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A comparison of surface metrology techniques

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Abstract. The study of surface metrology is becoming more and more commonplace in industrial and research environments. Because of this expansion there are more and more technologies available for looking at the surface and each has its own applications. Stylus profilometry, white light interferometry and confocal microscopy are common techniques used to measure surface metrology. Strengths and weaknesses of each of the techniques are discussed with examples. The use of scanning probe techniques as metrology tools is also briefly discussed.

1. Introduction

The need for accurate metrology measurement is becoming more and more important as structures and surface features become smaller and smaller. This expansion of interest in nanotechnology is giving rise to issues about the best technologies to use when looking at micron and submicron measurements. One of the major challenges when moving to smaller measurements is selecting the correct metrology tool for the desired measurement. The different methods currently available have advantages and disadvantages depending on the sample and the properties required. Therefore it is important to be aware of how techniques can affect the measured parameters.

2. Stylus profilers

2.1. Introduction

Stylus profilers have been around for many years in one form of another. Typical of the early applications is the use of the Talysurf 1 (1941) for measuring optics used in the film industry. The need for such measurements has increased greatly over the years and there are many different types of stylus profiler available today. Two common technologies used for the control of the stylus are discussed in the section below.

2.2. LVDT

One common way of controlling the system involves taking measurements electromechanically by moving the sample beneath a stylus. The high precision stage moves a sample beneath the stylus

according to a user programmed scan length, speed and stylus force. The stylus is mechanically coupled to the core of an LVDT (Linear Variable Differential Transformer). As the stage moves the sample, the stylus rides over the sample surface. Surface variations cause the stylus to be translated vertically. Electrical signals corresponding to stylus movement are produced as the core position of the LVDT changes. The LVDT produces an analog signal proportional to the position change that in turn is converted to a digital format through an analogue-to-digital converter. The digitized signals from a single scan are stored in computer memory for manipulation.

2.3. Phase grating interferometer

Another way of controlling the stylus consists of a mounting a cylindrical holographic grating such that its axis is coincident with the pivot axis. Directing a laser beam at normal incidence onto this grating then generates two first order diffraction beams; any movement of the stylus about the pivot is transferred to a rotation of the grating. This in turn Doppler-frequency shifts the emerging diffracted beams. Finally, super-imposing these diffracted orders generates an interference signal, the phase of which corresponds to the position of the stylus.

2.4. Typical characteristics of stylus profilers

There are some similarities between all the techniques mentioned which are important when considering when to use a stylus system for metrology measurements. The most important factor is the measurement is the tip. The tip is constantly in contact with the surface and therefore it is vital that as much information about the tip dimensions is known. Hard materials are normally used to make the tip because of the need to avoid wear as much as possible. However hard tips can lead to damage of the surface and non-repeatable measurements. Another important parameter is the diameter of the tip. The smaller the tip then the smaller the features that can be measured but if the tip is too small it can scratch the surface. Therefore accurate control of the surface force is important to obtain good measurement data. The rate of scanning is also critical to the measurement. If the tip is moved too quickly across a surface then the stylus may not follow the contours or the surface correctly and this will lead to errors in the collected data.

It can be seen from above that the two important considerations when using a stylus profiler for measurements are the hardness of the sample and the required speed of measurement.

3. Optical profilometry

3.1. Introduction

The use of optical techniques to study surfaces has been very popular for a long time and there have been many developments over the years to improve the accuracy of the metrology. In recent years the use of interferometry and confocal microscopy has become more and more widespread and much is now known about the pros and cons of the techniques.

3.2. Interferometry

Interferometry [1-7] as a measurement tool is certainly not new but combining old interferometry techniques with modern electronics, computers, and software has produced extremely powerful measurement tools. Typically are two different techniques commonly used in interferometry, phase shifting and scanning white light.

Phase-shifting interferometry has proven to be extremely powerful and many commercial interferometers use phase-shifting techniques. The technique involves measuring the phase shift as the sample is scanned in z. While phase-shifting interferometry has great precision, it has limited dynamic range. It can easily be shown that for phase-shifting interferometry the height difference between two adjacent data points must be less than $\lambda/4$, where λ is the wavelength of the light used. If the slope is greater than $\lambda/4$ per detector pixel then height ambiguities of multiples of halfwavelengths exist. For example, if the light source has a wavelength of 633 nm then the maximum step that can be measured is $633/4 = 158.25$ nm. In order to overcome this limitation in phase shifting typically scanning white light interferometry is used.

