Oral History of Tom Yamashita and Mathew Mate

Interviewed by:
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Marchon: Today is June 15th, 2022. It's a great pleasure to introduce Tom Yamashita and Mathew Mate to our oral history series dedicated to the history of digital recording. Doctors Yamashita and Mate have contributed immensely to the field of hard disk drive tribology. Tribology is the science of sliding bodies, which usually involves friction, wear and lubrication. The reason why it is so critical to disk drive technology is because the magnetic head is writing and sometimes sliding very close to the spinning disk surface under very high velocities of close to 100 miles per hour. In the disk drive industry, tribology therefore refers not only to the reliability of the device, but also the push to lower and precisely control the head to medium spacing known as HMS. During their careers, doctors Mate and Yamashita have helped reduce HMS from a few micrometers to just a few nanometers. This has enabled over a million-fold increase in storage densities. Dr. Tom Yamashita played a key role at Komag Incorporated, a company that played an important part in the introduction of sputtered thin-film media used in small form-factor disk drives, the 5-1/4 and 3-1/2-inch disk drives. Tom Yamashita obtained a BS in chemistry and an MS and PhD in materials science from Stanford University. He began his career in the disk drive business by joining Komag at its inception in 1984 and worked there until 2007, when the company was acquired by Western Digital. He continued to work at Western Digital until 2012, when he retired. He has developed many of the processes used in the manufacture of thin-film media at Komag, with 34 patents to his credit and many publications. His last position at Komag before it was acquired was Chief Technical Officer. Dr. Mathew Mate worked for 30 years in industry doing research and development of materials for nanotechnology and nanotribology applications. He started his industrial career at the IBM Almaden Research Center after completing his PhD in physics from the UC-Berkeley in 1986. Later, he worked in the disk drive divisions of Hitachi and Western Digital. He retired from Western Digital in 2016 to pursue other interests, including writing the second edition of his book, Tribology on a Small Scale, and conducting surface science research at Stanford Linear Accelerator (SLAC) as visiting staff scientists in the Applied Energy Division. Mathew Mate is best known for his research into the molecular and atomic level origins of tribology. And in addition to this, Mathew has been extensively involved in the research and development of new technologies for disk drives. Finally, a little bit about myself. My name is Bruno Marchon. I was born and raised in France, where I got a PhD in physical chemistry in 1983. My career spans over 27 years in the disk drive industry, starting as an engineer at Seagate. I then held various senior management positions at Seagate, IBM and Hitachi, mostly in R&D, developing and implementing new technologies that enabled higher storage densities and improved drive reliability. I would also like to acknowledge Dr. Tadashi Yogi, who helped me put this oral history interview together. Tadashi is also a pioneer and key contributor to the history of hard disk drives. Unfortunately though, he could not make it today and he asked me to conduct the interview on my own. I'll try the best I can. Mathew and Tom, welcome. Let us start the interview with you, Tom. Can you tell us about your childhood? Where did you grow up?

Yamashita: I was born in Kyushu, island of Kushu in Japan, and a small city called Kushikino. I was there until I was ten years old. I immigrated to the United States with my mother in 1965. My father was here five years earlier. He came on his own, so we came to join him. I first grew up in Sunnyvale for about two years. And then we moved to Salinas, California, where my parents were involved in growing flowers, a farming business. And from there, I entered Stanford University and, as Bruno said, I majored in chemistry, and graduate work in material science. I worked under Professor Robert Sinclair. He was an expert in transmission electron microscopy. That's where I focused most of my attention, specifically on doing very high-resolution transmission electron microscopy. I was trying to push the limit of the performance of electron microscope for most of my graduate career, trying to image a near-atomic resolution in electron microscope. I did quite a few numbers of things in that line. I was looking at the material called cadmium telluride. It is a solar cell material, and I was looking at various defects in solar cell structures using cadmium telluride. During my early years in Stanford, I was assigned to a project with Xerox Palo Alto Research Center (Xerox PARC). And there, I was assigned to Tu Chen, Dr. Tu Chen. He was developing thin-film magnetic media at the time. I worked for him for about a year, looking at the thin-film media that he was producing, basically by transmission electron microscopy. But then I moved on to do these photovoltaic materials but I kept in contact with him, and because of that, when he started Komag, he asked me to join. And so I joined Komag in 1984. I was the 12th employee. So it was there from the ground, up, basically.

Marchon: Let's rewind a little bit about your childhood. You started as a chemist, a BS in chemistry. Even before that, what age do you start thinking that perhaps you were driven to have a career in science?

Yamashita: As I mentioned, my family was involved in farming. And that's what I did. I worked under my father. We built greenhouses and grew the flowers and sold them all over the country. But (for) my father, the farming was not his choice. And he encouraged me to pursue other things. And I guess I was always fairly good at science. Not so much at math, but I was very strong in science. I think that led me to pursue that direction. When I entered Stanford, I fairly quickly got into chemistry. That was a very good field for me. I didn’t know much about material science, but I took the first course that Professor Sinclair taught when he came to Stanford, and that made a big impression on me. And that's how I got into material science.

Marchon: Mathew, same question. Where did you grow up?

Mate: For the first 14 years of my life, I grew up in Columbus, Ohio, where my father was a professor of physics and my mother taught in the history department there. A lot of my early interest in physics and science came from during that time when I was in Ohio, and my father was bringing home stuff from the lab and showing me all these neat things. And he encouraged my interest in all sorts of technical stuff. I built my own little crystal radio set. And then we built little devices from Heathkit and things like that. And the space age was a big thing back then, because of the moon landings and the things of those-- fun time, growing up in the '60s in Middle America. Because so much new technology was coming along, so much social change was going on as well.

Marchon: Did your father do his own research? And what field was he in?

Mate: He was a condensed matter physicist. His specialty was low-temperature, particularly liquid helium type physics, which back then was a pretty popular thing. It's not so much popular now. And at one point, I went back and looked at his PhD thesis, and it was actually on contact at low temperature. How do you measure contact areas at low temperatures?

Marchon: Mechanical or electrical contact?

Mate: Mechanical contact. His specialty was thermal transport at low temperatures, so he came up with a measure of the contact areas at low temperatures due to the thermal transport. He'd do all sort of transport properties of liquid helium, which have a lot of interesting behavior depending on what type of liquid helium you've got. And so I was always playing around with all sorts of electronics and science stuff when I was a kid. I had my own telescope and things like that.

Marchon: Did you have your own lab in your bedroom, doing little experiments?

Mate: No. My father had a workshop that I sometimes helped at. He was into carpentry. My brother eventually became a carpenter. We both learned from our father our own life passions, as it were. And my mother, like I said, was in the history department. So I also have a passion for history as well. And my father actually passed away when I was 12, so my mother had to find a more permanent job. She only had a temporary job at Ohio State University, so she eventually got a permanent professorship at University of Oregon. So when I was 14, I moved to Eugene, Oregon and went to high school there, and continued-- by that point, I started, "Hey, I want to be a scientist." Or an engineer. I hadn't quite made up my mind by the time I was in high school.

Marchon: Were you good at math, physics, chemistry?

Mate: I was very good at math, and the physics came pretty easily to me. So I didn’t see why everyone else had trouble with it. The standard geeky stuff.

Marchon: So why Berkeley, then?

Mate: Well, by that time, I was in Eugene, Oregon. I said, "Well, I'll apply to the four best engineering schools on the west coast." And in the end, I decided, "Hey, Berkeley would be a good place to go." Stanford didn’t accept me, so I didn’t go there. And Cal Tech, I decided that that wasn't really the right place for me. So I was an undergraduate at Berkeley in engineering physics, because like I said, I couldn’t make up my mind between engineering and physics. One interesting thing that I did as an undergraduate was that I spent my junior year abroad at Oxford University doing their second-year physics course, which is a very different type of instruction than the American system. They do a tutorial-based system, where a tutor sort of guides you through “everything you ought to know about physics”. That's what the tutor said. So that was a very interesting experience. And that sort of solidified in me, okay, I wanted to really focus on the physics side for future work. At that point, I decided, "Hey, I'm going to apply to do a PhD in physics." And I decided I'd do solid-state physics, because at that time that was what interested me the most. A lot of it has to do with a lot of interest in semiconductors back then, and other solid-state stuff, and getting interested in materials science as well. And again, I applied to what I thought were the four best physics departments for solid-state physics. And I got accepted to all of them, and so I said, "Well, I enjoy Berkeley so much, I'm just going to stay here."

Marchon: Yes, so both of you stayed for your PhD in the same..

Yamashita: Too lazy.

Mate: Well, I mean, they always tell you that you should go to a different place for grad school, to get a different experience. I didn't really see the point of that.

Marchon: Yes. If you were at one of the best, then..

Mate: Well, I know. And up at-- you've spent time at Berkeley. It's hard to move on from Berkeley. It's very nice, and I've stayed in the Bay Area, because again, it was hard to move on from the Bay Area.

Marchon: So then how did you decide your PhD advisor?

Mate: Okay, that got to-- there is a story behind that. I got past the Prelim qualifying stage. The physics department at Berkeley wants you to past your Prelim Exam the first year, through written, oral exams. And so, it gives you a sort of hunting license to go out and find a research group. And the original person I wanted to work with was Professor Ron Shen, who's a very famous optics guy and solid-state physics guy as well. And when I talked to him, he sort of told me, well, he didn't really have space to take on any new students. But he suggested what I ought to do is go talk to professor Gabor Somorjai in the chemistry department. He talked about possible collaborations with Gabor and his group-- and also, the part of Ron Shen's work that most interested me was using laser diagnostics to study surface science phenomena. (I had started getting interested in surface science as the interesting part of solid-state physics I wanted to concentrate on.) Once I mentioned that, he said, "Go talk to Gabor Somorjai, because he's the top person in the surface science field, and likes to hire or bring on a couple of physics graduate students. So I went to talk to Gabor Somorjai, and my first impression with Gabor Somorjai was, "This guy is just so enthusiastic. Just a ball of energy." I just really liked the way he thought and expressed himself, and the way he thought through science. That first meeting was very pivotal for me in terms of being sold on working for Gabor Somorjai. Now, Bruno knows Gabor Somorjai very well. On a good day, he's fantastic. On a day where he's disappointed with you, he's very rough.

Marchon: Yes. He drives his people hard.

Mate: Yes. Very colorful language at times. At least back then. He's much more mellow nowadays.

Marchon: And then he suggested you work with what? Hydrogen on surfaces or something?

Mate: No, that came later.

Marchon: That came later. Okay.

