Alfred Cho Oral History

David Brock Interviewer

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Alfred Cho: ...but this is a different format here now. Instead of I give a talk and then you just ask questions I'll answer you.

David Brock: Okay, great. Well, I'll just start this. And as I mentioned, maybe we could just begin our conversation by starting at the beginning and asking you about your early life, the lives of your parents, where you were born, what your father's occupation was, things like that.

Cho: Yes. Well, I was born in Beijing China. After I was born then [there was] this war, Japanese were invading China. My parents ran away with [all of] their children to Hong Kong. So after a while in Hong Kong---I was very little at that time---my father went from Hong Kong to Chongqing where the Chinese Government moved to when the Japanese took over Beijing and Shanghai. So then my mother brought her four children back to Beijing and dumped me in Beijing and took [the] other three to Chongqing to reunion with my father.

Brock: Why were you the exception?

Cho: Exactly, that's what I was asking. I said, "How come [you] dump[ed] me in Beijing with my grandparents?" And then [my] mother said, "Well, you were about three or four years old. Your older brother is old enough to help carry [possessions]," my younger brother [was] about one year old [and could be carried]. My sister was two years older than I [was] and she [could] walk. "But you are too heavy to carry and too young to run." So I am dropped, dropping out in Beijing to accompany my grandparents.

In some sense, I felt I got left out, but then I benefited a lot [from the experience. My grandfather [was] a very famous calligrapher in China. He is the authority in a kind of calligraphy called Jantal [ph?] which is a very old, ancient Chinese calligraphy. Also he writes poems and so on. He himself actually he was educated in economics. He graduated from the University of Beijing and then [did] graduate work in Tokyo University in Japan. Of course, my father is also in economics, banking, insurance. He actually graduated from Beijing and then Yānjīng University, and then went to Columbia University here [in the U.S.] in the 1930s. Got his graduate degree from Columbia University, United States, and then went back to China.

Brock: In economics?

Cho: In economics. So in that generation my father, my uncle, they're all in business as a profession. Actually my uncle graduated from London University, so all went out to get advanced degrees and came back to China to serve. So, [to] start from the beginning. My mother just felt-- well, the time is after the Second World War, we reunited. Then my grandparents took me from Beijing to Shanghai, and then my parents and my older brother, older sister and younger brother [were] all reunited in Shanghai for about two years time. Then they came to China; in 1949 [they came] to [the] Shanghai area. Then at that time actually, my father didn't need to run away. But then he still felt like maybe he wanted to live in the western world because he was actually educated in this country [the U.S.] in the '30s. So [he] took us [at] the last minute to Hong Kong. So, therefore I actually went to high school in Hong Kong, Pui Ching High School from-- that six years of high school was done in Hong Kong.

Brock: May I ask what your education was like before high school because it seems like you were living in such tumultuous times. What was it like?

Cho: You know, the time while [I was] in Beijing [was when] I went to the first grade to about fourth grade. That's [when China] was under the Japanese occupation. That was a time that my grandparents sent me to a very nice private school, so I was well educated at that time in the very careful schooling by my grandparents. So at the same time I learned a lot of calligraphy, Chinese painting and that kind of brushwork with my grandfather. So that's why I was saying [that] I benefit[ed from staying] behind in Beijing, while my siblings went to Chongqing. In the wartime it was very, very difficult. It's just a hard life there [in China at that time].

And after the Second World War finished, [we had] that reunion in Shanghai. Of course, at that time [I] was in fourth grade. The difficultly [of the transition] from Beijing to Shanghai schooling [was] very traumatic for me. I was the best student in Beijing before and then, all of sudden [I] go to Shanghai fourth grade [and] they speak Chinese. I had no idea how to speak Chinese. I speak Mandarin. In Beijing they speak Mandarin. So I learned total different dialogue [dialect]. In those days the language was not-- the dialogue was [the dialects were] not unified [into a single spoken language]. Now the whole China speaks one dialogue [dialect], it's Mandarin. They can speak Chinese, Cantonese, it doesn't matter, but you always know how to speak Mandarin. That is the national dialogue [dialect]. Interestingly, the writings are the same. It doesn't matter in Chinese, Cantonese, [all of the] the Chinese writing is exactly the same. You just pronounce differently the different dialogues [dialects]. So anyway, besides the language problem there in school, the English level in Shanghai is higher than in Beijing because Shanghai is more like the city of New York, more metropolitan, you know, go out to...

Brock: Commercial ports and everything, yes.

Cho: Commercial, whatever it is, so the English is at least one year higher than in Beijing, so I only learned very short sentences of English, and when I come to Shanghai they talk about stories. I mean, I had no idea how to read stories, so I felt totally lost in that discontinuity in English [class?]. My mother played a very important role in my upbringing. She sat down with me with English [and] tr[ied] to help me to catch up with my one year behind in English there. And just about [when] I was trying to catch up---I was a senior in high school then---the Communists come.

We run again to Hong Kong, and as you know they're totally using a different language again. They use Cantonese. I went there I said, "Oh no! I don't understand what you're talking about, again." So the worst yet is, I remember clearly, they have a Chinese dictation in Cantonese. The dictation means the teacher [is] reading the Chinese poem or literature or whatever [and] you write and see if you can know how to take [understand it?]. I got probably a zero on that. I had no idea what he's talking about. So I was again lost. So you start all over again.

So this movement from place to place really made my studies very, very difficult, but when I think back, I benefited again. Now [when] I go to restaurants, it doesn't matter if it's Cantonese, Chinese, whatever. I can speak their language. I can speak their dialogues [dialects]. And in fact, at home when I was talking to my grandparents, they were speaking their home dialogue [dialect] which is Fokien, another dialogue [dialect], so even when I was very little I can speak Fokien dialogue [dialect] and the Mandarin, the national dialogue [dialect]. So now I can actually speak four different dialogues [dialects]. I can go from north to south I can speak most of the dialogue even when they didn't want to speak Mandarin, so I can communicate with them. It's a benefit of this.

And also I benefit[ed from] the art, calligraphy, Chinese literature, that kind of training, early from my grandfather. And of course at that time when I'm about to graduate from high school, my mother says, "Well, what are you going to study?" So she knows that I like art. She knows that I'm good in art, but then she said, "If you major in art you'll be very hungry." And she said, "When you were little you were always sick. We paid so much to doctors when you were little. I want to see you get some money back. Maybe you should be medical doctor." And of course she said, "Well, maybe you should major either in medical doctor or in science and engineering," which she can see is a future for my generation. So I was doing okay in biology tests in school, and chemistry, but I sort of hesitated in dealing with blood. I thought maybe medical doctor is not quite my cup of tea.

So then I said, "Okay, then maybe I should study engineering and science in that area." At that time my older brother, who was ahead of me five years, he's five years older than I am, he already picked mechanical engineering. And then my older sister, who was two years ahead of me, she picked architecture. So I said, "Oh, what's left? What can I pick?" I said, "Okay, I better pick something like electrical engineering." So that's [how I] ended up with my field of electrical engineering.

And so, as you know, my parents ran from place to place to place and then [they were under] the regime of Chiang Kai-shek. In those days the money just kept on inflating, and furthermore they have different kinds of currencies. They [the government] say, "Well, everybody should turn in all their gold and silver and we [will] make sure this time the currency will not inflate." So my parents [who] are so reputable and honest, turned in all the gold and silver we have. In China in the early days, the gold and silver they [people] wanted to save in their home as a base and a security. "So, I'll turn it in," I still remember that clearly that they [my parents] decided, "Oh gosh, we'll turn it in." The thing is, if you don't turn it in, they put you in jail. So for my family [with] the training, the reputation, [it was] unthinkable [that] you [would] go to the jail. They turned in all they have. That currency, after no time, just like any other ones [currencies], inflated and turned into nothing, so we lost everything. We don't have any money left in Hong Kong and [so we] started all over. After they sent my older brother and sister out. The rest [of us], we had no more money anywhere. Even I still remember my mother turning in her rings, sell[ing them], whatever, the last bit of jewelry they have, [just] to support us. And our uncle [who was] maybe a little bit better off, helped us with a little bit of money. Then the time when I was going to come to this country in 1955, I got this scholarship from Oklahoma Baptist University. That is a connection from high school, Pui Ching High School that my Sunday School teacher is related. Her sister was the foreign student advisor at Oklahoma Baptist University, that is how that they made the connection and gave me a scholarship to go [there].

Brock: So it was a Christian private school that you went to?

Cho: Baptist.

Brock: The Baptist [secondary] School in Hong Kong.

Cho: Yes, Baptist High School in Hong Kong. Of course, in Hong Kong in those days, only the private schools [were] considered as good schools. The public schools are not run as well. And the very best Chinese [secondary school] is Pui Ching High School. And then, of course, there are many good British high schools, colleges, in Hong Kong. And again, it's my mother's decision that she said, well, she wanted to make sure send all her children to United States to get educated.

Brock: Had she been there when your father went to Columbia?

Cho: Ah, okay. That's one thing. She wanted so very badly to come to this country to get educated also, but at that time she stayed behind in Beijing because at that time, I think [that my] older brother was already born, so she had to stay back to take care of the babies. And in fact, even my oldest brother he had one elder brother too. He died. In those days, they didn't know how to handle those little babies. He didn't make it. He died after one year, or something. So anyway she didn't come out [to the U.S.], but she want[ed that] her children all come out. She would try her very best.

Also she picked Pui Ching High School for me to go to learn as much Chinese as I can, because she knew that she would send me to the United States to learn more English later on. So then I would have English, have more opportunity to learn later in my life. But 18 years old, before I graduated from high school, she wanted me to have as much Chinese education as I can receive. So I went to Chinese high school, the best Chinese high school for learning Chinese and also that school is very strong in science and mathematics, and physics, chemistry and biology. So in fact Dan Tsui, [who got] a Nobel Prize, was two years behind me in Pui Ching High School. We are from the same high school, same high school. Another very famous person Yau,Shing-Tung is in mathematics. He's a professor in Harvard now, department head of mathematics at Harvard, Yau. He was also from Pui Ching High School.

Brock: At the same time?

Cho: He is behind me, younger than I am. And he got the Fields prize. The Fields Medal is the highest [prize] in mathematics, because there is no Nobel Prize in mathematics.

Brock: Why do you think that there was-- well, a couple of questions. It sounds to me in listening to you that your education in Beijing, especially, was very, I don't know how to describe it, maybe was it very formal? Was it a very sort of classical education, if you will, or how did it compare to the other people's education?

Cho: In Beijing, my education, it's just a private school. It's very well---the best run private school in Beijing at that time. Of course besides going to school in those days, [I] came home [to] my grandfather [who] would teach me calligraphy, art, poems, all the other things. So,I have a childhood life that not quite ordinary like some of them [who could] go out play with the [other] kids and hang out in the street and all that. I don't have that situation. I still remember [that] I want[ed] to have a ball so badly. I wanted to have a ball, and then my grandfather would take me to a sports shop to buy a ball, and he didn't know how to play [with] these balls himself, so he [said], "Pick one." So I'm going to pick, pick, pick one and I didn't know [which one to pick]. I picked a baseball.

Brock: Oh man, not very good for bouncing.

Cho: That [ball] was beautiful, but then it doesn't bounce! This is my childhood. That was one of my very best toys, but it doesn't work. <laughter>

Brock: Would you say that from those days through your high school days when you had time outside of the classroom, time to yourself, were you continuing to pursue calligraphy and artistic pursuits, or was there any science or engineering, anything that would have led somebody to believe, "Oh, this person is going to do notable things in science and technology."

Cho: In Pui Ching High School they're known to be good in science and mathematics, and all of us had very good training in physics, chemistry, biology and mathematics. And that is very, very intensive, [with] very, very good teachers, I think the best teachers, even today. All of us [who] graduated from there still reminisce about our teachers. I think that's what makes a difference, the teacher and their caring. They were good, they were really extremely personable to each one of us and made sure we know what it was going on.

That's how---in Hong Kong we [went] to school from eight o'clock to five. And the first class at the Pui Ching High School, the first class, is Bible. We all get-together in the morning. It's in the auditorium. It's religious, and after one short religious get together and then we start our class. It's that religious in Pui Ching High School in those days.

