Oral History of Jiri Marek

Interviewed by
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Steinbach: All right, for the record this is the oral history of Jiri Marek, recorded today on the 29th of August, 2017 at the Computer History Museum in Mountain View. Welcome, Jiri, and thank you very much for agreeing to donate your history to the museum.

Marek: Well, good morning, Gunter. It's a pleasure to be here.

Steinbach: I asked you for the interview because you are the “father” of the MEMS, Micro-Electro Mechanical Systems business of the Robert Bosch Company. MEMS are at first glance not very much connected to computers but only at first glance, because they are the sensors and actuators for embedded computers like those in automobiles and cell phones. But we won't restrict ourselves to just your MEMS work. The oral history is about all of you, your life and career up to now. So let's start with your background. Where did you grow up, your family, hobbies as a child?

Marek: Actually I was born in the Czech Republic. I was born in Prague, the capital of the Czech Republic. In 1968, the Russians occupied the country, that was still during the communist time. Our family had the possibility to move to Germany. My father had a research assistantship at the University of Stuttgart and we came for vacation for a visit and then we've been able to stay there in Germany. So I grew up in Germany, had to adapt to the different cultures. In the Czech Republic, the border was closed; the country was still very communistic, not really very advanced in terms of technology, economy, and Germany was very different ; at the same time the language was completely different as well. I mean Czech is a Slavic language so the language difference was huge and I didn't know any German as we moved to Germany.

Steinbach: Okay.

Marek: So I grew up in Stuttgart, which is a town in the southwest part of Germany. I went to school there. After graduating from high school I wanted to either go for physics or electric engineering. The physics studies at university in Germany were quite theoretical. I wanted to do something more practical so I decided for electric engineering. But after my bachelor I specialized in a field which they at that time called physical electronics; this was for a combination of electrical engineering and physics which suited me well. I had classes on plasma physics, on semiconductors, optoelectronics. Solar cells at that time was a very hot topic due to the first energy crisis in Germany and worldwide. I completed my studies at the University of Stuttgart but during the last year I had the possibility, via a scholarship that I received from the German Studienstiftung to go for one year abroad - I did my research at Stanford University in 1978/79. I did my research on my master thesis topic at Stanford in the Department of Material Science with Professor Bube, which was a really exciting time and great experience.

Steinbach: What was the topic?

Marek: So the topic was - on solar cells, as mentioned before.

Steinbach: Okay.

Marek: That was the first wave of solar cells industry in 1970's. Seventy-eight was the first oil crisis, the prices of gasoline doubled, tripled. There was quite a shortage of oil so alternative energies and the research on these became very popular. Both at the University of Stuttgart and then later on at the Max Planck Institute, we did basic research to support the analysis of the solar cell materials to improve their efficiencies, to improve the stability – this was the topic of my master thesis.

Steinbach: Okay. Just for the non-German readers or listeners, the Studienstiftung is the German National Scholarship Foundation.

Marek: Yes, thanks for the clarification. .

Steinbach: Okay. I had it too. And it's--

Marek: I saw you're a member as well?

Steinbach: Yes.

Marek: Okay. Good.

Steinbach: And it's something akin to the National Merits Scholarship but even more prestigious than that. And Max Planck Society that you mentioned, I read up on this, is a non-profit corporation with 22,000 employees at 83 sites all over Germany and a budget of about $2 billion, mostly but not exclusively from government sources. So those are the two organizations that you mentioned.

Marek: Yes. And the Max Planck Society in Germany is really a very big organization to support basic research. . The Fraunhofer Institute, which is also very large with several billion of revenues and also, I think, 15 to 20,000 people is doing more the applied research, also lots of government contracts more on the engineering side. And actually with that, that's the next step, I had the possibility to work with Professor Queisser. My PhD advisor, Professor Queisser has actually a very long history with Silicon Valley. He studied physics in Göttingen and Professor Shockley, he got him as one of the first associates with Shockley Semiconductors.

Which was very much the first semiconductor company over here; it was located in Mountain View on San Antonio Road where the Pacific Stereo was; they just took down the building a couple of years ago as they were rebuilding.

Steinbach: Yes.

Marek: And it's from Shockleay Semiconductors, the company where Fairchild was started where the six traitors went, started Fairchild and then from there Intel started. So my supervisor was telling me many stories about, you know, how semiconductors and how Silicon Valley started, so <laughs>.

Steinbach: And later this year, they'll erect a plaque where the Shockley laboratory was.

Marek: Oh, really?

Steinbach: Yes. It's a big shopping center now. And I think IEEE and local-- and the museum is involved. They'll have a big plaque and I think some kind of sculpture of a transistor with three legs and so on.

Marek: Oh, okay. So you have to tell me when it's happening.

Steinbach: Yes.

Marek: I would love to see that because that's actually the origin of Silicon Valley, even though lots of people trace it to Fairchild on Miranda Avenue, where the Fairchild Research Center was, but Fairchild was actually the second company. Shockley Semiconductors was the first one. Shockley was not very successful commercially but he was a great inventor and a great physicist. Actually he was too advanced. At that time he didn't want to put transistors into volume production but thyristors because according to his physical understanding, which is right, the thyristor with the four-layer NPNP structure will have lower power consumption because it will go to a bi-stable state, one or the other one, and therefore it should be better than the transistor which always needs a current to stay in one state. Therefore his ideas were correct but the technology was not mature yet - the transistor made it to the market and the thyristor didn't make it. So sometimes you have to be more pragmatic and go with an available solution to create the economic impact.

Steinbach: All right, so we got your PhD and what did you do after that?

