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Measurement of Sub-micrometer Features Based on The Topographic Contrast Using Reflection Confocal Microscopy

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We describe the design and the implementation of video-rate reflection confocal scanning microscopy (CSM) using an acousto-optical deflector (AOD) for the fast horizontal scan and a galvanometer mirror (GM) for the slow vertical scan. Design parameters of the optical system are determined for optimal resolution and contrast. The OSLO simulations show that the performances of CSM are not changed with deflection angle and the wavefront errors of the system are less than 0.012 λ. To evaluate the performances of designed CSM, we do a series of tests, measuring lateral and axial resolution, real time image acquisition. Due to a higher axial resolution compared with conventional microscopy, CSM can detect the surface of sub-micrometer features. We detect 138 nm line shape pattern with a video-rate (30 frm/sec). And 10nm axial resolution is archived. The lateral resolution of the topographic images will be further enhanced by differential confocal microscopy (DCM) method and computational algorithms.

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I. INTRODUCTION

Confocal scanning microscopy (CSM) has been one of most useful techniques for the observation of micrometer and sub-micrometer sized samples together with scanning electron microscopy (SEM) and scanning probe microscopy (SPM). SEM requires a conductive surface for good contrast and must operate in a vacuum. And SPM risks damage to a sample surfaces. However CSM is non-invasive and has the advantage that the plane of measurement can be accurately located. Improved axial resolution capability of CSM gives sufficiently high contrast for high resolution imaging.

Reflection confocal microscopy uses the light reflected from the focal plane of sample. The depth discrimination capability is from a confocal aperture, usually a pinhole or a slit, which prevents the light from out of focus planes. The depth discrimination capability of CSM produces a good topographic contrast. This means that two points, which is located closely and has small height difference, which cannot be seen in conventional microscope, can be resolve by CSM. Based on topographic contrast imaging, we can often obtain sub-diffraction-limit images using computational algorithms such as deconvolution technique. In differential confocal microscopy (DCM), 2 nm depth resolution on surfaces with homogeneous reflectivity is archived [1].

For practical samples such as a VLSI, the aspect ratio is usually 5-10. Therefore tens of nanometer depth resolution is required to measure features of lateral dimensions of sub-micrometer. This is why CSM is suitable for dimensional measurements in modern semiconductor and nanotechnology industries.

To produce a 2D image using CSM, a focused spot of light must be moved in a sample. The beam scanning system provides fast scanning speed and has advantages compared with the object scanning system. However, the video-rate (30 frm/sec) image acquisition is not easy, fast scanners as well as special methods to process data quickly are needed. Besides in the beam scanning system, the optical path must be varied to scan one point to another point. This variation of the optical path brings several aberrations and results in performance change or position error. These are unwanted results. To minimize these errors we must design an optical system carefully.

In this paper, we present the design of a video-rate reflection confocal scanning microscope and method to make images with a video-rate.

II. DESIGN OF CONFOCAL SCANNING MICROSOCOPE

1. System configuration

To reach video rate x- and y-axis scan speed should be faster than 15.36 kHz and 30 Hz for U.S./Japanese, respectively. One of common methods to reach video-rate scanning is to use an acousto-optical deflector (AOD) for the fast horizontal scan and a galvanometer mirror (GM) for the slow vertical scan. The resonant galvanometer can be used for a fast scanner, however, is difficult to use. Since it operates in a resonance mode, the motion of the galvanometers is sinusoidal and the scanning speeds are different among the points. Thus the electronics will be very complicated to reconstruct the image from the serial data [7].

An AOD can simplify pixel acquisition and has a higher scanning rate than the resonant galvanometer. An AOD uses sound waves generated by a transducer, usually PZT actuator, at the end of a crystal to make a refractive index variation. Collimated light is diffracted by these pressure-induced changes in refractive index. The AOD has no mechanically moving parts and negligible inertia, so that it can produce high scanning rate up to several tens of kHz. A GM is a small flat mirror that executes an angular motion of which scan rate is less than 1 kHz.

