Confocal Scanning Microscopy : a High-Resolution Nondestructive Surface Profiler

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Confocal scanning microscopy is a measurement technique used to observe micrometer and sub-micrometer features due to its high resolution, nondestructive properties, and 3D surface profiling capabilities. The design, implementation, and performance test of a confocal scanning microscopy system are presented in this paper. A short-wavelength laser (405 nm) and an objective lens with a high numerical aperture (0.95) were used to achieve the desired high resolution, while the x- and y-axis scans were implemented using an acousto-optic deflector and galvanomirror, respectively. An objective lens with a piezo-actuator was used to scan the z-axis. A spatial resolution of less than 138 nm was achieved, along with successful 3D surface reconstructions.

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1. Introduction

Confocal scanning microscopy (CSM) can provide optical sectioning. Out-of-focus signals are rejected by the confocal aperture in front of the photo detector so that the technique only collects signals from the focal plane. CSM can be used to obtain optically sectioned images, extended focus images, and 3D surface profiles.[1,2]

CSM is actually far-field optical microscopy, which implies that there is a diffraction limit in the resolution due to the long wavelengths. However, in the past decade, the resolution of far-field optical microscopy has improved to the sub-diffraction-limit regime. There are several ways to improve the resolution of fluorescence microscopy. Image restoration algorithms [3] or structured illumination [4] can be used. 4Pi confocal microscopy improves the axial resolution [5], and quenching pulses, which decrease the point spread function, can also be introduced.[6] In reflection microscopy, a lateral resolution of 0.15λ has been achieved using differential CSM.[7] The lateral resolution can be enhanced by 38% using simple confocal self-interference microscopy.[8]

Scanning probe microscopy is typically used for high-resolution applications. Scanning electron microscopy (SEM) has about 1 nm resolution, while atomic force microscopy (AFM) has sub-nanometer resolution.[9] These are very useful tools for measuring 3D profiles of precise samples. However, AFM may scratch the sample surfaces and the measuring speed is quite slow since it scans the sample or the probe tip mechanically. SEM requires a conductive surface or a coating on the sample as well as a vacuum environment. CSM does not require any sample preparation or a vacuum environment. There is no risk of scratching because CSM is a nondestructive optical technique. Also, CSM can provide high-speed imaging up to 1000 frames/s.[10] Applications for high-resolution reflection CSM systems include reviewing semiconductors or inspecting MEMS devices.

In this paper, we describe the implementation of a CSM system, starting with the design method and ending with an experimental performance test using the actual microscope. An acousto-optic deflector was used for the x-axis scanner while a galvanomirror was selected for the y-axis scanner to permit high-speed operations. The confocal aperture was a narrow slit. A controlled piezo-actuator was attached to the objective lens to provide high precision z-axis scanning. Relay optic components that relayed beams to the aperture of the objective lens were designed to induce low aberrations. A short wavelength violet laser and a plan apochromat objective lens with the highest available numerical aperture among dry lenses, NA = 0.95, were selected to achieve the desired high resolution. A spatial resolution of 138 nm was achieved, and a 3D surface profile was reconstructed.

2. Design Specifications

The specifications of the high-resolution reflection CSM system are as follows:

lateral resolution < 150 nm,
height discrimination < 10 nm,
scanning speed = 30 frames/s (512 × 512), and
scanning range = several tens of microns.

