Using Atomic Force Microscopy to Characterize Optical Disc Topography

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Atomic Force Microscopy (AFM) is a high-resolution imaging technique used to create topographic maps of sample surfaces. In Constant Force AFM, a tip mounted on a cantilever maintains constant contact with the surface and the height adjustments of the cantilever necessary to procure this equilibrium are used to reconstruct the sample's topography. This technique is highly effective for studying a wide variety of samples, such as optical discs, devices that store media information in their surface topography. This paper details the characterization of three types of optical discs, as well as an investigation of the effects of physical damage on information storage capabilities. With the use of AFM and Gwyddion software, it is shown that there is an increase in information storage capacity from CD to DVD to Blu-ray optical discs, and that physical damage can destroy the data stored in disc topography.

I. Introduction

Atomic Force Microscopy (AFM) is a high-resolution imaging technique that uses a sharp, nanoscale tip to probe the surface of a material. In AFM imaging, a tip mounted on a cantilever (an arm that extends out above the sample) interacts with the sample surface through atomic forces and physical contact. Tip interactions are quantified by the deflection of a laser off of the top of the cantilever to a photodiode detector. When the tip's displacement changes due to varying regional conditions, the cantilever warps and the laser deflects to a different location. The varying deflection positions are recorded throughout scanning and are used to reconstruct a topographic map of the sample surface [figure 1][1-3].

Constant-force AFM, or contact mode AFM, is a non-destructive, highly precise form of this technique. In constant force mode, the instrument maintains a constant force between the tip and the sample surface, thereby preserving the distortion of the cantilever. This is achieved by continuously adjusting the height of the cantilever as the tip moves across the sample using feedback from the laser beam's position on the photodiode. These height adjustments are then used to create a detailed map of the surface topography. Although slower than constant-height AFM due to the need for real-time feedback adjustments, Constant Force mode is highly advantageous for acquiring accurate and reproducible measurements and minimizing sample damage.

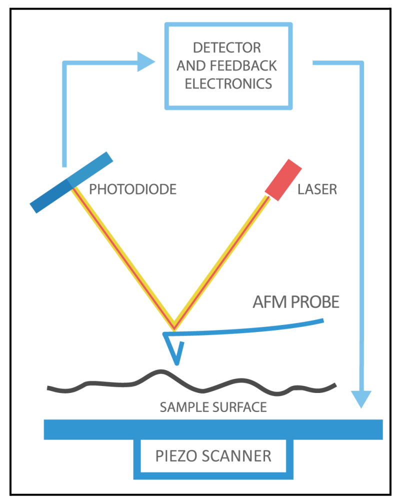

Figure 1: Constant Force AFM Schematic [4]

We will be applying this technique to study information storage on optical discs, such as CDs and DVDs. Optical discs work by using small divots in a polycarbonate surface to represent binary code. Changes in surface heights represent binary ones and constant surface heights represent binary zeros. A reflective layer, typically made from aluminum, is added next to the polycarbonate layer so that changes in height can be read by a laser in a disc reader [5-7]. Divots in the surface are called "pits" and spaces between divots are called “lands” [figure 2A]. Pits and lands are engraved into optical discs in a spiraling pattern, with information moving from the center outwards [figure 2B]. Through this process of encoding binary information, each disc’s topography can hold large amounts of data.

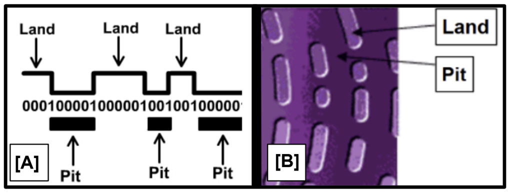

Figure 2: Visualization of Optical Disc Data Storage [5]

With the use of AFM, our group studied the different information storage densities of three types of optical discs (CD, DVD, and Blu-ray) and inspected the effects of scratches on disc function. First, we quantified the variations in disc information density by obtaining AFM scans of each disc’s surface. We used these scans to measure parameters such as pit width and track pitch and compared our results with the accepted values for each optical disc type. Then, we compared two disc samples, one with its initial state preserved and the other which had been damaged with a razor, to see how the mishandling of these discs can impact data integrity.

II. Experiment

To pursue this experiment, we used the Thorlabs Educational Atomic Force Microscope kit. In figure 3, this kit can be seen, with the laser, detector, and sample platform highlighted in red, green, and yellow respectively.

