Zoological Studies 34, Supplement I (1995)

Zoological Studies

Differential Confocal Microscopy for Imaging Surface Microstructures

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The depth resolution of conventional confocal microscopes is limited by the confocal parameter. In the visible spectral range it is possible to make the confocal parameter as small as 0.5 μm. Yet as with any microscopy, one always finds many applications which demand better resolution than available. In this paper we report our development of a new confocal technique, tentatively called differential confocal microscopy, which can be used for imaging and profiling surface structures with depth resolution as large as 20 nm. We demonstrate the potential of this technique by profiling calibrated nanometer semiconductor structures and micrometer optical ridge waveguides, and by imaging a layer of collagen fibers whose diameter is about 100 nm.

In conventional confocal microscopy, the signal light comes mainly from the focal point by fluorescence, reflection, or scattering. Light from outside of the focal region is heavily attenuated by spatial filters. A typical response curve is shown in Fig. 1. The depth resolution is equal to the width of the response curve, which is in the best case equal to the confocal parameter. Although at the focal point the response is largest, in the case that the signal light comes from a reflective surface, placing the sample at the focal point is not the most advantageous. At the focal point the derivative of the response curve with respect to the sample position is zero, which means the response is least sensitive to sample height variation. In contrast, if one places the sample slightly away from the focal point, so that its position is at the slopes of the response curve, the sensitivity is the greatest. At the slopes the sample height variation causes a differential change of the signal. The sensitivity is sufficiently large that the effect can be utilized to profile surface structures with depth resolutions as large as 20 nm.

Our experiments are done in two types of setups. One uses a superluminescent laser diode (Spindler & Hoyer DC25E) in a confocal feedback configuration (Lu et al. 1995). The other uses a He-Ne laser (Melles Griot 05-LHP-121) in a conventional feed-through configuration. The confocal feedback configuration is almost self-aligned, but due to the multi-mode nature of our laser diode, the lateral resolution is not as good as that of the He-Ne laser. Fig. 2 shows the He-Ne laser feed-through configuration. The laser output is focused by a 40× microscope objective onto the sample. The position of the sample at the *z*-axis is controlled by a piezoelectric transducer, and the sample point in the *x-y* plane is set by computer-controlled translation stages. Before the measurements, we first move the sample to the focal point by maximizing the reflected power. Then we raise the sample by about 1/2 confocal parameter, so that the reflection changes linearly with the sample height. Finally we scan the sample in the *x-y* plane and profile the surface structure with great depth resolution.

Fig. 3(a) shows a 3-dimensional image of an H-shaped trench on top of an InGaAs surface. For comparison, we also show in Fig. 3(b) its profile measured with a mechanical contact probe, the Dektak 3030 surface profiler made by Veeco Instruments, Inc. The measurements show that the confocal laser-feedback technique not only has much better lateral resolution, but also contains less noise. It is clear that the sensitivity of our experiments is great enough to see features in depth on the order of 20 nm, even though the lateral resolution is still limited by diffraction.

Unlike with scanning tunneling microscopes, atomic-force microscopes, or the recently developed scanning near-field optical microscopes (Betzig et al. 1992), our experiments are conducted in open loop; no servo control is used to lock the sample distance to a constant value, nor is lock-in detection applied to enhance the signal-to-noise

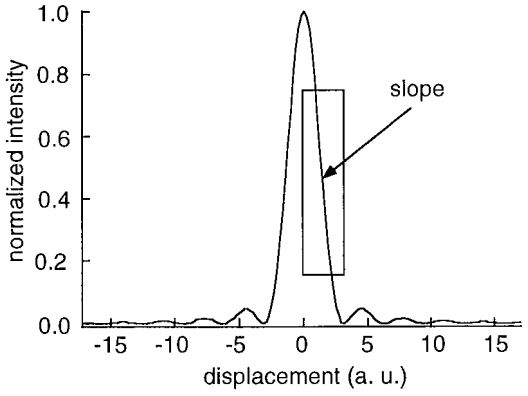


Fig. 1. Axial response of a confocal microscope.

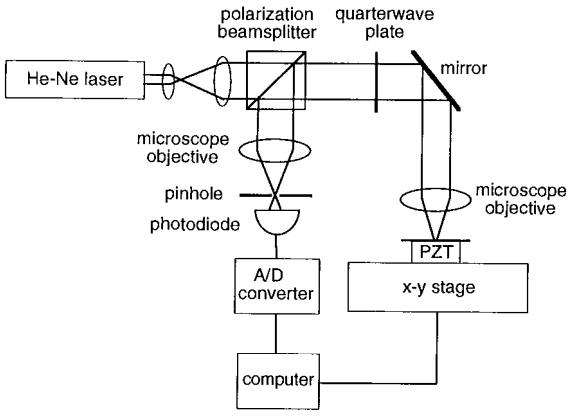
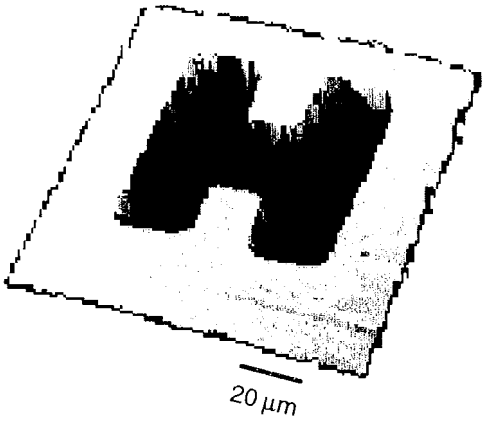
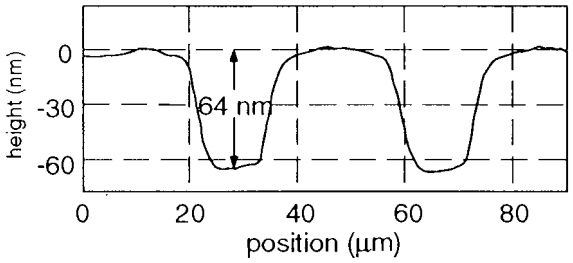


Fig. 2. Experimental setup.