Marek: Well, I mentioned I was at Stanford and I liked the place over here. We just got married, my wife and myself. And, you know, for a young engineer it was a very challenging and very exciting thing to go to

Silicon Valley. I applied to several companies over here and I started as a postdoc at IBM at the IBM Research Center in San Jose.

Steinbach: Almaden?

Marek: Yeah. At San Jose, this was a IBM big plant producing magnetic memories. They had a huge operation with many thousand people. And actually the Research Center was down at Cottle Road and a year after I left they moved up to Almaden.

Yes, this was the Almaden lab but it was at that time still integrated with the manufacturing plant, which was sold off later on to Hitachi. And after the postdoc, I looked around and I started a job as a development engineer with Hewlett-Packard. I was working on reliability of LEDs and detectors in III/V-technology, mainly aluminum gallium arsenide. This part of HP became Agilent and lateron this part became Lumileds. We started at a building on Page Mill Road and El Camino in Palo Alto which was very close to HP labs. At that time it was a very young technology, so we had to do lots of basic research and lots of testing. I was going to HP labs for some measurements and for analysis almost every week or even more than that, which was very nice and convenient. Our business has been expanding, and HP was doing many investments to ramp up volume manufacturing. In Singapore, we started a wafer fab and assembly in Malaysia, in Penang. HP at that time was number one company in LEDs, huge growth, very high tech - we expanded into a new building which we built on Trimble Road in San Jose close to the airport.

Steinbach: Okay, which is where it still is now.

Marek: And that's where the building actually still is. Recently Lumileds was supposed to be bought by a Chinese company but the Obama administration objected due to cartel laws. And now I think it's owned by some American investment company.

Steinbach: Okay.

Marek: Well, with that my wife and myself were for a couple of years in Silicon Valley. This was my second stay in Silicon Valley, for my wife the first one. - Please remember, this was still the time of communistic regime in Czech Republic - the border was still closed to the Czech Republic, i sSnce we are both originally from the Czech Republic and our parents lived in Germany - they were the only relatives and could not visit the remaining family. Being in California e didn't see parents for a long time and we decided to move back to Germany to start a family. We then got two daughters which we raised in Germany. So I--

Steinbach: What year did you go back?

Marek: I went back -- at the end of 1986.

Steinbach: Okay.

Marek: I interviewed with various companies in Germany as electrical engineer, mainly companies in southern Germany, being Siemens, Infineon, also HP, Boschand IBM with the research lab in Rüschlikon in Switzerland - Google has a lab now also now in Switzerland - ABB in Switzerland..., so there was lots of high-tech industry interesting for electrical engineers. Bosch made me a very interesting offer - at that time there were the first MEMS-structures made in silicon by MIT and also researchers at Berkeley. they were using the standard silicon wafers and polysilicon which was used for the gates of the transistor to produce free moving structures. They etched away selectively the oxide. The oxide was the gate oxide and they were able to do moving structures out of this polysilicon. they had very thin polysilicon layers. They made them free moving and they made small wheels, moving structures, bridges, these were the first steps of micromachining or MEMS, the Micro-Electro Mechanical systems, as people call it, where they were able to do the first moving structures. These were pretty much academic, not very much of application but it was an exciting technology. The manager who interviewed me, the executive vice president at the electronics division of Bosch, thought this is something exciting to combine mechanical parts with electronic parts and use the same technology, the semiconductor technology. And as the semiconductor technology was making great advances of making things smaller and cheaper, and really increasing the performance, he thought it would be very exciting for Bosch as a company involved in many electrical but also mechanical systems to combine these technologies and to develop it and to have a look if it has some applications for Bosch. hHe hired me in December of 1986. I spent one year as a trainee to learn about the division, about the development department and about the manufacturing, to learn the division and its technology. I was ciculating through the different departments about 6 weeks or 8 weeks in design department, simulation department, layout, manufacturing, testing to really learn the basics, how industrial operation at Bosch was working. And then after a year, I became a group manager to set up this technology. Well, to make the long story short, I've been responsible for this area for quite a while. It was 20, 25 years. After 6 years, we started production with the first sensor which was the manifold air intake sensor for engine management system, which is a device about 5 milimeters big , in a metal can package because it has to be under the hood with environment. It gets the exposure to the very tough media; the air coming inside with salt, spray, chemicals. You wash the car, right? You travel in Nevada through the dirt roads - it has to be very robust. And after 6, well, very exciting but sometimes very tough years, we made it to volume production. We--

Steinbach: Okay, that was one of my question, how long does it take from zero?