And of course, my mother also tried to make sure I had a balance of what my talent is in art. With whatever little money she has left, [she] sent me to a Chinese painting master in Hong Kong, [to] have private lessons. Very few lessons, but very important [ones], which planted seeds of another way of how to paint, Chinese painting, is [what] I learned. Even today, that still very much influences the way I paint in Chinese painting. So even [though] she told me [to] study science, she didn't forget that my talents are actually in art. And then the time when I tried to come to this country--- there's just not that much money left. My suitcase was a present from my uncle because there was no money to buy a suitcase. I still have the suitcase in my closet today, as almost like something for me to remember how I started. And then [we] didn't have [enough] money, of course, to fly over to this country; [so I came] by boat. And of course [the] boat had different classes: first class, second class, student class, whatever, the lowest class we can get here; just wanted me to get to the United States. And then my room in boat is a conversion from the cargo [hold]. There is no window.

Brock: Just down in the lowest levels.

Cho: Just down in the lowest level, and then when the day is good, they lifted the ceiling up so get some fresh air, because when it was a cargo hold obviously the roof can be lifted because they would take the cargo out, right? So [we] just smelled canvas, where they wrap cargos and things, but we had a good time coming over. And then when I...

Brock: Would you pardon me for just one moment. I think I need to change the battery on this machine. It seems to be running a little bit low and I don't want it to run out on us. Pardon me. Sorry about that. Nothing would be worse than losing that. I brought a lot of batteries. I'll just stop this.

END OF AUDIO 1 / BEGINNING OF AUDIO 2

Brock: Okay, great. Well, we were talking about your travels by sea to the United States.

Cho: Yes, finally, you know, I got a bed in the cargo room cabin. It [took] 18 days to cross from Hong Kong to San Francisco. And I was so excited to come. When I left, my mother and my father took me to the doctor and then they give all they can---$200, $300--- [they] give it to me. [They said], "Here, make good use of this and goodbye." And then sort of like swim or sink, that's it. That's all they can do. And you work your way through school. You have to, [I] didn't have scholarship. And when I get off the boat, 19 days in San Francisco I had to go from San Francisco to Shawnee, Oklahoma Baptist University. And then [I had to] think about how to get there the cheapest way. So the cheapest way I could find at that time was Greyhound bus. So back to---$50 out of my $300. [The] Greyhound bus in 1955 from San Francisco to Oklahoma was $50.

Brock: Expensive.

Cho: So I think, three days and nights and I was sitting in one seat. But I get to-- I got to Shawnee, Oklahoma and--

Brock: Just a quick question, pardon me, your classmates, were others of them also heading abroad for their college educations? Were other of your fellow classmates traveling to the United States or--

Cho: High school class?

Brock: Yes.

Cho: Pui Ching---I came from a very good high school, as I told you. And a big percentage of the classmates came to this country. But only very few, they were able to have the opportunity to come out of here right after high school.

Brock: Okay.

Cho: Most of them, they go to college in Taiwan, Hong Kong and various [other] places, and afterwards, they graduated they came to this country. I think that when we have 50 years high school reunion in Hong Kong a few years ago, and at least 20% or more had their degrees from United States.

Brock: Wow. But it was a much smaller proportion who went abroad for their undergraduate.

Cho: Undergrad could come out-- I think 150 graduates, we had three classes and each class was 50 [people]. Three classes graduate, about 150 people maybe, only three or four at best [came to the U.S. to go to school?].

Brock: So unusual.

Cho: Very unusual that you can come out, because very, very difficult to come out to this country--

Brock: In terms of the immigration?

Cho: In terms of the immigration laws and I was very lucky that I got to come to this country. Also in those days, you wanted to make sure you graduated and you go back to your country. The United States wanted you to stay here after you graduated. But I came in '55, 1957 actually this country had a new law, called Chinese Intellectual Immigrants, Refugees. Chinese Intellectual Refugees. [It is] a new law that allows a certain number of the Chinese refugees to come into this country. Because my father was educated here in the 1930s---he was, as I said, [at] Colombia University---that he qualified as an Intellectual Chinese Refugee. So he got me a visa to come into this country in 1957.

You know, again it created actually a problem for me. The reason is the American law says, “Okay your parents immigrated to this country”. I came [on] a foreign student visa to this country in 1955. I became a nobody at that time. You were a foreigner because you have no more family in Hong Kong. But you can be under your parents because you're [still] a student [and] a child [of] your father, so you'll be under the immigration law and become immigrant to this country under him. But, you had to give up your earlier coming into this country [U.S] [on] a foreign student visa. That signature created a problem. They can not just sign for me while I was a student here. I had to go all the way back to Hong Kong to sign that one signature at that ceremony and [then] come back here again.

Brock: Very expensive to do.

Cho: Very expensive. I didn't have money, so I had to borrow money from people to get back.

Brock: Did you have to take the boat back and forth again?

Cho: I had to make the time to make the signature. So I flew back, let me see. Maybe I-- I flew back [to Hong Kong?] and then I came back [to the U.S.?] with the boat. Because I don't have enough [money] to-- fly back-- flew back and came again on the boat. So same thing happened to my sister. She had to do that same thing. I think my brother at that time was over 21 years old and had already become a different status. We were [still] under 21, [so] we were under this law. So my sister and I both had to go back at the same time to Hong Kong to make that one signature and then take the boat back at the same time.

Brock: Two questions, one I imagine that Oklahoma was very different from Hong Kong, so I was wondering how you adjusted to that difference? And the other was, when your family did come in 1957 to the United States, where did they go?

Cho: Oh, okay. When I first came to this country to Oklahoma, I think that is a major blessing for me. The reason is in the South, people I felt, [were] extremely friendly, and [in] those days in '55 they looked at me, maybe as Martian or whatever, [I was] so foreign, so different. Every time---Thanksgiving, Christmas---they invited me home. In fact, I find even today, that love, that care is imbedded in me, which I never forget, you know. They took me to their home when it was Christmas time. They're not rich. They're from a small town called Sapulpa, Oklahoma. The father is a mail man. The mother is working in the shoe store selling shoes. And then [at] Christmas time, the kids wanted to go the movie. I didn't have money to go to the movie, and the mother gave me $5, $5, big money. We went to the movie. I even today, I say, “Gosh I wish I had the chance to go back there and pay her, five, 10,000 times”. This is something she gave me which I never did forget how the love and care, [the] generosity of the people in United States in those days. The doors [to their home] were open, they didn’t even lock [them]. It was that safe, that good. It's not [that way now], that's for sure. It's different than in '55 years, in small town in Oklahoma. Of course, I left Oklahoma [in my] sophomore year.

Brock: What lead to your departure directly from there to Illinois?

Cho: The reason is that when I was in Oklahoma I [found] that it's a very nice school. I learned English nicely, the people [were] friendly. In fact, if I went to a big school like Illinois, I'd be lost. In fact, people there are trying hard to just help just one person. The school's small. I think the whole school only had 1,000 people. And, most of the graduates are either becoming a priest or, a good school is in Pre-Med, but engineering is very, very---not quite up to the top.

Brock: Right.

Cho: In fact, when I was a freshman, I got their mathematical prize, [I was] best in whole university. [But, I] tied with a senior. We were both in calculus class. They were judging [which student] [was] the best in calculus. They had a mathematical prize. You know, in '55, math in South is not very high. Calculus they think is very high math, which the senior people [were] taking, especially in Oklahoma Baptist University. I already had calculus in high school, in Pui Ching High School. I already had calculus. So I was there, and it was a breeze to me. I got all perfect scores all the time. And then in fact, we had a tie breaking between me and David Roper, who was a senior, to see who get the prize. And then in the tie breaker test the two of us, especially given to us to see who [would] win the prize. Then the chair says, "Well, you're still tied." So finally we have a tie, the two of us get the prize at the same time. So even today, my name is still carved in that math award in Oklahoma Baptist University. And, so of course, at that time I'm very honored, but I felt, well, “I want to be good in engineering science. I need to change to a different school, which is more into this—“

Brock: Yes.

Cho: So at that time, my older brother and older sister were already in Illinois.

Brock: They were already at the University of Illinois?

Cho: Yes, yes. They didn't go in there first time [start there] either. My sister was at Pepperdine in California.

Brock: Okay, right.

Cho: [For her] freshman, first year and then [she] transferred. My older brother [was] also from OBU (Oklahoma Baptist University) and transferred [to the University of Illinois] earlier, seven years earlier. So anyway they were already there and I went in '56 to join them after I worked in Chicago for a summer job to earn some more money.

Brock: Did you have relatives in Chicago or….?

Cho: No, but I guess we [did] have a relative in Chicago, an uncle, but [the] University of Illinois Urbana-Champaign is 150 miles south of Chicago. At that time, I think my mother's younger brother [was] in Chicago for a while. But then, they were actually moved to California. Because his wife was getting a medical degree from Chicago, that's why they were in Chicago at that time. When I went there, they were already gone. But, my brother was there when they were there.

Brock: Okay.

Cho: So although we didn't live in the same place, my brother and sister [and I], we all lived in a single room because renting [a single] room was the cheapest way to live. And then I learned from my older brother how to survive. There is---we have something called “meal job”, I don't know if you ever heard of that. A meal job is you work in the sorority or fraternity [houses] serving meals. You don't get money, but you got free meals. But that was---one thing very important is, you don't waste much time. The reason [for that is], you got to eat anyway [while you were there]. For instance, I worked for Phi Beta Phi sorority and then maybe---the girls there [were] maybe about 60 people, 60 girls in there. And then they have five waiters, and then they have one dishwasher and they'd have their own cooks and everything. So the five waiters, we rotated who set up a table each day and who cleaned up [the] tables each day. So you know, we all served. We all came out, served and then we went to eat [by] ourselves and then, after we eat, we go back to school, to class. So only [on] the days [that it is] your turn to set up the table, you come in there 15 minutes earlier, just put silverware on the table.

Brock: Right.

Cho: [It] didn't take much time. I think the total time [that you were] there---you work and you eat--- is probably similar [if] you had go to a restaurant and you walked into the cafeteria itself and not much difference in time. So you got a free meal and didn't waste that much time so you can study. So that took care of the four years in Illinois to get my Bachelor's Degree. The reason it takes four more years, is because the first year [that I spent] in Oklahoma---because I took the courses, had all As---but, then they transfer your credits [from] there, but they said, "Well, they're not the [Illinois] requirements.' In Illinois you graduate with super credits. So I graduated [with] more credits than I need, but you still-- you spent one more year to fulfill all the requirement courses.

Brock: Right.

Cho: So I graduated in 1960.

Brock: Now, I know that one of the attractions for you to the University of Illinois must have been the reputation of the Electrical Engineers there.

Cho: Yes.

Brock: Did you have an opportunity to do any sort of undergraduate research or work closely with any of the faculty or?

Cho: Yes, in fact, this is a very good question [about why] I went to Illinois. I had [the] fortune that in my sophomore class I took a class in electromagnetic fields, which was taught by Professor Charles D. Hendricks. Charles D. Hendricks [was] the one [who] taught me the first electronic class. And even at that point, he had [an] eye on me. He says, "You're a good student." So [I finished my] sophomore year and then at the time I graduated, after I graduated, he picked me as the first graduate student to set up his laboratories. He was a new teacher. At that time, he was new, he was an assistant professor. First, after he graduated, he served the country in the Army, and then [when he came] back out of the service after four years, he came to teach in the University. [His first year of teaching] ---I just happened to take that class.

Brock: Okay.

Cho: And then we [got to] know each other in that class, and then after two or three years later he wanted to set up his own laboratories. Sort of establish his empire at the University. He picked me as the first person to set up his lab. So I have the [good] fortune to work with him. You know, when you set up a person's laboratory of that kind, you start with bolts and nuts and basic things from beginning. You learn how to solder pipes. You learn how to put sinks together, a vacuum chamber together. Rather than ---if you're student [today] they walk into a lab, all they do is push a button, right? [They] don't know how this thing is put together. "Why is it doing this?" [If you build it from scratch], you see how it runs. You know how to fix it, you know how to change it. You know how to improve it, right? So I had the fortune to learn from scratch, from starting [the] first equipment, how to build the equipment to study at that time and so forth. He wanted to [do] something with charged particles in the vacuum, and accelerate it. He was also working earlier in TRW for ion propulsion work as a consultant. So he knows the charged droplet particles for possible propulsion: charging from a needle for accelerating it, getting the impulse for ion rockets.