In the case of using AOD (AA.DTX.400, A-A) for a scanner we found that the transmission efficiency of an AOD was low (below 70%), we decided not to descan by it. In this configuration, the reflected light from a specimen is descaned by GM (6860M, Cambridge Tech.) and collected through a slit rather than a pinhole, thus partially sacrificing confocality and resolution. The roles and effects of these apertures are studied and in the case of slit there must be depth discrimination capability [6]. Fig. 1. shows the optical configuration of the CSM.

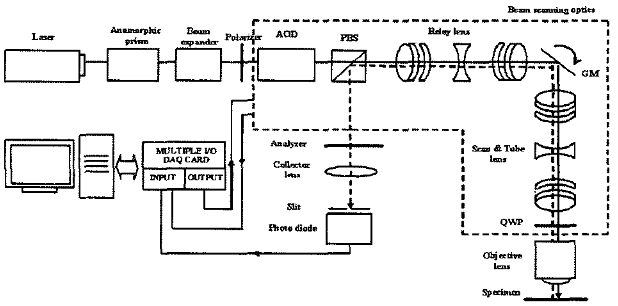


FIG. 1. The layout of the beam scanning confocal microscope using acousto-optical deflector (AOD) and galvanometer mirror (GM). The beam scanning optics is made up AOD, relay lens optics, GM, scan lens, tube lens and quarter-wave plate (QWP) sequentially.

2. Design of optics

An UV laser diode (402 nm) emitting a linear polarized light is used as a source for the illumination. A pair of anamorphic prisms is used to enlarge and circularize elliptical beam from diode laser. The circularized beam is expanded to cover the aperture of AOD whose size is 6 mm.

The scanning of the beam is realized by an acousto-optical deflector and galvanometer mirror. Usually for a GM apart from an AOD, the light deflected by the AOD is deflected away from the aperture of the GM. For ideal scanning the light deflected by the AOD must be stationary at the position of the GM. To do this a relay lens system which connect AOD and GM is required. Regardless of the deflected angle by AOD, the relay lens keeps the light from being out of the GM's aperture. Otherwise the variation of the optical path brings several aberrations and results in performance change or position error [4]. The relay optics consists of five lenses, two doublets (L1, L5), two meniscus lenses (L2, L4) and one concave lens (L3), and designed telecetrically (Fig. 2 (a)). It is designed to have ignorable aberration over the full-field. Two doublets ensure that scan pivot apertures of the two scanners are optically conjugate to each other. The meniscus lenses shorten the effective focal length and reduce astigmatism and spherical aberration [5]. The addition of the concave lens helps reduce field curvature and astigmatism. We used commercial products that are most close to the designed values. Commercial products have the advantage that they are less expensive and easier to get.

We analyzed the designed relay optics with the OSLO and the results are shown in Fig. 2. We assumed that the objective lens is infinite corrected and a perfect lens whose numerical aperture (NA) is 0.95. The maximum scanning angle of AOD is smaller than 2dgree. We didn't analyze the whole system, but just the relay optics for convenience. OSLO simulation shows that the field curvature is nearly eliminated at deflection angle of 2 degrees. (Fig. 2 (b)) In Fig. 2 (c) we could see that the modulation transfer function is identical though the deflection angle is changed. Therefore we can say that the optical performance is constant according to the deflection angle. The wavefront error of the system at the entrance pupil of the objective lens is 0.012 λ (Fig. 2 (d)) which is less than $\lambda/4$, which is called the Rayleigh criteria. We used this result for scan and tube lens system because the role of scan and tube lens system is same that of relay optics. The light deflected by AOD and GM enter into infinite corrected objective lens (NA 0.95). The spot size (diameter of airy disk) on a sample is simply estimated 520 nm.

Light that is reflected from the sample retraces its path through the objective lens and GM. A quarter wave plate (QWP) is used to block out the reflected