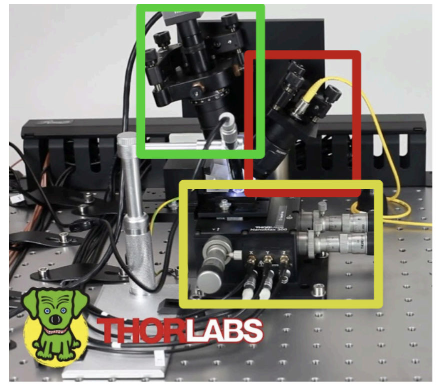

Figure 3: Thorlabs AFM Equipment [8]

This kit supplies optical disc samples that don't feature the encapsulation (label and plastic) layers typically featured [figure 4]. This allows the AFM probe to directly interact with the pits and lands during a scan.

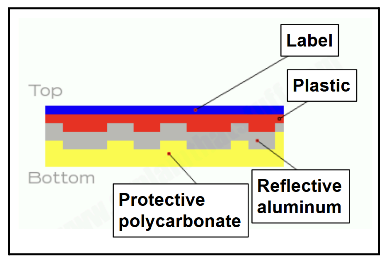

Figure 4: Illustration of standard layers of Optical Disc [9]

We began the experiment by fixing a Pt/Ir probe to the instrument’s cantilever by loosening a screw, inserting the probe using tweezers, and re-tightening the screw. Next, we aligned the laser with the cantilever by turning it on to a power of 0.1mW and turning its adjustment dials.

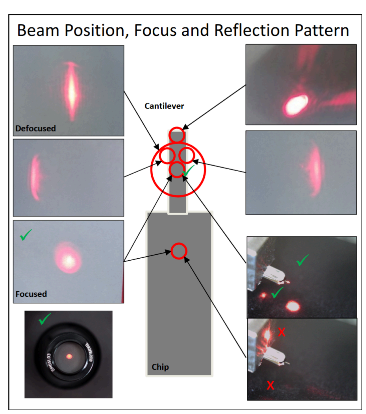

Figure 5: Guide on laser alignment

Once the laser was focused and directly hitting the cantilever [figure 5], we increased the power to 2.5mW and began detector alignment. While adjusting the top dials, we monitored the detector's state in the interface software, EDU-AFM [figure 6]. We specifically watched the values of XDiff and YDiff, which represent the distance of the laser from the cantilever lengthwise and widthwise respectively. We calibrated YDiff to be near 0V (to keep it as close to the center as possible) and XDiff to be near -0.1V, an agreed value that yields a stable pin-sample connection [6].

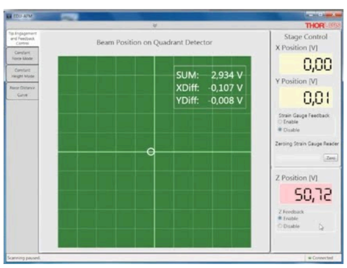

Figure 6: Tip engagement interface

After laser and detector alignment, the sample was loaded on the sample platform beneath the probe and the Z feedback necessary for constant force mode was engaged [figure 6]. This enabled us to raise the platform using the middle dial [yellow box, figure 3] until probe-sample contact (indicated by XDiff and YDiff locking at 0V and a decrease from the Z-position set value (50 V)). We ensured that the Z-position value decreased below 50V, but did not decrease below 0V, as this could cause damage to the probe.

Once the instrument set up process was complete, we began scanning by switching to the "Constant Force Mode" tab on the left [figure 6] and selecting our parameters. We chose a resolution of 250x250 pixels at a rate of 50 pixels/s (pps) for the CD and DVD samples, covering an area of approximately $5\mu m \times 5\mu m$. For the Blu-ray sample and the damaged DVD sample, we increased the scan speed to 100 pps and the area to approximately $12\mu m \times 8\mu m$ for the latter to increase our chances of observing a damaged area.

After performing these scans, we used Gwyddion analysis software to clean and analyze our data. Gwyddion is a widely used software that is specifically designed to aid in AFM image analysis. Our initial data featured noise and visual artifacts that we were able to remove using Gwyddion's polynomial filtering of degree one. We also used Gwyddion's interface to remove visual blemishes and horizontal lines present in some scans.

The data displayed in each initial scan is representative of piezo voltage. To create a topographic map of our sample's surface, we subtracted the data from the maximum measurement present and inverted the resulting values [figure 7]. One dimensional cuts from each topographic map allow for careful analysis of each sample's data structure.

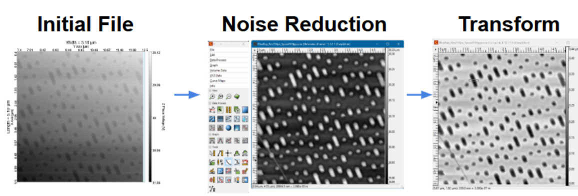

Figure 7: Noise Reduction and Transform using Gwyddion

III. Results

Section 1 - Investigation of Varying Information Densities: Our results give insight into the nature of data storage in the topography of each disc. Figure 8 shows topographic scans alongside 5 micrometer long one dimensional data cuts for both the CD and Blu-ray samples. Figure 9 shows a corresponding 3D rendering of each sample's topography.

