chromatic confocal systems, even if they can meet the speed required for real-time measurement on the industrial production line, a desired high-speed and high-precision scanning platform is still needed to achieve three-dimensional profilometry. However, continuous stage displacement may introduce various inevitable measurement uncertainties, including vibration, positioning errors, and mechanical deformation induced by uncontrolled temperature variation. Therefore, in recent years, the development direction of chromatic confocal systems has shifted from stage-scanning to platform-free full-field measurement to avoid the above problems. Most full-field chromatic confocal systems are based on multipoint scanning [2-7]. However, the current multipoint scanning development has some crucial disadvantages, such as low optical efficiency and the trade-off between the wavelength resolution and the measurement speed. As a result, many developed systems cannot simultaneously achieve high measurement speed and resolution. Thus, a significant technological breakthrough is urgently needed.

This study proposed to develop a new chromatic confocal system [8, 9] combined with an optical galvanometer to perform one-dimensional lateral line scanning. The proposed method can realize the full-field measurement within the entire FOV of the objective lens without scanning by the platform while keeping high speed and high resolution and avoiding the disadvantages mentioned above.

2. Proposed system design

The system configuration is shown in **Error! Reference source not found.**, which can be divided into three modules: illumination module, chromatic confocal scanning module, and image detection module. The exist light of the illumination module is reflected to the optical scanning galvanometer after passing through the beam splitter. According to the received digital signals, the galvanometer is rotated to a specific angle. The rotation angle can change the incident angle of the light beam entering the F-θ scan lens so that the position of the middle image plane is changed. The light beam is then focused on different lateral positions of the sample by the bi-telecentric chromatic objective to complete the scanning of the entire FOV. Because the system is designed for coaxial illumination, the light reflected from the test sample can re-enter the bi-telecentric chromatic objective , scan lens, and galvanometer and transmit through the beam splitter to form another light arm. The imaging lens then focuses the reflected light, and an optical slit is placed at the conjugate focal plane of the system. After the second spatial filtering, it will enter the spectrum detection module.

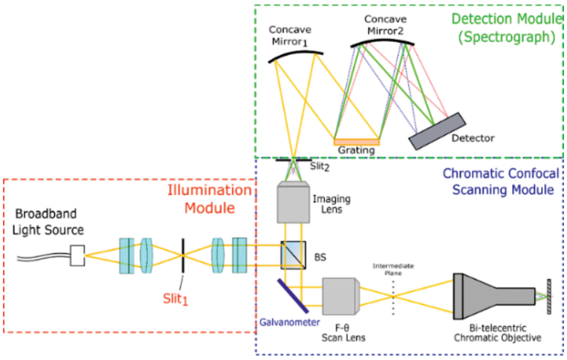

Fig. 1 Schematic diagram of developed chromatic confocal micro scopy.

2.1 Chromatic objective design

To maintain the measurement quality of each point in the full-field measurement, the optical system has to follow the characteristics of an optical telecentric structure. The telecentric structure can make all the light reflected by the test sample back to the optical system so that both the light loss and the measurement error of the full-field system can be controlled to a minimum. Given this, we designed a bi-telecentric chromatic objective based on the abovementioned characteristics. Table 1 shows the optical specification of our objective. In the design, the linearity of the dispersion curve, as shown in Fig. 2, appears to be almost an ideal line in which the wavelength change of 1 nm equals the depth change of 1μm.

Table 1 Objective Optical Specification

Optical Specification		
Magnification	8X	
Wavelength Range (μm)	450-650	
Dispersion Range (μm)	200.0	
Object Plane	Numerical Aperture	0.32
	Field of View (mm)	ϕ1.735
	Telecentric (Y/N)	Y
Image Plane	Numerical Aperture	0.04
	Field of View (mm)	ϕ13.88
	Telecentric (Y/N)	Y

2.2 F-θ Scan Lens

Since the chromatic objective selected for the development is not an infinite correction system, a spatial filter is placed on the image focal plane in general. However, it usually cannot be directly placed with a scanning device for beam scanning due to space constraints. Therefore, a scan lens is added between the galvanometer and the chromatic objective to make the galvanometer work. Here, the scan lens can be regarded as a relay lens, increasing the conjugate focus so that the above spatial limitation can be resolved and the design can facilitate beam lateral line scanning. It is necessary to select a scan lens with telecentric characteristics to maintain better light efficiency.

Since a uniformly rotating motion of the galvanometer can introduce an undesired variant exposure time for all scanning positions (or called image height). To precisely control the galvanometer and keep the exposure time constant within the scanning range, an F-θ scan lens can be used to achieve this. Besides, the F-θ lens group was designed to have a specific distortion on purpose so that the image height has a linear relationship with the incident angle.

Based on the conditions listed above, the develooped system uses a commercial telecentric achromatic F-θ scan lens (LSM03-VIS, Tho rlabs). The simulation result of the wavelength to focal shift is shown in Fig. 2. It can be seen that the axial dispersion curve still maintains fairly ideal linearity. As seen, the simulation result demonstrates that the system's optical scanning can achieve the expected measurement performance when the F-θ scan lens is integrated.