Mate: What he suggested at that time (and I think it was part of an ongoing program) what are the structures of molecules adsorbed on surfaces and the structures of the surface atoms? What's the structure of molecules on surfaces? How do they bond to surfaces? And there are various ways he did that in the group. One was low-energy electron fraction [LEED], analyzing through what they call the

Intensity-Voltage [IV] curves, basically using electrons to diffract and get crystallography out. But in addition to that, he was also ramping up his vibrational spectroscopy work, doing low-energy electron loss spectroscopy at high resolution. So he really needed some more people to do the high-resolution electron low-energy loss spectroscopy [HREELS], to do the vibrational spectroscopy. The initial guess of what the molecule structure was from HREELS which we would tie into the low-energy electron diffraction work. So that's where our focus was. And initially, I was on doing high-resolution electron energy loss spectroscopy. First, working with one post-doc who already had a system set up for that, and then building my own system up, a new system that would do that in my own project. And once I got that up and running, it's sort of like, well, you just clean the surface on ultra-high vacuum, get it nice and atomically clean, dose it with the molecules, take the vibrational spectra, write up the paper and publish it. And that got Gabor very happy, because you could generate publications very easily that way. And I even made him more happy when I discovered that you could-- by introducing CO molecules into the system, I could order certain molecules like benzene-- so that's fantastic, because now you can do the LEED crystallography on these structures. And we had a good idea from the vibrational spectroscopy what was going on. So that was sort of my big discovery as a grad student was an ordering reagent for the low-energy electron spectroscopy and LEED. Also during my thesis work, Gabor also kept telling me how one of the frontiers for surface science was tribology, how friction and lubrication work, because that's where two surfaces come together. It's a buried interface that's very difficult to probe. How do you understand, let's say from the molecular structure, how that affects, say, lubrication? And I thought, "Hey, that is a great idea. Because, if you're going to be a famous scientist, it's best to go off and work in a field where not too many other people are working on." And while there was a lot of people doing, say, lubrication work or wear work, they're all not doing it at the molecular level. And Gabor said, "Hey, do it at the molecular level."

Marchon: And that's what started it all. So, we'll get back to this later on. Tom, you also worked in vacuum during your PhD, with electrons, although the energy level was quite a bit different. Tell us how you chose Professor Sinclair and this research topic.

Yamashita: Professor Sinclair was still very early in his career at Stanford, and he wanted to do electron microscopy. So, first thing he did was to purchase this very expensive electron microscope. And his main effort was to push the resolution of the microscope to the highest level possible. But you need a material to look at. And it turned out that cadmium telluride was an excellent material. Very heavy, high-contrast in the electron microscope, and it had a very large lattice constant, which made it easy to image. Compared to-- everybody else was working on silicon, which is actually quite difficult. So those two things kind of came together, and he basically let me have free rein on this brand-new microscope. It probably cost over a million dollars back then. And I was able to spend a huge amount of time to push the instrumentation to the best possible. And I started to get these fantastic images of atomic structure defects. And we hooked up this video camera, and we could actually see defects in motion. These are dislocation (in) crystalline structures, or crystalline defects in cadmium telluride. And I don’t think this has never been done before to the extent that we did. And so, it was-- he took all these movies that I took and he went to all the conferences and it was a big hit.

Marchon: Did you publish in some very highly..

Yamashita: Oh, he showed them all over the place. That was good for me, too. But very appreciative of Sinclair to give me that kind of access to this fancy instrumentation. I did get a lot out of the equipment.

Marchon: And how did you get involved, then, with the Xerox PARC team?

Yamashita: That was something that before he got going on this high-resolution electron microscopy, I was just starting as a master's student. I needed a project, and while Sinclair was, just by happenstance, was assigned to me as advisor. And I said, "Bob, I need to do some work to get my feet wet in doing scientific work." So he had a strong connection with Xerox PARC, and gave me this project, which happened to be looking at thin-film media that Tu Chen was working on. Xerox PARC, by the way, back then, was an incredible place in the late '70s. They had this Alto computer..

Marchon: Alto, yes. The mouse and the..

Yamashita: And they were developing ethernet. They had a laser printer. They even had a color laser copier, which was a-- I've never seen anything like it before. And I think about two years later, Steve Jobs came through and took everything.

Marchon: Saw the light. Did you see all the beanbags in Xerox PARC?

Yamashita: Anyway, so that was a very, very interesting experience, working for Tu Chen. I learned how the magnetic recording is done. I learned how to use a VSM, for example, vibrating sample magnetometer, those kind of things. So Tu Chen showed me a lot of things that I didn’t know about, that's where I learned magnetic recording, in a way. But I didn’t stay with it for too long, only about a year. And I moved on to focus on electron microscopy, but Tu Chen would call me up every so often and say, "I want to look at this," and such. So I used the TEM to analyze films for him.

Marchon: Did you publish anything with Tu Chen then?

Yamashita: Yes, several papers. So, it was a good experience for me. We also shared the love of fishing. So, he would take me out fishing. And so that was another connection.

Marchon: We're going to get close to the disk drive industry now, so we’ll go back to Mathew on that. So Mathew, you mentioned a little bit about your early interest in tribology and using surface science tools to understand the molecular, atomic level of tribology. So can you tell us a little bit about this and what led you, then, to the IBM <overlapping conversation>.

Mate: The story there is one of the things that I worked on when I was finishing up my thesis work at Berkeley. Gabor Somorjai was interested in getting into the field of tribology. So, he had me build a pin-on-disk tester in Ultra-High Vacuum [UHV]. So, I think I got that sort of built and demonstrated in my work, and then I left with my thesis. But while I was building it, I'm going, "This is not really the way to do it to get atomic resolution. The way to do this is some sort of scanning probe with a very sharp tip that latches on to just a few atoms, and then measure the forces on it." This was before the invention of atomic force microscopy, so it was turning around these ideas in my head, going, "Really, I ought to invent the atomic force microscope [AFM]." But I didn't realize that Gerd Binnig and Cal Quate were already in the process, and were already six months ahead of my thinking on this, and were just about to publish that.

Marchon: The STM or the AFM?

Mate: STM was already out, right.

Marchon: STM was already out.

Mate: I knew what the STM was. I needed something like the STM, but where you can measure the force on the tip. And I even talked to a professor in the electrical engineering department, how you can do that with microfabricated cantilevers, which was also very ahead of my time when I think about it back then. So I would have been much more famous if I had started on my PhD thesis on this rather than thinking about it in the last six months of my PhD thesis, or the last year of my PhD thesis. So, my thinking was, "Well, I don't have time to do this on my PhD thesis. I ought to get a post-doc to do this." And I thought I really liked the work at IBM Almaden, as I had actually done a summer position there doing perpendicular media recording back in '81, way before perpendicular media came out. I knew the people at IBM Almaden, and I go, "That's a great place to work." And a friend of mine, Shirley Chiang, who had graduated from Berkeley a few years before, was at IBM Almaden Research Center. So I called her up and said, "Hey, I'm looking for a post-doc position where I can do something like this to probe the forces on atoms." And she goes, "Well, we just happen to be looking for a post-doc to do that project," because she knew about the Gerd Binnig and Cal Quate thing because Gerd Binning was an IBM employee. And she was working with Gary McClelland, who was responsible for tribology at IBM Almaden Research at that time, with a few other people. So, they brought me in for an interview, hired me pretty much on the spot, and I went to work there as a post-doc. But by this time, Cal Quate and Gerd Binnig had published the first paper on atomic force microscopes. So they already demonstrated how it could be done, and the issues there. And we just decided (particularly Gary McClelland had some very clever ideas of different ways of building an atomic force microscope) we'd build one based on optical interference, that we then used to measure the first atomic scale friction forces. So that was the thing, okay, Gerd Binnig had measured the forces acting normal to the surface. We measured both the normal forces and friction forces and built the first microscope to do that, scanned it over graphite, got atomic scale friction, and "Voila!" I'm a famous guy in the atomic scale tribology field.

Marchon: It was a PRL?

Mate: A Physics Review Letter. And here's the-- this is the only time that's ever happened to me with any paper. I submitted the publication, a month later, they called me up and started saying, "We're going to publish this as-is." Never happened to me ever before.

Marchon: Any other time.

Mate: Any other time.

Marchon: So that was the very first time that people put a strain gauge to measure the lateral force?

Mate: It wasn't a strain gauge, it was by optical interference. But those people who are familiar with strain gauges, it measures the strain-- the displacement of the thing there. We did a very crude sort of optical interference setup. There are much more sophisticated ones that we came up with later at IBM Almaden. And now they do it all by beam deflection off the microfabricated cantilevers.

Marchon: Excellent.

Mate: Yes. So that's how I got into IBM Almaden doing tribology research. And then after about-- it was a great time to do an atomic force microscope, because whatever you did was an exciting new result, and you were the first guy ever to do it. You'd publish a paper and everyone would go, "Oh, wow, that's great and wonderful." But eventually your post-doc, it's going to come to an end. You got to go, "Well, I got to get a permanent job." And I happened to run into Bryan Street, who at that point was a department manager at IBM Almaden Research, but in what they called the Storage Function. That's the part of IBM Almaden Research Center that researched for the disk drive business at that time. And he was the department manager for that part dealing with the tribology issues, the head-disk interface issues, and the magnetics of the disk, the disk media part of it. I met him at lunch one day, and I said, "Hey, I'm looking for a job in tribology." And he said, "Well, we happen to be looking for people to hire in tribology." So, he basically is the one who pulled me in as a permanent employee of IBM Research into the disk drive tribology research business for IBM's disk drives.

Marchon: Tom, tell us a little bit more about your interaction with Tu Chen and what was important in the research he was doing at Xerox PARC, and how did that research, they thought, could apply to magnetic recording?

Yamashita: Let's see, fairly early on, he was doing things like magnetic bubbles. And he kind of went through the motion of looking at various technologies. Certainly perpendicular recording, he was heavily involved in that. But somewhere, he decided that he could start a business, and it had to be longitudinal recording. And he was working on a material called cobalt rhenium system to make recording media out of it. And somewhere during the time that he was at Xerox PARC, Xerox was trying to create this new business office of the future. And that involved the Alto computers, storage systems. They bought this company called Scientific Data System, I believe, I don't know, for like a billion dollars or something. And they had a storage division, too. So he was trying to make an actual device for their product line.

Marchon: So the disk drive already existed?

Yamashita: Yes. They had the business already. I think it was called Century Data, and they were making oxide disk packs for this computer division that they had. And you've seen the Alto computer. It had this big oxide disk pack. You just slide into the bottom of this computer, you had the operating system, storage, ten megabytes or something. They wanted to improve the capacity and performance of these kind of drives intended for this office of the future. And it had to be thin film. That's because that's the only way you could get the recording density. He had this idea to do all of that, but somehow Xerox kind of lost their way and decided to just cancel everything, kind of forced him to consider going into business of his own. So in 1982, '83, he started to try to formulate a business plan to start a company to make hard disk media.

Marchon: And was thin-film media already existing? But it was plating technology, perhaps.

Yamashita: Around 1982-83, the plated media was already starting to be used. The plated media actually goes back a little further. It was used for things like instant replay machine made by Ampex. Those used plated media, I believe. So the first thin-film media was all plated. And the 5-1/4 was a format that was going to be used in PCs and so on. So, by the time Komag had started in 1983-84 timeframe, there were already many plated media companies. But the kind of film that Komag was trying to make, was by sputtering. It was considered maybe a little bit too expensive compared to plating, so there weren't very many, but there were already several going by the time Komag had started.

Marchon: So, it was thought that perhaps the performance was going to be better, but the cost maybe not so much.

Yamashita: Eventually, eventually. The plated media capacity must've been five, ten megabytes at most. But there was a limit to the coercivity that you could get with plated process. And there wasn't much of a pathway to get further. So, I think Tu Chen saw it correctly, that the thin-film media was the way to go. You could create-- use all kinds of different alloys that has much higher coercivity and has higher recording density as possible.

Marchon: Before we go deeper into the technology now, I think Mathew, you've prepared a little tutorial. And perhaps you can tell us a little bit about what the technology involves.