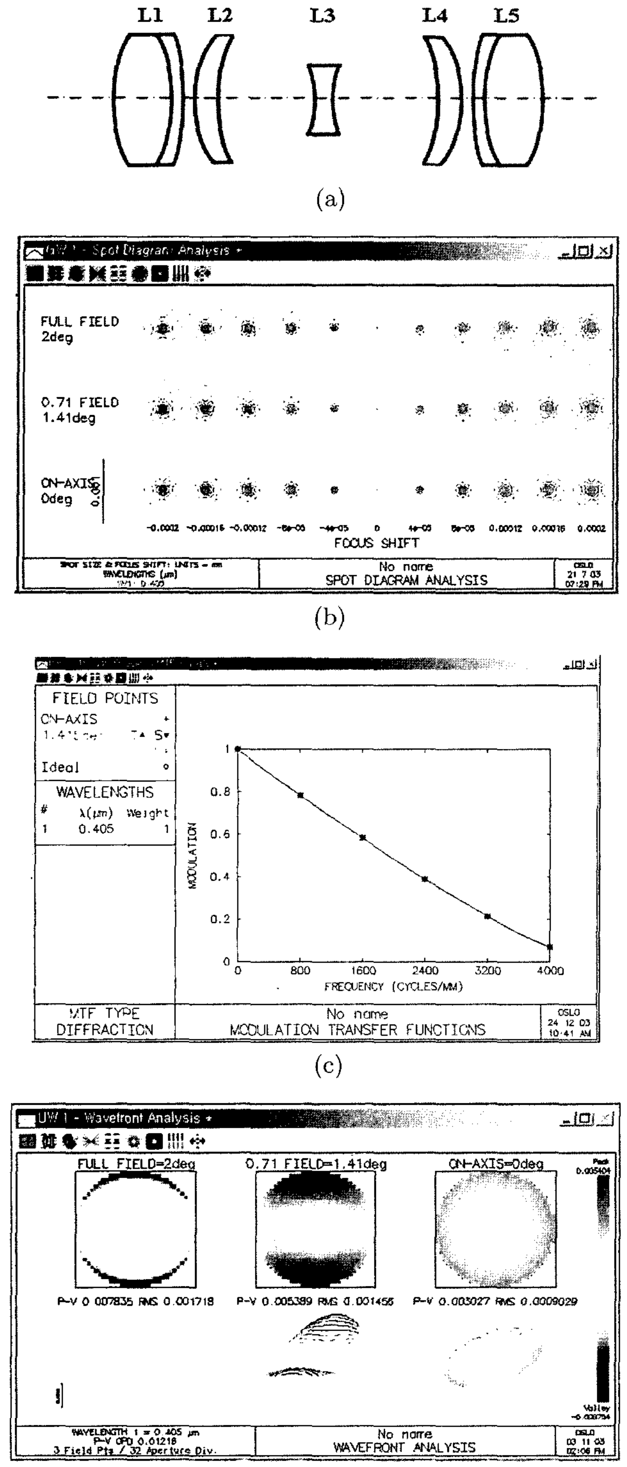


FIG. 2. OSLO simulation results (a) Schematic diagram of the relay optics. (b) Spot diagram analysis (c) MTF analysis (d) Aberration of relay optics.

light from intermediate optics. Beyond a polarizing beam splitter (PBS), the reflected light is detected through a slit by a photo diode (PD).

3. Video signal electronics

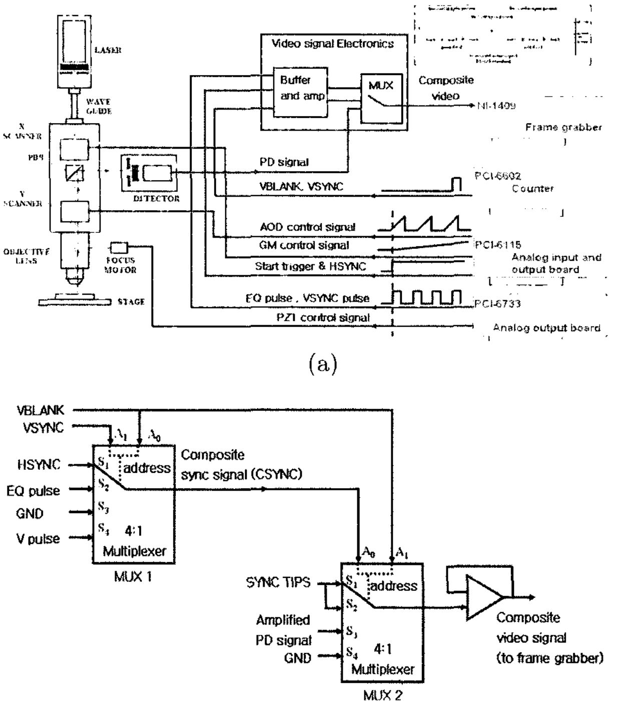
Usually in a true confocal system, one can get intensity information of one point of whole sample at once. For making a 2D image, scanning must be performed and the serialized data of each point must be rearranged. To display the image, we often need a software algorithm that transfers the serial data to an image. We did all these works with a single computer and it was difficult to attain real time imaging. Even though the scanner rate is enough to archive real time reach to data processes, such as saving and loading data, image formation and multi-taking process, were problem. These are time consuming works and obstacles in real time imaging.

