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APPLICATIONS OF ATOMIC FORCE MICROSCOPY IN OPTICAL DISC TECHNOLOGY

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Introduction

Since its introduction in Japan and Europe in 1982 and in the United States in 1983, the compact disc (CD) has become the dominant digital storage medium due to its large storage capacity, fidelity, and low cost. CD-ROMs, with a storage capacity of 680MB, are now the media of choice for the distribution of read-only software in the western world. Current applications which require 35 floppy discs at 50MB can be placed on a single CD-ROM utilizing less than 8% of its capacity. Worldwide production for 1996 was about 5.5 billion CDs and is expected to be 7.9 billion in the year 2000[1].

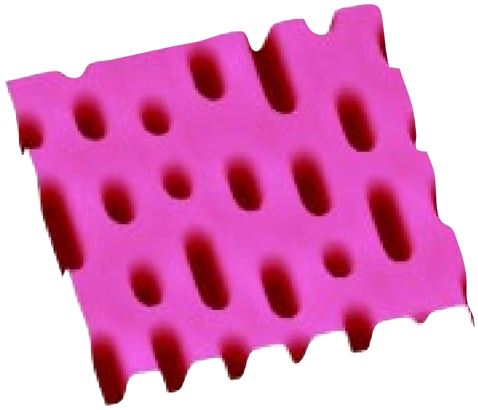


Figure 1: TappingMode™ AFM image of CD surface. 10µm scan.

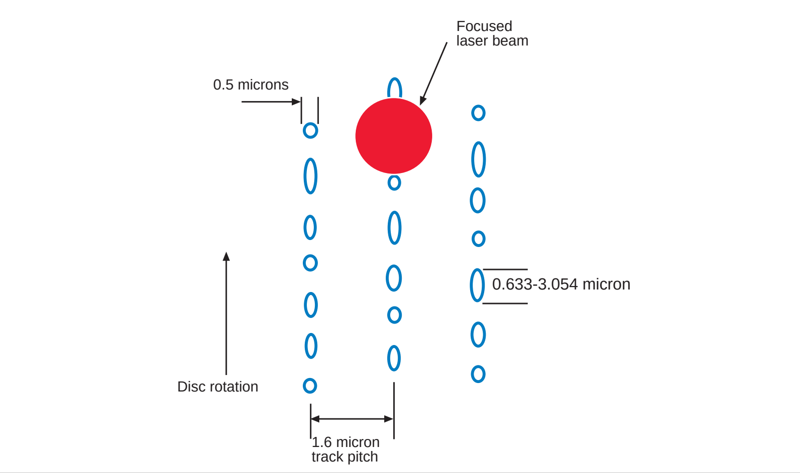


Figure 2: Compact disc data surface.

CD and CD-ROM

The CD pit (Figure 1) that forms the digital data is one of the most miniature mass-produced details on any product in the world today. The discs are made by injection-molding polycarbonate thermoplastic resin and the pits are formed by insertion of a nickel "stamper" into the mold. The stamper's surface consists of bumps of nine different lengths, which then form pits in the "replica" disc, or CD. Current CD and CD-ROM formats contain up to two billion pits per disc (Figure 2), with injection molding cycle times ranging from about three to five seconds per replica.

After molding, the pit surface is metallized to produce a surface that reflects a laser beam to a sensor for reading. After metallization, a UV-cured lacquer coat is applied to protect the soft metal surface. Lastly, the disc label is printed on the lacquer (top) surface, as shown in Figure 3.

Pit fidelity is a determining factor for the playability of a disc and the error rate of the disc. The final CDs produced for sale are not free of defects. Defects in the pit surface may be caused by mastering errors, stamper defects, and manufacturing

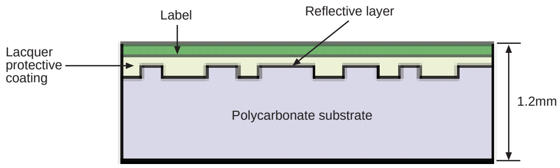


Figure 3: Compact disc cross-section.

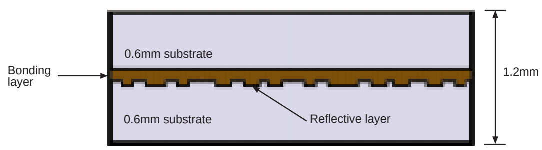


Figure 4: DVD cross section.

(molding) defects. An elaborate error correction scheme with data redundancy is utilized to allow the compact disc to offer robust performance in the presence of some errors. Atomic Force Microscopy (AFM) has proven to be a valuable tool for manufacturers to identify defects and their causes on both the stamper and disc surfaces.