Mate: Okay. Let's start off with this demo here I've been holding up near my head here so people can see. And I guess this is the inside of disk drive. I just pulled the cover off here. And the way a disk drive works is you're storing information on the magnetic film, which is on this disk surface. That's why it's called disk drive. And this disc rotates around. And as it rotates around, there's a-- okay, let me back up here. And this, like I say, this is stored magnetically on the thin film on top of the disk surface as ones and zeros. Those ones and zeros put out little magnetic fields into the air above it. To read those magnetic fields, there's what's called a recording head, which is located-- I don't know how well you can see this. Right at the end of this long suspension going out here on this thing here, and that reads the magnetic fields that are going across there. So as this rotates round and round, this actuator here puts that recording head back across the disks so that you can read and write the information that you want it to be stored on the disk drive there. And this is explained a bit more on the slide I've brought with me here. And again, on the left side of the things-- again, that open view of the disk there-- and from the area, you can see that illustrates the disk rotation that goes around underneath the recording head. That recording head is mounted on the trailing edge of a slider, which is shown in part B here. And that slider, the bottom of that slider that you see here is patterned with what they call an air-bearing surface. That air-bearing surface is designed so that when the disk rotates, it pulls air underneath the slider. That air interacts with the air-bearing surface and causes the slider to fly over the disk surface. That's a very important function, because as it flies, it gives a big clearance between the head and the disk. So hopefully most of the time, the head does not contact the disk surface. And the reason why that's important is this disk is spinning around 5400 RPM or 7200 RPM. And that means the linear speed can go up to 100 miles an hour, like Bruno was saying here. And so you don't want any contact between that head at 100 miles an hour. So if you can fly it up some distance, you can minimize that contact. But contacts do happen, and that's where all this tribology is becoming important here. Because when they contact, you've got friction, you've got wear, you've got adhesion. And as Bruno mentioned, the word tribology means that study of friction, lubrication, wear and adhesion.

Marchon: What's the distance between the head and the disk?

Mate: Well, that's a..

Marchon: Oh, you're going to bring that up.

Mate: Yes. I'll talk about-- I think I'm done with this one. And the point I want to make, last point here is what's mentioned at the bottom here, is if you have too much contact, you've got too much friction and wear, eventually the thing will fail. We used to call it a head crash. Basically, the head would just crash and kill the drive, and whoever owned the disk drive would lose all the data that was stored on there and be very unhappy. And they'd go off an buy their next disk drive from someone else. You wanted to avoid that, those head crashes. So that's why tribology is so important to the head-disk interface. And I tell people that's why people paid my salary, so that we can make a more reliable disk drive. Okay. On the slide number two, here, on the left-hand side is that image we were showing before of the cutout of what the inside of a disk drive looks-- the inset here shows that recording head and slider flying over the disk surface. And as it flies, if the animation works on this, there's a little bit of flutter on there that you can see vibrating up and down. The issue is if it flutters too much, then you're going to get a contact with the disk surface at 100 miles an hour. In today's drive, this clearance is less than two nanometers. It's very small. Whereas as a plot here on the lower right shows is that it used to be much higher. It used to be about-- Bruno told me the other day it was just over 20 microns in the first disk drive shipped in 1956. So over the years, they've sort of reduced this down to less than two nanometers. And the reason why they're doing that is because over time, they've been trying to get more and more bits onto the disk surface. And the reason why that was the first disk drive, the RAMAC in 1956, only had three megabytes of data stored on-- five? Okay. I think it depends on which model you're talking about. Five megabytes, let's say, in the size of about a small refrigerator. Which nowadays the small mobile drives can hold terabytes of data. It's a very impressive improvement over the last almost 70 years now, right? And I'd say it's got more bits down there-- the magnetic fields have gotten close to the disk, so you've got to get that recording head closer to the disk to be able to read and write those high areal densities, right? So that's sort of driven this clearance to go down to below two nanometers in today's disk drives. It must be around-- I don't know, Bruno, maybe you know this number. What is it? One nanometer or less, now?

Marchon: Less.

Mate: Less. Less than a nanometer, which is just a few atomic distances thick of clearance, of gap.

Marchon: By the way, Mathew, it was five mega characters for the RAMAC, but the character was six bits, so it's actually-- five mega characters at six bits each is actually three megabytes.

Mate: Okay. Okay, that's what's confused me, probably. For those people who have no feel for what a nanometer is, one of the things people will do in the disk drive industry as they scale up is they take that slider with the recording head on it and scale up to the size of a jumbo jet airplane, like the 787. So how close do I have to fly that to a surface, scaled-up distance, to match the two-nanometer clearance. And it turns out to be about 0.05 millimeters, or about 50 microns, which is the width of a very thin human hair. So you think about a big jumbo jet trying to fly over the ground with a clearance of just the width of a very thin human hair. Okay, so we're talking about slide number three here. Again, there's this concept of head media spacing that Bruno mentioned a while back. And as we were saying, to get the high aerial densities, you want to get the recording head as close as possible. The critical parameter is this head media spacing, which is, as illustrated on the right side of this, is the distance from the bottom of the sensor in the head that's going to do the reading and writing of the bits on the disk, and the top of the magnetic layer on the disk surface. So that's the head media spacing. The problem is for-- like I said, the problem is that this magnetic media that's on the disk is actually fairly soft. And you've got this recording head flying over it at 100 miles an hour, let's say. And so if you have contact on that soft, magnetic media, you're going to get a lot of severe wear. So what we've done in the disk drive industry is coat it with a hard material, a hard carbon overcoat is the standard one nowadays. And that provides a lot of protection against the impacts that can happen when there's a hard carbon overcoat. But it's not enough. They also put a monolayer of lubricant on there as well to further protect it and give it-- so you can last through the warranty period. And today's coated head sliders also have a thin carbon overcoat on the head side to protect the head side as well, because that magnetic sensor that's in the head is very sensitive to impacts and corrosion as well. So you've got both sides are coated there. So all these thicknesses from the overcoat, the lubricant, and also the roughness of the disk play an important role for the tribology to have to fit in that very small magnetic spacing. And if you look at the plot on the left here, that's been going down steadily over the last-- the time period here is from 1980 to 2010. It's been systematically going down, down to ten nanometers in 2010. So I mean, all your carbon overcoats thickness, lubricants thicknesses and clearance and roughness must all fit in that magnetic spacing budget. Now, I think since 2010, this whole thing has sort of plateaued out a bit. It's very tough to get much more improvement now. So it's fallen off the straight line on this semi-log plot. But still, getting down to ten nanometers head media spacing has been very impressive, because the clearance, like I was saying before, has to be less than two nanometers. The carbon overcoat thicknesses are getting down to just a few nanometers. Lubricant thicknesses are just one molecule, where that molecule is lying flat on the surface. The roughness had to go down from where it was before, and I'm sure we're going to talk about roughness here in the future, right? So that's sort of systematically coming down here.

Marchon: Yes, and I guess as a tribute to people like you, not only all the dimensions have reduced dramatically, but the reliability of a disk drive has improved dramatically over the last 30 years, right? Thirty years ago, it was not unheard of that your disk drive would just stop working in your computer. But today, disk drives are extremely reliable.

Mate: Well, one thing I want to point out, you notice how this is a nice, linear plot here. And the reason why is not due to any technological thing. More of a marketing guy, the people in marketing just kind of said, "Two years from now, you have to make a disk drive product that has twice the aerial density." And that meant-- okay, that means the magnetic space had to go down a certain amount. And not matter how good a job you did on the last disk drive, well, you've got to do twice as better two years from now in terms of improving the aerial density. And preferably we're improving the reliability as well. So there was always a big pressure to: “Okay, you did a great job last time. Now do better next time.”

Marchon: Could you tell us a little bit about some of the failure mechanisms of a disk drive? You mentioned a head crash. Were there other failures that you had to deal with? People mention stiction, for example.

Mate: Well, that's a-- on this disk drive here, this is a powered-off disk drive, so the head is sitting on the disk at the inner diameter [ID]. And there's actually a texture zone here, which has extra roughness to prevent this phenomenon of stiction, which is basically: If there's too little clearance between the head and the disk where it's sitting, all the lubricant will wick up around the head and cause a big adhesion problem, and so much friction force that you can't start the drive up again. Basically this thing can't spin because there's too much friction there between the head and the disk due to lubricant wicking up in this small gap. So all sorts of texturing schemes were put in to minimize that stiction problem.

Marchon: And I guess we're going to talk about that later, but some of your job was also to understand the atomic nature of that friction.

Mate: Oh Yes, all the physics of the lubricant. And you're talking about other failure mechanisms. One, which it didn’t cause a head crash, was lubricant pickup on the slider, which would then coat the slider with a thin film of lubricant that would raise the fly height, lose your magnetic spacing, and then the drive wouldn’t be able to read the data anymore, because you're just flying too high now. Because of lubricant pickup. We also try to understand how did the lubricant get from the disk to the slider. And we also have problems with lubricant spinoff, because we used to make the lubricant too thick. A whole range of funny lubricant issues. Lubricant degradation from incompatible materials in the disk drive.

Marchon: Tom, we just talked about some of the failure mechanisms in disk drives, and I think that's something that you’ve experienced as well in the early days at Komag. You told me that you didn’t go to tribology by choice, but by necessity. So can you tell me a little bit about some of the early experience at Komag, and some of the problems you guys were facing in the field of tribology.

Yamashita: When Komag got started, there was sort of a specification out there already, because the plated disk was out there. And of course the so-called CSS drives, Contact-Start-Stop, was pretty well-established. The market that Komag was going for was this small form factor, 5-1/4-inch, and it was clearly intended for a PC market. And there was this requirement of 20,000 start-stops. Basically, you turn on the drive several times a day. It's supposed to last ten years or whatever. And every time you turn on the disk drive, the head will actually land on the disk. The motors that these small form-factor drives had was not very powerful. They were relatively cheap and didn’t have so much torque. So the contact-start-stop requirement had built into it a requirement for a friction force that was specified, so that the motor can turn it on. And if the disk was starting to wear out, for example, the friction force would build up eventually, and you wouldn’t be able to turn on the drive. So this 20,000 start-stop cycles was actually quite challenging. Assuming the earlier drive, the first 5-1/4-inch drive was made by Shugart, and it was starting to be put into small computer systems, including PCs. And they clearly met those kinds of requirements. But the thin film couldn’t get there initially. And so that required a lot of innovations to make it last this 20,000 cycles. The testing equipment needed to do these kind of tests was not-- was fairly in infancy also. So it was difficult just to measure. You could put them in the drive and test it that way, but that wasn't really available. So we had instrumentation problems as well to test it. So anyway, so this 20,000 contact-start-stop cycles was an issue. And another issue was the drive environment itself was relatively poor. Literally the motor was leaking oil. There were various materials that would outgas inside the drive enclosure. And when the drive is running hot, things would outgas. And these things could react with the lubricant. Many, many things happen between the head and the disk. A muck could build up between the interface between the head and the disk, and this would compromise-- if it stopped flying, like Mathew said, you could have a head crash. So those were some of the parameters. And then it's not really tribology, but the other issue was corrosion. The thin film disk, particularly the plated media, was very prone to corrosion. And so in a drive environment, if corrosion occurred, you could have these corrosion byproducts that would actually protrude out of the disk surface, and that would also muck up the interface. So these were some of the issues that we were dealing with initially.

Marchon: Komag as a company started straight into making sputtered thin film?

Yamashita: Yes.