3. Design and Implementation of the Confocal Scanning Microscopy System

3.1 Schematic Diagram

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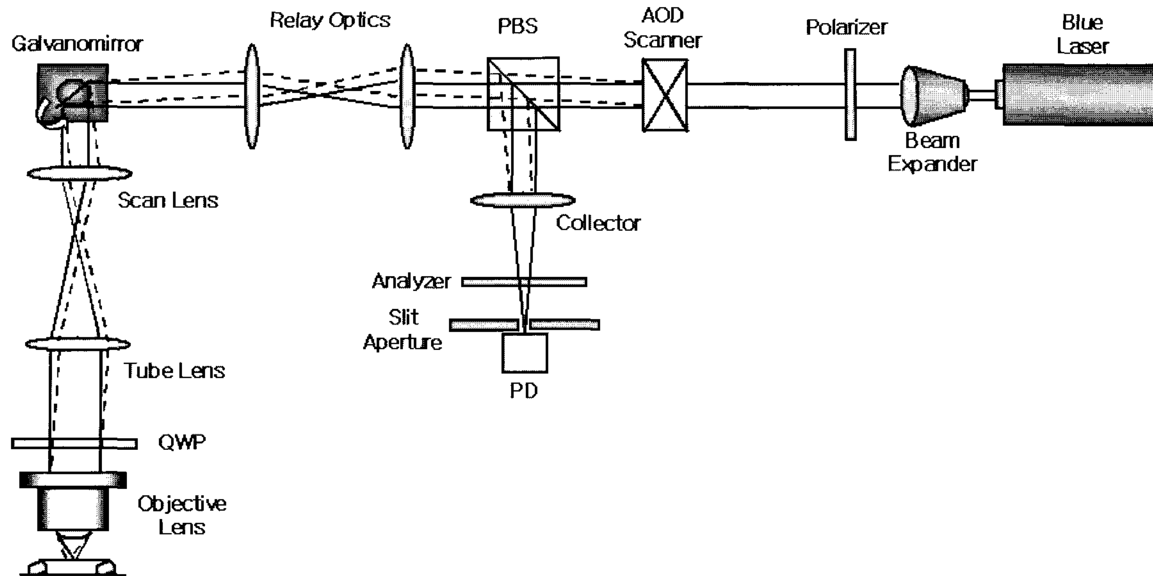


Fig. 1 Schematic diagram of the confocal scanning microscopy system

Fig. 1 shows a schematic diagram of the confocal scanning microscopy system. The beam originates from a diode laser and arrives at the center of the objective lens with a deflected angle after passing through two deflectors and the relay optics. The light from the specimen is de-scanned by the galvanomirror and reflected by the polarizing beam splitter (PBS). Light reflected at the focal point of the objective lens that passes through the confocal slit aperture is detected by the photo detector (PD). Any light from the out-of-focus plane is blocked by the confocal aperture in front of the PD and is rejected. The specimen is scanned by deflecting the acousto-optic deflector (AOD) and the galvanomirror, and an image is generated from the detected PD signal.

3.2 Laser

Better resolution will be achieved from a shorter-wavelength laser. However, many optical problems are encountered in the UV region, for which there are few optical materials that have sufficient transmittance. Thus, the design of a UV optical system is very difficult. Even if the designer finds the appropriate rare and expensive optical materials and succeeds in designing the system, its cost will be prohibitive. Therefore, we used a violet laser (405 nm, 20 mW, coherent), which has the shortest available wavelength in the visible light region. Most optical components, such as aspheric lenses, mirrors, and objective lenses, are designed to operate well at this wavelength. Violet continuous-wave (CW) diode lasers or diode pumped solid-state (DPSS) lasers are available from many sources.

3.3 Beam Deflectors

A CSM system is a type of point scanning device. It scans a 2D area, point by point, with a focused beam to generate an image. To achieve high-speed imaging (30 frames/s), the x- and y-axis scan speeds must be at least 15.36 kHz and 30 Hz, respectively. A galvanomirror is adequate for the slower y-axis scanning because it has a bandwidth greater than 1 kHz and an efficiency of 90%. There are several choices for the faster x-axis (fast-axis) scanning. A resonance galvanomirror can operate at high speeds up to 8 kHz. Therefore, it can be used as the fast-axis deflector if the signals are obtained bidirectionally. However, since it operates in a resonance mode, the motion of the galvanomirror is sinusoidal and the scanning speeds vary at different points. Thus, complex electronics are required to reconstruct an image from the serial data. A polygon mirror, which has many mirror surfaces, can also scan quickly if a high-speed motor is used. However, the scanning angle cannot be changed once the number of mirrors is determined so that zooming is impossible. An AOD has no mechanically moving parts and negligible inertia so it can produce sawtooth scanning with great accuracy and almost instantaneous flyback. Even though it has a relatively low efficiency (~70%), it is the only scanner that can perform random-addressing.[11] Therefore, we chose a galvanomirror (Cambridge Tech.) and an AOD (A-A) to provide the slow and fast scanning, respectively, due to their fast response and flexibility.