Figure 1 Schematic of a white light interferometer

A schematic of a scanning white light system [8-10] is shown in figure 1. The upper beam splitter directs light from the light source towards the objective lens. The lower beam splitter in the objective lens splits the light into two separate beams. One beam is directed towards the sample and one beam is directed towards an internal reference mirror. The two beams recombine and the recombined light is sent to the detector. When the path length to the sample and the reference are the same interference is observed. The detector measures the intensity as the interferometric objective is scanned. The schematic in figure 2 shows how the detector takes a series of snapshots as the sample is measured. This gives as series of images of the intensity. The area of interest for the measurement is the interference area. These intensity images are used to characterise the surface being measured. White light is used rather than monochromatic light because it has a shorter coherence length that will give greater accuracy. Different techniques are used to control the movement of the interferometer and also to calculate the surface parameters. The accuracy and repeatability of the scanning white light measurement are dependent on the control of the scanning mechanism and the calculation of the surface properties from the interference data.

Figure 2 The detector captures the intensity as the sample is scanned

Another important factor in white light interferometry is the interference objective that is used. A low magnification objective can be used to look at large areas but the resolution is controlled by the resolution of the detector. Higher resolution images need higher magnification objectives but a smaller area has to be measured. The current resolution limit for white light
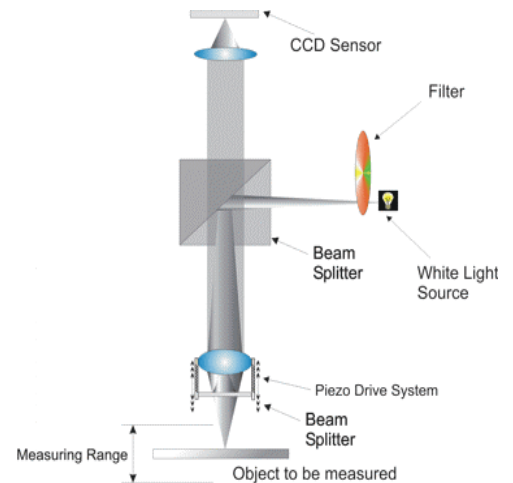
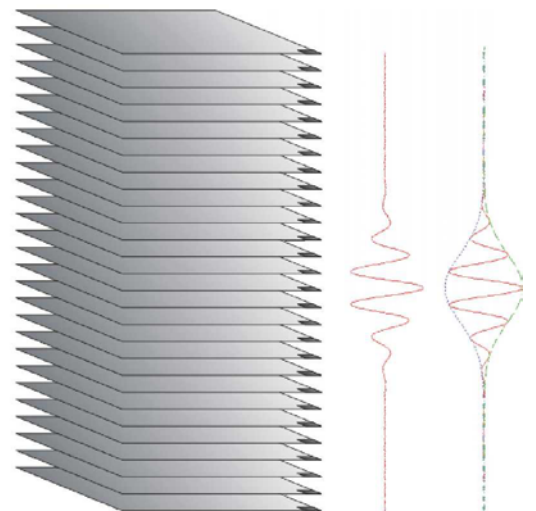interferometry is about 0.5 microns because diffraction effects limit the maximum possible resolution. Another consideration when choosing an objective is the numerical aperture. The numerical aperture (NA) is related to the angle of the light that is collected by the objective. The higher the NA then the greater the angle that can be measured. Normally the higher magnification objectives have a higher NA. Problems in white light interferometry can arise from the presence of thin films which can generate a second set of interference fringes. The two sets of fringes can cause errors in the analysis. Also materials with dissimilar optical properties can give an error in the measurement.

3.3. Confocal Microscopy

The technique of confocal microscopy, first described by Minski in 1957 [11, 12], has become a more and more powerful tool for surface characterization. The basic principle of confocal microscopy (Minski named it double focusing microscopy) is shown in figure 3 and mathematical considerations are discussed in the references [13-16]. Light emitted from a point light source is imaged onto the object focal plane of a microscope objective (MO). A specimen location in focus leads to a maximum amount of light through the detector pinhole and light from defocused object regions is partly suppressed.