Marchon: Were you guys the first ones to do this in the industry?

Yamashita: I don’t believe-- there were several companies already trying to do similar things. So I don’t think we were the first, but we certainly were the first to actually put out on the market a disk that worked to meet these 20,000 contact-start-stop cycles.

Marchon: Who were your first customers?

Yamashita: Most of them are no longer around. They were a company called Vertex. Priam was another one. Maxtor was already starting to ship many products.

Marchon: Did Seagate buy from you?

Yamashita: Seagate, Quantum, and there was just a host of a bunch of smaller companies. Although there were the big players, like DEC and IBM, Control Data, those companies were starting to put thin-film disks. I believe most of them was initially plated disk. But soon they themselves were working on sputter films. So I don’t think we were the first one, but I do think that Komag was first to really make a sputter thin-film disk that had all the components. It had the 20,000 CSS cycles. We achieved that by putting a lubricant successfully on it that stayed put. As Mathew said, it can spin off. It could just wear out, all those things can happen. But we were the first to be able to get a real disk that actually met the specification.

Marchon: And I guess at the time, molecular tribology was still in its infancy and people didn’t really have the understanding of friction and wear processes that was needed to understand all this. So did you rely mostly on empiricism and just trial and error?

Yamashita: A lot of trial and error. We couldn’t even measure the thickness of the lubricant. So it was basically we had this jig with ten gram of weight which we glued the head to. And it was dragged across the disk with a string. At the end of the string, we had a strain gauge. And so work out the math, you get a ten-gram lateral force, and that defined the stiction requirement. So that was a kind of a quick way to test. But we did have a contact-start-stop tester that had a very specialized strain gauge setup. It was an octagon-shaped copper ring which I think had a four strain gauge attached to it. And at the end of this was the suspension with the head, and we would mount the head-- the disk, and run the start-stop like this. And the strain gauge was calibrated to measure the friction force while it's running, and then the start friction to dislodge it out of the surface, the static friction. So that was-- actually, I think it came right out of IBM. Two of our founders were from IBM. And one was a mechanical engineer. His name was Jim Shir. I think he worked on a lot of the tribological problems at IBM. So it was a person that was most familiar with these kinds of issues. Tu Chen, on the other hand, he had no knowledge of tribology. Very little. But he developed all the materials, the things like overcoats, things of that nature.

Marchon: So Mathew, early time at IBM. So you moved to more of a product..

Mate: Yes, I moved to the storage department, the function of IBM Almaden Research Center which their goal is to do the research for future disk drives. And my boss, Bryan Street, said, "Okay," he wanted me to focus on lubrication on thin-film media. And he was also happy to have me continue to do atomic force microscopy work, so I started using the atomic force microscopy to study lubricants on disks and particularly on thin film media. And one of the first experiments I did was just bring an AFM tip into contact with the disk surface. And when you bring it into contact, you get a little force down when you first touch the top of the lubricant film, and then you can detect that little deflection there and calculate the meniscus force that's acting on it as lubricant wicks up around the tip. Then, when you go through the lubricant, you can push into the hard contact with the disk underneath the lubricant and get a nice, strong repulsive force. And what I realized very early on is that you can measure the lubricant thickness this way, when you first touch the top of lubricant layer and when you first contact the hard wall of the overcoat. As Tom was saying, one of the issues is how do you measure that lubricant thickness? So I thought, "Hey, the AFM can do that." And we had a way of correcting for the amount of lubricant that gets transferred to the tip, so we could correct for that. And it happened to be-- one story I have is that one day I was in the hallway and I ran into my third-line or function manager who was responsible for all of disk drive research. And he asked me what was going on. I said, "Oh, well, I came up with this fun little thing that I'm working on in the lab." He says, "Well, that's a great idea. Instead of thin-film media, you ought to do that on particulate disks. And we really want to know what the thicknesses on this particular product that we want to ship, but we're having problems with." So I got switched over from thin-film media to studying lubricants on particulate disks.

Marchon: So the particulate was the oxide media?

Mate: Yes, the particulate media is iron oxide particles. The magnetic information is stored in iron oxide particles, which are magnetic. And they are bound together by a polymer, which was designed to be very porous. And the reason why it was designed to be porous is because then you get to load up those pores with lubricant. Because they really wanted to have as much lubricant as they wanted on these disks. And they particularly designed this thing to have a porous magnetic film, and an even more porous anodyne layer underneath it, which could hold a lot of lubricant. They measure the amount of lubricants on a disk in milligrams. And the way they decide how much lubricant was on the total disk was by weighing it as so many milligrams. If you worked it out in terms of Angstroms, it was 1,000 Angstroms of lubricant. But they knew that all wasn't on the surface. They really wanted to know how much was on the surface of this porous media. But all their measurement techniques were giving them a big background from the stuff that was in the pores there. So I used the AFM microscope to sort of tap my way across the surface, measure the distribution across the surface on the various particulate disks they were interested in, and I showed that on a particulate disk of that time period, which is about 1988, that, when it was new, it was about 50 to 70 Angstroms, because there was quite a bit of variation there. And then over time, it would spin off to about 30, 40 Angstroms, which is still quite a bit of lubricant. About a radius of gyration of a lubricant molecule. And the reason why the function manager was so worried about this lubricant thickness is they found out if they didn't put enough lubricant on there, they would have problems. They wanted to know what the lube thicknesses were of these stressed drives, because they would fail the stress test. And one other thing I started working on at that time, which beneficially tied into this problem, was okay, when this tip comes down and contacts, you get this meniscus force, so you can work out what the meniscus force is on there, and go from capillary action pulling up around the tip. But I was curious, well, what determines that meniscus force of how much lubricant is there? And I go, "Well, that's kind of balanced by the disjoining pressure of the lubricant on the film." And I didn't know where the disjoining pressure was from, but I figured it was some sort of force that the lubricant molecule feels with the underlying disk substrate, which is mostly van der Waals forces in these particular lubricant systems. So you'd have those van der Waals forces trying to pull the lubricant onto the disk. When the tip comes up, you have the capillary pressure going up and making a nice meniscus. And there was a balance between the two, which explained a lot of the physics of how this tip interacted with the surface. And also, once the slider landed on the disk, it explained the stiction forces that we're seeing, the adhesion forces that we're seeing.

Marchon: Yes, and this is when Seagate then read all the nice papers that you wrote.

Mate: Yes, eventually published in the-- you actually did a nice job, along with Jing Gui, solving..

Marchon: There's physics in the stiction problem.

Mate: Yes. You actually worked out this analytically. On the porous particulate media, there was a balance between the shape of the pores and the lubricant that was on the surface. And you can show that actually you have a fairly flat profile. As you spun off lubricant, you maintained your lubricant thickness because it came out of the pores, until you got to some critical point when the lubricant thickness would drop dramatically as you lost lubricant within the pores and the capillary pressure in the pores would go away. And that's really what impressed my function manager, that hey, we could actually do science on this problem. We can actually understand why this product was failing the stress test, and that the stress test was over-stressful, and that they could ship the product and not worry about fulfilling the stress test.

Marchon: So was IBM still shipping particulate media then?

Mate: Yes, this is pretty much the last-- what do they call it? They're shipping it in mainframe computers. Which was when I joined them, they're shipping what they called the 3380. And then the last sort of mainframe large disk drive.

Yamashita: 3390.

Mate: 3390 was the last one. That disk size was 11-1/2 inches, which was down from the 14-1/2 of the 3380. So you had this pretty big, large, heavy disk and a pretty large enclosure. And I think at that point, one third of IBM's profit came from selling those 3390 disk drives. So it was a big deal when I sort of said, "Hey, Yes. I understand the science behind this problem you're having with this product you want to ship that you're hoping to make so many billions of dollars of profit every year off of."

Marchon: Tom, back to Komag. So we understand a little bit about lubricant and stiction, and also the topography of the media is important as well. So tell us a little bit about how you guys controlled the texture or the topography of the media, and also in relationship with the lubricant.

Yamashita: As Mathew was saying about the particulate media, you had this huge reservoir of lubricant. In the thin-film media, you've just got the hard surface. So you can't put very much lubricant. So there's a phenomenon where you could see this very easily. If you put two smooth surfaces together with liquid, take a plate of glass and put it together with liquid water in between, you can’t separate these two glass plates. That's the stiction effect. So the same thing happens if you put a smooth surface of the head on top of a smooth surface of the disk with a liquid lubricant. You've got to somehow arrange it to separate the two. And the way that's done is to put certain amount of roughness on the surface of the disk. And so that was the initial challenge for Komag, how to put that roughness so that you could still have the lubricant there, and keep this liquid from wicking the surface between the head and the disk. So the substrate that we used, this is still true today, is starting out with a base aluminum substrate, and on top of that, there is a plated nickel phosphorous alloy that was plated on it. And then this is polished, as plated is too rough. So we have a polishing machine to planarize it and then make the surface smooth. So this is something that Tu Chen came up with. At the very last moment of this polishing process, he put a slightly rougher slurry, so that you end up with sort of a scratch. And the scratch is enough to separate the head and the disk. So that allows you to put lubricant on it. So we started out that way, and the lubricant that we started to use was basically a type of-- same type of lubricant that was used in oxide disk. These are, I guess, Krytox family. Krytox is a brand name for Dupont. And it's a perfluoro polymer, molecular weight of several thousand. Very long-chain molecule. Fantastic lubricant. I think it's used in vacuum grease as well.

Mate: IBM used Fomblin YR. The key feature is it's a linear chain, but actually with branches off of it. So those branches really help protect the ether linkages.

Yamashita: It's a fantastic invention, as lubricant goes. It's used in even satellite, space application and so on.

Mate: Yes. I think that's why we chose it in the disk drive industry. People started, "Hey, this works pretty well in satellites. It's nonvolatile." That's a key factor.

Marchon: That's right. Very low vapor pressure.

Mate: Very low pressure, very chemically inert. That's another key factor. Because your slider hits this at 100 miles an hour, you don't want degradation of the lubricant molecule. If you don't do it right, you've got degradation going on with hydrocarbons and they get frictional oxidation due to contacts.

Yamashita: So anyway, so we took care of the surface roughness that way and put this Krytox lubricant, which is-- there's this term called polar versus nonpolar lubricant. These are long-chain molecules. You could put end groups at the end of these long chains of molecule. And when we say nonpolar, it means that it doesn't have chemical end groups that cause things to attach more strongly. So the type of Krytox lubricant that we tried first were nonpolar lubricants. And when we did that and started to do contact-start-stop tests, we couldn't make 20,000 cycles. I think they were just flowing away. So somehow, we needed it to be more strongly adherent to the disk surface. Now, back then, things were rather hand-waving and there really wasn't any polar lubricant per se. And set out of trying a bunch of these kind of existing lubricant, out of desperation Tu Chen talked to-- or his partner, Jim Shir, talked to this supplier of this lubricant. We were getting this from Montefluos. It's a division of Ausimont in Italy. And they were making this lubricant. And I think their trade name was Fomblin.

Mate: Yes, Fomblin YR is what the Krytox-- Krytox is made by Dupont, and Fomblin was the..

Yamashita: Fomblin was the trade name for the Ausimont.

Mate: For Ausimont, Yes.

