Don Scharfetter

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Good Morning, and thank you, John for your kind remarks. And a special thanks to you, Hermann, for being here. Thank you, members of the EDS awards committee, for this award. Let me begin by saying I'm very happy to be here. Yes, I have cancer, cancer of the head & neck, which is not a very kind cancer. In fact it's a down right nasty one, but my family and I are fighting back. I have the best doctors at Stanford University Medical Center. After surgery and radiation treatments I'm now undergoing chemotherapy. Chemotherapy's side effects are nasty and my doctors have worked hard to make me strong enough to be here. Getting some strength back and feeling good makes me happy.

I'm excited that my family is here today. Like many workaholics, my family really doesn't know much about my work life. They have seen me happy to work seventy-hour weeks and must think Dad is a little odd. They watched me try to spend time with the family on weekends by hauling my 1970's era terminal poolside with a 100-foot extension cord. But I guess they say to them selves "we'll just have to put up with what we got".

There are some very special people I'd like to thank for being here today. I'd first like to introduce my wonderful, loving and understanding wife of 45 years and now the world's greatest nurse, Marie. Without her support and willingness to put up with all those long hours I would not have been able to accomplish my career goals. Thank you honey, from the bottom of my heart for giving me that opportunity.

Also here are my three wonderful daughters, Lou Anne, Linda and Deborah, and my sons-in-law, James and Walter. My six grandchildren are also here. Catherine and Martin, ages sixteen and thirteen, Teresa and Trevor, ages eight and five and Nathan and Rene, ages six and one. Note that each daughter had a boy and a girl. Deborah and Walter were under a lot of pressure to produce the third girl we call the Princess Rene. Grandma has a wonderful time shopping for the grandchildren. Someone said, "Who needs Santa Clause when you have Grandma". Daughters, sons in law and grandchildren, I love you all.

My wife's twin sister and her husband are here from Virginia. Marie and I have taken numerous vacations with them and enjoy their company very much. Louise and Jack, thank you for being here and I love you.

A special welcome to Hermann Gummel, who these days doesn't attend too many conferences but made an exception to attend today. Thank you, Hermann, for making the trip from New Jersey. I'm looking forward to seeing you again after so many years. Hermann, I do love you, too.

And thank you Fely, for all your help in arranging rooms for my family and all the things you do for me at Stanford. Fely, I love you.

Although I have many good friends, I have to especially thank Bob Dutton, Paco Leon and Paul van Wijnen for being my best friends. Paco, Bob and Paul, I love you too.

And my youngest daughter, Deborah, gets special thanks for being my "voice" today.

Funny, but when you are dealt the blow I have been dealt, you change. You're embarrassed at nothing. You're not shy to say what you feel. You say what ever you want to say. So all of you, I love you too, just as I have loved every minute of my work and the wonderful people working in the SISPAD area that I have come to know.

I'd like to share some personal history while I have this captive audience. In 1952 I was the first member on either side of my family to graduate from high school. I immediately joined the Air Force during the Korean War to take advantage of the GI bill. In January 1953 I was assigned to McCoy airfield in Orlando, Florida near Winter Park, home of Rollins College, where my future father-in-law, George Saut, headed the math department.

George started an evening program called "operation bootstrap" which allowed airmen to take college courses on base in the evening. His daughter Marie, whom he was quite close to, was a senior in high school at the time. He asked her to take his college algebra course so he would have company on the drive to the base and so she wouldn't have to take it the next year from a professor he didn't like very much. Well I guess it was close to love at first sight. George would pass our love notes back and forth in the sent/returned homework. Our wedding announcement read "Romance begins in Math Class".

We were married in June of 1955 and I entered Carnegie Tech (now Carnegie Mellon University) in the fall of 1956 after my discharge from the Air Force. Our three daughters were born November 1956, May of 59 and February of 62. I was highly motivated to finish college and get my family out of the subsidized housing projects and I received my BS in 1960, my MS just one year later in 1961 and my PhD the following year, 1962. Here's a slide from the 1962 publication of my thesis.

