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Short communication

Measurement of thin coatings in the confocal microscope

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Abstract

The use of the confocal microscope for measurement of the thickness of thin transparent coatings, such as the varnish layer on compact discs, is described. The relationship between true and apparent thickness varies in a non-linear fashion, but intensity profiles show a good correspondence with calculated profiles. This provides the basis of a nomogram for prediction of coating thickness. © 2001 Published by Elsevier Science Ltd.

There are many important applications for measurement of film thicknesses in the range of a few microns to several tens of microns, including those in the semiconductor and polymer industries. One such application is in the manufacture of compact discs, audio or CD-ROM. The CD is pressed from the non-reading side, which is then given a coating of aluminium and a protective varnish coat (Fig. 1). The varnish is applied as a drop to the centre of the spinning disc, centrifugal force then spreading it out into a uniform coating. For this to give the required result, precise quality control is vital. We were asked by a compact disc manufacturer to investigate the possibility of using confocal microscopy as a quality control tool, to measure variations in coating thickness between the inside and outside regions of the disc.

Usual optical techniques for measurement of thin film thickness are based either on absorption, or interference between reflections from the top and bottom surfaces (Wesson et al., 1967). Interferometry exhibits an ambiguity problem for layers thicker than half a wavelength (Françon, 1966) which can be overcome by using two wavelengths, or even white light, or by changing the effective wavelength by tilting the sample relative to the beam (Matsuda and Namiki, 1988). These methods, however, require the lateral extent of the layer to be large, whereas we needed to measure the thickness of the layer in the small areas between pits (Fig. 2), so that an imaging system was necessary. The three-dimensional imaging capability of confocal microscopy offers an alternative approach to measurement of the layer thickness.

Coatings were measured using a BioRad MRC 600 confocal system on a Zeiss Axiophot microscope using 488 nm argon laser illumination and a x50, 0.85 NA Epiplan objective. The pinhole was closed to its minimum size. Fig. 2a presents a conventional *xy* view (an extended focus image from a stack of optical sections) of the upper (coated) part of the disk, showing several imperfections in the varnish coating. A vertical (*xz*) optical section from the mid-line of this image is shown in Fig. 2b. The *xz* section of the CD surface (Fig. 2b), shows a complex pattern of intensity distributions, particularly at the aluminised surface. Fig. 3 shows representative plots of the intensity profile through the layer from two different regions of a disk. Images of this sort (*xz*) can be 'cleaned up' to show a single line of maximum intensity by applying a simple erosion algorithm (Cox and Sheppard, 1999). On a simple basis, one might then assume that an 'apparent depth' correction based on refractive index (Visser et al., 1992; Hell et al., 1993; Visser and Oud, 1994; Sheppard and Török, 1997; Cox, 1998) would be adequate to predict the film thickness.

However the reality is far more complex. The axial image of the thin film structure can be calculated using

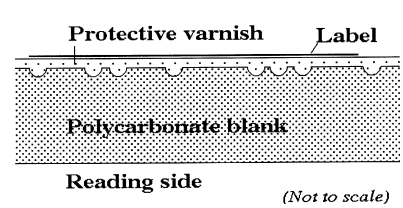

Fig. 1. Diagrammatic view of the structure of a compact disc.

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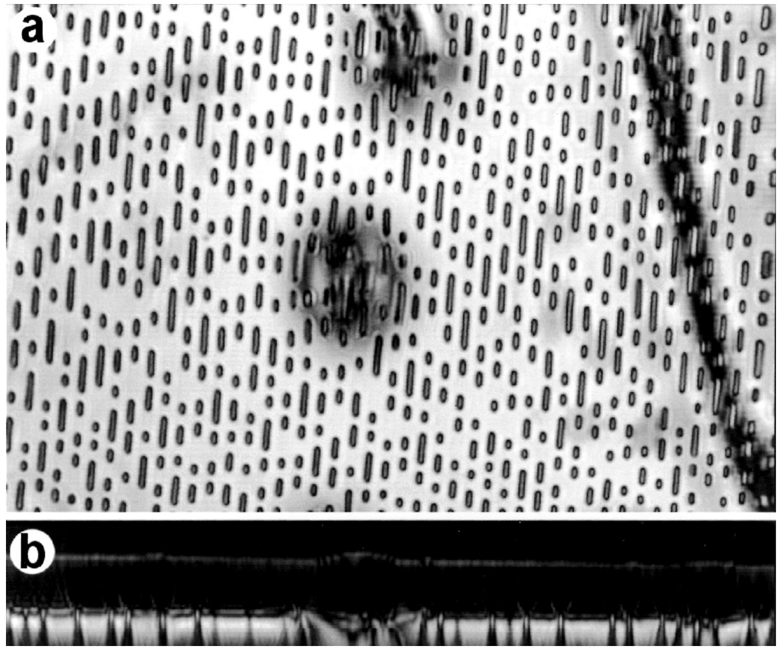

Fig. 2. (a) Surface view (extended focus image) of the upper surface of a faulty compact disk. Several blemishes are visible in the varnish coating. (b) *xz* section taken from the midline of the image in (a). The images of the pits are very complex, emphasizing the need to measure the coating thickness in smooth regions. The perturbing effect of the 'blister' in the coating is also evident in the apparent depression of the alumised surface beneath it.