Yamashita: And today, Ausimont is purchased by Solvay. So there's Solvay and Dupont, so they're in the business, too. They spun it off. Anyway, so the contact-- Jim Shir contacted Ausimont, Montefluos, "Do you have something else?" And Tu Chen remembers seeing some scientific paper two years back that talked about polar lubricant that had-- I think it was an OH group or something that caused the lubricant to bond more strongly to the disk. This is a paper done by NEC at the time. They were doing this on plated disks. And they reported some very, very good results. So Jim Shir went to Montefluos, "Do you have something similar?" And so we got one. It's called ZDol. And it wasn't even intended for disk application. I think it was maybe some space application. They had a small jar of it, so it was ordered, we paid very exorbitant air fare. As soon as it arrived, he put it onto the disk, and lo and behold, it worked. So that was the key, to put a polar lubricant. To get some amount of adherence between the lubricant and the disk, because as Mathew mentioned, there's no reservoir. So that was kind of an eye-opening realization.

Marchon: So the whole industry followed suit, right? Because ZDol became the de facto lubricant.

Yamashita: Became the type of lubricant. So I think after that, people started to really look at, well, how do you measure the amount of bonding? How much is sufficient? Obviously you can't have everything bonded, right? And even how you measure it was a problem. You could use different solvents and you'd get different numbers. So that was kind of interesting.

Marchon: Mathew, tell us about what lubricant was used by IBM, then?

Mate: Well, like is started saying, when I was doing particulate media, they were actually trying to decide whether to go to a Fomblin Z backbone, which is without the branched groups. And they had a lot of problems with that on the particulate media. The reason why they had problems was it would interact with aluminum oxide particles in there, that would cause lubricant degradation. So then they switched back to Fomblin Y, which was a branched molecules, which the branching groups would protect the ether linkages within the Fomblin backbone. But the great thing about the particulate media is you had that big reservoir you could spin off forever, because you'd never empty out the reservoir, because the capillary pressure would sort of hold within the pores enough for you to keep it on the disk. But when you go to the thin film media, then you go flat, and you have to start worrying about spinoff. If you don't have the functional groups, it'll spin off very fast, and you'll lose all your lubricant. And also, you have a lot of mobility, so you get your stiction problems very quickly if they're going to happen. So people talk about-- Zdol is what the standard came to be. At IBM, we were exploring also AM2001, which is another Z backbone with a different group. Various sort of Demnum molecules which have only a functional group at one end. That had a lot of advantages, but in the end it wouldn't work out. I'm trying to remember other functional groups that we looked at once with acid-end groups.

Marchon: Diac?

Mate: Z-Diac is the name. And actually, IBM, for a while we were actually shipping product with a stearic acid lubricant. Which they had a reservoir there that would vapor deposit onto the disk. But that vapor deposition had a lot of problems. They managed to ship working drives with that back in the mid-80s and early '90s.

Marchon: What technique did IBM use? I know Komag, maybe Tom will discuss that, but was using a different deposition technique? Did IBM use a dip?

Mate: For thin film, as far as I know, it was always you dissolve it in a solvent, dip your disk in it. You pull it out and it sort of pulls out a thin film of the solution with the lubricant dissolved in it. And initially, freon was the solvent, and the freon would evaporate and leave behind the lubricant. Eventually, freon got banned because of its effect on the ozone layer. And they switched over to-- I'm trying to remember.

Marchon: Vertrel?

Mate: Vertrel-XF was one, but there was another one IBM used.

Marchon: HFE?

Mate: HFE is probably the one I'm thinking of. You're right. You remember these better than I do.

Marchon: Or PF-5060.

Mate: PF-5060, that that I think was the one. My lab had them all, because I was playing around with all these things, but PF-5060 I think was the final choice. And that was reasonably environmentally friendly. And that was a nice, simple, low-cost way of putting it on. But we looked at all sorts of things, like vapor deposition and vacuum deposition, and putting drops on and wiping them down. And that's what the particulate media did. You just spray on lubricant in a freon solution, and then you wipe off the excess.

Yamashita: So when we started to put ZDol, we had tremendous problems trying to spread this around. We did like what the oxide people were doing, which was a spray mist in the freon solution. And then you wipe it down. And it was literally done by hand. It was a little product that Texwipe had. The Texwipe wand. It was a cotton swab stuck on plastic, and you wipe it down.

Mate: I remember trying that. Basically, you look at it and go, "It looks de-wetted." And that's the problem with pretty much any functional group on a lot of these surfaces. The functional groups go down, bond it, and they put a very hydrophobic surface up, very low surface energy up. The next monolayer of lubricant comes down, it sort of says, "Well, I don’t want to sit on this thing, because there's no end groups for me to do my bonding with. So I'm going to ball up and form de-wetting droplets." If you put on too much, it just de-wets it, and as you wipe it, it just smears it around. Whereas the Krytox's and the Fomblin YR, they would spread out very nicely. And the surface tension would pull them flat, but it would be fairly thick. Like I said, on a particulate disk it would be, like, 50, 60 Ångstroms.

Yamashita: So this ZDol with the end group would get all mucked up as soon as you tried to wipe it. And it turned out that you had to apply a tremendous amount of force and try to spread it around. So this was one of the other innovation tricks that Tu Chen came up with. So the mist that we were using wasn't fine enough. So he went to his wife's perfume bottle, emptied it, and he had the fine enough mist. So that was one key step. The second step, instead of using freon, he decided to mix some methanol into it. And this was kind of an interesting idea, too, because when you mix the methanol and freon, they do mix together, but when they evaporate, the freon will go first. And the lube is not dissolvable in methanol. So you get these little puddles of methanol, and the lubricant molecule is kind of spread in between, you see? And it provided just enough liquid, it's like a-- what's the word for it? It's like an immiscible mixture of lubricants.

Marchon: Emulsion?

Yamashita: Emulsion of methanol and lubricant. And that allows you to wipe it down. So that was all done by hand, and we had just banks of these high-torque motors, and the operator ladies to spray and then you wipe them down.

Mate: So how long did that last?

Yamashita: Six months. Until our automation group came up with the equipment to do this.

Mate: I mean more when did you switch over to, say, dip-coating or something else?

Yamashita: Oh, that was a long time later.

Mate: A long time later?

Yamashita: We couldn't make the dip-coating work. And this is kind of a side story, but there's probably a reason why we couldn't make it work. This buffing-- we call it buffing, because it kind of resembled putting wax on a car. You get this little sort of a mass, and you've got to just use a machine to buff it until it gets very, very clear and slick. It behaves exactly like that. Once you do that, the surface was really slick. So when we were doing this wipe-down, you put so much force on the disk that the disk was really, really pretty hot. So we were applying heat on top of it, right? We had no idea how hot it was getting on the surface. So it was a combination of this polar lubricant and this buffing process, mechanical force to put the lubricant. And that was kind of a secret for a long time.

Mate: At IBM, by the time I joined the storage function in '87, they were already doing dip-coating on thin-film media.

Marchon: Yes, so since the whole industry had converged into Zdol mostly by dip-coating, and that seems to have addressed most of the reliability issues with stiction, wear, et cetera. But I think two things happened. One thing is that people moved away from the mechanical texture with a rough abrasive, but using a laser, a pulse laser to create the little dots on the landing zone. But also, IBM started to move away from landing on the disk and moving the head out of the disk on power off. So since Mathew, you were at IBM, could you tell us that transition and perhaps what other problems started to happen then.

Mate: Okay. Like I was saying before, when the-- for the thin-film media, I think initially they were doing landing on the ID. And originally they would texture the whole disk surface to get the right sort of stiction values in the landing zone. After a while, they sort of say, "Well, on our data zone, where we're reading and writing our information, we don't want it to be that rough because of this clearance problem. But we want to keep the roughness in the landing zone." So they do one texture first on the data zone as they needed some texture there to get the magnetic films to grow there, they were textured a particular way with the circumferential textures, so that all the magnetic domains lined up in the right direction. And then the landing zone, they'd go do a separate roughening up process with an abrasive to get a much rougher surface, so when the slider landed, they wouldn't have the stiction problem. And they'd have to spec these differently, and it would actually add cost because you'd have to do the separate textured zone and you lose through the transition in and out of the zone. And the other problem they would have, okay, they could fly all right in the data zone, and when they come back to the landing zone, well then now this roughness is higher than their fly height. So they would actually grind a bit as they landed in the landing zone. That would create wear problems for them, because they solved the stiction problem by making it too rough. But of course, now it's very rough there, and that roughness will be an abrasive on your recording head as you come in and land during powering off the drive, or when you try and spin up to fly onto your data zone. So this was a very unsatisfactory situation. And anyway, my boss, Bryan Street said, "This is a stone age technology, because you're using an abrasive to texture this up." And at IBM Research, there was Andrew Tam and various other people like Thao Nguyen, knew about-- Andy Tam, particularly, was an expert on laser processing and manufacturing. He was in manufacturing research at that time. So I think these guys said hey, maybe we can do a pulse of a laser and sort of create little bumps on the disk surface. And by putting an array of those, we can then custom-tailor the landing zone with not this rough mechanical texture that's kind of uncontrollable, but a very precisely-defined texture with the bump, which has a nice, round curvature on it, which is much less abrasive against the head. And we can, sort of by dialing in the energy, here, change the bumps so we can set that sort of the optimum height for stiction and give nice, good, uniform control.

Marchon: So by the way, just FYI, IBM thinks they invented laser texture, but as I was at Seagate at the time, I think laser texture was invented by Control Data. The original patent was from Rajiv Ranjan at Control Data, working with some CMU professor.

Yamashita: Dave Lambeth.

Marchon: Dave Lambeth, exactly. So the original patent was theirs and not IBM's.

Mate: Okay. I'm sure Andrew Tam was probably aware of that and that's probably what motivated him to pursue this. My boss, or various bosses were looking at, "Hey, how do we solve this stiction and wear problems that are coming from our rough landing zone?" And this was kind of an elegant way of doing that, where okay, as Bryan Street said, get it out of the stone age, into the modern age using laser texture.

Marchon: That worked out okay, right?

Mate: Well, I mean, it took-- I wasn't directly involved in this, but it took them quite a few years to sort out all the issues of, "Okay, how do you set up the laser system? How do you make it manufacturable? How do you optimize it?" And quite a few people got involved at that stage. I played a small role in sort of how do you characterize these laser-textured bumps?

Marchon: How about at Komag, Tom? Did Komag also use the laser texture.

Yamashita: I think we should backtrack a little bit. Initially, on the magnetic side, there were the two ways of doing it in sputter thin film. And one was called the oriented media process. This was invented by a guy named-- or discovered by a guy named Eltoukhy at IBM.

Marchon: Atef Eltoukhy.