Many designs of confocal microscopes for the acquisition and evaluation of topographic data are possible. Serial x–y scanning techniques have been developed for the acquisition of depth-discriminated sections in confocal laser scanning microscopes. A further z scan is necessary to acquire all the data for the evaluation of 3D topographic maps [17, 18]. Recent applications of these types of confocal microscopes are in biological and medicinal cell analysis [19] and the analysis of smooth engineering surfaces [20-22]. Common to all these applications is the use of highly magnifying microscope objectives with high numerical apertures ($0{:}6 < NA < 1{:}4$). One of the limitations of confocal microscopy is due to the large NA objectives leading to a small field of view.

For x–y scanning of a depth-discriminated section a Nipkow disc can be used. The disc consists of pinholes of 20-micron diameter, separated by 200 microns and arranged in a spiral shape [23]. The rotating disc is illuminated by a plane wave and acts as a scanning multiple-point light source, which is imaged onto the object focal plane of the microscope objective, after the reflection or scattering of light at the specimen, each Nipkow pinhole acts as its own detector pinhole.
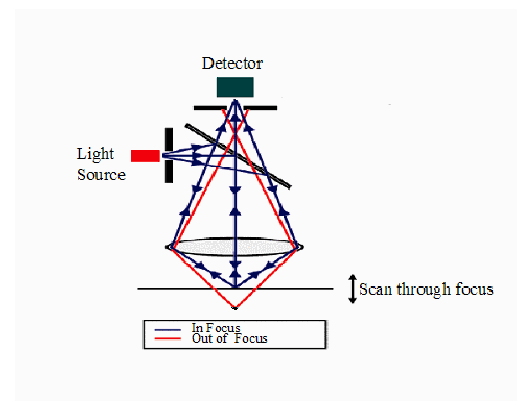

Figure 3 Schematic of a confocal microscope

4. Measurement of grating using different techniques

Three different instruments were used to measure a grating and the advantages and disadvantages of each technique are discussed. The grating used was an 80 um pitch square wave Al-coated etched grating with a nominal step height of 187nm. AFM was not used in this study because the maximum range of the AFM is typically about 100 microns and it would be difficult to directly compare AFM data with the other measured data.

4.1. Measurement

The sample was measured using three different techniques, an interferometer (Taylor Hobson Talysurf CCI 6000), a confocal system (Taylor Hobson Talysurf CLA) and a stylus profiler (Taylor Hobson

Talyscan 250). Step height analysis for the three systems is shown below (Table 1). It can be seen that the measured step heights for each of the techniques are similar. The similarity in the result is because each system had been calibrated with a calibration sample that was not very different from the sample being measured.

Table 1 Step height measurements

Measurement Technique	Step Height Value
Interferometry	187.5 nm
Confocal	188 nm
Stylus	187 nm

If we look at the measurement information in detail we can see differences in the quality of the data collected. Figure 4 shows the data from the interferometer. The steps and period of the grating can clearly be seen and the measured average step height is 187.5 nm. Important features of the measurement are the measurement time, which was about 15 seconds and the fact that the method is totally non-contact. The measurement shown was carried out using a white light scanning (CCI) technique, which scans through the whole range of the sample in the vertical direction. Phase shifting interferometry is also often used to measure similar samples of this type, however the wavelength of the light would need to be at least 750 nm in order to get reliable data. One common problem with optical systems is that mixtures of materials that have very different optical properties can give errors in measurement. In the past it has been overcome by adding a constant to correct for this dissimilar material offset. This correction is not ideal when you are regularly changing materials or if you have a blended material. It is now possible to correct for this problem during the measurement by using coherence correlation interferometry.
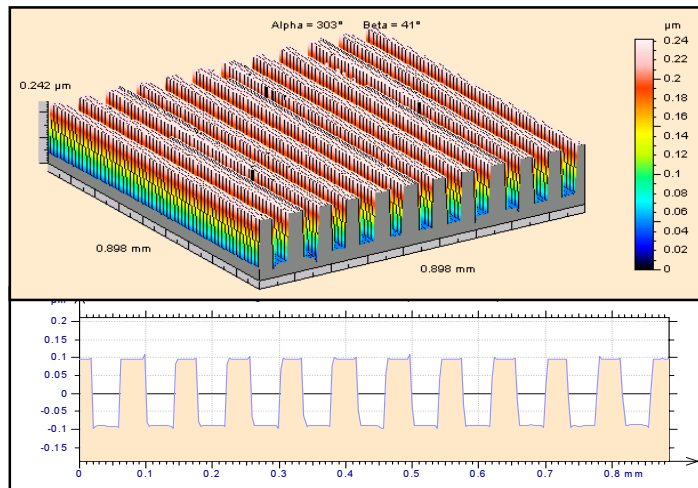
Figure 5 shows the data from the confocal system. Artifacts can clearly be seen at the edges of the steps and this gives a step height of