Brock: So this was to ionize material off a sharp point?

Cho: Yes, exactly. In fact, later on these things developed into ink printing, right. I mean, these are for charging, spraying and ink printing.

Brock: So--

Cho: My master's thesis is actually charged particle droplets from a needle spray out an ionized mist of particles. Because you put liquids through a hollow needle.

Brock: Yes.

Cho: You put a high electric field at that needle there, that electric field puts charge onto that particle to draw the particle out and ionize…the particle is ionized. And you accelerate the particle, then you got the thrust. And this how ink jets--

Brock: Interesting. So it was actually through a narrow aperture, through a hollow needle, interesting. And--

Cho: A very high field at the needle point. You put a--

Brock: Sure because it's …

Cho: And then ionize it and it will spray out, spray out, yes. So that was in 1960. So it was extremely important in my life to see how [that] experiment was done, how to build up a laboratory and then Professor Hendricks is such a brilliant person. He also has a photographic memory.

Brock: Lucky.

Cho: Extremely bright. I still remember, we had an open house that-- [to] show students, people walk through, showing our charged particle laboratories and [all of] that. And after that exhibition, we lost a drill. Somebody stole our drill. He can remember the serial number of the drill.

Brock: Wow.

Cho: That kind of--

Brock: That is very unusual.

Cho: Photographic memory.

Brock: So when you were working with him to set up that laboratory, you were building the high vacuums or the vacuum system that this whole set up had to live inside of, as well as all the electrical equipment or you know, did you both build your own vacuum system?

Cho: We built our vacuum system from scratch and we-- of course there were parts we had to buy.

Brock: Sure.

Cho: You know, the pump itself, we buy the pump. And then you had to do all the plumbing, therefore I learned what you mean by silver solder. You know, there are these details. Usually you think [that] people just solder things together, you know, they use lead solder, whatever. But in ultra-high vacuum, lead solder is a “no no”.

Brock: Right.

Cho: You had to use silver solder at high temperatures. How do you do [that]? How do you solder these? What kind of material are you putting in here for compatible in ultra-high vacuum? You had to have the full HFC copper, not any other copper.

Brock: Right.

Cho: You had-- you sink at high temperatures, you use what, you use different metals. You use tantalums.

Brock: Yes.

Cho: You use molybdenum. You use tungsten. You know, you had to know, and when you solder things because it was a silver solder, you need some kind of flux. What are you going to use? [Are] you going to use nickel? You're going to use something. You know, you have to have all these tricks of how to put things together in ultra-high vacuum compatible. And this is very, this is, you know-- the details of things. I worry about today's [students]---they just look---“Oh, go to Ebay, look at, which one you want?”

“Here it is.” Then they complain when it didn't work, whatever. Do you know how it's put together? [Do you know the] details to the point of what solder you use to solder the thing together? Think about it to that details.

Brock: Yes.

Cho: So this is kind of training education you get from University of Illinois. The thing is, you have a very broad education. And the thing I think that education is important to us is once you have a very broad education, you can never learn the latest, because there will be another latest later on. What you need to do is have such an education, broad, that you can jump into that [new thing], and then you can go into [the] details later on, whatever it is.

Brock: Right.

Cho: So this is the kind of education you need to have.

Brock: Were you also exposed to semiconductor electronics in this period?

Cho: Yes. You know, [an] interesting thing is [that by] ask[ing] the question, is [that it] remind[ed me] how that [it] was. And then, after I finished my master's degree – charged droplets -- I told my Professor Hendricks that, I said, "You know, Professor Hendricks"---in those days I [was] a student. Today I still call him “Professor Hendricks”. Lot of people call him “Chuck,” [by his] first name. But to me he is my professor. You know, I still call him Professor Hendricks. I said, "You know, I feel so tired of working and studying. I need a break." And he is so nice that he said-- he says, "Okay, go take a break." And he said, "Where do you want to go?" And I said, "You know, I came to this country six years, seven years, I have never even seen the East Coast." You know, [it was] just work, work where you are and try to earn a few dollars and you have a new job, feed your mouth and you pay $28 a month for the room, a single room an old lady sublets, leases her room out.

Brock: Right.

Cho: There are no cooking facilities, but [I] shared a bath with other students. You have one room. So this is how I've been living and getting very tired. I want to have a break and I need to earn some money and live life a little bit. So he let me go. He said, "Where do you want to go?" I said, "East Coast." So he said, "Well, okay." He wrote a letter to High Voltage Engineering Corporation,[in] Boston. He had friends there. He was [a] consultant [to them].

Brock: On their ion engine project.

Cho: Ion engine, yes. They immediately gave me an offer. So I went there. So of course when I went to Boston, as you know, Bostonians [are] very proud of Boston, but for outsiders who came at that point, it is [a] very new thing because you get lost in the streets. You think you make a right turn and right turn and get back there. No, you never get back. <Laughs>

Brock: Those streets are-- it's true.

Cho: You know, when I was first there [in Boston] and [I] was complaining to [a] colleague, “How come the streets here are not [on a] grid, not like other places, that [are] rectangle based?” He says, "Well, [the Boston streets are] where the horses went and they paved it."

Brock: I think that's right.

Cho: The streets are all stars in Boston. <laughs>. So I learned lot of things. Also, in the early days I needed some kind of driver license and some places you never get tickets and some of them you do. And then, one other thing I [found to be] most interesting is [that] I can no longer use the insurance [from] Illinois. I had to buy insurance in Boston. The insurance company, a Boston company, insures Boston cars. All these things I thought “oh, new way of living”. But anyway, I really enjoyed it. I learned a lot over there. I worked on charged particles between parallel plates -- micro particles accelerated out from the center and then I used a Van de Graaff for high voltages, producing charged particles, solid particles in that laboratory there.

Brock: And so that instead of charged droplets, it was charged solid--

Cho: Charged solid particles. I put micron-sized particles between two parallel plates.

Brock: Okay.

Cho: And then the plates were concave in a way, they all [were] bouncing between. The charges on the plates had the particles just bouncing back and forth between the two plates. If you make the field in there so that the field concentrates toward the center there, you have a hole in the center, the particles go shooting out from the center.

Brock: Out of the top.

Cho: Out of the top, and then you start with high voltage, that's how you get the propulsion charged particle…Solid particle propellants for rocket engines.

Brock: What sort of material were you using?

Cho: We were using all different kind of metals. We were using nickel particles. We were using, you know, all different metallic particles.

Brock: When you-- so at this time Ion Physics, that was in Burlington, Mass.?

Cho: Burlington, yeah.

Brock: And--

Cho: IPC [Ion Physics Corporation], and then you know, Burlington.

Brock: How many people were there at this time?

Cho: By that time we have maybe the Ion Physics Corporation, maybe have about 15, 20 people.

Brock: Okay.

Cho: Small. And they have-- are in the same facility as the van de Graaff. Ion Physics Corporation is a subsidiary of High Voltage Engineering.

Brock: Right.

Cho: So we are in the same location and then just one section of that, High Voltage Engineering or Ion Physics Corporation has that. Besides I was doing the-- some charged particles and then there's another person doing some droplets, and another person using Kaufman source for the nitrogen accelerators. The Kaufman source finally developed today's ion implant sources.

Brock: Okay.

Cho: All of these are a spin off and become something very useful in today's electronics. You were asking me earlier, the question and I didn't answer you, "[When] did I learn electronics, solid state electronics?".

Brock: Oh yes.

Cho: I didn't answer the question is because there is a time lag. When I left to Boston in those days electronics are vacuum tubes. All electronics are triodes, diodes, pentodes, you know, they are vacuum tubes: glass and they accelerate electrons in there, and there are no transistors in those days. So although [the] transistor is invented, but it just not in the class, in the book.

Brock: Right.

Cho: So then the story. After I was in Boston for a year, I enjoyed living there, but then I know I want to go back to University of Illinois to study. But also, I haven't seen the West Coast. And my parents, [who had] immigrated to this country, [were living] in California, Los Angeles. I didn't even have money to go back home and see them ever since they moved over there. I was in Illinois, studying, I went to Boston to work, I haven't seen them. So I told Professor Hendricks again, I said, "Can you find me a job in L.A. area? I haven't seen my parents." I guess in American life [at that time], he felt like [it was] unheard of, “what a weirdo, are you crazy? You haven't gone home?” <laughs>. But we were just knowing how to study and to work.

Brock: Right.

Cho: So of course I went to California, then [I saw] my parents often. I didn't stay [in their] home because I lived in Manhattan Beach. TRW is in Redondo Beach, [the] very next town and my parents lived in L.A. in the north. So I—again, I worked with a person Professor Hendricks introduced to me, [in] that group. His name is Haywood Shelton. He is a graduate from MIT and I think he's a student of Nottingham, who at that time was the master of physical electronics.

Brock: Right.

Cho: At MIT, [he is a] big professor and Shelton’s from that very famous professor Nottingham – there was a Nottingham symposium years and years for physical science about electronics, about emitters. Emitters are very important for how you make vacuum tubes.

Brock: Right.

Cho: Nottingham is famous for doing electron emitters and Haywood Shelton [was] probably at the end of Nottingham’s students. Langmuir was his first. And then, Dick Langmuir was a relative of the famous Langmuir and alos was a Director [at] TRW.

Brock: Okay.

Cho: That's how my professor made the connection over there to get me a job. But I was working under Langmuir as a director and Haywood Shelton was my immediate supervisor. I learned so much electronics from Haywood Shelton in doing absorption, desorption. And that's why in the report on ion emitter studies, the authors are Al Cho and Haywood Shelton.

Brock: Okay.

Cho: And in there we studied-- we made these cesium ion emitters for cesium ion engines.

Brock: Right, which was the big--

Cho: The big thing.

Brock: With cesium, right?

Cho: Exactly, cesium ions. So you can see here, this is very similar looking as the MBE I finally developed diffusion cells. These are wrapped with high temperature foils for heat shielding, tantallum heat shields.

Brock: Okay.

Cho: And heating it up, the cesium in the back there, with thermocouples for sensing the temperature, negative feed-back systems. Everything here, is similar to the MBE effusion cells.

Brock: Interesting.

Cho: So I'm saying, you know, I learn all these things and of course, I went back and wrote my PhD thesis in this area absorption, desorption…things that [are] all building to the final…my career is [the] invention of this MBE technology. But at TRW I was so happy, my parents were there. [I] take my father out to eat---every Friday after work I drove 40 minutes to see my parents, take my father out to eat, [my] parents out to eat. At that time, I used to take only my father out because my mother is working in a Hollywood movie star's home, babysitting for a child, for babies. Again, they were very poor. She tried to make ends meet, living as nurse for rich Hollywood movie stars.

Brock: Living in their homes?

Cho: Yes, but my father, [was] very unhappy since he taught in China, in Hong Kong. But in 1957, those days, if you did not have experience in this country---I don't care if you had a degree from Colombia---he can not find a job in United States. So he worked as a clerk in L.A. banana distributor. Got up at five o'clock in the morning, you know, they distribute banana early to places, like five in the morning.

Brock: Right.

Cho: Counting banana, accountant, he's accountant. Can you imagine, a professor in economics, now as a clerk counting bananas?

Brock: Very, very dispiriting I would think.

Cho: He is so depressed. So that's probably what finally killed him, that even in those days, the days when I was there, I felt at least I had opportunity to be with him, my father---on weekends and take him, he always looking forward-- as a banana distributor. Can you imagine? Go over there at five o'clock in the morning, work all the way until about six o'clock at night. And I, after work at TRW, 5:30, drove another 45 minutes to take him [out to dinner]. He's still in working clothes. From there [I] take him to Chinatown, and then [I] take him [back home]. So every week, and I felt that's the only time I was very close to my father.

And after three and a half years, Professor Hendricks [was] still a consultant to TRW. Every time he came, he lived in my apartment at Manhattan Beach at the time. Finally, after three and a half years, he said, "Al, if you don't come back now. You're out." It's probably true. You know, you can only tolerate that long being outside.

Brock: Right.

Cho: But I was so happy [living in] Manhattan Beach as a drifter, and I do painting. I joined a group [to] do oil painting. Meet every weekend. We go climb down Palos Verde rocks, paint ocean rocks, waves. Paint different places in Manhattan Beach, different beautiful places. I was so happy. I felt, “Oh this is the life”. Then I tried to learn guitar, I tried to hang [out] on the beach, become a beach bum. I say, “This is life”. But then Professor Hendricks says, "No. Get back to your studies." So I immediately quit everything. I went back to Illinois.