Yamashita: Atef Eltoukhy. And by doing a circumferential texture on the disc, and he put chrome on first and then put the magnetic layer on top of it. You get this sort of orientation effect. A lot of debate as to what that was, crystallographic or stress-related. Anyway, you get this orientation of magnetic moment circumferentially, which is very beneficial for recording. But I think the reason why he put the media on the circumferentially-textured disk was it was put there for tribological reasons. It was to solve the stiction issue. So he just had, I think-- this is my speculation, but I think he just happened to have that kind of substrate, so when he put this chrome underlayer process, he observed this orientation effect. So right away, he formed a company called TriMedia. It was a competitor to us from the very beginning. It was started about the same time as Komag. But the Komag magnetics did not require a orientation. It was isotropic. So we didn’t have a chrome underlayer, so the texture was there strictly for the purpose of stiction. But for the oriented media folks, initially this orientation effect would not happen unless you had a very rough texture. And you needed a fairly thick chrome. So for a while, the texture required for this orientation effect was much greater than what would have been needed for stiction reasons. So we thought that we had, definitely, an advantage, because we could make texture or roughness much smoother, right? And so we even could put the texture just on the landing zone at the ID. So we had a product like that for a while as well. But eventually, the oriented media process got to a stage where texture was much, much smoother, more smooth than required or needed for stiction issues. So that's when the idea of laser texture started to make sense. So actually, I knew about the laser texture, because I hired Rajiv Ranjan. So you see, when I hired him, he said, "Well, this is what I've done. It's laser texture." And then I thought, "Wow, this is interesting." But I didn’t think it was really practical at the time, because there's so many things that could potentially affect it. And it does. The nature of the nickel phosphorous surface, cleaning conditions...

Mate: I know at IBM, it took a long time to sort out all these issues.

Yamashita: Yes, it's tough. So to my surprise, Rajiv goes to Seagate. Well, long before that, Seagate purchased all of CDC and ends up with their patent portfolio, too. And there it was, the laser texture. So Seagate was one of our customers, and one day, to our surprise, they said, "Oh, we're going to go do this laser texture. So if you're going to sell us the media, you have to have the same." So we had no choice but to develop it ourselves, too.

Marchon: Yes, I remember when Seagate purchased Imprimis, the division of Control Data, and my boss’ boss went to the first technical exchange back in Minneapolis and came back laughing, saying, "Do you know what these guys are doing? They're crazy. They're trying to do laser texture. They're trying to do texture with a laser. It is such a stupid idea." I said to myself, "That's not such a stupid idea. I love that idea." And yes, sure enough, two or three years later, every disk was laser textured. So did laser texture bring new problems? Did it solve problems, Tom?

Yamashita: I think it was superior, in my personal opinion, for tribology reasons. But implementing it was much more difficult, of course. Developing the tool itself, the system that has a stable enough laser and be able to control the power and vary it and so on. We had an incredible laser expert in Komag, so we were able to create our own equipment very, very quickly. Within three, four months, we had a tool. But once we started to try to apply it, turns out your plating conditions and so on, definitely had an impact. How you clean it had an effect. How long you wait between cleaning to the laser texture had an effect. All kinds of issues like this that you have to control.

Marchon: I think some of the science coming out of IBM explained all this. I don't know if you were involved.

Mate: Yes, the team there worked quite extensively on all these issues, and I understand the science. That's one thing IBM was always very good at was we had this research division that wouldn't feel comfortable with a new technique unless it understood a fair amount of the science behind it. So they did a lot of science of understanding what these bumps that form those different shapes that you would see. And from my standpoint, the study of the lubricant, okay, here's a nice, well-defined geometry for the study here as well. So that's the same thing when you were at Seagate, Bruno, right? "Okay, hey, we can really analyze stiction and decide up-front what sort of heights you want on the bumps and what sort of distributions."

Marchon: Yes. And as usual, would just read the IBM papers and learn all the science behind the empirical measurement we make.

Mate: Yes. We were very good about publishing the work. At least my boss' philosophy is if you want the smartest people, you've got to let them publish. Whereas at Seagate, they probably didn't let you publish and that's why you left to come to IBM.

Marchon: There was another transition where all of a sudden IBM said, "Okay, we're going to stop landing on the disk. We are going to park the head on the outside of the disk." And that was driven mostly by mobile application and putting drives in laptops. So could you maybe tell us about this?

Mate: The drive I showed you before, if it's powered off, it lands here. Whereas this one, when it powers off, it lands out here off the disk. And there's a little-- the white thing here, is this load-unload ramp. When the disk drive spins up to speed, the slider comes-- the actuator pushes the slider onto the disk; so it comes down the ramp, develops its fly height and right away goes out there. So it never has to actually land on the disk and grind against it. Now you just do the texture across the whole disk for the data zone, you don't have to do any separate texturing process. So you lose the cost of making the texture zone, but you gain the cost of the load-unload ramp.

Marchon: And was it done primarily for reliability? For shock performance, maybe?

Mate: There were a couple reasons. One was when you're on the ramp here, you don't worry so much about shock anymore. Whereas if you're landing in the data zone for a mobile drive, if the drive gets dropped, there's a risk that the-- when it hits the floor, the shock will bounce the head off the disk and come back and slap back down again. Whereas on the ramp, well, you're kind of safe out there when you power off. The other reason, which is probably more important, is that when you're on the ramp, it takes less energy to spin the drive. So most of the time, when you're working with your laptop, you're not really reading and writing through the disk. So what you do with a load-unload is when you're not reading and writing, you go up to the ramp and wait for the read-write command. And so if I go up there, I'm losing less power to spin the disk to have it ready here. So it's a fairly significant power savings or energy savings on the battery, if you have a load-unload ramp, compared to..

Marchon: And maybe you can use a motor that's cheaper because it doesn’t have as much torque.

Mate: That's another part, like I say, it's a cheaper motor for less torque to do this stuff. Because that's what they used to do is they-- what you do is at the landing zone, when you're not reading and writing, they go ahead and land there. So rather than being 20,000 stop-starts, you're up a million stop-starts that you have to potentially worry about, right?

Marchon: So IBM developed the technology for mobile application, the small disk drive. And then they decided to apply it to even desktop and server-class disk drives. Is there a reason for that?

Mate: There's all these tradeoffs there, but one of the key reasons for going to load-unload and other products besides mobile is you can standardize in one technology. You don’t have to say, "Okay, I'm developing a stop-start for the server products and a load-unload ramp for here. Let's just go all load-unload. Since we need that in the mobile drive, you might as well have it in your server drives. So our research and development costs will be less." So that was the final reason for doing it, but I think they also liked these other advantages as well in terms of not having to put the cost of a laser texture zone and have to worry about those issues.

Marchon: And so all of a sudden you don’t have the stiction problem anymore. You don’t have the start-stop problems anymore. Did that create more problems? Or did companies then go all out in lowering spacing and creating more problems?

Mate: Well, the problems you get with load-unload is that you come down this ramp. Sometimes the transition isn't always smooth. Sometimes a corner of the slider will gouge into the disk. And so you have to sort of design your system properly so that you don’t contact the disk with enough force that gouges it there and damage your disk. And there are various ways people do that. Western Digital's philosophy was that we're just going to do a good mechanical design. IBM's philosophy eventually became, "Well, we're going to have all our disks be glass substrates." Glass is much tougher for these sort of head impacts when it comes down the ramp and contacts for the disks out there. So you get fewer gouges there and you can meet your spec that way. So again, that's another way that drove the standardization, at least with IBM, and I guess at maybe at that point Hitachi, where they said, "Hey, let's go to glass substrates for all of our products." Where I think Western Digital, I think kind of what they're still doing is we'll have aluminum-magnesium substrates for a lot of their disk surfaces, even in mobile products.

Marchon: So Tom, tell us about the transition from CSS to load-unload.

Yamashita: I always kind of wondered, well, why didn't the drive guys do this much, much earlier? If they had, we wouldn't have had all these tribology issues to solve. I mean, a good amount of our resource was put on tribology issues in terms of people, R&D resources and whatnot. I think it was great that it was done, because not having to land on the disk, solved so many issues now. I think all of that was made up for by just pushing the fly height much, much lower, which probably caused other issues to pop up.

Marchon: Yes, so then having a couple of more iteration in lubricant technology, right? So could you tell us whether at some point Zdol didn't work anymore?

Yamashita: We used ZDol for a very, very long time. Not that we didn't try, but it just worked really, really well. But eventually, one key change was the addition of phosphazene additive, X1P. This was to deal with the lube breakdown phenomena that was being observed. And I believe IBM-- I believe, Mathew, you worked pretty hard on that, too, right?

Mate: Well, I know the problem very well, Yes.

Yamashita: And this occurs-- it is observed that the alumina, these kinds of ceramic type of material can cause Zdol to break down. And the thin film heads had this aluminum oxide, titanium carbide composite material. And this was probably one of the big, big reasons why such things were happening. And this breakdown phenomena started to be observed when you were going lower and lower fly height. And this phosphazene molecule as an additive prevents the breakdown of the lubricant. So we had to start putting that in. And I think some of the drive companies were doing better. Maybe there was some other contaminant involved in the issue, too. But the thing that we hated so much about the phosphazene was that these guys that were making it wanted a per-disk royalty. And they got very rich doing this.

Marchon: It was a cent or two cents per disk or something.

Yamashita: Yes, a couple cents.

Marchon: A couple of cents.

Yamashita: There was a lot of disks being made.

Mate: Yes. Okay, let me just give a couple of backstories to what Tom was saying here. You talked about the slider-- sintered aluminum oxide and titanium carbide, and the backstory on why that was chosen, well, it's a very hard material. That matches the hardness of the aluminum oxide particles in the old particulate disks. And you might ask, "Well, why didn't you switch to something else when you went to thin-film media, where there's no longer aluminum particles in there?" Well, basically because all the manufacturing lines were set up to handle-- make sliders and recording heads off of what was called N58, which was the name for this sintered aluminum oxide titanium carbide. The problem with aluminum oxide, particularly within these slider heads, and this is the same thing within the particulate media, is aluminum oxide was called a Lewis acid. And it turned out that these perfluorinated polyethers like in the Fomblin ZDol molecule, or the Fomblin Z, are very sensitive to these Lewis acid sites that causes degradation there by breaking the molecules apart, I think reactively, and they go off and form this degraded lubricant, which just sort of gums up the works, basically inside of a disk drive. And the way IBM had a little difference. Tom said how they had to use X1P and pay the one or two cents per disk that the company was charging then. Whereas IBM solved this problem by putting carbon overcoats on their sliders, very early on. And that would sort of coat the aluminum oxide on the slider surface. And I actually knew the guy who came up with putting carbon overcoats on this thing. He didn’t set out to do this, but he noticed that if he used sliders against a disk, they would get coated with carbon and that actually-- he could go off and start another start-stop test that this improved their durability, largely because you had this carbon overcoat on there, which would then wouldn't degrade the Fomblin ZDol lubricant that they were using in the this time period. So, we were able to solve a lot of tribology problems very early on by putting on carbon overcoats on our sliders. Which I think the rest of the industry went to-- when they went to MR heads.

Marchon: I think they, yes.

Mate: To protect it from corrosion, right? But you know, IBM never had to put X1P and pay the royalty on that. Because, "Hey, we don't have this problem that these guys are solving with this."

Yamashita: So, the thing that made it even more frustrating for Komag was that we had a head company also, Dastek and Headway. What we noticed was that how you lap these sliders made a huge difference in the way the tribology worked. So, what was happening was that these sliders were lapped, and if you don't do it properly, the surface sheds particles. And a lot of it was aluminum oxide. And so, for example, you took a poorly lapped head and just sort of banged it on the disk. We had created an especially rough disk and just kind of ran it for a while. And then used that surface to conduct start-stop test and get fantastic results. <laughs> Which kind of says that a lot of the problem where this lube breakdown was caused by the head guys. <laughs> Right? Get them to fix their problem and you won't have--

Mate: And you worked for a disk company, so all your problems were always the head guy's fault. You know, when you work for the drive company, which has both the disk component and the head thing, you have to sort of figure out how do you get these two guys to work together, right? And as for the mechanical design as well, right? How do you get everyone to work together in the system. And that was always the--

Marchon: And trying not to point fingers.