DVD

The new high-density DVD format offers enhanced storage and performance for consumers, but also adds new challenges for optical storage media producers. The initial single-sided, single layer DVD product has a storage capacity of 4.7GB (about seven times that of a CD). With this large data capacity, DVD can deliver a full-length, studio-digital-quality movie, as well as improved computer multimedia graphics. Along with the increased data capacity, comes the added challenges for optical disc producers to mold and analyze discs with smaller pits and reduced track pitch. The DVD format consists of two 0.6mm-thick discs which are bonded together. This new thinner disc substrate creates further challenges to produce quality discs. Figure 4 shows the DVD disc cross-section. Table I compares the CD audio/CD-ROM format with the DVD format.

Advantages of AFM and TappingMode™

Optical disc manufacturers continue to push for faster cycle times to increase capacity while maintaining disc quality. This creates the need for improved methods to analyze the quality of the disc and stamper surfaces. AFMs are ideally suited to the characterization of nanometer-sized pit and bump structures in CD and DVD manufacturing. AFM provides quantitative, three-dimensional imaging of the disc or stamper surface within minutes. Similar quantitative information is possible using SEM or TEM, but these techniques are destructive, time consuming, measure in only two dimensions, and provide a limited field of view. Another major advantage of AFM over other techniques is that once an image is captured, cross-sections can be obtained in seconds to provide pit depth, pit width, pit

Feature	DVD	CD
Disc diameter	120mm	120mm
Disc thickness	0.6mm x 2	1.2mm
Number of sides	2	1
Number of layers	1 or 2	1
Smallest pit size	0.4µm	0.834µm
Track pitch	0.74µm	1.6µm
Laser diode wavelength	650/635nm	780nm
Lens numerical aperture	0.6	0.45
Playtimer	133 min./side	74 min.

Table 1: Compact disc vs. DVD feature comparison.

side-wall angle, and track pitch anywhere in the data set – and without physically damaging the disc (Figure 5).

For pit characterization with AFM, the discs may be examined after molding and before metallization. Representative three-dimensional AFM images of CD and DVD stamped discs (replicas) are compared in Figure 6. Both images were obtained at the same lateral magnification; the increased pit density and reduced track pitch for DVD are readily apparent. The types of measurements which AFM can provide for CD and DVD characterization are listed in Table 2.

For this application, TappingMode AFM (patented by Digital Instruments) is preferred over conventional contact mode AFM for three important reasons. First, the silicon probe tips have smaller opening angles (i.e., steep sidewalls) for more accurate sidewall and pit depth measurements. Note that the accuracy of these measurements requires prior calibration with suitable standards, as well as consideration of the probe tip shape.

Second, the lateral shear forces in TappingMode are minimal; with contact mode these forces can lead to sample damage or surface alteration during scanning.

Lastly, TappingMode avoids the tip-sample electrostatic attraction problems associated with contact mode imaging of glass masters, which can also lead to measurement artifacts.

Examples of Disc Problem Analysis with AFM

The following discussions demonstrate situations in the mastering of stampers and the manufacture of quality optical discs where AFM has been utilized to isolate and correct the cause of disc defects. Dimension™ Series Scanning Probe Microscopes with CD/DVD adapter set were used to generate the images and measurements in this application note.

High Error Rate at Beginning of Play

High error rates were observed in the digital output signal of discs molded on several presses. Error rates gradually decreased as the discs were played toward the outside

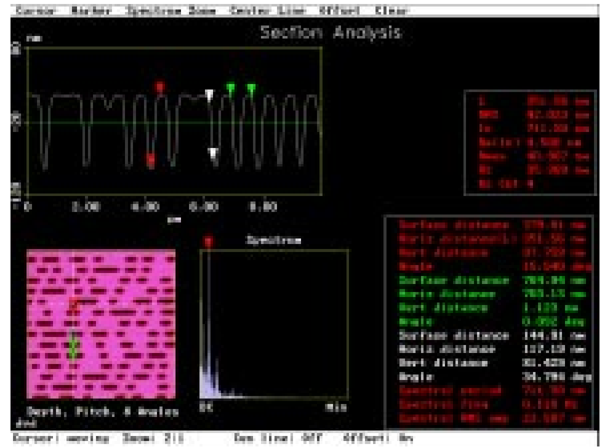
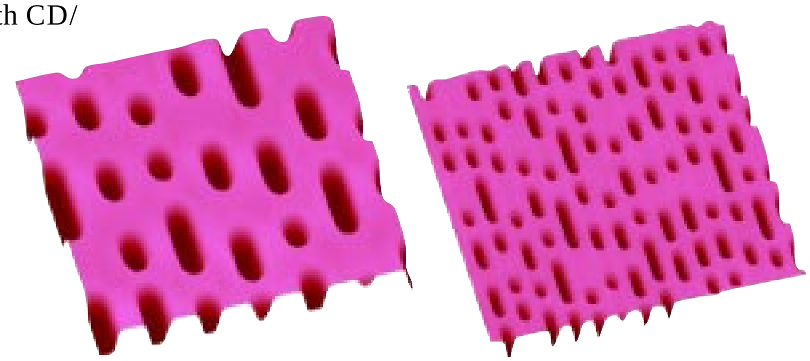