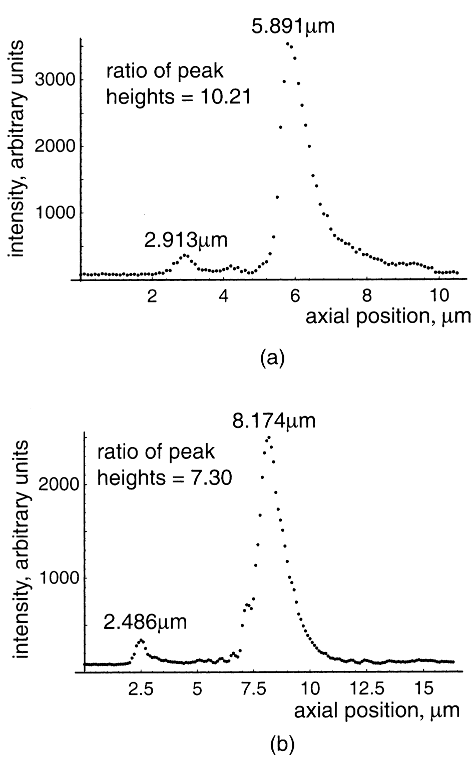

Fig. 3. Measured axial intensity variation for $\lambda = 488$ nm and 0.85 NA on two disks with different coating thicknesses. The data points correspond to individual voxel values, the spacing of which is limited by the precision of the stepper motor. The positions of the peaks were therefore derived by parabolic interpolation from the data points. The ratio of the peak heights is another feature which can be compared with theoretical predictions.

an angular spectrum approach. The reflection coefficient for the thin film is calculated as usual (Born and Wolf 1975), taking into account multiple reflections, and is then integrated over the different illumination angles (Sheppard and Gu, 1992; Sheppard et al., 1994a,b). This method fully takes into account polarization effects, assuming plane-polarized illumination and detection without an analyzer. In the theoretical results presented, we assumed that the lower surface of the varnish, an interface with aluminium, is a perfect reflector. This simplifies the computation and produces little change to the profiles. The refractive index of the varnish was taken as 1.508. The objective is assumed to satisfy the sine condition, to have an aperture stop in its back focal plane, and to be aberration-free. The pinhole is assumed to be very small. If the layer is thin, less than 5 μm, interference effects dominate, displacing the peaks, especially the reflection from the top surface, considerably from their geometric positions, as seen in Fig. 4. The relationship between real and measured thickness, as shown in Fig. 5, becomes a rather jagged line. Nevertheless, the true thickness can be estimated to within about a wavelength (0.5 μm). When the thickness is larger, spherical aberration effects come into play and the peak can become doubled (Fig. 6). At thicknesses either side of these double-peak values peak hopping takes place, and one or other peak can be higher. This limits accuracy of the thickness measurement to about 1 μm. Similar peak hopping has been observed previously in theoretical investigations (Sheppard et al., 1994b; Sheppard and Török, 1997). Oil and water