Marek: It took quite a while because the automotive industry is a very conservative industry for a very good reason, because we are making systems which are really to the Bosch Motto is “Invented for Life”, right? I mean you have an engine management system, it has to accelerate/decelerate. If it doesn't do that then you might not pass the car or it will stop in the middle of the freeway. We same we do with our sensors braking systems. We manufacture airbag systems where you will have to rely on the performance of the sensor in the system of complete electronic sensor and actuator system to really actuate the airbag. And if there is some fault it might put you really in danger and really even not save lives, like an airbag or on breaking systems really might put you in very dangerous situations if not functioning well. And therefore it has to have a very high reliability. At, the same time, in the automobile we have very high temperature range going all the way from minus 40°C to 125°C or even 140°C. If you imagine you have a car in Alaska, in Canada then you have to start it up also when it's winter and when it's very cold. You rely on these systems also under these conditions. If you park your car in Arizona, inside the compartment it will get 80°C, 90°C. But if you are under the hood where the engine is, the engine obviously being a combustion engine gets very hot, so there we have conditions of 125°C. And if you even put electronics on the braking system, - , the hydraulic systems are close to the engine - they get also pretty hot. But when you go 100, 120 miles an hour and you do a full braking there's a lot of energy which gets dissipated in the braking system. And we have peak temperatures going all the way to 140°C, this is a very high demanding ambient. We also have electronics which are integrated into the transmission system. The electronics is actually inside the transmission and it's inside of the transmission fluid, and that gets also very hot; threfore we have a very high temperature range. We have also very long operating time of cars as they are very reliable now. This means that they will be on the road for 10 and more years. Generally a laptop, a smartphone doesn't last 10 years, right, and you don't expect that. And even after the car is older you want to have some spare parts. There are lots of old-timers which are 25 years old and they still have to be on the road. We have very long times in the field for operation. As mentioned before, you go and you drive the car off-road - it becomes very dirty. You have sand, you have lots of particles going into the engine onto all the electronics. Then you wash the car, then you have detergents; you have different fluids, so all the electronics have also to be stable. We have really very demanding conditions which are very close to the aerospace or military applications. At the same time, the costs have to be very low and that creates quite a bit of pressure onto, well, the cost and the technology and reliability. Therefore the automotive industry is more conservative in terms of applying new technologies because we really have to be about a factor of 10 or 100 lower in the failure rates than consumer. If you've got this morning in the car and you started driving, in the case your phone had some problems then you are pretty angry. But on the way home, you will stop by at Verizon or T-Mobile or AT&T, you will get a salesman, and you will be very angry. They will give you a replacement phone and they will give you a 20 or $50 voucher and you're happy. Right? But if you go-- if you start the car in the morning and it's not going any place, you get real angry. Right? You don't get to work. Your boss is angry at you. You see, the consumer electronics and the automotive electronics, they have quite a bit of different expectation also for us as customer and that creates quite a bit of different reliability levels for them. therefore the automotive industry has generally a fairly long qualification cycle, from design to ramp up of high volume, it takes about 2 to 3 years depending on how novel, how demanding this technology is. Because we have to deliver, we have to put in the production line in place which is capable of producing 100,000 to millions of devices. Then the car companies will install the device on a new car or a new platform but they will take those cars and they will test the whole car. Inside their labs they will do crash-testing -- but they will do also lots of track-testing. In the summertime, they go to very hot places like Death Valley which is very popular for car companies all over the world to perform testing in the summertime. And there you have, you know, 50 degrees Celsius, 140 degrees Fahrenheit, and they do testing under those conditions.

Steinbach: So does each car company have to do their own qualifications? Or is there a body that can qualify a type of sensor that then everybody can use, or do they actually want their own model, their own tweaks on the sensor? The different parts.

Marek: As mentioned before, car companies perform the summer testing in hot places like Death Valley or Spain , they do winter testing, in Canada; in Europe it's done in Sweden. They rely on qualification testing of the device itaself which we did as Bosch before. We would have a sensor being designed for pressure sensor for engine management or air bag sensor, or one for vehicle stability control which is the device over here. And we will perform qualification testing according to industry standards, which are set by different bodies. But some of our customers demand additional testing. On the component level, we will do the testing at Bosch. We have to show the results to the car companies and then they will either approve or they will require additional testing and they will check those results. Then these sensors being sensors and also actuators and electronics, they go into the electronic control unit, into the system. This system is then installed on the car and the car companies will then do the testing on the overall system.They assemble the car as prototype, they put in the engine management, the braking system, the vehicle stability system, the body control and navigation..., all the systems which are required. And now there's a couple of dozens of microcontrollers and computers on the car and then they have to test it under those extreme conditions. And they also test, the performance of the car overall, how the systems are communicating to each other; if the systems are performing well asthe combination of them. They also have to set parameters, each car has a different dynamical performance, right, how it's handling in the curves and as well as the braking. The car conmpanies have to adjust the parameters for the vehicle stability control to set all the parameters to really perform in the best way. And the same applies for engine management. There is a ECU, the electronic control unit for engine management which companies like Bosch would deliver. But then the car manufacturing, the OEM, he codes his software and the parameters to adapt this system to his engine being a 2.8 liter, a 6 cylinder engine or what ever for this car. They have to do all the testing then on their own. And with these results then they go to the certification companies and obtain approval from them to put these cars then on the road.

Steinbach: Okay. So and going back to-- you were building up the MEMS department or subsidiary, in those first 6 years-- or at the end of 6 years, how many people did you have working starting from 1, you, right?

Marek: So I started pretty much from scratch in 1988. I started then as group manager, as I mentioned before. Then 3, 4 years later I was promoted to department manager. I think at that time I had about 3 groups and we are about 30 to 40 people - on our sensors we did everything. We did the mechanical design because it's a mechanical system; how thick the membrane is, where to place the resistors, how wide it is, how thick the wafer is, . We did the layout like on integrated circuits. We did the process development for the micromachining part to really etch these small structures into silicon. Then we did the assembly, the testing. We developed both the device and also the process technology. And we worked very closely to the manufacturing guys, because when they hit the button, “let's start the production”, they had to deliver suddenly a couple of devices to 100,000's with excellent quality and excellent performance to the customers. That's about the size of the team we had – but we had also lots of support from manufacturing people and application people within the Bosch corporation to support that activity.

Steinbach: Okay, so you used existing manufacturing plants.

Marek: Yes, we used the manufacturing infrastructure but we had in place; at the same time we had to develop some of the processes, which are special to MEMS, both on the semiconductor, on the wafer part, and also on the testing because we had to test for pressure which you don't do with integrated circuits. We had to do a special assembly to put these devices into a package which suits the special application. . We used the infrastructure, the manufacturing process guys at the plant, but they had to adopt quite a bit and do quite a bit of changes; we worked with them very closely as simultaneous engineering teams. We had a simultaneous engineering team as it was called at that time. We put the development engineers, the manufacturing engineers, the quality engineers into a special project room where they worked separately from their home department, and that's where they developed and ramped up the volume production for the sensor about the last 2 or 3 years before the start of production.

