Face to Face

This section features conversations with personalities related to science, highlighting the factors and circumstances that guided them in making the career choice to be a scientist.

The IGBT and its Creator

Jayant Baliga talks to Hareesh Chandrasekar

The Insulated Gate Bipolar Transistor is a power switching device that combines the advantages of the BJT and the MOSFET (see *Box* 1) by using a short channel MOSFET to drive a wide base p-n-p BJT [1]. It was first reported experimentally by Jayant Baliga, who was then at GE, in the year 1979 as a V-grooved MOSFET device with the drain region replaced with a p-type anode region [2].

The IGBT works as follows. The application of an appropriate positive gate voltage causes a channel of electrons to be formed underneath the gate terminal that can carry current from the n+ emitter through the p-type body to the n– drift region (base region) and onto the p+ collector. The electron flow in turn gives rise to hole currents from the p+ collector region into the n– drift region and the device conducts current. This injection of holes from the p+ collector to the n– drift region decreases the resistance of this region leading to a much lower voltage drop, like in a P-i-N rectifier, as compared to power MOSFETs. The switching speed on the other hand is lower in case of the IGBT as compared to power MOSFETs due to the recombination time of the injected minority carriers in the n– drift region. The integration of the MOS structure gives rise to a high input impedance as with MOSFETs. The injection of minority carriers into the n– drift region gives rise to its BJT-like high current handling capabilities as compared to power MOSFETs for similar blocking voltages. This in turn reduces the number of devices required for handling a given current and has a huge saving in the die area.

The slow switching speeds of the IGBT were addressed by Baliga in his paper ‘Fast Switching Insulated Gate Transistors’ in 1983, where he showed that by using a high energy electron irradiation process the lifetime of carriers in the n– drift region reduced significantly leading to higher switching speeds. But this in turn leads to an increase in the on-state voltage. These two parameters can then be optimized by the electron irradiation process itself to produce IGBTs of varying switching speeds and on-state voltage for various applications. The IGBT contains a thyristor-like NPNP structure. The latch-up of this thyristor was prevented by using the D-MOS

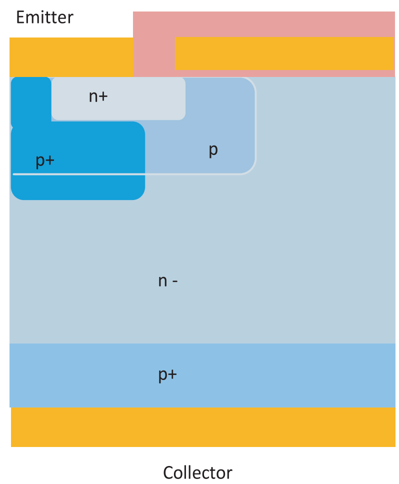

Figure 1. A schematic of the IGBT structure [1].

structure with a p+ deep diffusion layer (as shown in *Figure* 1).

Today, IGBTs are ubiquitous in their usage in the high power product sector. They are used in motor controls, heaters, ignition control systems of cars, inverters, heat pumps used in air conditioners, running compact fluorescent lamps (CFLs), etc. To quote Baliga [3], "The impact of the improved efficiency of IGBT-enabled applications has been a cumulative cost savings of $15.8 Trillion for worldwide consumers over the last 20 years. At the same time, the improved efficiency produced by the IGBT-enabled applications has produced a cumulative reduction in carbon dioxide emissions by 78 trillion pounds worldwide in the last 20 years."

Jayant Baliga

Baliga is currently a Distinguished University Professor at North Carolina State University, where he directs the Power Semiconductor Research Centre (PSRC) and serves as the PSD sub-thrust leader in the NSF-ERC 'FREEDM Systems Center'. He has received numerous awards such as being made a Coolidge Fellow at GE (GE's highest scientific honor) in 1983, IEEE Fellow in 1983, being elected to the National Academy of Engineering in 1993, named 'One of the Eight Heroes of the Semiconductor Revolution' by *Scientific American* in 1997, IEEE Lamme Medal for Invention and Development of the IGBT in 1999, inducted into the Electronic Design Engineering Hall of Fame in 2010, the 2010 National Medal of Technology and Innovation from the President – the highest honor given by the United States Government to an engineer, the 2012 North Carolina Award for Science the highest honor given by the Governor to a civilian, among many such recognitions. He has authored/edited 18 books and more than 500 papers.

References

[1] B J Baliga, The Future of Power Semiconductor Device Technology, *Proceedings of IEEE*, Vol.89, No.6, 2001.

[2] B J Baliga, Enhancement and Depletion-Mode Vertical Channel MOS Gated Thyristors, *IEEE Electronics Letters*, Vol.15, No.20, 1979.

[3] B J Baliga, *The IGBT Compendium: Applications and Social Impact.*

Box 1. Transistors – MOSFET vs BJT

A transistor is a 3 terminal device that has a 'gate' electrode that controls or 'gates' the current flowing from the input to the output terminals. It is this control that enables transistors to be used as switches, amplifiers, etc.