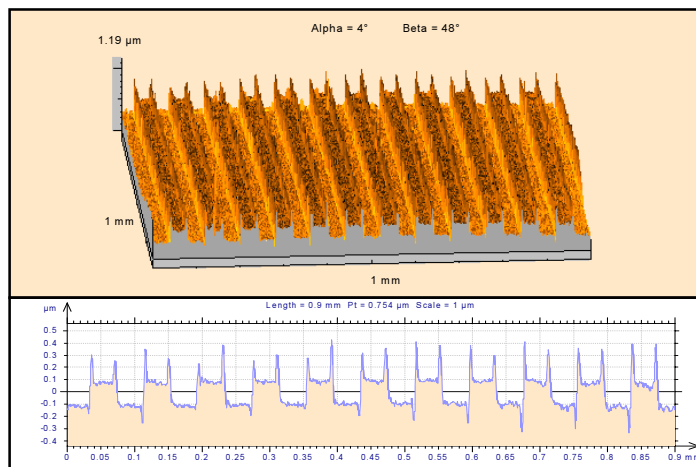Figure 4 White light interferometer measurement

Figure 5 Confocal Measurement

188 nm. The edge effects are due to pixels that fall at the edge of the step and can lead to errors. This artifact can give the situation where samples with the same step height but different width might give a different step height reading. The time taken to measure the sample was about 5 minutes, which opens up the possibility of drift during the measurement. This problem of drift is common issue with measurement techniques that need a long time to collect the information. Other confocal systems are able to able to carry out the measurement much more quickly and therefore are not as susceptible to this problem. Figure 6 shows data from a stylus system. The measured step height (187 nm) is close to the other two measurements and the measurement looks good. Stylus systems have been traditionally been used for single scan measurements but these single scan measurements are not always ideal to describe a surface. It is also possible to carry out 3D measurements of a surface with the

Figure 6 Stylus Measurement

stylus profiler and treat the data in the same way as the above measurements. The Stylus 3D measurements are a collection of individual scan lines and therefore can take a long time to collect. For example the measurement shown took about 30 minutes to complete. Because of the long scan times the environment needs to be very stable in order to avoid drift in the system. The other issue with the stylus is the problems with contact measurement on a surface. If the force of the stylus is too high it can scratch a surface and permanently damage it in less extreme cases the surface can be deformed during the measurement and recover when the stylus is removed.
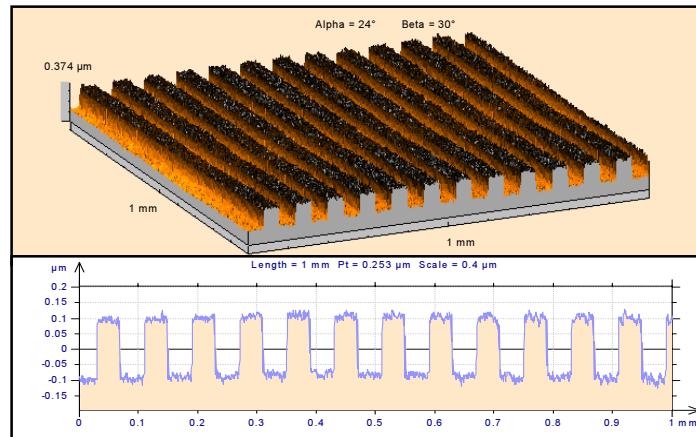
5. Scanning Probe Microscopy