Steinbach: So how different would you say is the-- how many steps are different from, say, making a power electronics device which Bosch had been making for a long time, like in percentage of steps that you had to develop?

Marek: If you look at the wafer side, I would say about 80 percent is really based on the semiconductor process. Twenty percent, perhaps 30 percent depending on the device is then done specifically to MEMS. . As we do the testing, we go onto standard wafer probers, wafer testers, so we are able to do that but we have to change the handling a little bit because the structures are much more brittle, much more fragile. We have to handle the wafers with a little bit more care. In terms of wafer testing it's perhaps 10 percent. In terms of the packaging, , then obviously we have to go for special packaging like really going for automotive type of package and then the packaging becomes very different. On the final, built-away package , I would say that's almost 100 percent because not very much of other equipment can be used. So to do the packaging and the final testing before it gets deliverd to the customer as the plastic package with a connector, with the pressure port, then it's really 100 percent dedicated.

Steinbach: Now, your MEMS devices I assume in many cases displaced previous technology, large or-- like there have always been pressure sensors in the car, right, and they were like vacuum cans or something like that? So was there some friction of the established departments?

Marek: Yes, there was a little bit of friction. In terms of the sensors in the car, as you mentioned, the first sensors to realize electrical and then electronic system were mechanical. Like for the manifold pressure sensor there was really, you know, like metal container, enclosure . And as the outside pressurewas changing, the volume was changing and this volume change was picked up by a Hall sensor. Also for acceleration sensors, there was a mechanical structure which was a metallic beam. The beam had a weight which was soldered at the end; there were piezo resistors in thin film technology. The weight moved and up and down and the resistors changed there value. These were the first acceleration sensors for air bag which were used, I think, in 1984 to make the first air bag sensor which Bosch and Mercedes put on the market. Unfortunately I don't have those samples with me, they are in Germany. And then this technology was changing and went into-- actually as an intermediate step into hybrid technology. At that time, because of the high temperature requirements and reliability requirements, people used ceramic substrates. They printed thick film resistors on it and conductors. We were also making a sensor structures on these substartes; , the second wave of sensors was then hybrid sensors which used a ceramic substrate. We printed different layers in hybrid technology - there was a layer which was based on carbon. The carbon burned at high temperatures and created a cavity. The change of the cavity between the substrate and this bubble, which was now on top, was picked up also by piezoresistors. Also for acceleration sensor we used the ceramic substrate. We would assemble piezo-electrical beams, really piezo ceramics,on top of an circuit in hybrid technology, During the crash these beams would bend due to the seismic movement of the mass. The piezoelectric materials have a very high charge generation during mechanical strain and this charge was picked up and amplified, and was sent then to the electronic system.

It was the mechanical systems in the '60s, s, then the thick film technology, ceramic technology, in 70's and then it continued into silicon in the 80's. And obviously with all of these generation changes there was a little bit of friction - always the old technology tries to push the performance and to lower the cost as much as possible. But by the end you can't beat the new technology: economic and performance-wise it was the best solution; , In terms of the electronic systems in the car, I would say micromachining was the third wave after the mechanical system sand ceramic thick film, technology for the sensors.

Steinbach: Were you sure at the beginning where you worked that you could achieve the reliability? I mean the hours of operation aren't so very long, right, for a car? But the environmental conditions are very harsh.

Marek: Yes, exactly. The car will be driving for 3,000 hours on average but it has to have a very long lifetime because it will be on the road for 10 years, 15 years or even more. So--

Steinbach: Which matters for contamination and things.

Marek: Exactly and also for long-term stability. Yes, we were very much worried about all the aspect of this technology in terms of reliability, long-term stability, offset performance and all these things. And as the technology was pretty new, we actually also had quite a bit of collaboration with universities, Fraunhofer Institute, Max Planck Institute, and did some basic research. , Lateron we introduced thick polysilicon, the so called epi-poly: we were looking into the material properties; what's happening with this thick polysilicon. If you stress it are there changes in grain boundaries like there are on metals, on steels? Is the doping changing over lifetime? Will the doping segregate? And the boundaries, will they change the mechanical properties? Silicon is an excellent mechanical material: the single crystal silicon, which is used for semiconductor, it's one of the best studied materials in the world with excellent quality with, purity, which is really exeptional. I don't think there is any other material in the world which you can obtain at such a high quality, quantity, performance, and purity at this type of cost. And therefore there's lots of information about silicon - but most of this information is on electronic properties and not on mechanical properties.

We also use polysilicon, not only the single crystal, and therefore we studied the mechanical properties of polysilicon. So we gave out a whole bunch of these topics to universities, to Fraunhofer Institutes, to study these questions that we had about stability of resonators, of grain boundaries, polysilicon over lifetime, over lots of cycles s of movement, of acceleration, overstress, and all these type of things. And there were a whole bunch of PhD theses that we did together with these institutes, to study the basic properties and to really achieve the performance and reliability which is necessary.

Steinbach: And so, nowadays you are confident to predict a lifetime from-- I guess you do accelerated life tests on your designs--

Marek: Yes, we do a lot of testing and we have lots knowledge about the materials, in terms of the mechanical properties. And now we have a very sophisticated design process. At the same time we've got lots of data from the field. Bosch, last year(2017), was making 1.4 billion sensors every year. Accumulated, we manufactured 8 billion sensors which are in the field and we have lots of data on these sensors. So we really know by now that all the predictions that we did are really becoming true. And that our models, our material knowledge, our design coefficients are really performing well.