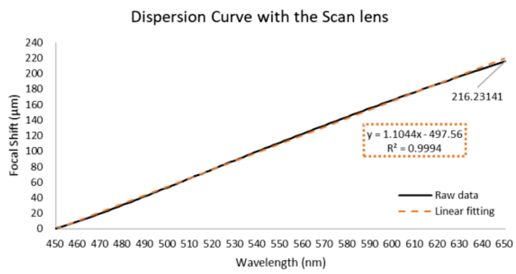

Fig. 2 Dispersion curve with the scan lens

2.3 Housing and mounting

The plane optical path on the optical table has to be established into a three-dimensional space structure through optomechanical mountings to make the system's optical path compact and stable. Therefore, the 3D mechanical CAD software SolidWorks is used to design each optical component's fixing mechanism and assembly method. The optomechanical module is divided into an illumination module, chromatic confocal scanning module, and image detection module. These three modules are integrated with a few right-angle mirrors to fold the optical path and miniaturize the probe size. The CAD of the system housing is shown in **Error! Reference source not found.** and the hardware system image is shown in **Error! Reference source not found.**.

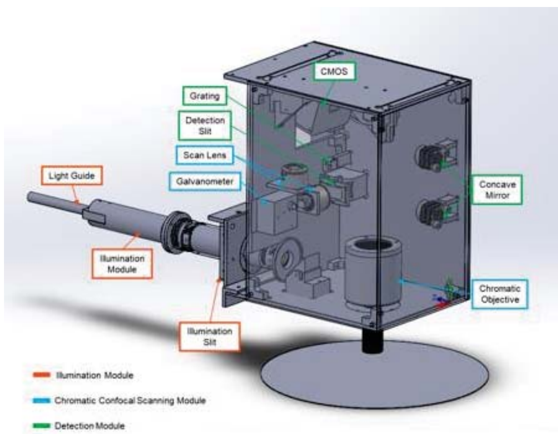

Fig. 3 System design with Solidworks

3. Experiments and results

In this section, A unfilled solder paste groove was used as the test sample, as shown in Fig. 5. The top surface is rough with a low reflectivity, and its bottom is a silicon wafer surface with high reflectivity. The reconstructed 3D image measured by the system is shown in Figure 6, and the cross-section at the white line is shown in Figure 7. As seen, the system can measure the concave disk on the bottom surface but not on the edge of the groove since there is an insufficient numerical aperture of the objective to receive the reflected light for detection. The height from the top to the bottom disc of the solder paste groove is 76.363 µm. Fig. 8 demonstrates the measurement reference result from the commercial confocal laser microscope Keyence VK-X1100, in which the corresponding dimension is 75.573 µm, and the measuring bias is 0.790 µm.

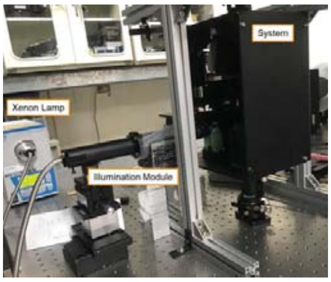

Fig. 4 Hardware of developed confocal optical probe.

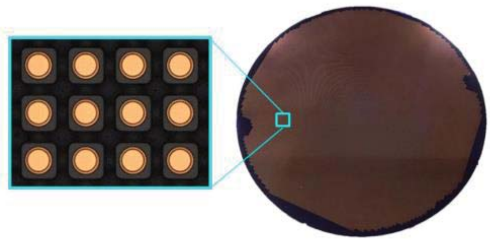

Fig. 5 The unfilled solder paste groove image.

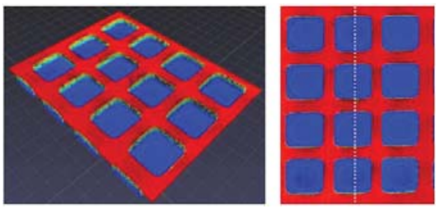

Fig. 6 The unfilled solder paste groove image surface reconstruction image.

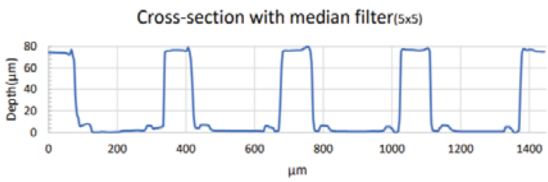

Fig. 7 Measurement result of the unfilled solder paste groove from our system

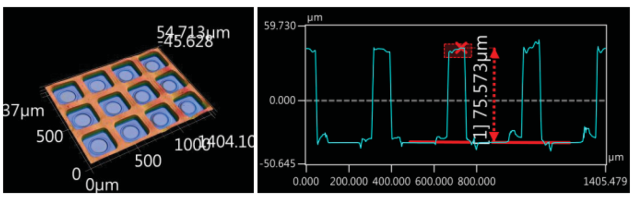

Fig. 8 Keyence measurement result of the unfilled solder paste groove.

3. Conclusions

Due to its coaxial structure and no shadowing effects, chromatic confocal systems have great potential for detecting compact microstructures in the semiconductor industry. A new galvanometer-scan full-field chromatic confocal microscopy measurement system was developed to reduce the cost of high-precision stages and programmable spatial modulators. Meanwhile, designing the chromatic objective compatible with telecentric properties can increase the proportion of reflected light returning to the system from off-axis points, thus maximizing the light detection efficiency. As proved by the experimental results, the repeatability of the depth measurement capability of the system reaches 0.126 µm, and the accuracy of 30 measurements of the standard step height gauge reaches 0.239 µm. The measuring speed of the developed probe can reach up to 8000 lines per second when the galvanometer reaches its design specification when sufficient light reflectivity is obtained.

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