Figure 5: Cross-sectional analysis of DVD disc (Figure 4b).



a

b

Figure 6: TappingMode AFM perspective images of a) CD disc and (b) DVD disc. 10µm scans.

Pits (disc)	Bumps (stamper)	Tracks
Depth	Height	Pitch
Width	Width	
Left/right sidewall angle	Left/right sidewall angle	
Roughness of pit floor	Roughness of bump surface	

Table 2: CD and DVD measurements readily accessible by AFM. Note that the position at which the width is measured will have to be determined depending on the ability of the tip to measure sidewall angles accurately.

edge; however, in some severe cases the disc would not play at all. When the molded polycarbonate disc replica was examined with AFM it was found that the pits were severely smeared, which rendered the discs partially or totally unreadable (Figure 7).

The most severe smearing was observed at the inside portion of the information area, and was gradually eliminated approaching the outside of the disc. The stamper utilized to press these discs was then also examined by AFM, but the AFM images of the stamper did not display any smearing. Further AFM analysis of the molded disc at several locations around the disc revealed smearing occurred at different directions depending on the position and orientation to the polymer flow on the disc. Smearing was directed towards the center of the disc at 12 o'clock. At 3 and 9 o'clock it was oriented diagonally, pointing to the 6 o'clock position on the disc where there was little or no smearing at all.

The average length of the smeared area was measured to be between 1.5 and 2µm. Prior to AFM imaging of the stamper and discs, it was suspected that the two halves of the mold were shifting vertically relative to each other upon separation. However, it would be unreasonable to expect better than micrometer mechanical stability from the mold set. The AFM imaging subsequently lead the production staff to examine the mold cooling channels and related equipment. It was discovered that the efficiency of the cooling channels had deteriorated, resulting in the discs being separated from the stamper while they were too soft due to inadequate cooling in the area of smearing. AFM played a key role in the analysis of this problem and determining its cause.

Microscopic smearing of pits as seen by the AFM can manifest itself as a stain on the disk surface which can be seen under reflected-light. In the optical disc industry, this staining phenomenon is variously referred to as smearing, clouding, sticking, or ghosting.

Pit Morphology and Block Error Rate (BLER)

Visible disc staining may or may not indicate playability problems. Figure 8 shows a reflected-light optical image of a disc which was deliberately processed at an excessive temperature and short cooling time to induce severe staining. Severe staining is observed near the hub and to a lesser extent around the perimeter.

Much of the staining is cosmetic and does not lead to playability problems. Evaluation of this particular disc revealed very high BLER that *would* lead to

Figure 7: An example of pit smearing leading to poor playability on an audio CD. 7.3µm scan.

Figure 8: Reflected light image of a severely stained CD.

playability problems. The yellow shaded area located within a severely stained area exhibits very high BLER (Figure 9).

TappingMode AFM images of this disc were obtained from visibly stained areas with [C] having extremely high block error rates and [B] substantial block error rates. In region [A] no visible staining was observed and lower block error rates were measured (Figure 9). The corresponding images in Figure 10 show changes in the CD pit structure which accompany both the observable (by eye) staining and BLER measurements.

In Figure 10a, the pit structure is uniform and replicates the stamper accurately. In Figure 10b, the pits are locally deformed with polycarbonate piled up or smeared toward the perimeter of the disk. This deformation is manifested as visible staining and can lead to high block error rates depending on degree. In Figure 10c, the polymer surface is severely distorted and some of the pits are barely recognizable.

In the lands (surfaces surrounding pits), the polymer appears to have stuck to the stamper during disc ejection leading to severe deformation. Note that the molding conditions used here to demonstrate severe staining are atypical; area [C] in particular represents surface deformations which are rarely seen in actual disc production.

Track Pitch Variations

Variations in track pitch on an optical disc cause crosstalk on the output signal and, in extreme cases, poor playability. Track pitches which are too low cause high crosstalk. Track pitches which are too high may cause the player to lock into a track. Variations in track pitch generally occur during the recording of the glass master. These anomalies in track pitch are then transferred to the stamper during the manufacturing steps. Because of its resolution, AFM can detect small anomalies in track pitch with a quick and simple measurement (Figure 5, green).