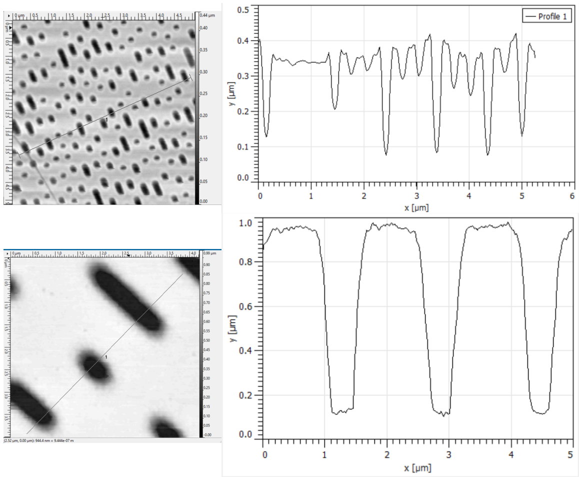

Figure 8: Top image shows topographic scan of the Blu-ray disc, alongside a graph of a 1D cut of data. Bottom shows topographic scan of the CD, alongside a graph of a 1D cut of data

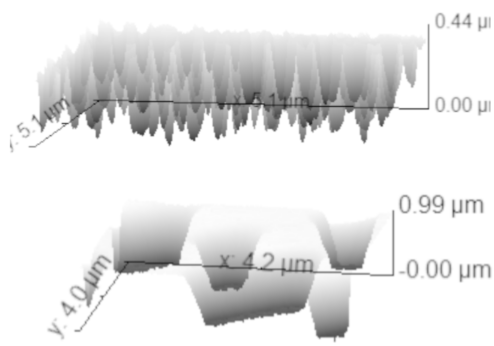

Figure 9: Top shows a 3D rendering of the Blu-ray topography. Bottom shows a 3D rendering of the CD topography.

Qualitatively, Figure 8 shows that despite the similarity in image size, there are clearly far more pits/features in the Blu-ray disc as compared to the CD. Both the pits and the spatial separation between pits in the CD sample are significantly larger for the DVD samples. In addition, the track pitch on the CD is much larger than that on the Blu-ray, signifying that less data can be encoded.

The graph of the CD shows a fairly uniform pattern of pits and lands, roughly equally spaced and equally deep. The uniform pattern arises due to the simplicity of encoding information on a CD. Since the pit sizes are large, the readability of the data is a nonissue, and no special design is needed. The Blu-ray disc shows a bit of uniformity in spacing between pits; however, the variations in pit depths are far more sporadic. The width of the pits for both the Blu-ray disc and CD are fairly standard at roughly 150 nm and 600 nm respectively. The accepted values for these are about 130 nm for the Blu-ray and 600 nm for the CD [8]. As our data shows, the pits on the Blu-ray sample are narrower and more closely spaced together when compared with the CD sample.

These results show that the information density on the Blu-ray disc is significantly higher than it is on the CD. A greater number of features on the Blu-ray results in more transitions between pits and lands, creating a larger amount of binary-encoded information. As the track pitch of the Blu-ray disc is smaller than that of the CD, the CD also has fewer spirals of data encoding, which further leads to it having less binary-encoded information

Section 2 - Impacts of Damage on Data Storage: Figure 10 shows topographic scans alongside 5 micrometer long one dimensional data cuts for both the intact and damaged DVD samples. Figure 11 shows a corresponding 3D rendering of each sample's topography.

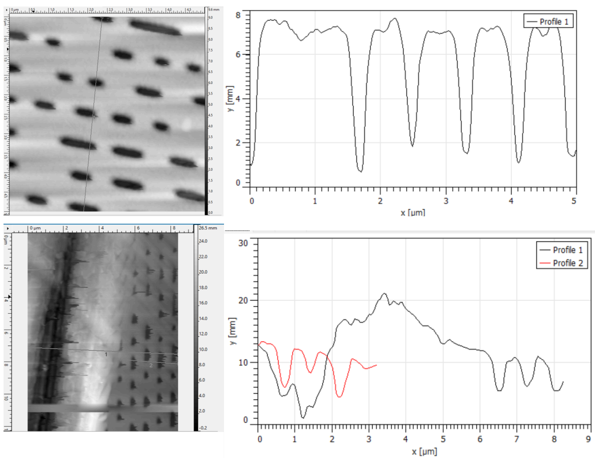

Figure 10 :Top shows the topographic scans of the intact DVD, alongside a graph of a 1D cut of data. Bottom shows the topographic scans of the damaged DVD, alongside a graph of a 1D cut of data. The red line on the bottom graph shows the profile of the undamaged section.