Steinbach: So how many sensors are in a car of 2017 model year?

Marek: So a typical car nowadays would have about 50 sensors.

Steinbach: Fifty sensors.

Marek: Yes, it's amazing.

Steinbach: So that includes airbags and things, right?

Marek: So, well, the car is driving, right? So you have the drivetrain, the combustion engine, and on these engines you have a sensor to measure the air intake. So, depending on the oxygen that you are taking in, then you can inject the fuel - that's either a pressure sensor or it's an airflow sensor, which measures the airflow coming into the engine.

Steinbach: How does it do that?

Marek: So, well, that was the next development . After pressure sensors we developed airflow sensors because the airflow sensor is very accurate, in terms of the measurement of the air, mass of the oxygen that you are taking in. For this measurement, we created very thin membranes. TSilicon is also a very good heat conductor and therefore it would not be very good to measure the airflow. We created a dielectric membrane which is etched out of the silicon wafer, but it consists only of layers of oxides and nitrides. We really remove the complete silicon and we create a membrane, a bridge with oxides, nitrides. We have to stress-compensate it because oxide and nitride have a different expansion coefficient compared to silicon. And we deposit platinum thin layers on top:we manufacture a heater this way. On the surface, we create a temperature increase which is very local and due to the air flowing over the chip, this hot wire, this hot platinum wire is cooled down. It transports some of the heat downstream and therefore we can measure the temperature transport of this heater.

We can measure the heat transport to one side , where there is a temperature increase; there will be a temperature decrease at the temperature sensor on the other side. At the same time we can measure very fast because the structure has a very low thermal capacity. We can measure also the direction of the flow, which is very important because the sensors in the past were very slow and on new engines, if you have a four cylinder downsized engine with two valves, four valves, there is even a backflow. As the sensors were very slow in the past, they would not detect this back-flow. So it was actually detecting the-

Steinbach: The sum of the two, basically--

Marek: The sum of them two, which is wrong.

Steinbach: But you have to look at the vector sum, yeah.

Marek: Exactly! The electronic management system for engine management system was receiving the wrong values. It was injecting too much fuel or not enough fuel, and therefore, it didn't have the appropriate combustion and higher emissions. It was in the nineties that we've been able to manufacture prototypes - car manufacturers were very much interested because our sensor was very small and it was very fast. Therefore they could detect the airflow and the profile of the airflow very accurately including this backflow action.We could obtain very accurate values of the air, of the oxygen which is going inside the engine and therefore we could improve the combustion and would add not only the combustion but also the emission and the fuel economy performance of the car, which was very interesting to the car manufacturers. fter the pressure sensor for engine management, the airflow sensor in 1995 came to volume production because that was a very interesting device for the engine management application.

Steinbach: Okay and then I guess you have all kinds of inertial sensors.

Marek: That's right. We have all kinds of inertial sensors. Well, the first were the airbag sensors. The airbag came onto the market in the eighties with a mechanical sensor that I described before. But then the electronic systems had to be cheaper and smaller, and therefore we came with the acceleration sensor made also by MEMSa s solution. For this sensor, we take the silicon wafer, we etch on the surface structures which are comb structures facing each other, and due to the acceleration they will move. One of the structures is really fixed to the substrate very rigidly. The other one is flexible and therefore during a crash, it will start moving this way. As the fingers are moving, then there is a distance difference and therefore a capacitance difference, right? A capacitance change is very easy to measure electronically; using this concept we were able to manufacture acceleration sensors which were very small, very reliable and also very cost effective for airbag. Then after airbag came the electronic stability system, which is a system which improves the stability of the car in critical situations where it's very close to skidding. The ESP, the electronic stability control system is controlling the dynamics of the car. It's measuring the steering wheel angle - the steering wheel angle indicates the wish of the driver: do I want to go right or left and with what kind of,, angular speed I want to do that. We are measuring the pressure on the wheels, the breaking pressure. And we are measuring the rotation of the car along the perpendicular axis of the car. And then the system is comparing the steering wheel angle with the rotation of the car, if it's really driving into the curve as I as the driver, have put my wish onto the system. So if you are skidding, if there is ice, if it's raining, if the conditions are very bad and I've been driving into the curve way too fast I would start skidding. If the steering wheel angle and the angular motion of the car are different, then the system will apply different pressure on the front wheels and the back wheels or on the right and left wheels, and it will correct the car movement and put it back again on the path which I as a driver using the steering wheel, which I am commanding. And it's really amazing. These systems under critical situations improve the stability drastically. They cannot do more than the physical limits of course. . If it's really icy, the friction is very low, well, then the system cannot correct it any more; but they can do it much better than any kind of human can do; therefore in critical situation, these systems can improve the stability drastically. And we worked very closely with the European agency but also with the U.S. agency, with NTSA and we've been able to verify that such systems are making an improvement which is saving thousands of lives in the U.S. only. Therefore with introduction of the system in the nineties, this system's really saved quite a bit of lives both in the U.S., Europe, but also in Asia. These systems are now compulsory in the U.S., in Europe, in Korea, Japan, and also coming in China with 100 percent requirement.

Steinbach: And I assumed the laws of what exactly is required are based on what you say you can do, right, in terms of what's technologically possible?

Marek: Yes. Obviously, the experts within the automotive companies, the experts at Bosch as the supplier of the electronic system, of the mechanical system, we can show what the possibilities, what the limits are of these systems. And then we are working with the regulation agencies to show them systems' possibilities but also the limits and then we try to work out the impact in real life on the road. I mentioned before, Bosch Motto is “Invented for Life” - to really improve the stability of the systems in a way where we can make the cars safer but also improve the fuel efficiency and also the emissions. In order to provide progress and give back to the society in terms of the performance of the system.