Brock: Just a couple quick questions about TRW and the TRW Space Technology Labs. It must have been-- I imagine it was an enormous operation in those days. Was it a large, very large organization?

Cho: It's a very large organization. They have all different way of making the ion engines and then the-- of course not only the ions. TRW has a lot of other space [technologies] also. Chemical rockets, materials, you know, with the chemical rocket we have, with time, the materials, corrosion, elements, it involved everything. So packaging for everything to shoot up in outer space. All these things.

Brock: Were people at TRW using ion sources for doing ion implantation at this time?

Cho: At that time, people were studying that, but at that time, it wasn't that advanced yet, that ion implantation. It takes, I think next wave of electronics. To answer your original question, is where I learned electronics, I finally went back to-- this time it's February, I went back [to] the cold winter [in] Illinois after the nice beach, California, on the beach. [It] shocks your body and soul.

So anyway, I went back there, [this time I was] even more shocked [than] when I left. I don't know, five years, all the requirements changed. No more vacuum tubes, it’s solid state electronics. <laughs> The semiconductors. So and then five years ago to go to PhD thesis, PhD program is [decided by] your professor [with] a little stroke of a pen, you could go on and study for PhD program. There are now new rules. You got to pass qualifying exam that qualifies you to get into PhD program. The qualifying exam now has semiconductor transistors, all those things in there. I had no idea [about those things], I was in vacuum tubes. So again, is Professor Hendricks, he knows that I will not be able to take that exam right away. I need a little time to prepare for the exam.

Brock: Right.

Cho: And he also knows that not one person, he himself, can pull me out of this fire. In the qualifying exam there were 30 questions. A one day examination, each professor only makes one-- gives one different questions and he corrects [only] that one question. He can't give you…he wont' tell me the question. Even if he gives you the whole thing, you only have 1/30th. You know, you fail. So he said, "Take the first semester, don't even take any courses, just audit. Go in there auditing [the] semiconductor courses and do all your preparation for the field all these past examinations, [review] all [the] books, need to go view all the courses." So I was studying from seven o'clock to ten at night, very day. [You need to review] all those books, besides [auditing] the classes at that time. I did the back of each chapter questions, you know, each chapter at the end there's some questions.

Brock: Sure.

Cho: Well, if you take courses, the teacher, "Well, do the odd number or the even-numbered questions."

Brock: Yes.

Cho: I do every one; one, two, three, four every single question. I did, the whole book from the first chapter to the last chapter, all these courses. That one semester was very a major shock.

Brock: I'm sure.

Cho: Then I took the qualifying exam. There were 30 people took the qualifying exam. Eleven people passed. I was ranked number two. My professor was very happy with me. He said, "Okay, now you can go on to your PhD program." You know, because after pass[ing the] qualifying exam, you had to take eight more courses. After eight more courses, [you] write your thesis. After you write your thesis, you defend your thesis.

Brock: Right.

Cho: Of course at the time you defend your thesis you're supposed to know [more about] your thesis [topic] than anybody else. So and of course I have very tough committee. They call him Nicolas Holonyak.

Brock: Oh sure. Yes, a very tough person to have on your committee, yeah I would think.

Cho: He didn't know what question to ask. He was really, you know, tough.

Brock: Well, let me just ask ….

END OF AUDIO 2 / BEGINNING OF AUDIO 3

Brock: Okay. Great. What we were saying—- We just left you after passing your qualifying exams and learning semiconductor electronics.

Cho: Yes. Finally. You know, after I passed the qualifying exam. But ,first I went out and took eight more courses and then wrote my thesis. Turned out, doing that thesis work is very simple, because it basically is a similar kind of experiment [as the one that] I [had] set up in TRW, just using different elements.

Brock: And was it a simpler—- That image that we looked at before of your ion source for cesium, was it a similar sort of apparatus?

Cho: Okay. So, I wasn't doing a cesium ion engine. I was doing an experiment. The study of the cesium ion engine. For instance, like those days at TRW, I also doing one work…when you do the cesium ion engine, you have to have electrodes to accelerate the cesium ions. And when it gets started, the cesium ion, then I don't care how good you design the electrical lens, that the ion beam will not hit the lens. Because you hit the lens, hit the accelerator grid, [it] will sputter back onto the porous tungsten surface. That changes the work function, and changes the property of ionization. That Langmuir equation or that, efficiency of ionization, rather than 99.9 percent, you drop lower, lower, when the work function goes down.

Cho: Okay. So it is very, very important those studies. We try to design how that absorption lifetime of this sputtering of the electrode, of the cesium ions onto the porous tungsten surface which will not effect the ionization efficiency.

Brock: I see.

Cho: What kind of material you're going to use, how do you avoid that back spreading onto the surface. At first you say, "Well if you design a good lens, it doesn't hit there." Right. So it turns out the problem is this. That even you can design a lens, theoretically will not hit the electrodes. What happen is, the ionization efficiency, even [if] you have, let's say 99.9 percent efficiency, you have point one percent which is neutral coming out. That point one neutral has a charge exchange. Of the ionized one, when the neutral coming out of there, the ionized go <boop!> hit the neutral, so therefore that lets that neutral turn into a ion.

Brock: Yes.

Cho: So it's not born-- The neutral, the new beam is not born on that surface. You can calculate the electric fields. If the fields [are] over here, the ion starting from this point will not hit that.

Brock: <laughs>

Cho: But, the ion, it turns out, was born above that surface by the charge exchange of the neutral. Was born this point. So when he see the field, he hit this way.

Brock: So it goes in any direction, right?

Cho: It hit the grid.

Brock: Okay.

Cho: So then because—

Brock: Then it's going to hit that back.

Cho: Then it sputters the grid onto the surface of the ionizing surface, that changes the work function. Okay. So now I am trying to study—- Okay. This material gets on the surface. What is the lifetime of the surface, can it be re-evaporated away from the surface? So, we do the experiments say using quadrupole mass spectrometer [ph?], and then have some kind atom hitting out of this hot tungsten surface, and this how hot it had to be to re-evaporate the <inaudible>. The absorption lifetime is microsecond, or millisecond, or a minute, or whatever. That will change the work function. How many [are] coming on here, how many can re-evaporate on the surface. Or will not be accumulated on the surface. If the lifetime is longer than coming down—- More people [are] coming here than people [are] leaving, then you got more people on there, more and more and more, right? <clapping rapidly>

Brock: Right.

Cho: So if people won't leave faster than [people are] coming, then you get accumulation. Okay. So this kind of like, that means we study the adsorption lifetime of atoms of hot surfaces.

Brock: Now, that was the reason that you were looking at gold and silver, right?

Cho: Ah. Okay. At that time, in TRW, I wasn't looking at gold and silver. I was looking at materials for making the electrodes, like tantalum.

Brock: That's what I was just wondering.

Cho: Like tantalum. Like titanium. Like, you name it. Nickel. All these refractory things. So when I went back to you know, [to] write my thesis, I can pick any element. Gold and silver, sounds good you know? That's my thesis work. <laughs>

Brock: Okay.

Cho: So actually have no use, but is a exercise.

Brock: But these were better—- But in terms of surface science, and these sorts of surface studies; was it true at that time that there was a lot of more work with gold as sort of like a model system, if you will?

Cho: Ah. Yeah, gold is always inert. Silver, you know, also is [a] high conductivity material. And then you have a lot of silver solders in there, and all these things. It's not totally useless, I was just—

Brock: Right. But it wasn't—

Cho: Joke, that it's useless, but it's important element to study. But the time, at TRW, I was doing the real electrodes. That's what we were studying, adsorption life times of that. And here now, I come back, you don't know, I write my thesis, I just change it to gold and silver. Furthermore, it was so different then when I come back to Illinois, is—- I had [a] contract from NASA when I was at TRW. When I came back to Illinois, I know how to write proposals, I know how to get contracts. I wrote a proposal to National Science Foundation. And I got a contract. I got money. Myself. So Professor Hendricks, [who] did so much for my life, you know, for I paid [him] back a little bit. I came back as a graduate student. I have money to bring back to his lab. In fact, my [NSF] contract is big enough to not only just feed myself, but pay [my] tuition, my salary, the lab I use, and all that. It is enough to have another of his students on my contract.

Brock: Wow. Great.

Cho: So that was a—- I feel very good about that.

Brock: I'm sure.

Cho: So then after I graduated, then I interviewed. I got eight offers. TRW wanted me to pack and go back there. I got offers from IBM, I got offer from Xerox, I got offer from all these…RCA, all different laboratories, for those things. And I actually got two offers from Bell Laboratories. One is in Murray Hill, one in Allentown, Pennsylvania. And, all together, eight offers, and then of course I had to pick and choose for where I would go. I have also very good advisors, and friends, and they told me that, "You should go to Bell Labs. And you should only go to Murray Hill Bell Labs." They'll send you, a student, they don't know…they all look very good, they don't know details.

But I have…[I am] so very lucky…friends and advisors. And they say, "If you want to do real serious basic research, Murray Hill is the place." Which is absolutely correct. I picked the right place, here. And the difference working here is—- At that time, we were under AT & T. In 1968 February, I joined Bell Laboratories [which was] under AT & T. Then I have all the freedom to do research. Coming here, [they] give you one empty room, one desk, one pad of paper, pencil, start. Sky is limit. You have all the freedom [to do] what you want to do. It's just unbelievable. And then of course, you know, John Arthur was here.

He [was a lot of the] reason that I came here also. Because he is interested in studying adsorption and desorption on gallium arsenide surfaces. And he heard my talk. [The first time that] he heard my talk was in the American Physical Society. I gave a talk in the American Physical Society meeting on my thesis work. And he said, “Wow, this is a way we can measure adsorption lifetimes of semiconducting material, on semi-conducting surfaces…how we [can] grow materials right.”

Brock: Using the quadrupole as a detector?

Cho: Yes. Yes.

Brock: Okay.

Cho: At that time, we had commercial quadrupole mass spectrometer. The time when I was doing quadrupole mass spectrometer experiment, there is no commercial quadrupole mass spectrometer. I have to read a PhD-— German thesis. Translate from his PhD thesis of quadrupole mass spectrometer fields.

Brock: Wow.

Cho: Build my own mass spectrometer? There is not a commercial [one], not then. I was joking about, “Oh, go to E-Bay, buy a book. Buy equipment, whatever.” I build my own quadrupole mass spectrometer from scratch. Making the rods, making the electronics, making the power supply to drive this quadrupole mass spectrometer. And [I] built my own detectors. Yes. So this is how we do things [in] those days. So, when John Arthur heard this, he was very impressed, [he] really wanted me to come here. So I came, we collaborated. And then of course, after a little while, our interests [became] slightly different. He’s interested in just looking at adsorption, desorption, physical chemistries. I want to see what it can do. In fact I was extra motivated by that time, because I wanted to grow thin films. I develop—- In the early days, John tried to evaporate these things by putting a coil onto a quartz capsule, [to] evaporate the atoms out and so on. And then, I was doing a lot more sophisticated [work], because [of] the ion engine. I designed the effusion cells, with tantalum heat shields, with negative electrical feedback. Feedback to control the temperature of the cells.

Brock: To keep it constant?

Cho: Exactly.

Brock: As the charge depletes.

Cho: So, it’s not just a variator heating it up as it sinks.

Brock: <laughs>

Cho: I have very sophisticated effusion cells, that the source will keep the flux constant for very, very long time. Because of this electronic feedback system. Like an ion engine. Very very similar.

Brock: Right. Yes. If you're going to drive a space ship, yeah. <laughs>

Cho: Yes, it's not something you vary, something you turn by hand. You had to control the—

Brock: Right.

Cho: It's just such a precise mechanism.

Brock: Oh, interesting.

Cho: This is how the connections are. So, you know, again, I was asked in a lot of places, "How do you…? How [do] people invent things?" I said, "Inventing things is making connections." You connect one field of knowledge into another field of knowledge, you create a third field. That's how MBE [was] invented. It is invented because [I] can see the early effusion cells, cesium ion emitters, in ultra high vacuums. And then here and now I built the effusion cells using that [to] grow semiconductor materials. And then, plus my knowledge of using surface physics studies of electron diffractions through in situ monitoring of the atoms which are on the surface as a single crystal, amorphous, polycrystalline, whatever. How do you desorb oxides on the surface, to make the clean surface? You have to have reproducible materials to grow. These are all—- And then using this, plus surface physics, plus ion engines, and then to grow crystals, you create a new field.