To overcome these problems we built the control and video signal electronics for the RS-170 standard. Fig. 3 shows the electronics of the video-rate CSM. All signals are controlled by a personal computer (Pentium 4), in which four PCI boards (PCI-6733, PCI-6115, PCI-1409, PCI-6602), are installed. Data acquisition and image formation are conducted by video signal electronics and frame grabber. All time consuming works is handled with hardware which has fast than software. The operating program is coded with visual C++.

The PC outputs nine output signals. Three of them are for driving the AOD, the GM, and the focusing unit and the others are for making the video signal. The most important thing in this configuration is synchronization among them. Synchronization is guaranteed by connecting internal RTSI bus.

The RS-170 video signal is a composite signal which contains a horizontal synchronization pulse (HSYNC), a vertical synchronization pulse (VSYNC), an equalizing pulse (EQ PULSE), and an active image signal, etc. Six pulses from the PC are used for making a video signal. All pulse signals are made by general purpose counter in the boards. Video signal electronics consists of two analog multiplexers (MUX 1, MUX 2) and several op-amps. (Fig. 3 (b)) MUX 1 combines a HSYNC and EQ PULSE to generate a composite synchronization (CSYNC). MUX 1 is switched by the state of the addresses (A0, A1). MUX 2 similarly combines a synchronization pulse tip (-0.7V) and signal from the PD to generate a composite video signal, which then enters into the frame grabber. The op-amps are used for a buffer.

Three output signals from the PC control the AOD, the GM and PZT focusing unit respectively. We use PCI-6115 (National Instrument) board to control the AOD and the GM. It also generates the start trigger and the HSYNC. The maximum output rate and sampling rate of the board are 2.5 MS/sec and 10 MS/sec per each channel respectively. To assure that the scanning is working properly, we collect the horizontal position and the vertical position during the operation by



(a)

(b)

FIG. 3. Signal flow chart : (a) Schematics diagram of data acquisition (b) Video signal electronics.

the command voltage of the AOD and the capacitor sensor in the galvanometer mirror respectively. The output signal for the AOD is a saw-tooth wave with a frequency of 15.7 kHz, which is triggered by HSYNC. The output signal for the GM also is a saw-tooth wave with a frequency of 60 Hz, which is triggered by VSYNC. In RS-170 standard, two fields make one frame which contains 525 lines. (525 lines/frame × 30 frame/sec = 1570 lines/sec)