I must have impressed Bell Labs because they put me on the payroll half way through my last semester with what I thought was an outstanding offer for that time. Bell Labs was a remarkable place to work and I hope you'll enjoy hearing a little bit about those days and how Scharfetter-Gummel came about.

Hermann Gummel is a remarkable person, as I'm sure most of you know. Hermann was my second of four bosses at Bell Labs. Although I learned from all of them nothing can compare to what I learned from Hermann. I learned how to do good scientific programming. I learned to only trust my own programs. I learned to not trust my own programs.

I learned that there is no substitute for combining a good intuitive feel for devices with the predictions of your program. That is, if one has a good intuitive "feel" for devices, then the computer can be used to enhance that intuitive capability. You use your computer programs and enhance them, over the years, to continually build up your understanding. Well Hermann had an outstanding intuitive "feel" for devices, well before there were any numerical device simulators. When scientific programming came along Hermann was off and running. What a genius and humble person he is.

So how did Scharfetter-Gummel come about? Well Hermann had been working on the Gummel algorithm for solving the Van Roosbeck equations. These are the transport, continuity, and Poisson equations in every device simulator. Hermann was solving these differential equations numerically for a 1-D bipolar transistor. At the time Bell Labs was considering using avalanche diodes as microwave sources for a wave-guide, long distance telephone system. This was about 1963 or 4. The IBM computer, which was state-of-the-art at that time had basically no memory. I/O was punched cards and computer printout. Hermann's bipolar transistor programs did OK on p-n junctions, as long as the collector voltage was small. But these avalanche diodes had supply voltages of hundreds of volts! Any of you who have worked in this area know that conventional numerical techniques for conversion of the differential equations to difference equations and applied to semiconductor transport fails if the voltage change between mesh points exceeds two thermal voltages, which is two KT over Q. We could not use a finer grid, as there was not nearly enough memory.

So what to do? After discovering the thermal voltage problem we concluded we needed to derive a different set of difference equations based upon some realistic physical assumptions that would not have the thermal voltage problem. That is, conventional "text book" difference equations to replace the differential equations to allow a numerical solution, had to go. Necessity was the mother of invention. We were fortunate to be given the problem to model avalanche diodes when computers were in their infancy. If there had been enough memory Scharfetter-Gummel might not have come about and later in time someone else would have "discovered" our algorithm.

So here's a little about our algorithm, or our "invention", for the new difference equations. For those of you not into this sort of stuff, our invention is the solution for the holes, electrons and electric field derived over just a few, three to be exact, mesh points. The algorithm requires integration of the differential equations to yield our famous difference equations. The location of the nodes are like boundary values and assumed given. The values of the three variables would have a relationship, the difference equations, that we are seeking. Integration of the differential equations from the nodes, N-1 to N+1, yields Scharfetter-Gummel.

Restated with a little more detail is that what we were looking for is a relationship between the hole and electron concentrations and the electric field, expressed by values at nodes. We obtained this relationship by integrating the corresponding differential equations, with critical assumptions about how the holes, electrons & fields vary between mesh points. Each N-mesh volume contains charges, assumed constant from (N-1/2 to N+1/2) times dx , the local mesh spacing for charges. Each M mesh volume defined from (M-1/2 to M+1/2) times dm, the local mesh spacing for fields. The entire dm's and dX's sum up to equal the length of the diode. By Gauss's law, the M nodes live between the N nodes. When we do the integration, using only pencil and paper, out pops Scharfetter-Gummel. So it's really very simple.

The technique could not have the thermal voltage problem but had to be valid for any voltage change between mesh points. We tried lots of ideas searching for the right assumptions. We assumed quasi-fermi levels don't change for values between mesh points, which sounds reasonable, but fails to work. We finally came up with something simple and that works. As mentioned previously you actually solve the differential equations over five mesh points, N-1, N, and N+1 for the carriers, and M and M+1 for the electric fields, which by Gausses Law are defined in the regions between the charges in a very fundamental and physical way. When you solve this problem, by pencil and paper, what pops out is the set of difference equations that can be solved numerically over the diode's length – with no thermal voltage problem.