Brock: Hmm. Could we talk for a while about surface physics, the use of the electron diffraction so that you could know, kind of in real time, what's happening on these surfaces? Because when I talked to John Arthur, he pointed to this as a critical—- As just such an important thing that you did. And so I think it would be nice to know how—- Where you got that experience of doing it, and just talk about that for a little.

Cho: When I first joined Bell Labs here, you know," the sky's the limit": what are you going to do? John and I were started to look at absorption and desorption from the surface, and then growing crystals, tried to evaporate some gallium arsenide, grow on there. But then, one day they'd be shiny, one day hazy, one day shiny, one day hazy, actually no controls. "Why is it we did it the same way, but it didn't work? Today is a bad day, whatever." Okay, so I think, "Hmm. I'll put on better effusion cells, control the flux. Had right flux number on there. It's doing it on some days, hazy some days, not hazy [on some days]." So I have some problems. And then, so I thought I should really look at, you know, diffraction, how they look. In the early days, over here, you know, a lot of—- Lester Germer was here. He's the one [who] invented that the electron is a wave. Lester Germer and Davisson, you know, do the definitive experiments that say electron is a wave. Although, Davisson got a Nobel Prize, and Germer didn't. Right. It was Davisson-Germer experiment.

Brock: Mmmhmm.

Cho: That's how the ball bounces.

Brock: <laughs>

Cho: Anyway, I inherit Germer's experimental equipment. I have his glass electron diffraction system. When he left here, he went to Cornell to teach, I got his LEED (low energy electron diffraction) system. Doing the electron diffraction. But then I find, the low energy electron diffraction is electron beam coming out here, hit down the surface, diffract the beam back onto a screen, and look at the spots. So if I do it in crystal growth system, in no time this screen—- You know you evaporate here, you diffract there, this screen would be coated dark and no more, the fluorescent screen going to be no longer useful.

Brock: Okay. Because of the crystal growth going on, it'll knock, the electrons will knock material onto the screen.

Cho: So, what you had to do also first of all is this. Let's say you want to grow on this surface. So have you [have an] atomic beam go on here, evaporate on there. And now you want to look at it, look at the--what are the single crystals doing. Use the electron diffraction system. You have to stop the growth and then put the screen over here and the electron beam from this screen here, look at it. You are not simultaneously in real time doing it. Furthermore that big screen is in the system here that got coated with the materials. Not in the real time and furthermore [it] can get contaminated. And so again, in Bell Laboratory there's so many stars and doing things. There was one person doing high energy electron diffraction systems. I look and say, "Hah, this is what I need!" because they were mutually perpendicular, right? The high energy electron diffraction is, you have the electron beam impinging on a surface and grazing the angle. Diffract onto a fluorescent screen. And here now, you can in this direction, evaporate the beam on this surface. So you can evaporate on a surface here, I have the reflection electron diffraction is perpendicular. Look at it at the same time, I'm depositing material on it.

Brock: And if the electron is knocking anything of the surface it—

Cho: It was so far away compared with the other one. There can be even two in the area. There's no direct site of the molecular beams.

Brock: Oh I see.

Cho: So the system is, the screen is always clean. So I further make it more carefully, because I have a shutter in front of the screen. [I can] open [it], look at it, don't use it, then I can close it. So I have all kind of options compared with LEED. So I developed that into MBE system and so now I can put the substrate in here and look at the electron diffraction. At first, you know, you can chemically clean your system, doing all kind of things, there is the oxide on the surface. And if oxide [is] on the surface, you cannot grow. You just grow a so-called hazy surface because—

Brock: Which would be just a polycrystalline layer on the oxide. Okay, yes. Not single crystal. <laughs>

Cho: Because the oncoming atom on the surface, it didn't see the lattice.

Brock: Right.

Cho: It sees all of this amorphous oxide on it.

Brock: Right.

Cho: That's why it doesn't grow a single crystal? No reason.

Brock: Right, right, right.

Cho: So I used that HEED (high energy electron diffraction), looked at the surface. Heating up the surface to the point, again the gallium surface is critical. It's just enough heating up to the point that oxide desorb. [If] I heat up more, then the arsenic starts desorbing, you get gallium beads on the surface, and the game is over again.

Brock: I see, yes.

Cho: So there is only a small window, 15-20 degrees at best, that you can survive. In that range, you better grow. <claps> If you don't grow, at that time, you know, you get a hazy surface. So, I have all the tools now. I can look at the diffraction, desorb the oxide on the surface. Also, beside that, I can figure out how to prepare a surface, get the best way to desorb the oxide. For instance now, I use improved methods for cleaning the surface, get all the dirt and surface become single crystal clean gallium arsenide surface. <claps> Immediately, dip into de-ionized water. That forming a layer of water atom on the surface, and that putting in again I learned from TRW, had the spinning jig -- Spin the water off so the water is not in any drops on it really. Just very thin water atoms on the surface. That allows me to desorb [at a] lot lower temperature, and expose the clean gallium arsenide surface.

Brock: That's really interesting, because it's not exactly like a cleaning technique but it's a surface preparation technique so that you can then get a clean surface. Wow.

Cho: Yes. All these things, it's like all these links put together. Then of course, now I know I know at what temperature that it desorbs, giving me a clean surface, and then a this point <choom!> open this effusion cell at temperatures, with the shutters, the beam starts depositing. And furthermore I found out, in study I also find out to make sure to have stoichiometric gallium arsenide on the surface, sometimes it's better off have a little bit of arsenic background on the surface. Deposit on the surface. So that preserves the surface, you can heat up to even higher temperature, without turning into gallium beads on the surface.

Brock: Right. Oh add a little extra arsenic.

Cho: So all these things, all from surface—You asked me what surface physics. Not just that simple. A lot of knowledge there [is from my] from surface physics background, to give you how to grow a good shiny single surface gallium arsenide. So furthermore, I find out, after I grow [the] materials, that the electron diffraction changes in pattern. Okay, so you have clean gallium arsenide surface, that the diffraction of this angled beam coming down on the surface there. The electron beam may go through lot of protuberances on the surface. You can go ahead, have a chemically clean surface, there are micro facets on surface, <clap> it's not atomically clean, gallium arsenide, okay? So the beam will go through the protuberances on the surface, that's to be three dimensional electron diffraction. Because the beam had go through the little hills here, the three dimensional diffraction, that diffracted beam onto so called Ewald sphere, they have spots. But when you grow a very smooth surface, atomically smooth, then the electron beam goes through here by glancing, refracted, from the surface: 2D diffraction. Two dimensional electron diffractions. The two dimensional electrons are already in the reciprocal space as rods. The rods intersect the Ewald sphere as lines, instead of the spots. So [when] I see the diffractions go from spotty into streak patterns, I know [it has] become [an] atomically clean surface.

Brock: Hmm.

Cho: And then atomically flat surfaces. So to me, even when you can chemically clean the surface at the beginning, the surface is not atomically flat; it is microfaceted by chemical patching. Only MBE grows the surface -- in the beginning it grows in the valleys because growing the valleys the energy preference is there to grow in the valleys, formong the atomically clean flat surface. Now…

Brock: So it'll differentially fill in the valleys.

Cho: Exactly. So now, from that, you have an atomically flat surface, now you can talk about building atom layer by atom layer by atom layer in atomic dimensions. So this is where that quantum well of atomically abrupt crystals can be achieved, with MBE. See, I show you some of the pictures that, for instance, I even have a picture of the initial… So this is, you know, earlier I talk about in TRW making effusion cell look like that, and then you can see the today's MBE effusion cell, then that looks similar. Then of course, these are same tantalum shields, and flanges and so on. Okay. And then I will talk about the growth atomically, layers. An MBE is, you know… you draw pictures like that of atoms of different kinds, and one kind of atoms, another kind, open different shutters making different—- But this, how do you do that? I mean how can you make this? You have to have a base to grow these, right? This is what I was talking about a while ago. You have earlier chemically etched [the] surface, in the electron micrograph you can see the micro facets. Then you look at it with the RHEED, you see [it's] spotty. Because the electron had to go through the protuberances, and then three dimensional electron diffraction is spotty. After you grow a few atomic layers, and then it tends into the valleys, and it grow in the valleys because of the preferential energy. You can see it forming larger, smoother areas compared with original. And you can see the electrons reflecting, then they get more streaking, they are starting to form together. Furthermore, you see, between these lines here, they seem to have something happening here. These are so-called the surface structures. The surface atom reconstructed slightly different than the bulk refractions. Surface structures. So, you further grow with MBE, atomically flat. There's no more holes and valleys, anymore. Look at the electron diffractions here now. Streak patterns. These are in the one bar, one bar, one direction looking at it, okay? And now you can see, between that major diffraction lines here, here there is one half water.

Brock: Like a secondary line.

Cho: The reason is, on the surface, the gallium arsenide surface, the dangling bond not just a hanging and a dangling in the air there. They reconstruct themselves, on the very first atom layer, they reconstruct themselves into different surface structures, okay? Now, even more interesting is that this different surface structure, if you look at gallium arsenide, the arsenic atom [is] dangling this way, the gallium atom dangling this way in the <1 0 0> direction. Therefore by looking at the electron diffractions, I can tell that you are on an arsenic stabilized surface structure, or a gallium stabilized surface structure. I look at the surface structures! I can tell all these controls to the atomic dimension. Which atom [is] on the surface? Gallium arsenide in the <1 0 0> direction is a layer of gallium, a layer of arsenic, gallium…I have a model. Look at this. If you look at this, if you say this black one is [an] arsenic atom, the light one is a gallium atom. You can see, this is a <1 0 0>. If you look at in the slice, [there is] one layer of black atoms, one layer of arsenic. And then you look at [it] more carefully. If I have black atom on the surface here, the dangling bond goes this way [down]. And if I see the gallium on the surface, the dangling bonds are going this way [up]. They reconstruct different surface structures, because at the end, they are hanging on the top here that they don't want the bonds dangling on the surface, they want to lie down, reconstruct themselves into different structures. By looking at the different structures, I can tell which atom is on the surface. To that degree. Now, in the growth, there are a lot of interesting things. Later on, if you put dopant on there, the dopant on which site makes a difference. If you put -- gallium arsenide is a 3-5 compound. If you put a dopant of four on there, if you put a four on the three side, that's a donor. If you put a four on the five side, that's a receptor. You can pick N or P type! So doping gallium arsenide with germanium, you can make it N or P, by growing on an arsenic structure or gallium structure.

Brock: Using the same dopant?

Cho: The same dopant. Which site you are on. So from all these, my surface physics study and knowledge, I have all these controls. The growth of shiny atom layer by atom layer, to what site….how I grow these, I grow it this way, I grow it this way. Right. Furthermore, say, "How do you know how many layers [to] grow?" When you look at the electron diffraction, reflection, over time, what happens is that if you have a -- Let's say if you have a electron diffraction glancing on the surface here, a very shiny surface here. That the electron beam hitting on the surface, just think about, I shine a flashlight on a marble surface.

Brock: Yes.

Cho: The reflective marble and flashlight light is a lot. But if I on the surface here, let's say at a quarter atom level, the surface has little islands [here and there].

Brock: Mmmhmm.

Cho: They don't grow a single layer instantly, they grow in little islands and they coil back together into one layer. Quarter atom layer on there, then you have half an atom layer on there, more matter -- just one atom layer high now. The reflected electron getting smaller, the flashlight shine there a little less light because the surface is not as shiny, and it's not as flat, right?

Brock: Mmmhmm.

Cho: But when it grows further, you have three quarters [of the] atom layer covered. You [are] on the other side of the table now. You [are] getting [a] shinier surface now, more. You know, you finally grow… the whole atom layer [is] complete, you [are] back to this high reflected electron beam again. Okay so now what I do is here, I look at the specular spot intensity. I can count one atom layer by another atom layer.

Brock: By the oscillation cycle--

Cho: Yes, I just explained to you a while ago why you see the oscillation. You see I can count one atom layer at a time. I'm not just talking about, "Oh you [are] growing an atom layer." I can see. I actually [am] counting which layer I'm growing on.