Steinbach: What's the response time of, say, the stability control system?

Marek: The stability control system, will do measurements and updates on the order of milliseconds. The braking systems, I think are on the order of about 10 milliseconds. The airbag systems also has to make a decision fast - in the case where we have a crash from the front or from the back on the order of 10 milliseconds. However, if we have a crash from the side, these systems have to react faster because the crash is progressing very fast towards the passenger, towards the driver, and then we have on the order of just a couple of milliseconds to make the decision. These systems have to react and activate really at microsecond scale. We have to take the data; we have to update the data and we have to calculate the data, make checks that the data is real and stable before making a decision. Because if you blow up an airbag, and if you deployed it and it was actually an error, you don't want to have an airbag blowing up in front of you on the freeway. That's not a very good condition. Both situations, deploying too early or or deploying too late, are not very good for the driver, for the passengers - we have to really deploy acuratelly at the right time.

Steinbach: So the sensor itself is-- reacts on, like, in the microsecond scale?

Marek: The resonant frequency is on the order of a couple of kilohertz, therefore we can measure, really, in a fraction of milliseconds. And we provide then the data on a microsecond scale to the system to do all the calculation and checks, on time.

Steinbach: And so each airbag has its own sensor that activates it?

Marek: Well, actually,yes and no; each each airbag system has quite a bit of sensors. A really high end airbag system, will have an electronic control unit which is generally mounted someplace in the middle of the car, because we want to detect the movement of the car as the whole body, because you can have a crash from the front, from the back, from the sides, therefore we want to have it in a very rigid place where it's well coupled to the car body and receives the information from all sides in a very precise but also very timely manner. The system will have a safing sensor - a redundancy sensor - to check if the crash is really true. It could be that the sensor has some kind of problems -- it's blocked or it might have some electronic error - , so for reliability reasons there is a second sensor- - redundant sensor - and control system is always checking the signal of one sensor and comparing it with the other one and checking for plausibility to say: well, yes, my system is performing acurately. Then we have sensors in the front because if you have a high speed crash, you have to react fast, - you will have one or two upfront sensors, which are also mounted in a very rigid way and placed in front of the car. Then for the side crash, it's important to react very fast because you've got only about 10 inches, 15 inches from the body of the passenger, of the driver, to the door, to the first impact. And at the same time, if there is a side crash, our body is built in a way where, if you have some kind of crash from the side, then the injury, especially the neck injuries are pretty severe because your head will move to the right and to the left. And therefore we want to deploy the window air bags and the side bags very fast to protect the customer in a very reliable way. Therefore, we have only a couple of milliseconds to make the decision: we place side airbag sensors to the right and to the left. For larger cars like vans, we have them on the driver and the passenger in the front row but also in the back row and in some of the vans, even in the third row, to protect all the passengers. If there is a rollover accident, for example if the car is going down into a ditch, and it will roll over: f you look at that movement of the car in this case in terms of mechanics, there is not really a crash until you hit the roof, because there is no impact on the body of the car. There is only this rolling movement, and then you have a very severe crash either to the side or to even to the roof; the injury would be very serious to the passengers. Therefore we have a rollover sensor which is a yaw rate sensor, angular sensor, measuring the movement of the car along the driving axis. If that movement/rotation becomes too high, then the airbag system will deploy as well, before actually they is impact on the car body. -- So as you see, it's only one airbag system, but we can have dozens of sensors connected to the system to really protect the passengers in a very reliable way and under all conditions.

Steinbach: And those sensors are-- they are not in the airbag assembly, they are on the chassis and they talk to the central airbag system?

Marek: Yes; there will be the central sensor. There will be the redundant, the plausibility sensor, also in the ECU, in the center. The rollover sensor, this angular rate sensor, is also in the middle of the car because the whole car is moving. But because of the very fast time dependence of the crash, we have to placethe side and front airbag sensors really on the outside. There will be one or two in the front; there will be ones to each side, These sensors are connected via the wiring harnness to the airbag control unit and this control unit is making all the decisions.

The airbag system is then giving the signals to deploy the airbags. And modern airbags systems are also very sophisticated. We've got the passenger and the driver bag which are inside the steering wheel or inside the dashboard. Then for the side impact, we have one on each side for the shoulder. We might have also a window bag which deploys from the top. And on some systems, even a sensor for the knee, because the knee injuries as you are moving forward can be also very serious. And the same thing can be also installed for the second row where you have a side airbag sensor for the passengers in the back row to be protected. So as you see, those sensor systems are quite complicated with lots of actuators, lots of sensors and lots of electronics.

Steinbach: A central control unit that makes the decisions. It's not the bag senses itself, it's being accelerated and it blows up.

Marek: Yes. The computing is done in the central electronic control unit. The sensors will have a little bit of intelligence, - they do the signal amplification; they do some plausibility checking. They really provide some little additional signal evaluation within the sensor. New sensors will provide the information via a digital communication, in order to have a secure communication to the control unit.

Steinbach: And so that's electronics integrated onto the sensor chip.

Marek: Yes. There is quite a bit of signal evaluation on the chip.

Steinbach: Okay. So I looked at a list of your patents and I see basically four broad areas: Acceleration sensors; force and pressure sensors; valves; and mass flow sensors. Does that about cover what Bosch does or are there others that you didn't work on?