The publication where we first described our algorithm has the title "Large Signal Analysis of a Silicon Read Diode Oscillator", Transactions on Electron Devices, January 1969. You had to read the appendix to understand what became known as the Scharfetter-Gummel algorithm.

So how did avalanche diodes work? Well the generated charge was large enough to partially collapse the field, which could be called microwave conductivity modulation. Note that the conductive current component would be out of phase with the terminal voltage while the displacement component supported the high voltage, which initiated the avalanche mechanism.

After this work I went on to my third boss, Barney DeLoach, whose department had the job of designing the microwave diodes. In keeping with Bell Labs tradition at the time, I was only asked to help. And I could help in any way I wanted. Well I got a lot of publications at that time all using the program I wrote, which of course used Scharfetter-Gummel, to predict the properties of exploratory structures of my choice by means of computer experiments.

I would like to show you a film of computer output. Fortunately the Bell Labs computer facility at this time had an e-beam to 35mm film writer for your computer output. I presented this film at IEDM in1965, paper 2.5. It might have been the first computer-generated movie ever shown at IEDM.

But first let me explain what you are about to see. These slides are frames from the movie. Shown, evolving in time, are the holes, electrons and electric field over distance in the microwave avalanche diode. To the right side is the high field region of the diode. Note a phase plot is shown of current and voltage. Also note in the phase plot, which is the large oval circle located in the upper left of a frame, a small circle indicates the point in the cycle, for this frame, call this the top of the cycle. The phase plot, along with the frames, shows that when the voltage is at it's maximum, the particle current, which is the integration of the electron concentration, is at it's minimum. The next slide is 90 degrees later. The next slideshows the voltageat it's minimum, and the particle current is at it's maximum. This is the optimal frequency for this diode. The current is composed of displacement and conductive components. The conductive portions, whichare the electrons drifting from the high field p-n junction region to the N+ junction, are out of phase with the diode terminal voltage. Hence, a microwave negative resistance and sustainable microwave oscillation is formed. Note in the movie that the carriers are drifting when the terminal voltage is low, but not the total current, which is dominated by the displacement current component. This slide is the last before I show the movie. Look at the labels for electrons, holes and the electric field carefully, so you'll know what you are seeing.

The diode in that movie is an IMPATT diode. Barney Deloach, who was my boss and department head, and Ralph Johnston, the department's super technician, gets credit for inventing the diode, which they named Impatt for "Impact Ionization Avalanche Triggered Transit".

For this work and more described in a moment, I received the grade of IEEE Fellow in 1971. I'm shown in this picture along with the other NJ chapter recipients of the grade of Fellow on that cold January award's dinner evening. The suit I am wearing Marie made; she sewed a lot for the family in those days.

Shortly after this, I, Ralph Johnston a microwave technician and Bill Evans a PhD in microwaves, started working together. Bill didn't report to me but at Bell Labs that didn't matter. I just went to Bill one day and described what I was working on and he said that sounds interesting and we just started working together. I don't recall any management involvement. The problem I described to Bill was that a group at RCA published a paper on what they called an anomalous avalanche microwave diode, which showed efficiencies far greater than what others and I had predicted was physically possible

So how did we explain how such a diode worked? Ralph Johnston first built a wave-guide and diode source fixture, which reproduced the RCA results and then Bill Evans built a computer model for Ralph's experiment. I integrated Bill's computer model with mine for the diode. So in the mid-1960's we had a microwave circuit simulator, today it would be called mixed mode simulation that integrated a numerical device model into a circuit model. The idea was to run this and let the computer tell us what was going on.