Brock: And that's over a time scale of what? Two, two minutes, or something in there?

Cho: Depending on—

Brock: How you tweak it, yes.

Cho: Seconds, depending on how fast you deposit it, right? So, in fact, I didn't show you all these things here. In fact I was growing let's say aluminum gallium arsenide - gallium arsenide super lattice structures. Gallium arsenide [is] growing faster than aluminum gallium arsenide because I need to evaporate aluminum at a little lower rate. You know, it doesn't evaporate as fast. So therefore usually in MBE growth, you grow gallium arsenide layer a little faster than the aluminum gallium arsenide layer. So I look at these diffractions, I will see—- Oh I have a picture here. Let's say I want to grow, three atom layers of gallium arsenide, three atom layers of aluminum arsenide and then back to twenty atom layers of gallium arsenide. So what [do] I see? I look at the oscillating beam here now, I count one, two, three, I close <snaps fingers> the arsenic shutter. Open the aluminum shutter. And then I grow aluminum arsenide. You can see it's slower. Oh, [it] takes a little longer time [to] complete my three atom layers. And at the end of completing the third atom layer of aluminum arsenide, I close the aluminum shutter, I open the arsenic and then I go back to the gallium arsenide again. I can actually control the structure, real atom layer by atom layer.

Brock: When had you developed that kind of control? To be able to do that?

Cho: Ah. This [was not done] actually just my self. These are actually, lot of—- I say, I'm only representing the MBE community. It is the whole of my MBE colleagues that continuously advances these things. And of course, I started this by using electron diffractions, and then an in situ monitor and then mass spectrometers and all these things. These oscillations at first were starting in England. Colin Wood said, "These things are oscillating; [they] are dark and light, dark and light, dark and light." You know, then there was a lot of controversy over there, they tried to say who actually did the first, and all that. In that book I edited, Molecular Beam Epitaxy, [it] clearly stated which is the first paper [that] observed the oscillation of the beam.

Brock: When was that roughly, just in time, do you recall?

Cho: In 1983 or 4. Probably 5-6 years after I developed the growth. So again, there's an interesting thing. In 1970 I was invited to England, in Blackpool…

Brock: Oh, I think that we ran out of space on here. <laughs> I'm sorry, do you mind if we just take a break for a second while I download this and clear out the hard drive?

Cho: Sure. Maybe you want to go to the washroom…?

Brock: Yeah I think I will. I'll get this thing going.

Cho: I talked more than you wanted hear.

Brock: No, no, it's really fantastic. Let's see how do I get this going?

END OF AUDIO 3 / BEGINNING OF AUDIO 4

Brock: When we stopped talking we were talking about all these ways in which you developed the ability to control the deposition of these atomic layers of materials and the possibilities that control opened up, in part from having a lack of control in your earliest experiments in your collaboration with John Arthur, but I thought we could maybe talk about just this progression of how your thinking about MBE developed, and also when it became clear to you that this would be really good for making devices.

Cho: Well it's interesting [that] in developing from a research project that you get some results and publications to finally making it a mass production product used by the world, it is a long, long, long road. A long hard road. You have to have belief in yourself, you have to be persistent. I remember clearly that when I first was able to grow thin layers, atomic controlled thin layers, I gave a talk in England, when it ended a young kid, I don't know his name, in the audience, he stood up, he says, "Mr. Cho, all these beautiful layers you grow, what good does [it do]?" And then that triggered me, as one who has so much belief in this, to think about "Gee, I better show you what I can do with the thin layers." <laughter>

Brock: When was that?

Cho: 1970.

Brock: 1970? Okay.

Cho: So I came back and then I wanted to make…of course, at that time everyone is trying to make lasers, Mort Panish become [the] new department head and he's using liquid phase epitaxy to demonstrate the first room temperature CW laser. At first they have some problems of growing uniform layers with liquid phase epitaxy, and at first they have a problem of how to make more thin layers, thin layers down to less than a thousand atom layers. With liquid phase it is very difficult to grow that thin a layer. I thought, "Gee, I'm growing atom layer by atom layer. A thousand atom layers is duck soup. I can control that with my eyes closed." So, first in the meantime, I tried to grow the laser and people throw monkey wrenches in, "MBE will never make it, and the reason [that it won't] is you grow atom layer by atom layer."

If I want to have…in those days they cannot grow thin layers and all the structures are very thick. The laser you will grow, the active layer is a micron, maybe [it is] best is to try to aim for half a micron. And then, worse yet, the cladding layer is three microns, the final contact layer is five microns. To me [it] is like "Wow, it's like one week growth to grow that thick!" Because it's so thin, a second layer, a second atom layer, there [are] a lot of seconds to make a 30 micron thick layer. So people say, "You see? This is [a] totally useless technology you're developing."

As I said earlier, you have to be persistent, got to have vision, look further down the road, and your 30 micron structure is not the last structure. The future may become only a micron and then I can control [the] thickness. I have a technology for the future you will get to. So, I started grow the laser, grow the first layer, I was so excited to give [it] to people who fabricate it and it doesn't even lase. I thought it would be better than liquid phase, but forget it, it's not even close. Come back very disappointed. [I] wondered what's happening. And of course taking layer by layer, by parts, grow one layer at a time, give to people, look at the photoluminescence, how the light [is] going and how the doping layers are correct, not correct. How the interface looks by transmission and electron micrograph. One thing great about working at Bell Labs, there are so many experts, like I said, you can have the best electron microscopists here, have the best optical measurement of layers that you can have, and you can have the best fabrication of devices in the final structures, everything's the very best.

And then I just take it apart one by one, look at it and I realized my aluminum gallium arsenide layer had too much traps. And these traps kill the carriers and then it didn't lase. Then I keep on trying my very best to grow better layers [at] higher temperatures, lower growth rate, higher growth rate, you name it, [I] tried all the parameters. Then, as time goes on I realize [that] in the winter time I grow better layers, get better luminesence, better structures than [in] the summertime.

And then I realize that in New Jersey's high humidity room, in those days the MBE system, every time you changing the substrate, you had to open up the system, you put the wafer in there and you close it, pump it down. [When] you opened it up, the whole system absorbed [the] New Jersey high humidity water vapor, everything in there, and then you try to grow, there's water vapor. Even though you have liquid nitrogen shroud in there, it's not enough. When you heat it up, the water's coming out, so any water vapor reacts with [the] aluminum content layer, aluminum gallium arsenide. That aluminum is so reactive it forms oxide traps in there, so it kills it. I said, "Now what I should do?"

So again, you know in space travel [they have] air locks. So I say "I'm going to have an air lock MBE system." The growth chamber is maintaining an ultra high vacuum at all times. I have an air lock chamber here [to] exchange samples. Put the sample in there, pump it down to high vacuum, open the gate, transfer the sample into the chamber which is never exposed to air for months. Then I take it out, close it. This is absolutely oxygen water vapor free. So then, I would be able to lase –-

Brock: Now at the time you were making that accomplishment, was this equipment built by yourself?

Cho: I designed the structure and then I asked Varian and Riber to make it. In fact, there are other stories in developing technology, and in doing this, of course [it] took a long time [to] design, fabricate, mount, test and do it. In Bell Labs here, everything moves so fast. Each year you're counting how many papers are published, how are they using the things you do and I cannot sit on my hands, so I said, "Okay [a] laser is a minority carrier device – charge goes in there, there are traps, and it's very difficult to make it lase. I can make majority carrier devices like microwave devices. So, [at] that time when I was waiting for [the] development of [my new] systems, I switched to make microwave devices.

The first device is [a] hyper abrupt microwave device. I can make, demonstrate that MBE can make parabolic doping carrier concentration. No one else can make it precisely, dope the layer with a hyperbolic curve. Why hyperbolic? [It] is because with hyperbolic, making this, this thing that the voltage is proportionate to the capacity you have. Then I demonstrated that, and published immediately. Then I collaborated [in] making what's called an IMPATT diode, which is very abrupt sharp doping concentration in the highly doped, 10 to the 19^{th}, very sharp, very thin layer of doping in there. It's an IMPATT diode, which is interesting everybody at that time.

Trying to make…as you know, before the laser for communication, there was one short period they tried to use microwave. In fact, they even embedded the microwave in pipes from New Jersey to Washington and tried to demonstrate [it]. Then finally the laser went through with optical fiber that is easier, better and it took over. So in making that high frequency microwave transmission, the IMPATT diode is the source. So I demonstrated and published in 1974. So [after doing that in] 1974, after that making the MBE transistor, you can make it precise layer thickness, you can make the best high frequency transistors and then make 100 gigahertz diode for, at that time, collaborating with people doing astronomy studies. Even in the early '70s, we made 100 gigahertz microwaves.

Brock: Oh for radio –-

Cho: Radio astronomy studies.

Brock: Now, in, in choosing that sequence of devices, because they're majority carrier devices, they wouldn't be liable to the same traps that are happening?

Cho: They're not as sensitive as a minority carrier device. So they also are sensitive but not as sensitive as minority carrier devices. Minority carrier: it recombines and enters and no light come out at all. And also I can get away not making aluminum layers ,which is very sensitive to oxygen traps. I can make gallium arsenide microwave devices. So I published, so therefore from 1974, '73, '75 they were all very –-

Brock: Pardon me, I'm sorry. I'm sorry I interrupted you, but I need to change the battery again…you said the majority carrier devices were less –-

Cho: Less critical to make. So I made all the possible majority carrier devices, microwave devices, and then at that time my air lock sample exchange MBE system is completed and I am putting together the first one to lase.

Brock: And you worked both with Varian and Riber on that system?

Cho: Okay, that's a very good question. At the very beginning, in 1968, I joined Bell Laboratory in February and then first MBE machines were made by Varian. And then, I used even the second-generation MBE machine made by Varian. By 1975 or so, at that time Varian copied my design and then called it Varian 46, or whatever the number was, and then sold MBE machines to all the universities, to anybody that wanted to buy, so it sold like hotcakes. Air Force Research, Navy research---they were selling a lot of systems. And of course there's some fault in their [MBE systems] because they copied my system, but a lot of things were added or changed [in the Varian MBE systems].   That's like you try to change a car design but you don't know how to drive a car. There's a lot of things in their [systems that were] not quite right.

Then when I designed the air lock system, I want to have a whole big MBE machine with airlock, sample exchange mechanism and a MBE in there which can be faster, grow materials, and then be more reliable. I give [my new design] to Varian and say "Please, will you make this system?" And then, Varian comes back and says "No, because we are making this one [and it is selling] like hotcakes and I don't want to put in all the time to"---because my condition is, you make the first one, I get it for free. It's fair [because] you can take my design, copy it and sell it later on. Because at Bell Lab, even [though] that time is also called "the sky's the limit, you can spend whatever you want", but [that is] not really [true]. Each department has its own budget. You better convince your department head that you can spend half a million dollars to make a machine. That's not totally, you know, cheap. In fact those are people that are always joking at me, said MBE means "mega buck establishment". So people are pouring cold water on my [ideas] all the time: It's not a technology; it grows too slow; it's too expensive. And, of course, even today you see an MBE machine is the same price as an evaporator. It's as cheap as an evaporator. So

MBE machines is not---the price is basically, didn't increase today versus twenty years ago. It's the same price. Half a million dollars buys an MBE machine. And then the evaporator, now you can buy a good evaporator for a million dollars, so no longer will people even say those words to me anymore: "MBE machines are too expensive." All machines are the same price almost.

So finally Varian says, "We're not going to give you a free one. We're selling this, why do I want an engineer to do all new drawings and make a machine [when] I already have good business here?" So then I went to Perkin Elmer, where John Arthur was. And asked him, "Will you please make this machine? I have good design, air lock, sample exchange, MBE machine." And then PE says "We have John Arthur here, we don't want you." So then I was pretty desperate and I find Riber in France. I said, "Will you make this machine for me?" They said, "Absolutely!" Open arms.

Brock: Now had they made an MBE machine before?

Cho: No, they hadn't. They had tried –- they were doing some machines for European companies, research labs, some similar tried to copy some of my designs but different, not like this. So they took it, built it, gave me the first MBE machine free. Delivered it, it worked, and then they went off [to] sell more. Then at that time Varian realized, "Oh, we missed the boat." So then they designed the Gen Two, Varian Generation Two.