Scanning probe microscopy (SPM) is a recent technology that relies on a mechanical probe for generation of magnified images. An SPM instrument is operable in ambient air, liquid or vacuum; and resolves features in three dimensions, down to a fraction of an angstrom. Most SPM microscopy resolves a magnified image using data obtained by scanning the sample surface with a sharp, microscopic mechanical probe. A scanning probe microscope (SPM) is comprised of a sensing probe, piezoelectric ceramics for positioning the probe, an electronic control unit, and a computer for controlling the scan parameters as well as generating and presenting images. Each of these subcomponents is discussed in the following sections, followed by a functional description of the entire instrument. An essential component in the SPM is a sensor with very high spatial resolution. These sensors can routinely sense height changes as small as 0.1 ångstrom. Two common types of sensors are tunneling sensors (STM) and force sensors (AFM). STM uses a tunneling sensor to measure the current passing between a metal probe and a conductive sample in extremely close proximity. Because of the quantum mechanical tunneling effect, electrons can be transferred from the probe to the surface, even though the two materials are not in physical contact. The main limitation of this technique is that the sample has to be conducting. Non conducting areas causes the tip to crash into the surface. Unlike STM, atomic force microscopy allows scanning of non-conductive samples. AFM can be divided into two primary scanning modes, contact and tapping mode. In the contact AFM method, the probe tip (which is mounted to the end of the cantilever) scans across the sample surface, coming into direct physical contact with the sample. As the probe tip scans, varying topographic features cause deflection of the tip and cantilever. A light beam from a small laser is bounced off of

the cantilever and reflected on to a four-section photodetector. The amount of deflection of the cantilever can then be calculated from the difference in light intensity on the sectors. Hooke's Law gives the relationship between the cantilever's motion, d, and the force required to generate the motion, F:

$$F = -kd.$$

The latest fabrication techniques mean that it is possible to fabricate a cantilever with a force constant, k, of 1 N/m or less. Since motion of less than one angstrom can be measured, forces of less than 10 piconewton are detectable. As the cantilever moves across the sample surface in contact scanning, the lateral motion of the cantilever may cause damage to soft or fragile samples such as biological specimens or polymers. Because of this phenomenon as well as a number of other variables, tapping mode is often preferable. In tapping mode operation, the cantilever is oscillated at its resonant frequency. In this mode, the change in amplitude of the oscillating cantilever at it moves close to the substrate is being detected. This mode leads too much lower forces

Figure 6 Schematic of an AFM

between the tip and the surface so there is less chance of damage of soft materials. Tapping mode is the most common AFM measurement used today. AFM is a commonly used metrology tool and the high lateral resolution mean that it is ideal for measuring sub micron features. However there are some of limitations of the method. The main limitation is the maximum area that can normally be measured is 100 microns. Other commonly observed problems with AFM are the time taken for a measurement (normally 2-5 minutes per measurement) and the observed repeatability of AFM measurements.

Near-field Scanning Optical Microscopy (NSOM) is a technique that enables users to work with standard optical tools that are integrated with Scanning Probe Microscope (SPM) technology. The integration of SPM and optical methods allows for the collection of optical information at resolutions well beyond the diffraction limit. A tapered, metal-coated, single-mode optical or special AFM tips can be used as the NSOM probe. The sub-wavelength size of the probe aperture, and the ability to control the probe-to-sample separation within the near-field region provides for high spatial resolution. Conventional optical components and detectors are used to collect and measure the various properties of the near-field signal, such as intensity, wavelength, etc. Thus, to clarify the NSOM experiment, a laser with chosen optical properties is used to pump light through the optical probe in order to generate the near-field signal. An SPM instrument scans the sample surface underneath the fibre optic probe aperture. Optical components such as mirrors, filters, and detectors of appropriate sensitivity are used to detect the near-field optical signal. NSOM is still a relatively new technique and few studies have been carried out using it as a metrology tool.

6. Conclusions

There are many different techniques currently available for surface metrology analysis. It is important to understand the properties of the sample, limitations of the technique used and the analysis required before carrying out the surface metrology.
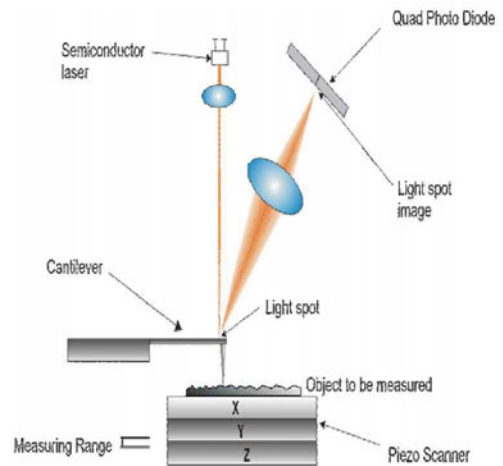
References

[1] Yu. N. Denisyuk, "Photographic reconstruction of the optical properties of an object in its own scattered radiation field," *Sov. Phys.-Dokl*. **7**, p. 543, 1962.