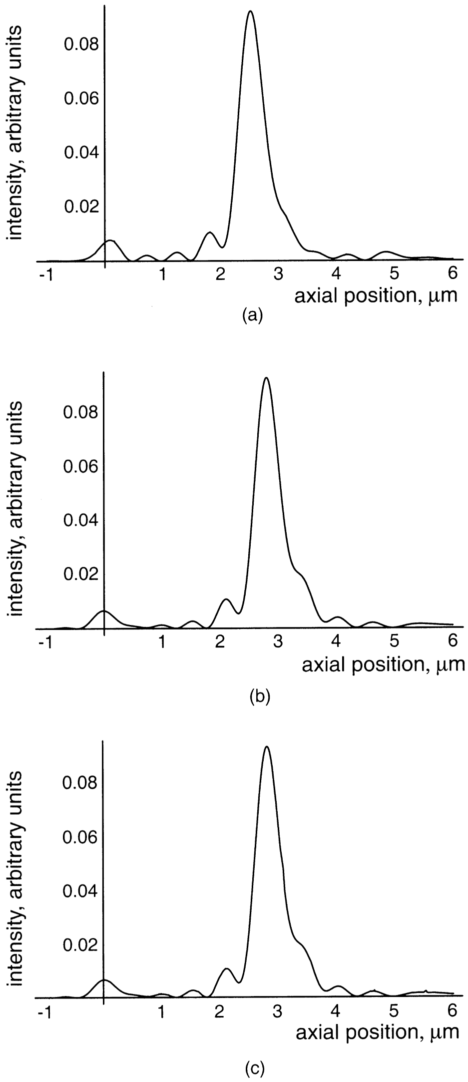

Fig. 4. Calculated axial image for $\lambda = 488$ nm and 0.85 NA for coatings of thickness (a) 4.5 mm, (b) 5.0 mm, (c) 5.5 mm. The position of the top reflection (left-hand peak) is seen to shift as a result of interference effects.

immersion objectives were tried, in order to reduce the effects of spherical aberration, but then the reflection from the top surface became too weak to locate accurately.

How well do these results match the theoretical calculations? Comparing Fig. 3a with Fig. 4c, and Fig. 3b with Fig. 6c, one can see that the relationship is not perfect but in general their shape agrees well, so that one can have considerable confidence in the theory. Using the predictions of Fig. 5, our estimates of the thicknesses of the layers in Fig. 3 are, for (a) 5.27 ± 0.22 μm, and for (b) 10.08 ± 0.41 μm.

What effect does using a lens of lower numerical aperture have? Sheppard et al., 1994b found that 'the resolution limit is similar for both values of numerical aperture…being actually slightly better for the lower numerical aperture…'. This is so because spherical aberration is reduced at the lower numerical aperture. In practice the peak spread with the lens of lower numerical aperture is so wide that the reflection from the true surface appears as a shoulder, though the apparent thickness is similar in both cases (Fig. 7). While the calculated intensity profile from the lens of lower numerical aperture is simpler, the measured thickness (~3 μm) is almost impossible to assign to a true value since it might correspond (Fig. 8) to either 3.5 μm or 4.5 μm! In fact a lens of higher numerical aperture, while giving a more complex image, is essential for meaningful measurements.

Measurement of thin layers of this sort is an important task in many branches of industry. Calculations of nomograms such as those shown here, together with comparison of the experimental and theoretical images, provides the means to make measurements accurate to about 0.5 μm for layers in the range of about 3.5–8 μm, and to about 1 μm for thicker layers. However for layers thinner than about 3.5 μm an unique interpretation may not exist, and here measurement at more than one wavelength is essential.

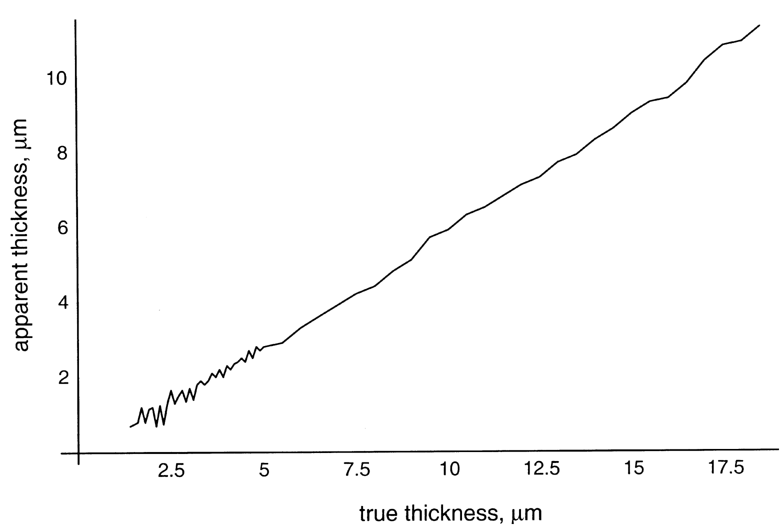

Fig. 5. The calculated dependence between real and apparent thickness, for $\lambda = 488$ nm and 0.85 NA.