Marek: For the automotive it's, as you mentioned, the pressure sensors for air but also for fluids like braking fluid; acceleration sensors for airbags as we discussed before, but also for acceleration like navigation systems to measure the acceleration, or deceleration; the braking of the car; the yaw rate sensors for stability control but also for navigation, we use gyros; then we have the airflow sensors as mentioned before. The silicon valves didn't make it to volume production because the ambient conditions are very, very tough in the car and in terms of performance and reliability, the requirements are so high that we were not able to really make cost effective systems to deliver all the protection neccessary. Silicon is very brittle - so in order to withstand the particles in fluids or in air, it becomes very difficult . And if you want to do an actuator, you need big forces to move the parts and then the devices are too large and not economical; in consequence the valves didn't make it to volume production in the automobile. But in medical applications, there are some silicon structures where people are very interested in handling very small amounts of fluids like insulin for diabetes – these applications are being followed up in that field.

Steinbach: Okay.

Marek: And I didn't talk about that yet, but in 2005, we created a new company as a startup called Bosch Sensor Tech to serve the consumer electronics fields. In the early 2000s, we looked into additional markets for MEMS structures besides automotive; we initiated a business field analysis for MEMS. We identified two possible fields: ne of them is being bio analysis of fluids, gene sequencing and handling of very small amounts fluids for analysis in bio applications and also the consumer electronics field. To remember: the iPhone just became 10 years old this year(2017) - it was 2007 that the iPhone came onto the market. At that time, it was Nokia and the other companies which were dominating the market The samrt phone manufactures were starting to use sensors on their devices. They were starting to use sensors for changing from portrait to landscape orientation; to switch the display on and off as you move the phone, and perhaps to use phone navigation in the future. The phone became really a smartphone at the time - in order to become smart, it needed to interact with the environment and therefore it needed also sensors for acceleration, for rotation . And now, we are even using sensors to measure the ambient pressure, in order to measure the elevation due to change of the atmospheric pressure, we can also measure the change in weather, humidity, air quality. These sensors were used in the car at that time -- not in the smartphone. Therefore in 2005, we started this internal startup financed by Bosch, in order to be really focused on the consumer market. We had quite a bit of discussions if we should do it within the framework of our division - Automotive Electronics Divisoon which was, very focused on the special requirements of the automotive. We decided to set up a separate team, even a separate company to serve this consumer field in order to serve the customer better. And now, Bosch Sensor Tech, as you know, they celebrated 10 years in 2015. We are the largest manufacturer in the field of consumer electronics sensors.

Steinbach: Really?

Marek: Yes, and -- we are the top manufacturer of MEMS devices overall. 70 percent of all the sensors that we produce are now going into consumer electronics. There is billions of smartphones manufactured worldwide and pretty much all of them have a Bosch sensor; , we are very proud to serve the smartphone manufacturers worldwide and provide these very important components to them.

Steinbach: And they presumably are easier to make and smaller because they don't have the same reliability requirements, right? People keep their smartphones for a couple of years.

Marek: They don't have the same reliability requirements, so you might think,, these are really much easier to be manufactured. But the problem is that the consumer electronics has much higher pressure in terms of pricing and also the size of the package. These devices have to be much, much cheaper and they have to be also much smaller.

Steinbach: It's not that much easier because of the price and size pressure I take it.

Marek: Yes, the requirements are also very high. We have still to deliver very high resolution signals. The requirements on the acceleration sensor and on the yaw rates are very demanding because we want to measure a very small angle for navigation, for indoor navigation, outside navigation, to supplement additional signals to the GPS with our gyro. They have to be very small, therefore the MEMS mechanical structures are very small, but the resolution has to be very high. The cost, as mentioned before, has to be low as well. And last, not least, the power consumption has to be very low, because if you have a smartphone, you don't want to drain the battery: we have to decrease the power consumption quite a bit compared to the car where you have a car battery and really also some power consumptions on the power electronics side – threfore the power consumption is not that much of an issue in the car compared to mobile devices. This creates a completely different set of requirements and also different designs, - therefore we have a separate organization to handle these requirements in order to provide devices to this market.

Steinbach: So I assume you will try to integrate as many sensors as you can into one device, right?

Marek: Exactly. aActually, this is now on the smartphone and it's called an IMU. This abreviation stands for inertial measurement unit - the inertial measurement unit is a combination of three axis accelerometer, because the smartphone can be held in any direction in space and also of a gyro in all three directions because you can rotate in the space in your room and navigate with a phone in all different directions, - we have really a complete inertial measurement unit. And this measurement unit is also going into these small packages with incredible accuracy at very, very low cost. These designs are very challenging and we have many engineers working on these projects to make it happen.

Steinbach: I found 27 patents of yours which-- where the dates kind of end in 2005. Is that when you moved away from the actual technology?

Marek: Well, thank you very much for researching into that; you know more than I know. . Yes., I became, a department manager in the nineties, then I was promoted to vice president and senior vice president at Bosch handling an organization of several hundred development engineers and several $100 million dollars of revenue- I was very busy, manageming this innovation and the organization. I had staff and an organization structure to work on the details and my associates then did the major inventions. I provided the impulses, helped to do the projects, but obviously, the detailed inventions were done by my associates. . At Bosch, as I mentioned before, we are a pioneer in the MEMS field. We were one of the first companies to go into the mass market. Now according to market research companies, we are the largest MEMS manufacturer with over $1.2 billion dollars of revenues and we have over 1000 patents in this area, so we did quite a bit of--

Steinbach: Okay, that was a question I was--

Marek: --basic research in order to put this technology into volume production and with 25 years of experience in this field and several hundred people, there are many thousands of man years of development which went into these MEMS systems.

Steinbach: Okay. We should mention that in 2008, you were awarded a Future Prize by the President of Germany. Can you talk about that or show us the prize?