Mate: Yes, that was always the "Our disk is great if you do it properly." "Well, you know, our head is great if you change everything you do, right? And when they put everything together, they sort of say, "Well, what's the easiest thing, or fix, we can do?" "Well, change the lubricant." So they would come to me, I was oftentimes the lubricant guy and say, "What fixes can you come up with, say, by tomorrow or the next day to solve this problem we've been having, so we can ship this product without having to go through another year of redevelopment to make everything work right?"

Yamashita: So, getting back to this lubricant change or design, the changing lubricant was one of the most scary thing that you could consider. And it's because I think we had a lot of former IBM people, and IBM seemed to have suffered a number of problems by changing lubes. You put the product out there in the field then something happens catastrophic. So, they say, "Well--" <laughs>

Mate: Yes, I remember, I worked in the research part, and a lot of times you had to go down to the development area. And for a while there was a guy who was the head of the development area, and the story he would always tell, "Well, the last guy who had my job decided he was going to change the lube. He was fired," and I guess he went to work for Komag, "because that lubricant change didn't work out well. So, you're going to have to be a tough sell for me to get--"

Marchon: And the saying at the time was, "Change the lube, lose your job."

Mate: Right, that comes from this guy who-- he was head of the disk development for a long time. But he'd always tell you, anyone who would listen, "Hey, this is the lesson I learned from my last guy." The change of lube he referred to was actually on the particulate media. They were trying to go from a branched Fomblin Y to the Z. Well, it didn't work because of the lubricant degradation problem. But Fomblin Z worked fine on the thin-film media. But okay, if you got ZDol on there, how do you fix the problems without changing the lubricant too much? And so, a lot of our work ended up being, "Well, how do you bond the Fomblin ZDol to the disk?" And people came up with various methods for doing that with like, "Heat the disk up, you could do a thermal bonding process." At IBM Research, we developed using ultraviolet light to bond the lubricant to the disk, and that was actually used in practice for quite a while.

Marchon: And then at some point, even that didn't work, because the fly height was so low that lubricant started to transfer to the heads, and so people decided that perhaps the one OH group at the end of the chain was not enough, so can you guys tell me about this?

Mate: Well, I think that in-- like I said, looking for ways of bonding this lubricant and like I say they had to come up with ultraviolet light and thermal bonding. Those all cost quite a bit, so they were then thinking, what's a cheaper way to bond the lubricant? And so, the next transition was, "Let's go to ZTetraol," which instead of one OH group at each end, had two OH groups at each end of the molecule, so four all together. And that, to me, really improved the bonding as measured by a solvent extraction method, and actually reduced spinoff as well. So, that was a good low-cost solution. But it took quite a while to get in there. And I remember going down and my boss saying, "Oh, what a better way to bond the lubricant to the disk?". "Well, there's Fomblin ZDol to ZTetraol," and they'd go, "Well, that's changing the lube, you know? " <laughter>

Yamashita: So, the ZtTetraol has four OH, right? It's a small-- much smaller, stronger--

Marchon: Two on each side.

Yamashita: -- bonding, Yes.

Mate: You double the bonding strength, basically, for very little cost. The same dip-coating process, you know, everything looks the same, just doubles the bonding there, right? And one other thing on this bonding that I didn't mention before is that the-- if you remember the plot I was showing earlier that as the magnetic spacing goes down, the roughness goes down. But as the roughness comes down, you have less wear problems than you once had before. So, but you tend to get more spinoff. Though, you start worrying about spinoff, because you're thinning down the lubricant to start with. So the way you solve the spinoff problem is by increasing the bonding strength, so you get less spinoff. So, there's actually a connection between roughness, which is going down, and the need for more bonding. Because when it's rougher, you want to have a thicker lubricant to protect against the wear. As you get smoother, you don't need the thickness anymore, but now you're more worried about lubricant spinoff more and lubricant buildup. So, you're trying to tamp down the mobility by bonding it to the disk. And that also helps some wear in terms of it's tougher to displace a lubricant that's bonded to the disk compared to one that's less bonded.

Marchon: Tom, did you have the same experience at Komag?

Yamashita: Yes, in terms of bonding, we tried various things also. You know, heating, we did plasma etching, to try to activate the surface if you will, a little bit, before applying the lube. That sort of thing. But finally, we kind of went on the UV curing. And so, the idea there was that you could use a certain type of UV wavelengths to basically, I think, you're breaking some of the bonds.

Mate: Right, right.

Yamashita: You know, you're actually degrading the lubricant to some extent to force it to bond stronger. So, we worked with the vendor in Japan to develop the tool, you know, work out the type of lamps, UV lamp that we need to use. Took over a year to do, I think, and but we were able to do this fairly successfully. But again, just like changing lube, I think there was some really bad experience at IBM, I don't know, that there was a huge resistance to using UV. I think it was because UV can cause ozone formation if you don't watch out. And so, we had to arrange it so that you evacuate the-- or it was nitrogen filled, while doing the UV process. And the lamp degrades over time, so you have to manage that, too. So, there was all sorts of issues. But we were able to successfully convert everything to a hundred percent UV. So, that was to increase the bonding to make it a little more immobile, and I think it happened that way because the texture was becoming smoother and smoother. You needed just more bonding was helpful.

Marchon: Okay, so we talked about roughness, texture. We talked about substrates, we talked about lubricant quite a bit. So, the one thing we haven't talked too much about is the overcoat. So, Mathew, can you tell me a little bit about the overcoat on the disk and the various materials that were used over the years?

Mate: Yes, carbon overcoat has been the main champ. I remember when I first joined there, they were looking at all sorts of alternative-- I think there were even ones being shipped with zirconium oxide was-- I forget the name of the company that was shipping zirconium oxide.

Yamashita: We did. Komag did. <laughter>

Mate: Komag, okay. <laughter> So, I spent a few months looking at zirconium oxide. But people really weren't that interested at IBM in zirconium oxide.

Marchon: I think some company in Japan. Glass?

Mate: So, I'm trying to remember, it was--

Yamashita: Hoya.

Mate: Hoya was the name of the company I was trying to remember how it was deposited. It was some chemical process.

Marchon: Maybe sol-gel or something?

Mate: Sol-gel type process, Yes. And here, I think, god, trying to remember the guy's name. IBM fellow, Kent something.

Yamashita: Kent Howard?

Mate: Kent Howard. That's what I was-- he was the first guy that did carbon overcoats. But even before that, the first thin-film media was made-- had a rhodium overcoat, which sticks in my mind because rhodium was one of my Ph.D. thesis topics. But that's very hard inert metal, right, but very expensive, so I think that went out of favor. But the reason why carbon overcoats have always remained the champ is there's-- the chemistry is so versatile, with various ways you can deposit it. Even though the conventional way is always best, but people looked at plasma depositions and all sorts of ways. And then you can add things like hydrogen and nitrogen, even oxygen in there to try to change the chemistry, change the hardness. So, people looked-- explored all these parameters, on the various degrees of bonding of carbon, the sp2 versus sp3, what's the right ratio there? And as your products change, you can sort of tweak the carbon process to change these parameters to get the most optimum process for that product. So, I'm sure when Bruno was at Seagate, he worked a lot with that.

Marchon: Tom?

Yamashita: So, the carbon overcoat is kind of an interesting history. The first reported paper on carbon overcoat is by a guy named Francis King at a company called Data Point. And this is in, I think, I'd like to say it was late '70s. Might have been early '80s. Anyway, it was on the plated disk that was deposited on. And somehow, they-- I think the drive was for some video recording purposes or something. That's my recollection of it, but that was the first reported in that paper. And I remember when I was starting to work for Tu Chen when he was at Xerox, he was actually talking about it. So, he was aware very, very early on. And most of the sputter companies had carbon overcoat right off the bat. And this makes sense because you're doing sputtering, it's just as easy to put something on the same equipment by the same method.

So, my recollection when we got going, carbon was it. You know, there wasn't anything else that was being considered.

Marchon: I believe some people called it diamond-like, right? As if it was made of diamond, but not quite.

Yamashita: Yes, it was just for purely sales purposes. <laughs> Had no idea, there wasn't any measurements done. "Oh, it's carbon, therefore it must be like diamond-like." The carbon overcoat when you sputter is basically amorphous.

Marchon: And mostly graphite-like.

Yamashita: Yes, it's more graphite-like than anything else. So, when we started it was about, I believe it was about 200 Angstroms maybe, 20 nanometers. That was kind of like the beginning. The interesting side story to this is that Tu Chen was putting carbon overcoat on the plated disk for the Century Data and he actually had some tribological testing and so on. And what he told me was that the performance was very, very good in terms of protection, corrosion, tribology, all of that. So, I think that's the reason why it was clearly the way to go when he started Komag. But the material that he used, this is all in hindsight, by the way. The material that he used for target was the type of carbon called pyrolytic carbon. It's made by sort of a high temperature decomposition of a petroleum product. And the key thing is that it contains a lot of hydrogen. So, but it's very difficult to make. Very expensive. And you can't use DC magnetron. It's too resistive. So, you have to use RF. And in all of those kind of conspired so that you couldn't consider this pyrolytic carbon. But unbeknownst to Tu Chen, what he put on in Xerox was this hydrogenated carbon that he was putting on, which is probably very good for corrosion resistance. But for us, everybody in the industry, in order to sputter carbon, it's got a very low deposition rate. And you need magnetron cathode to sputter this at a high-enough rate and the magnetron requires a very conductive target material. And for that you use just graphite. This is like the electrode material, you know? It's very porous, but it is very conductive. And that's what we used. But even then, the mismatch between the deposition rate of the carbon and the magnetic there was so huge that it took a lot of effort to create the cathode that had high enough power to deposit this even 200 Angstroms. I remember that was quite a bit of struggle.

Marchon: I think something Komag realized that maybe doping the carbon with some hydrogen was helping?

Yamashita: Yes, so that was kind of by accident. But before doing that, we were trying to qualify our disk with sputter carbon at IBM. And we couldn't pass the corrosion test. And you know, I tried everything. We put interlayer of chrome, tantalum, titanium, try to protect the magnetic layer. And we could not pass the corrosion test. And I swear we thought that this was on purpose. That there was such a resistance to using thin-film media in IBM at the time that this test was deliberately set to fail. <laughs> Fail the thin-film media, that's what we thought anyway. So, we couldn't make it work. That's why we came up with the zirconia overcoat, ceramic, right? Ceramic material. And it had fantastic corrosion resistance. And so, we were able to sell it to IBM. Fujisawa made a drive using this. We sold quite a few disks. But only to IBM. <laughs> And back then they were using ferrite heads. And with the ferrite head, zirconia worked great.