3.4 Confocal Aperture

The maximum efficiency of the AOD was only 70%, and the backward transmission efficiency was even worse. Thus, we de-scanned the beam only on the slow-axis with the galvanomirror. Therefore, the focused beam moved in the detection plane in the direction of the fast axis. A slit was selected for the confocal aperture rather than a pinhole. The width of the slit was 25 um, which is the optimal aperture size for signal-to-noise ratio considerations.[12]

3.5 Optics

A PBS and a quarter-wave plate were used to separate the illumination and detection paths. P-polarized beams were transmitted through the PBS while S-polarized beams were reflected by the PBS. The illumination beam was P-polarized; this was changed to S-polarized as it passed through the quarter-wave plate. Hence, the detection beam was reflected by the PBS and sent to the pinhole and detector.

A fraction of light was reflected from all the surfaces of the optical components even though the components were coated with antireflection film. The reflected light from the surfaces of the intermediate optics can act as background noise. But the reflected light that does not pass through the quarter-wave plate will not be reflected by the PBS since it remains P-polarized. Therefore, we can reject unwanted reflected light using the PBS and quarter-wave plate.

Relay optics were necessary to send the beam into the aperture of the objective lens after the beam was deflected by the AOD and galvanomirror. The relay optics had a telecentric design to perform this task, and were designed to have negligible aberrations over their entire field. Several concave, convex, and meniscus lenses were used to reduce the length of the total optical path. A schematic diagram and the aberration of the relay optics are shown in Fig. 2. The total length of the relay optics was 430 mm, and the peak-to-valley optical path difference (P-V OPD) was only 0.012.

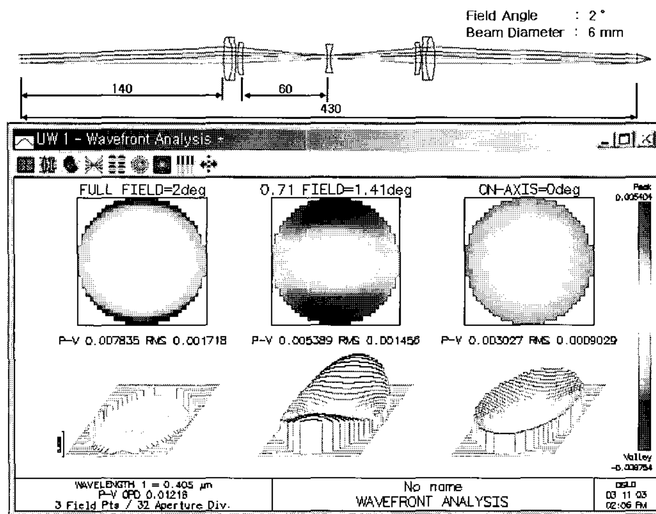


Fig. 2 Schematic diagram and aberration of the relay optics (simulation tool: OSLO)

The objective lens determines the image resolution. To obtain the best possible resolution, we selected a plan apochromat lens with the highest available NA (0.95). The cutoff frequency of the modular transfer function (MTF) must be higher than 3333 lines/mm to acquire a 150-nm resolution. For a light source with a wavelength of 405 nm, the cutoff frequency is 4500 lines/mm (see Fig. 3). If an ideal confocal aperture is used, the resolution is enhanced by a factor of 1.4.[13] Thus a 150-nm resolution can be achieved with these optics.

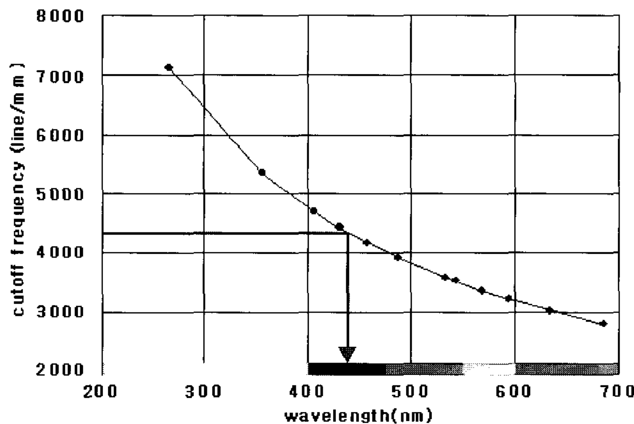


Fig. 3 Wavelength versus cutoff frequency when NA = 0.95

3.6 Photo Detector

A highly sensitive, low noise, and fast-response photo detector is required in CSM. The rise time of the selected PD (Hamamatsu) was only 17.5 ns. The sensitivity was 0.25 A/W, which is very high.