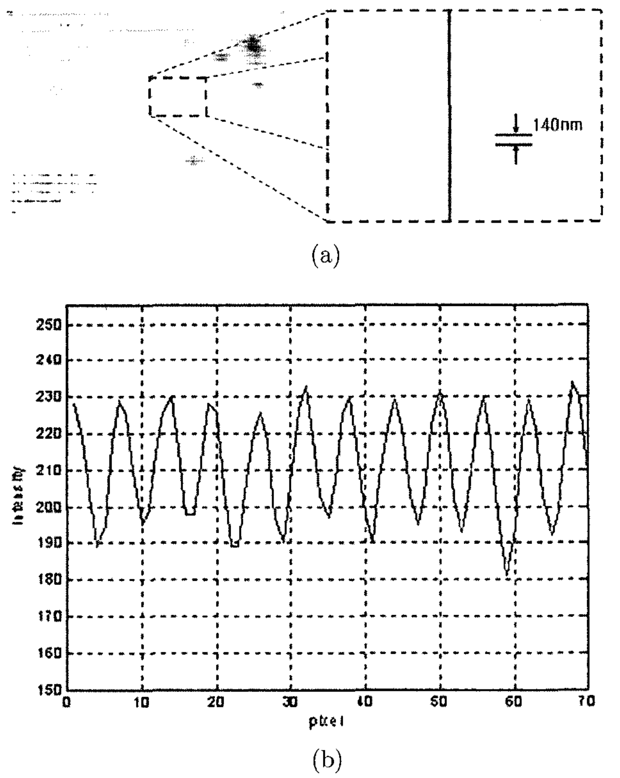
III. EXPERIMENTS AND RESULTS

The lateral resolution of optical microscope is defined by well known the Rayleigh criteria, which corresponds to a contrast value of 26.4 percent. However it is true that we can distinguish two closely spaced points visually even though they are closer than the distance by Rayleigh criteria. Practically lateral resolution can be defined by the distinguishable minimum line and space pattern. We measured various sizes of line and space patterns and could resolve a less 278 nm period of line and space pattern with 0.95 NA objective and 10 um slit. Fig. 4 (a) shows the result. The sample measured is a line pattern glass wafer and has 278 nm period and height less than 55 nm (TDG-01, NT-MDT). The size of single line pattern is approximately 140 nm and is clearly resolved. The profile of intensity is shown in Fig. 4. (b) and contrast is over 10%. Therefore we can say that the resolution of designed CSM has the resolution less than 140 nm.

Whereas a conventional microscopy shows little variation in intensity with z, a confocal microscope has an intensity peak that is sharper with objectives of higher NA and smaller detector size. Generally if the same NA objective is used, the gradient of the intensity profile in the slit detector system is much lower than that in the point detect system [6]. The sharper gradient of the intensity profile means the more sensitivity to the variation of z position.

A simple test that is the measuring intensity profile when a planar mirror is at different levels of focus is performed. Usually a PZT actuator is used to move objective in the direction of optical axis. We used MIPOS 100 SG (Piezojena) for objective positioning system. The range and resolution of the actuator are 80 um and 0.4/4.8 nm (open loop/closed loop) respectively. To evaluate the axial performance of CSM we measure two values, the full width at half maximum (FWHM) of axial response and the depth resolution.

FWHM is defined as the width at which the intensity drops to one half of the maximum value. Fig. 5. (a) shows the profile obtained with a 10 um-width slit.



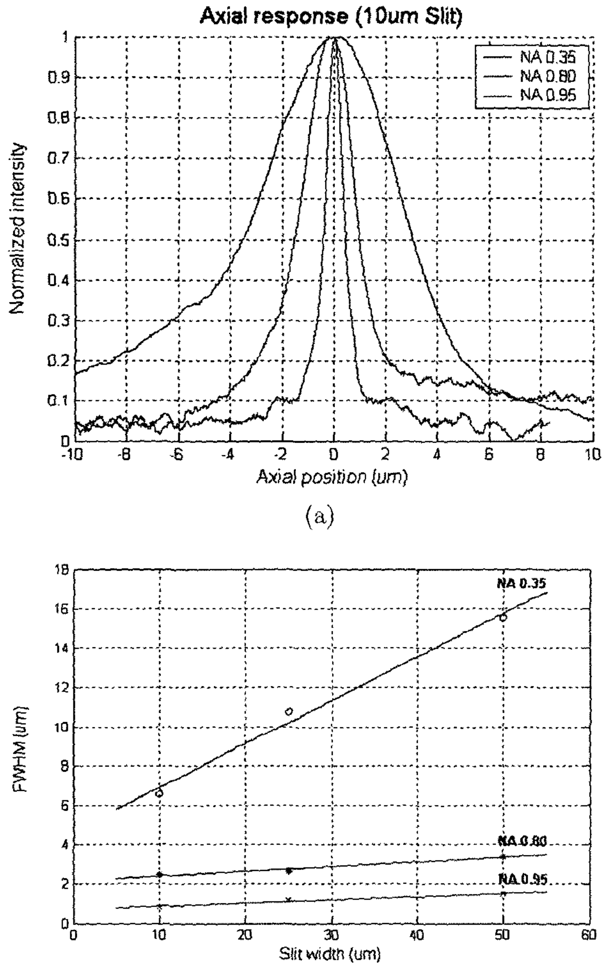
(a)

(b)

FIG. 4. Measurement of the line and space pattern which has 278 nm period and height less than 55 nm. (a) Image of the pattern (b) Profile of an intensity.