And then of course I'm in the United States, I helped anybody. My philosophy of developing an MBE machine is I do not keep anything secret, and you can ask anybody, anyone, they will know, Al Cho never kept a secret. Because I felt I want as many people working [with] MBE as possible. I'm always one yard ahead of you. Go ahead copy me, it is good to make people believe it's working, it's true results. And then more people [began] working [with] it, so I was very lucky. I had that capability. There were collaborators here with me, the best collaborators here with me, and then I can always run ahead of the crowd and then I just spread my message to everybody. Anybody that wants to learn, come to my lab and I'll show it to you, whatever I can show you. So I was helping Varian at that time, they realized they made a mistake, and I tried to help them to redesign some part of the Gen Two -- corrections. They made an air lock and I didn't take any patent, fee, nothing. I gave the knowledge [that] I have. So they sold a lot of Gen Two systems.

In the meantime, we have good results coming out, then we make the laser, we make all these optical devices without any problem anymore. With the aluminum content it doesn't matter anymore. The thing is, for me, to conquer the next mountain is mass production. You cannot make a production if you just make a wafer one inch by one inch. You'll never make money.

Brock: Was that what you were working with initially?

Cho: Yeah, one inch by one inch and that new machine was maybe one and a half inch, two inch, too slow, too small. Then I tried to convince Riber [to] build a mass production MBE machine. I realized, furthermore, what it means to have [a] mass production system is you don't need to hire a PhD to operate the machine. You had to design a system [so that] you [can pull people off the] street into your lab, train him or her [in] one week, he can run the MBE machines because it says, "button number three red and then it turns green, two minutes, five minutes," or even computer controlled, push that one button. Whatever: that simple. The thing's automatic, put in the system, take out of the system, everything's computer controlled.

I helped design that system with Riber. And then the Riber president came here and said, "I like you but I calculated, if I make this machine, spend all the money to build this machine, the world only needs two, two of this machine. You talked about mass production right, and then how many lasers [do] you need in the world? I can calculate we only need two machines in the world and how do I get my money back?" It's true, he's right, with that volume. It's sort of like today, you see the optic fiber, dark fiber for all these years. We're overdeveloped, Bell Labs was too good. Developed the multiple wave division; you kill your own job. There's such an efficient transmission and you don't need you any more, you're out of a job. Dark fiber for many years, they didn't need new fibers. <laughter> Same thing here, you make so good, they don't need anymore. But now things keep on changing. We need videos now. [Video needs more of this, more. So all the fiber is all live again. We need more fibers, we need more of this, we need more transmissions. So these are things people are shortsighted sometimes, "Oh we don't need it."

Brock: So it was the case that this time –- what was the time when you were collaborating with Riber on the mass production machine?

Cho: That's in the '80s, but before that was one big move. [In] 1978, I persuaded Riber [to] make the first system after that, and their president is very smart. He said, "First of all, we need that the world knows this." So the first international MBE conference is in Paris. Is totally funded and advertised around the world by Riber. And they invited Pierre Auger as the first speaker, [the] plenary speaker [is] Pierre Auger, so everybody goes. They want to see Auger, the Auger effect, the most famous live physicist at that time in surface physics. Pierre Auger gave the first talk, so that was a hit. Everybody finally, it took some time, but I convinced them to make the production on the MBE machine finally. See that wall there? See the person standing underneath that machine? That's how big the machine was. You see why they don't want to make it, to produce if you only want to make two of these. And then that machine, all you need to do, you push one button, the platen in there sending the wafers into the system, when it finishes and grows it comes out of the system. I have some pictures that are showing how [much] automation they have. Of course with that machine, at the present time in North Carolina the RFMD company is using this technology. They have thirty MBE production machines.

Brock: And these are making semiconductor lasers –-

Cho: No, semiconductor microwave devices.

Brock: Okay, for cellular telephones and things like that?

Cho: For RF components, cellular phones, WiLan, Bluetooth, GPS and all those things. They're making that actually in large volume. They make five hundred million chips per year.

Brock: For communications?

Cho: For cell phones. Each cell phone has four microwave swiches in there, switches for different bands and then the front end amplifier and power amplifier. Front end amplifier and power amplifier. The front end amplifier is sensitive, so the signal can be weak and still be amplified by the GA front end amplifiers. Difficult to produce with silicon integrated circuits. And power amplifier…GA is more efficient for power amplifiers so your battery will last longer; otherwise cell phones would have to [be] charged every couple of hours and [one] can't really talk [for more than] about half an hour. Now you can talk longer, charge spacing is longer, and are more sensitive for signals. So they produce five hundred million chips per year. Supply the whole world. In every cell phone you have in here is probably a piece made by a MBE. The switches and front end amplifiers made by a MBE.

Brock: What about with the lasers? When the president of Riber was saying, "Oh we can serve the world with two machines" I bet he wasn't thinking of the market expansion for —

Cho: You see that for making lasers, that was in the eighties, mid–eighties. This is an advertisement by a Japanese company called Rohm. You see the small words that say "using MBE for mass production," they produce two million lasers per month, supply you all the CD players in there at that time is a laser there to read the signals, that 0110. That CD player has a laser in there. DVDs, CDs, that laser in there is made by MBE.

Brock: So it came to pass that there were just a few companies that were supplying all of these components, is that the case? Using MBE, there were relatively a small number of firms that were supplying, for example, all of these semiconductor laser devices and then on the other hand all these communication chips, is that how it worked out?

Cho: See there are different markets for different things, and these are for mass production, for commercial products, which you can sell a lot more. For CDs, for DVDs and for cell phones these……are every person using these things, that's where the major company wanted to go into. And of course these days, not just these two companies, but a lot of companies, QEDs and all these other companies are making wafers with MBE. IntelliEpi in Texas is using MBE to grow GA phosphide for communications systems. Phosphorus isn't easy to use with MBE because phosphorus, it the system, if you [do] not know how to handle [it], it can catch fire. So they know how to handle it in IntelliEpi.

I was told [about] one of the very, very large MBE processing labs is in Singapore. They're producing millions of chips there for different applications with MBE production. So finally the production of MBE is flying [in 2010]. The reason is production system is important, the system qualities, that a production line usually has many of these systems. Let's say RFMD or IntelliEpi…IntelliEpi told me about how they control the system. Let's say you have ten MBE production systems. You have to have ten MBE machines producing exactly the same device. All the same. Not only ten machines can produce the same today, a month later you had to be able to produce the same one. One month later you grow that [same] structure. I want to have another million chips given to me. You had to give it the same, otherwise it won't work, so how do they do that? In the MBE machine, not only just -- I showed you earlier electron diffraction, the mass spectrometer, all those things. They have atomic absorption detectors in the MBE machine. They can detect in the effusion cell coming out, how many atoms in the beams. They have a number, they can reproduce that number one month later with which one, with what? That degree of accuracy, that's how amazing that is.

Brock: So it's again the power of control, of adding more instrumentation?

Cho: In real time! In real time, in situ monitoring. That is the secret: in real time. Not after you grow and take out and measure, you're lost. And also, better yet, in the wafer, you make let's say 5,000 lasers in there, you measure one laser in the production, the other 4,999 are the same. If you put a person in there to sort out, which laser is right, which laser is not right, you're lost. You put your probe down, one technician put it down there, six dollars gone, so your profit's gone. So you have to have the confidence, the reproducibility, the uniformity, the yields, that's the bottom line for production, to get the cost down. So the thing is, the road from the first look at absorption, desorption atoms on the surface, to this, you see the road, how long that is? That's the difference. We may have lost this in research, we go to universities, they can do basic research. We have students come in here, [they have] published papers from very good journals, and then the next person comes in doing a little different topic, because another Ph.D. can't do the same topic., right? And also you have different contracts from different [government] agencies. They want different things, so you're changing around. It's not like I'm telling about: developing, concentrating on one technology from basic research to demonstrating [working] devices, from demonstrating devices to the point of high yield, high production, reproducibility, most important, cost effective. Is it cost effective or not? If not, [it is of] no use. That is difficult to make a university do. That's what I worry about.

Brock: Related to that point, how does Western Electric play into your development of molecular beam epitaxy in terms of making devices that are going to be employed or deployed in the Bell network, and also the switch over, I guess you would –- I don't know how to say it -- but the move to optical communications for data and telephony by AT&T and the Bell system. How did the MBE devices play into that?

Cho: Even [with the] transfer [of] technology, even within our company, I'd say from Bell Laboratory to Western Electric, it took me a long time. At the time I have demonstrated the microwave devices. Western Electric at that time was interested in the microwave devices, for the testing for the first microwave transmission communication use. So I had convinced the director in Western Electric in Pennsylvania to go into MBE. I was driving from Murray Hill, New Jersey to Reading, Pennsylvania two times a week to try to teach people how to do it, to implement that system.

My publication of papers---earlier, before that, I published about 11 papers per year. At the time when I was trying to transfer the technology, it dropped down to two. My boss Mort Panish said, "Al Cho fell asleep." My performance dropped from the top of the quartile to…I don't know where. I said, "What did I do?" He said, "What happened to your papers? You went from 11 to 2, what did you do? Fall asleep?" I said "I'm trying to transfer technology". At that time, even the bosses in Bell labs didn't know what technology [transfer] means. They're all in research, basic, paper or Physical Review. How many Physical Reviews do you publish? So he didn't know what that means, even Mort Panish and John Galt, who was a Director, gave me a down arrow hand – from the double arrow hand up to the down arrow. I was so disappointed until finally I transferred [the] technology. Reading bought three MBE machines, installed [them] and the Director wrote a letter to my director here, [that said] how [much] Al Cho accomplished for this technology transfer. That was the first time [that] they realized what technology transfer means. Before that we were all playing in the clouds, we were all in the blue sky, we didn't know what making devices means. Most people were all, you know, in very, very fundamental research. They apologized to me, gave me double, triple raises to compensate [for] the error they made. It was very nice.

Brock: That's nice that they —-

Cho: Absolutely. That's one thing about Bell Labs. If they made a mistake, they admit they made a mistake and correct it, so it's not like some [other] places [that say] "I never make a mistake." [Bell Labs says] "So I made it, I made it, too bad." So here is a fair nice place to work. People [have] no real ego about themselves. If they made a mistake, they admit they made a mistake. And the one who did something good, they will be recognized for doing something too.

Brock: Then Reading got into —-

Cho: Reading got into and produced a high frequency device and then at that moment that the top manager made the decision to go to optical communication, that killed, killed the system.

Brock: But when they made the lasers for —-

Cho: Okay, that continued, we still have a lot of microwave stuff we needed to do. The thing is, in Reading at that time, [was] changing [the] guards. It is unfortunate, one thing, when changing [the] guards, they decided they didn't want to do this microwave, because they felt it had problems in the wave guide propagation, that canceled some of the managers in the Western Electric side, that canceled some. And then the last, the last hope was to try to get a government contract to support and the government contract at that time didn't go through, so the whole thing disappeared.

Brock: Did they have to restart it to create lasers for the optical communications?

Cho: Okay, for the optical communication at that time, at that time they were starting [to] use MOCVD (Metal Organic Chemical Vapor Deposition) -- the liquid phase first, the liquid phase down and then MOCVD to bridge it. So MBE in Pennsylvania missed the boat for the laser, but other companies picked it up. But Western Electric missed the boat.

Brock: And MOCVD, now did that develop around the same time as molecular beam epitaxy? Was that your rival, sort of?

Cho: In a way it is, but I know the whole history [of] the through my friends Dan Dapkus and Russ Dupuis. Both were from Illinois, they were Holonyak students. Then Dan Depkus actually came to see me and he asked me "Can MBE be made in mass production systems?" They were at Rockwell. I was very honest at that time, I said "At this time, I can only grow about an inch by inch size." Those were the days in the early seventies so then Dapkus hired Russ Dupuis to do the MOCVD. The MOCVD earlier was Manasevit. He was doing some basic research and he was the first one doing it, but didn't do too well, so Russ Dupuis picked it up, streamlined it to make it grow good gallium arsenide layers, so that's where the history started.

Brock: It didn't have that sort of atomic layer resolution, if you will?