We ran the program for as long as we were allowed on the Bell Labs computer, a few microseconds at best. Output was a box of cards, which was the solution to be read in to continue the solution. I recall we were allowed two runs per day not to exceed two hours of CPU time. Fortunately a 35-mm film of the solution could be made into a computer-generated movie. After weeks we finally generated a weak oscillation. I took it to Ralph and he said, "I've seen that kind of oscillation, you need to tune your fixture, or Bill's circuit model, this way". Bill made the change and we continued running the program and the solution was a healthy oscillation with the fifty percent efficiency seen in the experiments. So the computer did tell us what was happening. The charge generated was large enough to completely collapse the voltage; perhaps you could call it extreme microwave conductivity modulation. Of course you needed a circuit, which supported a natural high frequency IMPATT oscillation, and a lower TRAPATT frequency. TRAPATT is the name Barney and I gave to these TRApped Plasma Avalanche Triggered Transit time diodes. We got a few more publications.

In fact it is easy to tell the time frame for when we did this work. Check IEEE list of publications, for about 1967-8. In one of those years I believe I had the most publications as lead author or co-author of any member of the IEEE. Of course the time we actually did the work would be the previous two years or so, to allow time for the Bell Labs memo to be released, manuscript preparation time and review time.

In this slide you see Ralph and me in his lab comparing the computer-generated solution to his experiments.

Bill, Ralph and I got quite a few publications after that explaining and deriving performance of a variety of avalanche diodes which used early epi and ion-implantation and not simply diffusion doping. I began to attract a crowd of experimentalist in epi growth and ion-implantation who wanted to build diode structures with me and be co-author on the publications.

Then I had a little break from avalanche diodes. I was sent to Sandia to work with Chuck Gwyn to convert the diode program into a transistor program, which would model radiation-induced damage to bipolar transistors. As I understand it, that program is still in use.

When I returned from Sandia, Barney, my boss, called me into his office and asked me, “do you know what you are doing”? I said “what do you mean”? He replied, “you are working yourself out of a job. You have all these people now doing what you ask and you have grown people who can carry on your work. So you are ready for a new job”. So I was back under Hermann managing what today would be called a TCAD group consisting of Sam Poon, Charlie Wilson, Jim Blue & Jacque Ruch. However after a couple of years at that, a Murray Hill group designing a CMOS eight bit microprocessor, needed a supervisor. So I then became a designer, or at least a design supervisor. Bell Labs used the term supervisor to mean first level manager. We got that microprocessor design into manufacturing and I was asked to manage the next generation.

But instead I decided it was time to leave Bell Labs and went on to be Professor at CMU. I then joined Xerox Palo Alto Research Center where I was asked to start up from scratch an IC prototyping lab. I then did a stint at UC Berkeley to invent the BSIM compact MOS transistor model and finally on to Intel.

Let me tell you a funny thing that happened when I joined Intel in 1987. Recall I left TCAD to do other things in about 1972, namely design, including testing, and on to CMU, Xerox PARC and Intel, where I came full circle, back under Jerry Mar, in TCAD. That summer of 1987 a SISPAD, but I think it was called NUPAD then, meeting was in San Diego. Here I heard for the first time the words “Scharfetter-Gummel”, and I was shocked to learn that many people had built on it and it was still considered the way to solve semiconductor structures numerically. I spent so many years outside of TCAD, fifteen by my count, that the significance of Scharfetter-Gummel just was not known to me. I thoroughly enjoyed my time at Intel, where Jerry Mar and I had many “interesting” discussions. A few so heated I’m surprised I wasn’t fired. Well Jerry and I became good friends. I became friends’ with the people in my group. I made friends on my assignments to head the TCAD Roadmap committee, to SRC, Sematech and the National Labs. Thank you Jerry, for allowing me such freedom, somewhat rare at Intel. I had twelve great years at Intel, where at age sixty five, I retired.

A heartfelt thank-you to EDS for this award and I thank you, my friends and family, for being here today. I look forward to visiting with my friends and colleagues later today.

Thank you for your patience and enjoy what looks to me to be the best SISPAD ever, or maybe more topics of high interest to me are included this year. So I thank the program committee for doing an excellent job. Hope to see you again at next SISPAD, but God only knows, so, so long and God bless.