Various objectives are used for comparing the sensitivity to the variation of z position. In the case of NA 0.95 objective, we can get the maximum sensitivity. The smallest FWHM which tells the shape of the profile is 860 nm. The higher the NA of the objectives and the narrower the slit used, the smaller the FWHM. (Fig. 5 (b)).

Another representing axial performance, the depth resolution is defined as uncertainty of height measurement [1]. The axial response signal always has the intensity variations which are caused by the noise such as electrical noise and mechanical vibration. These uncertainty of height, represent depth resolution. We measured the axial response and calculated the standard deviation of the leaner region. Fig. 6 shows the linear region of the axial response with three different NA of objectives, NA 0.45, NA 0.8 and NA 0.95 and the standard deviations of each case are 25.7 nm, 19.2 nm and 10.0 nm respectively. For all experiments 10um slit is used. The higher NA of objective is used, the higher axial resolution is acquired.



(a)

(a)

FIG. 5. Axial response of the system. (a) Measurement of the depth resolution with various NA objective lenses. Slit width is 10 um. (b) Relation between depth discrimination and slit width for the system.

Fig. 7 shows images of a 3D array of squares which is formed on silicon wafer. (TGQ1, NT-MDT) Its side and height are 3±0.05 um and 19.5±1.5 nm respectively. In a conventional microscope with a white light source and a 0.95 NA objective, the squared pattern with a height of 19.5 nm (nominal) is dim, as shown in Fig. 7 (a). However, with the designed CSM with a 10um slit and the same objective we can detect the pattern with a higher contrast. (Fig. 7 (b))

IV. CONCLUSION

We have presented design of a video-rate reflection confocal scanning microscope. We have achieved a video-rate (30 frm/sec) with the AOD and the GM. We built video signal electronics and applied a proper algorithm

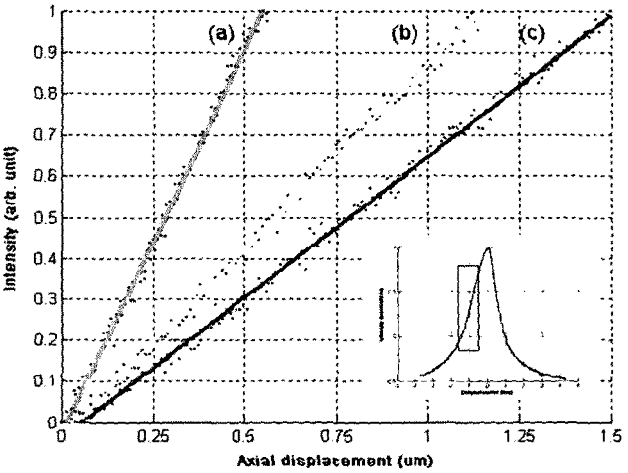
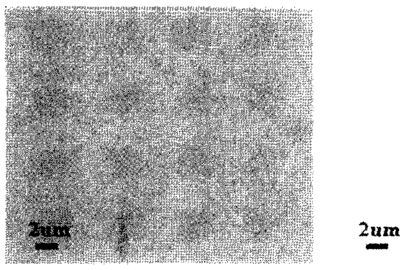


FIG. 6. Measured linear region of the axial response curve with different NA. (a) NA 0.95, (b) NA 0.80, (c) NA 0.45.



(a) (b)

FIG. 7. Image of the 3D array of square structures. (a) By conventional microscope (b) By designed CSM (NA 0.95, slit width 10 um)

to make a video signal from a PD signal.

We have demonstrated high resolution image with the designed CSM. Designed CSM has a lateral resolution less than 140 nm. Also the depth resolution is 10 nm approximately. High depth sensitivity of CSM gives an enough contrast to imaging hundreds of nanometers features based on the topographic contrast. With a nanometer depth resolution we could detect features of lateral dimensions of hundreds of nanometers. Moreover by use of maximum likelihood estimation algorithm, it is possible to obtain sub-diffraction limit image based on the topographic contrast [3].

Depth discrimination capability of CSM produces a good topographic contrast. CSM is one of the promising technologies for dimensional measurements in modern semiconductor and nanotechnology industries.

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