Cho: No, not at that time, no. At that time, they didn't need that accuracy yet. You could never have benn that accurate do it at that time because it was very difficult. They had a layer to decompose to grow the next layer, so that it's not that abrupt like MBE and the ability to count layers. Some of the things …people don't realize, how accurate that is. But for a lot of devices there is no need to be that accurate. Now at this present time, and then of course now for silicon MOCVD next generation devices, this oxide layer for the MOS devices require only a few atom layers thick oxide. The silicon dioxide on silicon ran out of gas, so they need to have high K dielectric on there to make the MOS devices. And then one of the things they work on very hard now at Intel, and especially earlier, the person who worked on it here at Bell Labs, Keh-Yueng Cheng went back to Taiwan. In Taiwan [he] received a teaching [position] at Chung Hua University. They tried to grow these high K dielectric devices with MBE, an atomic layer at a time. And of course, that's still very, very important -- that interface of that first atom layer on that silicon, how that maybe you need a surfactant layer on there first and then this layer. You had to be really engineered to the atomic dimension, one atom layer counting is not like the early days where we made a thin layer, we're talking about one atom layer. What is that interface to one atom layer dimension? This is where the frontier [is].

Brock: One of the things I wanted to ask you about was at a certain point in time it becomes clear to you that molecular beam epitaxy is going to be very interesting for making semiconductor devices for microwave communications, lasers, optical communications. At what point in time did it become clear to you that you could also use molecular beam epitaxy to make devices, structures, that were very interesting for studying fundamental physics, these heterojunctions and super lattices and all of that?

Cho: You know, again it's working in this nice place at Bell Labs here, you have talented people, so many around you that I was thinking about you know, you're growing heterostructures with atomic dimensions here. This is let's say, the large band gap energy. The large band gap is red, the other is yellow here. So you make one kind of materials, large band gap sandwiches, small band gap here, you make quantum wells here, right? This is like gallium arsenide in red, aluminum gallium arsenide in yellow. You can make gallium arsenide – aluminum gallium arsenide quantum-well structures. And then you can also grow different materials, what they call type two structures. They align in the way, that you see in this way that you make electron wells and the hole wells in two different places. Rather than up and down in the electron here, the hole on the bottom and recombine across. Here now it is cut by one layer, it's called type two quantum well structures. Electron holes are confined in separate layers and then you can have the third kind of quantum well structures: electrons and holes are confined in separate layers. And you can have the third kind of quantum well structures. In this case it is indium arsenide – gallium telluride. They make interface like this, quantum wells. So these electrons and holes are mixed.

Brock: And the same –- oh how about that?

Cho: So you can make all kinds of engineering of where you put electrons and holes, in what wells, in what layer. How to mix it, separate in the same layer? So, and at that time I realized, oh my god, this is in quantum physics, you are engineering at will, at what kind you want. So then of course, [we have] the invention of so-called modulation doping. The electrons and then the conduction layer are separated so that's why you have tremendous high-speed electron travel. Let's say you have, you want to make high-speed electron devices. How do you make high speed electron devices? You have to have higher electron mobility, [have] electrons go very fast in the layer so that you can have high-speed devices. How do you make a material where the electrons propagate in these materials faster than any materials God has given to us. You can't do it, how do you make it? How do you make materials better than existing in nature? They are man-made, how do you "man made" it?

Let's say, usually in the materials here, you want to have electrons [travel] in this material, you dope the material so that you have electrons. You put the donors in here, the electron comes out of the donor is a free electron, and travels through the layer if you bias it. But the electron in this layer here is scattered by this pair of donors here. Sort of like on the highway, there are rocks all over on the highway, you can't drive very fast. You're scattered by these rocks, so what happens here in so-called electron transport in the modulation doped semiconductor materials. What you do is, you dope the material with high band gap layers, for instance aluminum gallium arsenide, dope it N type and then you have the multiple layers, the next layer you grow is gallium arsenide, the gallium arsenide is as pure as you can grow it. No dopant, intrinsic, absolutely intrinsic, there's no impurities, no donors. So now in the physics here, the electrons in this higher band gap material the electron will drop into the gutter, into the intrinsic gallium arsenide layer. These are like water, drop in the gutter, and then the water flows into the gutter or the car driving now on the highway, [but there are] no rocks. So the electron can be very, very fast in this man-made, not-in-nature-existing modulation dopant layer. Again, this made by MBE.

Brock: So you dope those high band gap layers and those donors the electrons go into the different layer where they just –-

Cho: Drop into the lower band gap materials and then travels.

Brock: Flies.

Cho: And then here now it shows. The electron mobility now as a function of the temperature here, for different years. This is bulk gallium arsenide you can see the highest electron-mobility, eight thousand centimeters per one second, eight thousand, so as time goes in MBE on we know this structure works, which actually was invented earlier with MBE. Horst Stormer is the one who proposed this structure. That Horst Stormer then measured this structure in 1978, with MBE here that you can see that it already increased over 10,000 mobility. As time goes on we introduced the sample air locks here, as I just spent some time discussing with you, [we have a] better system now, higher purities—no more oxygen or water in the system. It jumped up to nearly finally get to a million. Today with a good cryopumping and the best system here, up to 31 million, 31 million per centimeters squared per second. This is what? How many? Ten thousand times more. We have electron speed that much faster than the nature-existing material. So now therefore we make very, very high frequency devices, you know for instance like here at Bell Labs, Chan had demonstrated in 2005, at that time the world's highest frequency device oscillator, 225 gigahertz and today, in Illinois, again using MBE materials over 600, over 600 gigahertz devices with MBE materials.

Brock: The frequency of the operation is more than 600 gigahertz?

Cho: Yes. So these are the things you can see pushing the envelope to the point. Again, I always say, with MBE, you are only limited by your imagination. You have good scientists, good engineers, you design new structures, we can make it. So it was like just a few years ago, Frederico Cappasso collaborated with me, invented using this band structure engineering, and then invented a kind of new laser, totally new kind of laser, not the ordinary electron-hole-recombination-across-the-band-gap making lasers, this is so-called unipolar device, called quantum cascade laser. It's a laser, only electrons, not electron-hole recombination. It's a new invention, a new, totally new approach. I think this is going to hit big, big.

How do you make this laser? It's not an electron hole across the band gap, like I said, the electron-hole recombination gives out light. The laser is limited what kind of material you use that gives you one kind of laser frequency because of what the band gap is. So the quantum cascade laser [has] the electrons in the conduction band only, in the conduction band you make the quantum well narrower and narrower, there's sub bands in there. The inter sub bands, the narrower the quantum well is, that means the thinner the layer is that the separation of the sub band is larger. So, the electrons dropping from the upper sub band down to lower sub band, giving out the light. And then you can make the sub band different heights, by changing different width of the layer, you can make different wavelengths of the laser using the same combination of the material, just by changing different thickness.

Brock: So changing different geometry will give you a different wavelength, rather than different material.

Cho: Exactly, it's not a different compound, yes.

Brock: That's very interesting.

Cho: That's the new laser we invented here in 1994, okay? So why do we say quantum cascade laser? It's sort of like a cascade waterfall coming down. We make not just one of these quantum wells here, we make let's say hundreds of these, in cascade. So every time the laser drops down here, it gets you the light, drops down more, drops down more and multiplies so that we can have very high power, than any other laser you have. It's a higher power because you had cascaded each –- one electron dropped down there to create two electrons and two into four and so on.

Brock: I see.

Cho: Like a multi-stage electron multiplier.

Brock: Okay.

Cho: So, so with that, we made these stacks, again with MBE we can easily do this, making all this, [although it is] not as simple as I said, just the quantum well, in making two layers usually you have to have the final stage being empty, therefore you have to have the electron coming down here so to make the electrons sweeping out there and then coming off, then go next stage go to the next stage, you have good physics design. You asked me earlier, in physics what is---these are real quantum physics, real quantum physics at work here. So, so you really had to understand how you make the next quantum well, for instance, the energy, just the plasma resonance energy so the resonance with the quantum well where you have the drop of the electrons giving out the light, where the sweeping out and final state by resonating with the next quantum well. And then cooling off and going to the next stage, you make another drop and do the same thing. So you make this repeating design structure over and over, let's say fifty times. You can see the uniformity here, you can see the reproducibility here. You can make fifty of these precisely designed layers thickness over and over again and emitting wavelenghts, they'll be the same. It's not just grow to the next layer, it's the same layer, you have to fool around with all of these other designs in physics. How to cool off a carriers, how to sweep out the final states here and then make another one, same as this one. After number 49 and number 50, the same as this one, can you make that, yes! Then you lase, okay?

First laser design by Jerome Faist here, was working here with me. First one he designed, that layers thing that we grew, that's structure lased and he called me, "You don't know how exciting that is, very exciting." Because earlier days there were very good scientists from Russia coming here, Kazarinov in Russia [he] is [the] father of quantum well lasers and he collaborated with me, Kazarinov thinks that if you just make a lot of quantum wells, okay, now with all this special design and all these things, you just make 1,000 of these and pump it as hard as [you] can. This will lase. And I mean we grow maybe 20 of these structures. We never did lase, we may get some light on there, but no lasers. Because it can make the sweeping out of electrons.

Jerome Faist understood the physics, what happened, what the problem was, he designed that first one, and it lased. With this laser, he's bridging out the wavelengths that the usual laser doesn't cover. So we fabricated the laser from that 3.5 micron wavelength all the way to 100 micron. Bridging to the terahertz. Terahertz oscillation of a microwave, we demonstrate terahertz microwave and with 3.5 and 4 micron, a lot of these things -- 4 micron, why it's so important is because most of them are molecules, vibrational energy is in that range. So very, very sensitive to detecting gases. So one of the, one of the applications we have here now of course is for medical. We find out from just detecting mouth breath, you have ammonia gas, CO gas or nitrogen oxide gas, they have different diseases. So in the future you'll have non-invasive personal doctor in your pocket here, when you go to work or go some place, just by testing your breath know you're okay today or not okay today.

Brock: So that would be sort of laser spectroscopy?

Cho: Yes, you're very smart. And I have some pictures I got and put in here from my later talks and I can show you some of that work. So very soon, you see there's another applications, you see there some of the things before in the, in the medical, now to detect your breath the machine here, or to detect the pollution or whatever, this big. In the future with quantum cascade laser it is this size, is keychain, is credit card size detection. So the size is your pocket size and I just mentioned in detecting ammonia gas, what happens now your breath here coming out, you have the bacteria and it's producing ammonia in your, in your system, here you're breathing out ammonia gas. We can detect that and we know you have the liver disease. So not only does one disease here, we have detections of –- already tested for the infrared range we have here. If you have nitric oxide here, you have asthma. You have this isotopes of CO2 here you've got ulcer. You have ammonia here you have renal disease. You have carboneal sulphide, you have liver disease. If you have breast cancer, you have alkaline. All these diseases, diabetes, you can detect it. You have all these different gas come out of you, your breath. We can detect all those things.

Brock: So it's a mid infrared laser?

Cho: Yes, which is a missing gap with a regular laser we have, and then of course we have also done a lot of work in pollution control of course.

Brock: Which is very important in that same region of the spectrum, right?

Cho: Same region. You see here now? This is what NASA did. NASA flew our laser in the U2 airplane across the United States, Canada and Russia and Sweden with our laser. They had detectors map out these whole upper atmospheres with nitric oxide gas and so on, and then they gave a report that reliable operation detection over 23 days. They had never seen a laser that stable over that long period of time.

Brock: Flying.

Cho: The detection limit is two part per billion, very sensitive. So you know we have done a lot of exciting work, inventing new lasers, inventing high frequency devices and I think most, like I talked to you about my mother and I just want to show you, her most pride of her day, I think. This is my mother; this obviously is Clinton, the President, and then my sister and me. That, he's not that short, they were on the stage. I was feeling inferior, so short, but I was not on the platform, they were on the platform, but my mother at that time, already in the '80s [she was] so very proud that with her push made me go into science and give her last few dollars to me to come to the United States to be educated. And I find that I accomplished so that I won the National Medal in Science, the highest recognition in science that President Clinton give my mother a hug in that Rose Garden ceremony in the White House and I think that made her day complete. The loop that her effort to educate me, put me thinking about education is foremost important for my future and then she succeeded.

Brock: Proof positive I think there. That's great.

Cho: That was, I always remember that day how happy she was.

Brock: Well Dr. Cho that is perfect timing, the batteries just ran out and that seems like an excellent place to pause.

END OF INTERVIEW