3.7 Data Acquisition Board

The target speed of CSM is 30 frames/s with 512 x 512 pixels/frame. This requires an input and output board with a sampling rate greater than 8 MHz. The selected data acquisition board (National Instruments) had a sampling rate of 10 MS/s, two output channels, and four input channels. Another high-speed output board was used for slow scanning.

4. Performance Test of the Confocal Scanning Microscopy System

4.1 Spatial Resolution

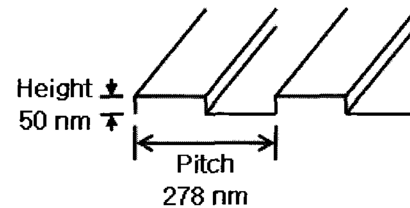


Fig. 4 Standard specimen (pitch = 278 nm, height = 50 nm)

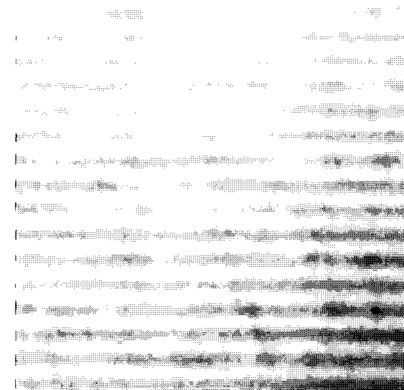


Fig. 5 Acquired image (field of the image = 4.5 um)

To evaluate the spatial resolution of the CSM system, a standard specimen (Fig. 4) with repeated narrow pitches was imaged. As shown in Fig. 5, the lines and spaces were clearly resolved. Therefore, a high spatial resolution greater than 139 nm was achieved with the CSM system. The limit of the resolution could be measured using other standard specimens with narrower pitches.

4.2 Axial Response

CSM can be used for optical sectioning. The axial response obtained when a reflective planar object was scanned through the optical axis is shown in Fig. 6. The greatest measurement intensity will be obtained if the object is placed in the focal plane. The sharp axial response indicates that the CSM system provided superior optical sectioning. The full-width half-maximum (FWHM) value is as indicator of the optical sectioning capability of a CSM.[13] The FWHM of this system was 800 nm.