Marek: I'm very happy to do that. In 2008, we were awarded this prize for our achievements. The ttrophy is very heavy. It's really a steel base and the symbol of the price in glass. This price is not well known outside of Germany, but this a sort of a scientific Oscar in Germany. Three teams can apply, three teams which are working on some new technology but technology which is really relevant to industry, to manufacturing, to the society and has been really verified and put into production. There is a TV show on one of the major TV networks in Germany which is scheduled at prime time about three / four weeks before Christmas with a very famous moderator in Germany. The three teams, they pitch their innovation. And at the end, the President of Germany receives an envelope which includes the name of the winner. He doesn't know who the winner is and then he opens the envelope like at the Oscar nomination event in the US. . And so we applied in 2008 and have been selected for the final round. to present our project in this TV show. It was a very exciting experience to be on TV with 5 or 10 million people watching you - and you don't know what the outcome is going to be and you are in front of the German President. It's like being on ABC or CNN and receiving an award from Mr. Obama or Mr. Trump, - , that's quite an event, which we were invited to; we were very happy that our technology, our contribution was really acknowledged with this award.

Steinbach: Congratulations, yeah.

Marek: Thank you.

Steinbach: So this is not for research but for technology that is proven in industry.

Marek: It's really for innovations which are proven and which went into or are just in the process of going into some industrial applications. -It's not like a Nobel Prize where pure research matters, It has to be a major innovation which is applied to application and is just starting production or has already entered the first couple of years of production.

Steinbach: Okay. And so what is your growth prognosis for the MEMS industry in terms of, well, volume, but also do you-- are there fields that you see it going into that are not covered yet?

Marek: Looking at the from the, electronics industry, we have now about 7 billion devices connected to the internet and the Internet of Things is growing. There are more and more devices. We are connecting more and more devices to the internet, being the car, being the home appliances, being a security system at home. And the expectation is that soon we will have 20 and 50 billion devices connected to the internet. And with this Internet of Things, obviously, we need input from all these devices. We need information: What's happening, what's happening in my home, what's happening in the car? And in order to obtain all this information, we need new, reliable cost effective sensors. In order to facilitate the Internet of Things, MEMS sensors will be necessary in order to provide these signals to these systems. That's one of the major areas on the consumer side. But also on industrial application side, what's called in Europe Industry 4.0. The transition of industry to really data-driven, internet-driven production where you can produce and control, small batches with very high reliability at very fast intervals, and deliver to the customer - more and more information is needed. So in order to control the machines for these type of production processes, more and more sensors are needed during the production, during the transportation of products to be delivered to the customer. Therefore, we foresee a lot of sensors to be used in this revolution of manufacturing and industry infrastructure.

Steinbach: Okay. All right. I think we are arrived at kind of today and tomorrow in your career. And what do you do outside of work?

Marek: Technology like this required quite a bit of dedication and also time - yes, I have been pretty busy during these times, but family was very important to me as well. My wife always supported me during these tough times - when I had to go and put in extra l hours or weekends or for some additional trips which were not planned, she always supported me. We have two children; two daughters. Family, spending time with my family was very important to us as well as raising the children. Now both of them completed college. They started this year on their jobs, both the older one and the younger one as well. Actually, since we've been over here now in Silicon Valley and since I've been managing the Research and Technology Center for Bosch, our younger daughter decided to follow us - she studied computer science at Stanford; just graduated in 2015 and got a job also here in Silicon Valley with one of the major companies. Outside of family t, I do have some hobbies. I like skiing and hiking in the mountains, both in the summertime and in the wintertime, it's always fun. I've been sailing since my university times. I've been sailing some small boats but also we chartered some larger boats and even spent some time cruising with the family. Both in Europe and over here in the U.S., we chartered boats for a week or two and the family including our children and the son-in-law, we spent time together – this is the kind t of the hobbies that we have.

Steinbach: Oh, great. And do I remember right, you told me you're retiring soon? So what are your plans?

Marek: Yeah. It's sort of interesting. As I mentioned before, I started my career in industry over here in Silicon Valley. After a postdoc at IBM Research in San Jose, my first job was in 1983: 35 years ago here in Palo Alto at Page Mill and El Camino with Hewlett-Packard. Now I am working at the Research and Technology Center of Bosch, which is about three miles from that location. And after spending all this time at Bosch building up MEMS technology and bringing it to the market, I spent five years over here managing the Research and Technology Center. Now in the fall (2017) I am going to retire from Bosch. It's sort of interesting: I started in Silicon Valley; I spent most of the time managing MEMS operation for Bosch in Germany. I spent then the last couple of years managing all of Corporate Research and Technology Center in North America in Palo Alto, Pittsburgh, Boston and I'm retiring after this assigment. . It tarted in Silicon Valley and now it's coming to the end of my industrial part of my life, here in Silicon Valley which is very exciting and I'm looking forward to spend more time with my wife and the family.

Steinbach: Okay. So you will be-- You will really be retiring, not like-- go into some other jobs or so?

Marek: Yeah. Well, I might do some consulting; there are some options. I am talking to both Bosch - we have a consulting service for managers retiring from the company where Bosch tries to leverage this knowledge of the managers on a part-time basis - that's an option for me. But there are also some other companies which are interested in my experience of both the German industry and the Silicon Valley technology and bringing these together. First my wife and myself will do an extended trip. After some very strenuous times, it's time to relax and enjoy travelling Probably in the spring of 2018, I will look more in detail and do some consulting and a part-time job.

Steinbach: Okay. Well, I wish you all the best for your retirement and thank you again for this interview. It was very interesting.

Marek: Thank you very much for inviting me.

END OF THE INTERVIEW