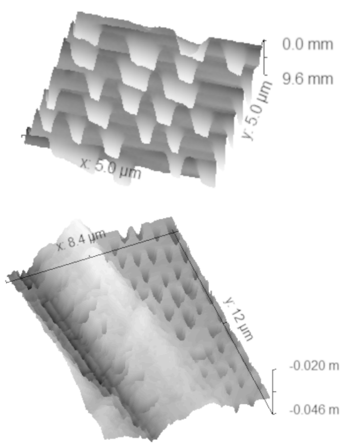

Figure 11: Top shows a 3D rendering of the intact DVD topography. Bottom shows a 3D rendering of the damaged DVD topography.

From these scans, several more observations can be made. Qualitatively, figure 10 clearly shows that the intact DVD lies in between the extremes of a CD and Blu-ray disc when it comes to pit size, pit amount, spacing between pits, and track pitch. By the same reasoning made prior, this implies that the information density on an intact DVD also lies somewhere between a CD and a Blu-ray, as expected. The graphed data also corroborates these findings, as the spacing between pits and the size of the pits is quantitatively larger than that of a Blu-ray disc, but smaller than that of a CD. Interestingly, the DVD has uniformity in pit depths akin to a CD rather than a Blu-ray. The pit widths are about 300 nm, which is close to the value of 320 nm put forth by a prior study [8].

The damaged DVD gives insight into the nature of data loss on a disc. Due to the scratching of the razor blade, a valley can be seen in the topography cutting through the DVD. The pits and lands previously there have vanished, destroyed by the force from the razor. The damage can also be seen in figure 10 from approximately 2 to 6 microns, where there are no visible transitions between pits and lands.

Therefore, we conclude that the binary encoded data of zeros and ones is lost in the damaged region. Interestingly, the pits in the undamaged region also appear to be distorted [figure 10]. If this distortion is not due to the imaging, this could imply that areas adjacent to scratched regions on a disk may also endure damage, increasing the negative effects of disc searching.

IV. Conclusion

We found that the Blu-ray disc has the highest information density, followed by the DVD, and lastly the CD. This is consistent with our expectation as the more advanced discs (such as the Blu-ray) were created to be more information-dense. Furthermore, the measured width of pits is consistent with values measured in previous experiments. In Table 1 of [8], the pit width is recorded as in Table 1.

Disc type	Pit width (nm)
CD	600
DVD	320
Blu-ray	130

Table 1: CD/DVD/Blu-ray pit dimensions from Table 1 of [8]

After careful examination of the damaged DVD sample, we concluded that the mechanical damage was able to erase pits and thus the information stored in the region. We also note irregularities in regions not directly damaged by the razor but could result in damage of the information.

To continue this project, we would like to run more scans on different samples to collect more data to eliminate noises and inconsistency in our data. Furthermore, we would like to scan samples with more common types of optical disc damage, such as disc rot, as mechanical damage is a lot less common in real life on optical discs. Scanning such samples would give us data of the change in disc topology caused by disc rot, which will give us insights in how it corrupts the information stored and potentially how the damage happens. Lastly, we would like to investigate topographical features of the discs that contribute to their durability and integrity to learn about how optical discs can be preserved.

V. Acknowledgments

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VI. References

[1] Allen Lab. Thorlabs AFM Overview. Accessed 24 Nov. 2024
[2] Allen Lab. AFM Quick Start Guide. Accessed 24 Nov. 2024.
[3] "What Is AFM? Learn about Atomic Force Microscopy!" NanoAndMore, NanoAndMore USA, www.nanoandmore.com/what-is-atomic-force-microscopy Accessed 24 Nov. 2024.
[4]Science Direct. Chapter 1 - Introduction to nanostructure and their microscopic characterization. In Micro and Nano Technologies 2025, Pages 1-18, https://doi.org/10.1016/B978-0-443-13819-5
[5]The Audio CD Accessed 28 Nov. 2024 http://www.transcoder.fr/CDaudio.html
[6] Young Jae Huh et al 1997 Jpn. J. Appl. Phys. 36 403 https://iopscience.iop.org/article/10.1143/JJAP.36.403/meta
[7] Stinson, Douglas. Optical Disks for Image Storage and Distribution. Digital and Applied Imaging. Accessed 24 Nov. 2024.
[8] Thorlabs manual
[6] Pressed Discs vs Burned Discs. RacketBoy Oct, 2016. https://racketboy.com/forum/viewtopic.php?t=50756