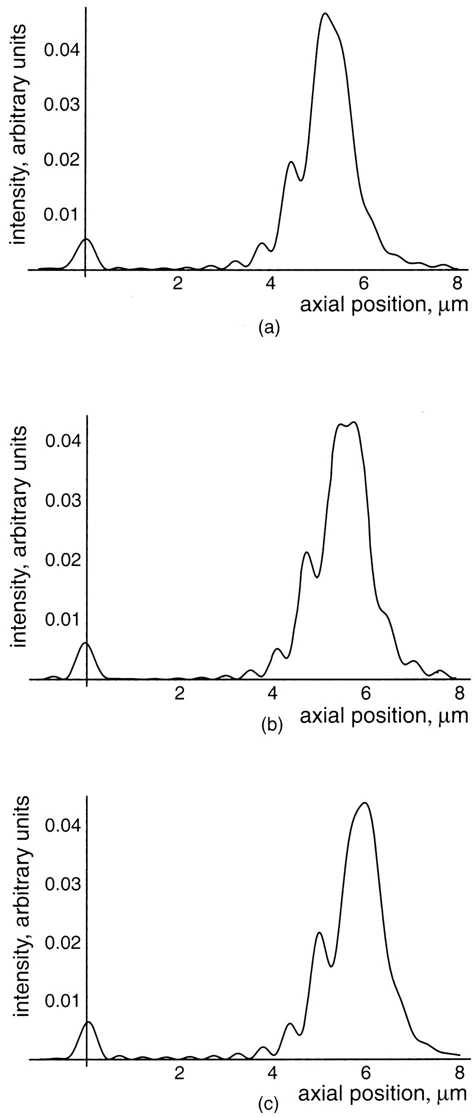

Fig. 6. Calculated axial image for $\lambda = 488$ nm and 0.85 NA for coatings of thickness (a) 9.0 mm, (b) 9.5 mm, (c) 10.0 mm. In (b) a double peak is seen, while peak hopping is observed between (a) and (b).

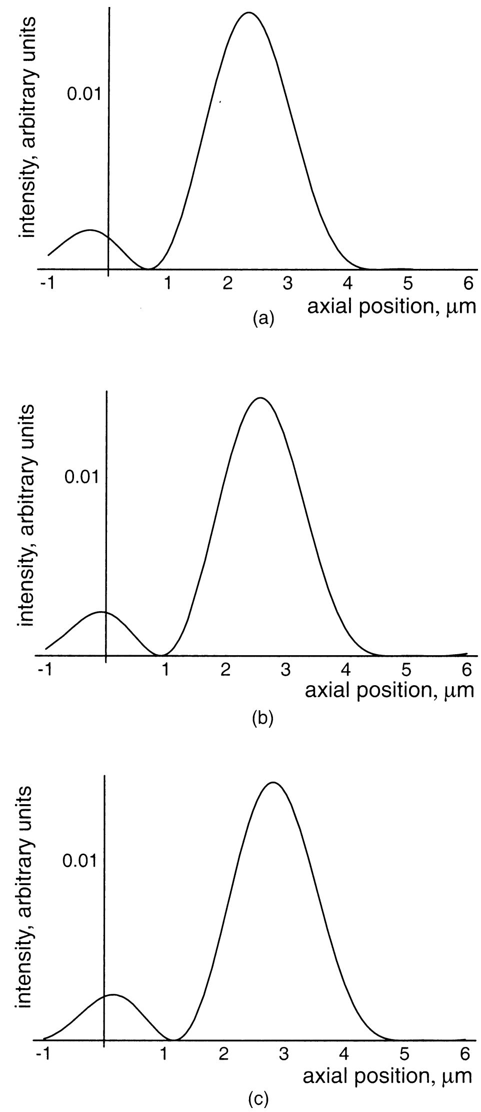

Fig. 8. Calculated axial image for $\lambda = 488$ nm and 0.5 NA for coatings of thickness (a) 3.5 mm, (b) 4.0 mm, (c) 4.5 mm.

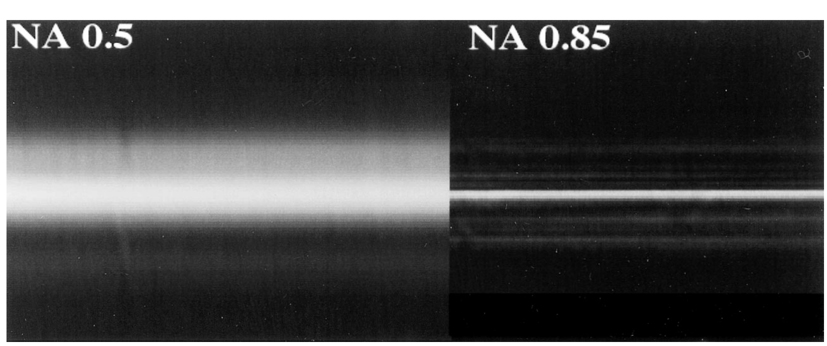

Fig. 7. Experimental *xz* images produced using lenses of numerical aperture: (a) 0.5, and (b) 0.85, $\lambda = 488$ nm.

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