[2] Yu. N. Denisyuk, "On the reproduction of the optical properties of an object by the wave field of its scattered radiation," Pt. I, *Opt. Spectrosc*. (USSR) **15**, p. 279, 1963.

[3] Yu. N. Denisyuk, "On the reproduction of the optical properties of an object by the wave field of its scattered radiation," Pt. II, *Opt. Spectrosc*. (USSR) **18**, p. 152, 1965.

[4] Byung Jin Chang, Rod C. Alferness, Emmett N. Leith, "Space-invariant achromatic grating interferometers: theory (TE)," *Appl. Opt*., **14**, p. 1592, 1975.

[5] Emmett N. Leith and Gary J. Swanson, "Achromatic interferometers for white light optical processing and holography," *Appl. Opt*., **19**, p. 638, 1980.

[6] Yih-Shyang Cheng, Emmett N. Leith, "Successive Fourier transformation with an achromatic interferometer," *Appl. Opt*., **23**, p. 4029, 1984.

[7] Emmett N. Leith, Robert R. Hershey, "Transfer functions and spatial filtering in grating interferometers," *Appl. Opt*. **24**, p. 237, 1985.

[8] J. C. Wyant, "White Light Extended Source Shearing Interferometer," *Appl. Opt*., **13**, pp. 200-203, 1974.

[9] Yeou-Yen Cheng and J. C. Wyant, "Two-wavelength phase shifting interferometry," Appl. Opt. 23(24), pp. 4539-4543, 1984.

[10] Yeou-Yen Cheng and James C. Wyant, "Multiple-wavelength phase-shifting interferometry," Appl. Opt. 24(6). Pp. 804-807, 1985.

[11] Minsky M.: Microscopy Apparatus, U.S. Patent 3013467 (19 Dec. 1961, filed 7 November 1957)

[12] Minsky M.: Memoir on Inventing the Confocal Scanning Microscope, Scanning 10(4) (1988), 128-138

[13] Jordan H.-J., Wegner M., and Tiziani H., "Optical topometry for roughness measurement and form analysis of engineering surfaces using confocal microscopy", *Progress in Precision Engineering and Nanotechnology*, Kunzmann H., Wäldele F., Wilkening G., Corbett J., McKeown P., Weck M., Hümmler J. (Eds.), Vol.1, 171-174, Physikalisch-Technische Bundesanstalt Braunschweig und Berlin, Braunschweig / Germany, 1997

[14] Jordan H.-J., Wegner M., and Tiziani H., "Highly accurate non-contact characterisation of engineering surfaces using confocal microscopy", *Meas. Sci. Technol.* **9**, 1142-1151, 1998

[15] Wilson T., *Confocal Microscopy*, Academic Press, 1990

[16] Jordan H.-J., Brodmann R., "Highly accurate surface measurements by means of white light confocal microscopy", *X. International Colloquium on Surfaces*, Dietzsch M., Trumbold H. (Eds.), 296-301, Shaker Verlag, Aachen, 2000

[17] Hamilton D K and Wilson T 1982 Three-dimensional surface measurement using the confocal scanning microscope *Appl. Phys.* B **27** 211

[18] Carlsson K and Aslund N 1987 Confocal imaging for 3-D digital microscopy *Appl. Opt.* **26** 3232

[19] Massig J H, Preissler M, Wegener A R and Gaida G 1994 Real-time confocal laser scan microscope for examination and diagnostics of the eye *in vivo Appl. Opt.* **33** 690

[20] Hamilton D K and Wilson T 1982 Surface profile measurement using the confocal microscope *J. Appl. Phys.* **53** 5320

[21] Xiao G Q and Kino G S 1987 A real-time confocal scanning optical microscope *Proc. SPIE* **809** 107

[22] Xiao G Q, Corle T R and Kino G S 1988 Real-time confocal scanning optical microscope *Appl. Phys. Lett.* **53** 716

[23] Petran M, Hadravsky M, Egger M D and Galambos R 1968 Tandem-scanning reflected-light microscope *J. Opt. Soc. Am.* **58** 661