Soon as they switched to thin-film heads, problems started to happen. And you know what, it was again, hindsight, it was lube breakdown. <laughs> You had the ceramic material and with an AlTiC head. Had two ceramic surfaces rubbing against the ZDol, I guess that was not a good combination with this. But all throughout, you know, once we developed the zirconia overcoat, the question was why the corrosion resistance was so good, right? It's very, very resistive. Of course, you know, being ceramic, high-density material, that helped, too. That was one of the key things that we had in mind. And now getting back to carbon, we were making this sputter disk with carbon overcoat, we had what's called an in-line sputter machine. The disks to be sputtered were put on the panels. And the panel would go in and out of this vacuum system through a load-lock chamber. It'd go into the load lock. It's pumped down, goes in and pass through the cathode, magnetic layers put down and the carbon, and then it comes out of the system. And the finished disk is pulled out, fresh disk put on. And this panel is coming in and out of the splutter system right now. Company like Seagate also had a machine like that, too, it's called in-line sputter system. The big problem with this kind of system is that this panel is picking up water vapor each time it comes in and out. And this was affecting the, not only the magnetic layer, but the carbon layer as well. And we didn't really realize what was going on. So, at beginning of the cycle, we would run this machine for two weeks at a time. And all this time, this thick layer of film is building up on the panel. And it's continuously absorbing water. But at the beginning of the cycle where we sandblast this and wash this thing and we would dry it, but it was still loaded with water. And at the beginning of the cycle, the carbon was coming out sort of with a yellowish tinge. And then as we go in several days, you start getting grayer and grayer. And we noticed that, but we didn't really pay attention, till one of our tribology guys says, "Hey, you know, the stuff you're making isn't performing so well, right?" And the disk he had was this grayish carbon. He says, "Give me this kind of disk." It was the disk with the yellowish tinge. <laughs> "I like this disk better." And I was like, "Huh?" So, it was the water that was breaking down inside the sputter chamber making its way into the carbon chamber that was incorporating hydrogen.

Marchon: And changing the optical properties as well as the mechanical.

Yamashita: Yes, optical property as well. And so, "Oh, this is it, right?" And then I checked the resistivity, it was definitely much more resistive with this yellowish carbon. So, that was the key discovery, if you will. And so, I started to get on this experiment mode to try to pump more hydrogen into the chamber. And it actually took a lot of hydrogen. It was like 20 percent. That's why we got this beautiful yellowish carbon. We called it the yellow carbon process. And that was the key. And that carbon had incredibly good corrosion resistance. It's as good as zirconia, and highly resistive. And so, that, I think we were one of the first to put out a disk like that. Now, most of the companies in the U.S. was using sputtering, but I know that in Japan they were using PECVD. You know, if you do that, you use like methane or ethylene. This kind of gas, then you know, you would automatically incorporate hydrogen into the carbon film. But I didn't see any disk from Japan back then so I don't know. Maybe they had better carbon from that perspective.

Marchon: Mathew, you were involved in the metrology aspect of carbon film and ways to measure the thickness?

Mate: Yes, the thickness of the lubricant and carbon. People found that challenging and didn't really have a good way of measuring it. Like I said, on particulate media they had problems measuring the lube thickness. We came up with a sort of clumsy AFM method. In thin-media, the way they came up with measuring lubricant thickness was by FTIR, calibrating against the ESCA measurement and at some point, Mike Tony and I decided we were going to calibrate that versus X-ray reflectivity, which is using X-rays to do a interference method to measure the lubricant thickness. And at the same time we also put down some carbon films and measured the lubricant thickness on top of that. And found out we can measure the carbon thickness as well by this technique. And so, that's akin to this sort of standard way of benchmarking other techniques against the X-ray reflectivity technique. Because the way a lot of people were doing it, lubricant thickness was measuring the escape depth of the carbon signal through there. And as the carbon film got thinner, like you used the escape depth there or they use X-ray fluorescent, which was another technique. But they really had a tough time, how do you go off and standardize the signal you get from these various techniques against some known thickness, you know, one way was just doing a cross section and doing like putting it into a TEM or something like that and measuring it there. But that's kind of not always that accurate. X-ray reflectivity measurement came to be a very good way of doing it.

Marchon: Now the reflectivity signal changes with the density of the materials, so--

Mate: Right, so as you have to, as you set them out with two adjustable parameters. One is the density, the other is the thickness. Because you're going through at various angles and you actually measure reflectivity, you get enough information there that you can fit the two parameters reasonably well. But another parameter you've got to model in there is the roughness, which as things just got smoother, that got easier, the handle.

Marchon: So, with one measurement, you can get three things.

Mate: Three, yes.

Marchon: Roughness, density, and thickness.

Mate: Yes, and doing it on thin-film media is tricky, because then you also have the different magnetic layers as well you somehow have to throw into your model as well. So, but that all got sorted out. I mean, our initial study was very simple carbon film on a silicon wafer. But once we demonstrated, hey, it worked very well there, it wasn't that so difficult to get it working on thin-film media. And other techniques we looked at was ellipsometry, which was another way we would do these things and measure thickness. The carbon was always the trickier one compared to lube thicknesses. But I know a lot of companies like Komag, there's a lot of debate about how to measure lubricant thickness and we talked about IBM and Angstroms especially--

Yamashita: Yes, that's right. <laughs> Well, as long we, are kind of consistent.

Mate: Once we showed that IBM Angstroms was the correct way to go, I think that resolved a lot of issues.

Marchon: So, we talked about quite a number of things. Lately, in the past maybe ten years, the industry went to thermal fly-height control. Did that change anything as far as reliability, tribology, materials? Tom, were you involved in that?

Yamashita: Yes, I think a lot of it happened after I left, so I'm not quite so familiar with all of the-- what went on. It was just starting to being used if I remember correctly, in combination with the touchdown sensing. I think that was a pretty amazing feat in my opinion to be able to do that.

Mate: I'm also amazed at how that got adapted at all, because it's, okay, a nice clever way of adjusting the control of clearance. Basically you sort of say, "Well, okay, when I'm not going to read and write, I'm going to have a high clearance. And then when I want to read and write, I'm going to reduce the clearance." And the way you do that is by having a heater built into the recording head. So, you sort of heat it up, and when it heats up, it gives a thermal expansion, that lowers the bottom of the read sensor and write sensor down towards the disk. You can actually then do clever things like you sort of said. Well, I can go over and actually figure out where the disk surface is by going out and touching it and have some signals that tell me when I'm touching on the disk, and then back off a certain distance, so I can sort of set the clearance to what I want, or set the magnetic spacing at the-- really, what I'm saying is set the clearance at a safe value, where I know I can clear. So, that sort of really helped minimizing fly-height variation. Because, when the slider comes down the ramp, it's designed at a particular average fly-height, but not all sliders fly at that high. Some fly high, some fly low. And you use this thermal controller to get rid of this variation in the slider fly-height by setting that at the value I want. And that really helps a lot in dealing with the bad actors in your batch process. If someone's flying too low, well, you just sort of raise the fly height by using this thermal control. And if one's flying too high, well, you just bring it into the right spec.

Yamashita: So, I think that was a huge innovation to do that because otherwise, for both tribology and magnetics, you have to design for the worst case. <laughs> For the worst case head that happens to fly a little higher.

Marchon: Or too low.

Yamashita: Or too low. <laughs>

Marchon: That's right, Yes.

Yamashita: And the magnetics has to accommodate the highest-flying head, right? So, the media guy-- and this was media guys' opinion-- we were getting pushed to accommodate the head variability, right? And this thermal fly-height control touchdown sensor, I think that kind of changed the ballgame completely.

Marchon: It did, Yes.

Mate: Well, one sort of related thing on that is over the years I counted up, I think it was like six or seven times I'd be working on what iss called a contact recording process. So, the idea is rather than flying with the clearance, you come down and choose the clearance to be zero, and try and fly in contact with some sort of interference. But what always the problem in the end was these wear issues. Oh, and your contact caused the head to bounce around a bit too much. So, you always wanted a little bit of backoff and this thing would allow you to do that. But the thermal fly-height, to come in and figure out where the disk is, you do get a little bit of contact, so you do have to design for some amount of contact in your system. You locate to--

Marchon: When you calibrate to touchdown and then back off, Yes.

Mate: Calibrate to, Yes, and there's always question-- I mean, there'll always be the desire, as things change in your drive like the temperature or something like that, you'd like to sort of recalibrate. But there's a limit to how many times you can go in there and contact before you've wore off the carbon overcoat on your head, for example. So, yes, before wear issues come up is how do we design the system so we can have as many contacts as we'd like to have but without damaging our head?

Marchon: So, we're almost through with all of our technical questions. Is there anything else you'd like to add, funny story, backdoor stories, things we forgot? Tom, anything you'd like to add?

Yamashita: Maybe a few comments about the lubricant. We didn't maybe finish the discussion there. You know, I think the lubricant used today are basically what I might call a designer lube. They're actually specialty made. So, we worked with a company called Moresco that turned out to be an incredible company. Very, very skilled in fluorine chemistry. And so, the first kind of a product that they made for us was the basically a ZDol with an end-chain that has X1P built into the lubricant. <laughs> So, Moresco, I guess they're a company that makes hydraulic fluids, very specialized hydraulic fluid, very small company, but they had this multi-million-dollar NMR, nuclear-magnetic resonance. It's absolutely a critical instrument for making, doing fluorine chemistry, right? So, they had that kind of equipment. And they had unbelievable distillation and fractionating setup. Never seen anything like it. You know, it's just rows and rows of distillation equipment. You know, because this fluorine chemistry, I think the key is you manufacture them, create it, but then you got to size it for the right molecular weight and so on. You really got to know how to narrow the molecular weight and things of that nature. So, they were really, really good at it. And so, Komag and WD we went that way to try to kind of custom-make a lubricant with some ideas about what you want to do. Whether-- what kind of end group, how many you might have, X1P, you know, type of molecular weight distribution and I don't know what they're using today, but I'm sure they're kind of doing that sort of-- continue to do that sort of thing. Yes.

Marchon: Thanks, Tom. Mathew?

Mate: Well, I've got one little story about-- we were talking earlier about this head of the disk development area whose motto was change the lube, and lose his job, right? I actually convinced him to change the lube for one product. And the way this story comes about is that at that time IBM was shifting their disk with Fomblin ZDol with a molecular weight of 2000 amu. Whereas, I think by that point, most other companies were shipping Fomblin ZDol with molecular weight of 4000 amu. So, the experiment I did was I took these two sets of disks, one lubricated with Fomblin ZDol 2000, another was lubricated with Fomblin ZDol 4000. And put them on the hotplate and raised the temperature. And every now and then I'd take it off and put it in the FTIR, measure the lubricant thickness, put it back on the hotplate. And after an afternoon of this, I had a nice plot that sort of showed that the disks lubricated with Fomblin ZDol 4000 had a nice constant lube thickness. Ones with ZDol 2000 quickly lost like a third of their thickness and then plateaued out.

Marchon: By evaporation.

Mate: By evaporation, simple evaporation, you know, at file temperature. And no one at IBM had ever clued into this, you know? So, I generated this plot. Drew it by hand because we didn't-- I didn't have a graphics program back then. And at some point showed this this head of the disk development area, said, "Hey, look at this plot here." And you know, he said, "Oh, it's a great plot!" And he goes off and starts showing it around, and within a month they switched the lube from ZDol 2000 to ZDol 4000. So--

Marchon: And nobody lost their job.

Mate: No one lost their job. <laughter> There was just really a few hours work on my part. <laughs> And I had a success in my year-end performance, "Hey, I changed the lubricant" No researcher's ever done that before." <laughs>

Yamashita: Good.

Marchon: That's great. So, this concludes our interview. So, thank you very much, not only for your contribution to the technology on the disk drive, but also for being good sports and accepting to be interviewed today. So, thanks very much.

Mate: Oh, glad to do it.

Yamashita: Thank you. Yes.

Mate: Thanks very much.

END OF THE INTERVIEW