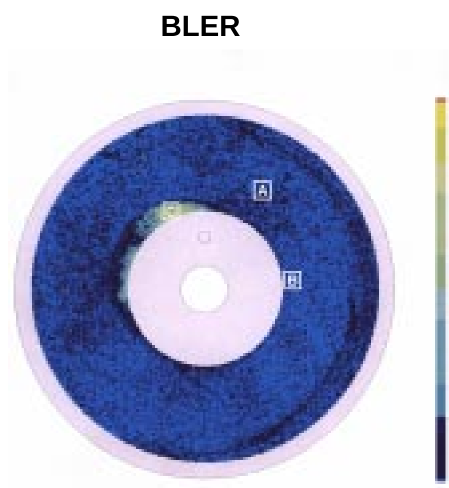


Figure 9: BLER map of the disc in Figure 8 (very high BLER indicated in yellow).

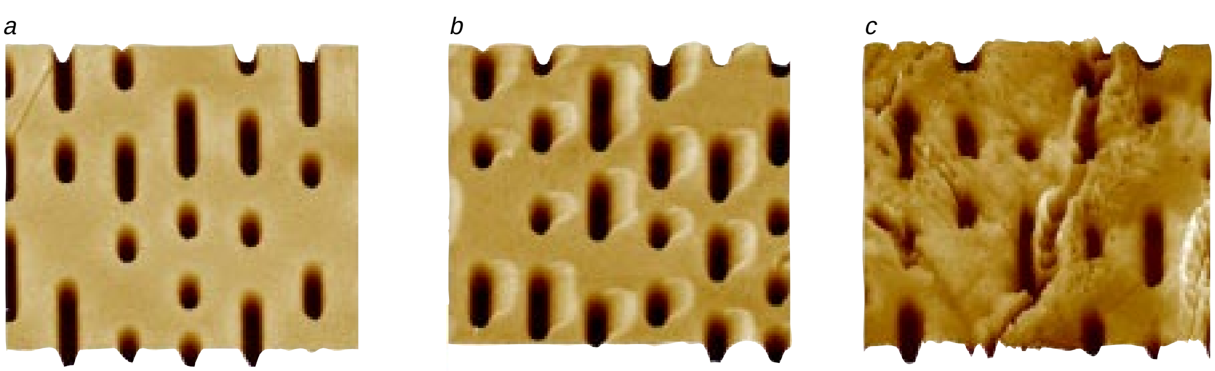


Figure 10: TappingMode AFM images of disk surface corresponding to regions labeled in Figure 9. 10µm scans.

Pit Depth Monitoring

The depths of the molded information pits affect the amplitude of the output signal from the disc. If the depth is too low, the signal becomes too weak and if the depth is too high tracking problems may occur on certain types of players. With its sub-nanometer resolution in the *z* direction, pit depth measurement is easily done with AFM and yields very accurate and repeatable results (Figure 5, red).

Automated Software for Process Monitoring

Because optical disks are made in large quantities with high through-put, quality needs to be monitored in a fast, repeatable, and automated fashion. One of the goals of pit monitoring is to maintain uniformity in pit parameters, including width, height/depth, pitch, and sidewall angle. Automated CD/DVD analysis using a Dimension DVD3100 AFM is dedicated to rapid measurement of these parameters. The system uses a "recipe" file which directs the system to capture AFM data rapidly at predetermined scan sites, analyze the data to determine pit statistics, and generate formatted output of statistical calculation and graphical presentation (cross-sections, histograms etc).

Summary

With its ease of use, three-dimensional measurements, rapid analysis, and minimal sample preparation, AFM is an invaluable analytical tool for evaluating the nanometer-level detail on stampers and molded optical discs. AFM becomes an even more valuable tool for evaluation of the new DVD format with its smaller track pitch and pits.

The patented TappingMode AFM technique is recommended for this application because it offers a more reliable image of the stamper or disc surface due to the increased sharpness of the probe tips used for this technique. This mode also reduces shear and electrostatic forces which eliminates the chance for sample damage or measurement artifacts. Using TappingMode, Dimension Series Scanning Probe Microscopes are ideally suited for rapid, reliable measurement, imaging, and problem solving for CD and DVD discs.

Additional literature and/or information on contract labs performing AFM analyses for CD/DVD are available on request from Digital Instruments.

Reference

[1] "CD Watch CD Survey Situation" Understanding & Solutions, 95-99, November 1996.

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