(a)



(b)

Fig. 3. (a) The 3-dimensional image of a 60-nm deep H-shaped trench on top of an InGaAs surface, compared with (b) that measured with a Dektak 3030 surface profiler.

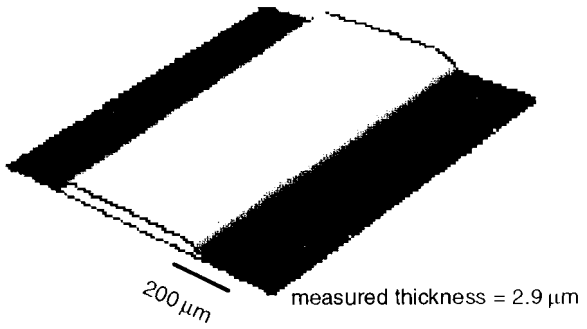


Fig. 4. The 3-dimensional image of a 3-μm high polymethyl-methacrylate optical ridge waveguide.

ratio. The response time of the detection is limited only by the amplifier and the analog-to-digital converter and the speed of the mechanical translation stages. If electro-optical instead of mechanical scanning is used, we believe that with optimized system components measurements can be performed in the 30 frame/sec video rate.

Fig. 4 shows a 3-dimensional image of a polymethyl-methacrylate optical ridge waveguide on a silica substrate. The measured thickness of the waveguide is by the Dektak 3030 surface profiler. This measurement demonstrates the large linear dynamic range of the technique, which is many times larger than that of interferometric methods. Large linear dynamic range is important for high speed scanning in open-loop measurements because it eliminates the need of shifting the base-height during measurements. With other techniques which have the potential of open-loop measurements but do not have a large dynamic range, such as interferometric confocal microscopy (Bearden et al. 1993, Juskaitis et al. 1993, 1994), the need of dynamic base-height adjustment greatly reduces the scanning speed when

the sample height variation exceeds a fraction of the wavelength.

The surface profiles shown in Fig. 3 and Fig. 4 cannot be seen under conventional optical microscopes due to lack of contrast mechanism. High resolution nearly contact techniques such as scanning tunneling microscopy, atomic-force microscopy, and scanning near-field optical microscopy can provide much greater lateral resolution, but their measurement speed is much slower than the differential confocal technique due to the necessary close-loop operation mode. Moreover, with the differential confocal technique the distance between the probe head (objective) and the sample can be as large as several millimeters, as compared to nanometers in nearly contact techniques mentioned above. This is important to *in-situ* diagnosis in the fabrication of surface microstructures such as semicon-ductor devices, or in studying the morphology of living biologic samples.

Fig. 5 shows the image of a layer of collagen fibers extracted from bovine skin tissues. Unlike in Fig. 3 and Fig. 4, the measurement was done with the He-Ne laser in the feed-through configuration for better lateral resolution. The diameter of the fiber estimated from pictures taken by scanning electron microscopes is about 100 nm, which is apparently beyond the 0.8-μm lateral resolution of our system. Yet the fiber structure is recognized. The lateral resolution could be further improved by using oil-immersed objectives and shorter wavelength light sources.

In summary, using the concept of differential confocal microscopy, we developed an optical scanning microscope capable of measuring surface microstructures with 20-nm depth resolution and dynamic ranges as large as micrometers. In several respects the technique is complementary to the nearly contact techniques discussed above, yet it costs much less and is much simpler to operate. We believe that this technique has great potential not only in surface diagnosis and metrology needed by the microfabrication industry, but also in biomedical applications in which rapid measurements of living structures are highly desirable.

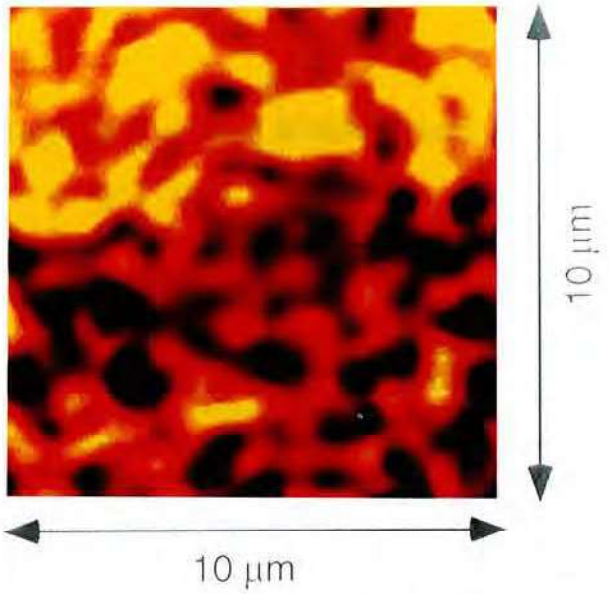


Fig. 5. The scanned image of collagen fibers. The actual diameter of the fiber is about 100 nm.

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