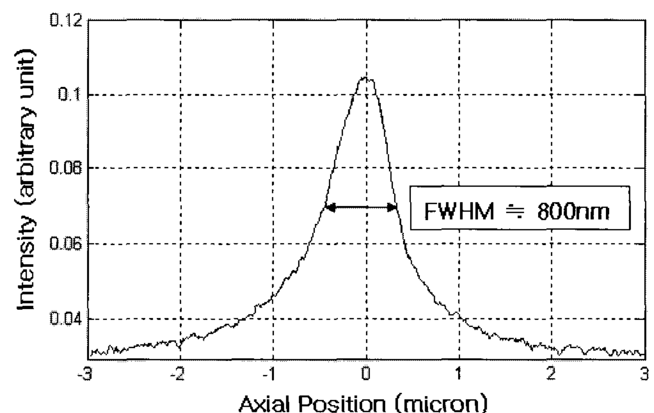


Fig. 6 Axial response of the CSM system

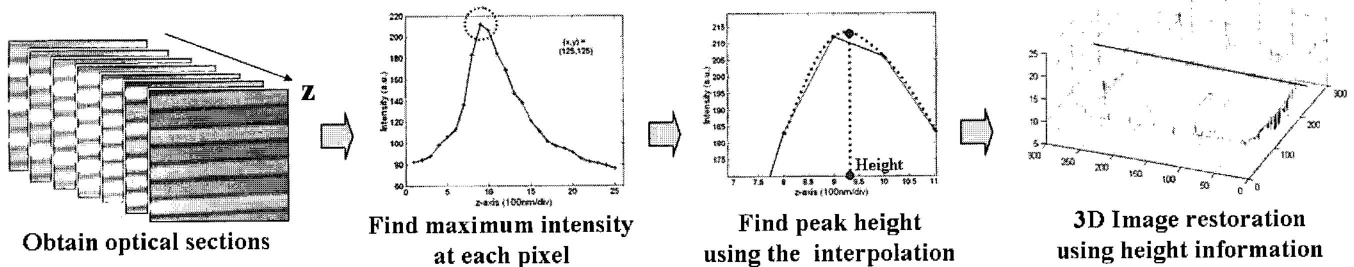


Fig. 7 Procedure followed to obtain a 3D surface profile using the CSM system

4.3 3D Surface Profiling

A 3D surface profile of a sample can be obtained using the optical sectioning characteristics of the CSM system. The procedure followed to obtain a surface profile is shown in Fig. 7. First, several optical sections are acquired by capturing images when moving the focal plane along the optical axis. The axial response can be acquired at each pixel so that we can determine the axial position having the maximum intensity. The peak height can be calculated for each pixel using second-order interpolation of the maximum point and its neighbors. Once we know the peak heights at every pixel, we can reconstruct a 3D surface image of the sample.

The plot at the right of Fig. 7 shows a reconstructed 3D surface image of a standard specimen that had a 3-um pitch and 500-nm height. An enlargement of this plot and a SEM picture of the same standard specimen are shown in Fig. 8.

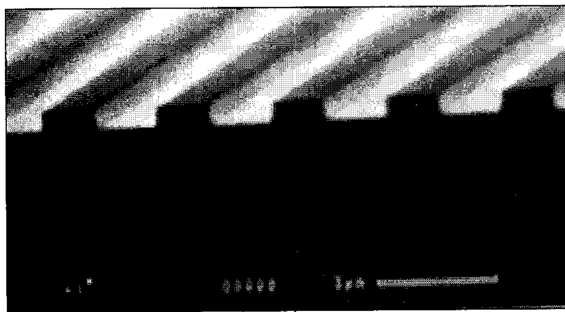
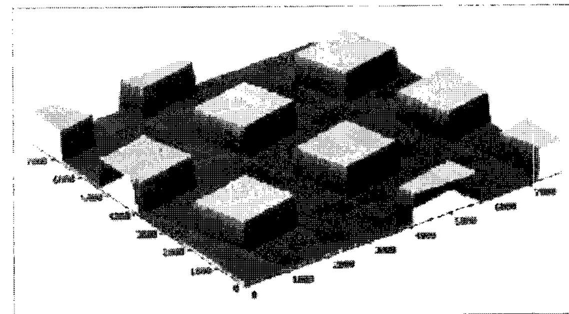


Fig. 8 SEM and CSM images of a standard specimen with a height of 500 nm

Another example of 3D surface profiling is shown in Fig. 9. The standard specimen used in this example had a 3-um pitch and only a 19.5-nm height. This precise specimen can be used to calibrate an AFM. Even though there was considerable noise, the sample features were clearly visible in the CSM image. The measured height of the features ranged between 10 and 30 nm and could not be evaluated exactly due to the electrical noise.



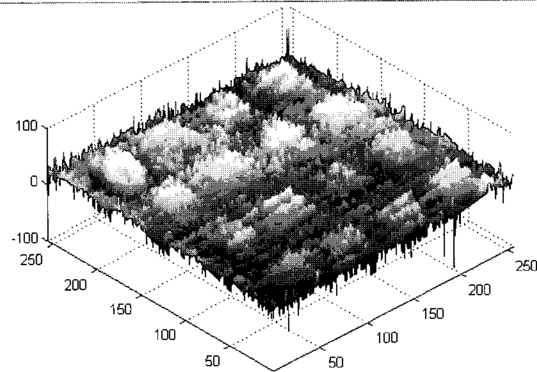


Fig. 9 AFM and CSM images of a standard specimen with a height of 19.5 nm (NT-MDT)

5. Conclusions

This paper reports on the design and implementation of a high-resolution confocal scanning microscopy system, and the performance of this system was tested. It had a spatial resolution greater than 139 nm and a surface profiling ability with several tens of nanometers of axial discrimination due to its axial response. In the near future, we expect to be able to achieve a 10-nm axial discrimination by reducing the electrical noise. The high-resolution CSM system was nondestructive, fast, and did not require any complex sample preparations. Therefore, the system can be used to review semiconductor products and MEMS devices.

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