The two types of transistor structures most commonly used are:
1. Metal-Oxide Semiconductor Field Effect Transistor (MOSFET)
2. Bipolar Junction Transistor (BJT)

The MOSFET uses an electric field applied to induce a 'channel' of charge carriers between the input and output terminals[1] (also called source and drain terminals respectively). A typical MOSFET structure is as shown in *Figure* A. It consists of a p-type material used as a body, and two heavily doped n-type materials as the source and drain regions. This makes sure that there is no current flowing from the input to the output terminals because there are now two p-n junctions present – one between the n-type source and the p-type body and the other between the n-type drain and the p-type body. A dielectric layer, most commonly an oxide, is put above the p-type body as shown and the gate electrode is made on top of this. When a positive voltage is applied on the gate electrode it results in electrons in the p-type layer getting attracted to the body-dielectric interface, like charging a capacitor. This gives rise to a channel of electrons in the top surface of the p-type body. Since the drain and source regions are also n-type and we now have a channel of electrons (also n-type), if we apply a voltage between the input and output terminals this channel of electrons now carries a current from the input to the output terminal.

If a negative voltage or zero voltage is applied to the get terminal, there is no channel of electrons to link the drain and source, and no current flows through the device. Here only one type of charge carrier (electrons) is used to carry current and hence the MOSFET is also called a unipolar device.

The junction transistor which was a forerunner to the Bipolar Junction Transistor was the first working solid state transistor that was demonstrated in Bell Labs in the year 1947 and secured for its inventors

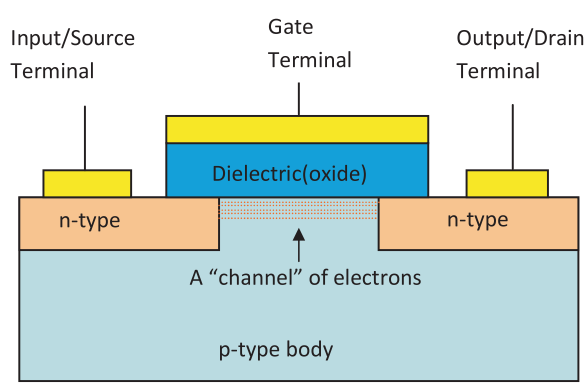

Figure A. A schematic of a MOSFET structure with drain, source and gate terminals marked. The channel of electrons is formed when a positive gate voltage is applied in this case.

[1] This device is called an n-type enhancement mode MOSFET. There are also depletion mode MOSFETs where a gate voltage needs to be applied to deplete the carriers from a pre-existing channel region. Using a p-region in place of an n-region and vice versa gives rise to a p-type device.

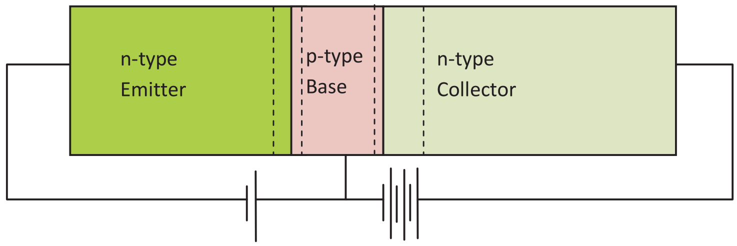

Figure B. The schematic of a BJT with the emitter-base junction forward biased and collector-base junction reverse biased. The depletion regions of both junctions are marked by dotted lines.

William Shockley, John Bardeen and Walter Brattain the 1956 Nobel Prize in Physics. It was the device that kick-started the electronic age as we now know it.

The BJT consists of two p–n junctions connected back-to-back in either an n-p-n or a p-n-p form. *Figure* B shows an n-p-n case. The current between the input terminal, also called the 'emitter', and the output terminal called the 'collector', is modulated by the gate that in this case is called the 'base' terminal. The emitter-base junction is forward biased and the collector-base junction is reverse biased (see *Figure* B) under normal operation.

When the emitter-base junction is forward biased, the electrons from the n-type emitter diffuse into the p-type base and the holes from the base diffuse into the emitter (identical to the forward biased p-n junction diode). Now, these minority carrier electrons injected into the p-type base come under the influence of the reverse field of the collector-base junction. Since the reverse bias encourages minority carrier conduction, the electrons from the emitter which are now in the base region are swept away into the collector region. It is important that most the electrons injected into the base are collected by the collector. As a result the base region is generally very thin and lightly doped.

If we supply a higher base current, more holes are injected into the base and these holes now recombine with the electrons from the emitter thus decreasing the number that reach the collector. In this way the base terminal modulates the current from the emitter to the collector. We see that both electrons and holes take part in the conduction process in this device and hence it is a 'bipolar' device.

MOSFETs generally have smaller power dissipation due to which they are the switches of choice for digital switching applications; can operate over a larger range of input signal frequencies i.e greater bandwidth than BJTs, etc. But BJTs can handle higher voltages/currents and are faster for a given bias current and provide a higher gain when used as amplifiers than MOSFETs among other advantages. Hence the choice between MOSFETs and BJTs are driven by the intended applications.

What follows are excerpts from my (HC) telephonic conversation with Prof Jayant Baliga (JB) where he holds forth on a wide range of subjects including the IGBT.

HC: You grew up in Jalahalli, Bangalore way back when Bangalore was a sleepy little city. Please share some of your childhood experiences with us. Were you interested in science and technology growing up?

JB: My father BV Baliga was appointed by the Indian government to head Bharat Electronics as Chairman and Managing Director back in the 1950s and that prompted us to move from Delhi to Jalahalli, Bangalore where the factory was located. Back then, as you pointed out, Bangalore was not the electronic city it is today. In Jalahalli there was hardly any housing or development and we were isolated in a rural area. We had a rather big house; it had about 20 rooms and a huge yard of almost 10 acres. It was a very old building which was left over from the Second World War and the yard was infested with snakes. When we played cricket in the yard, the ball would go into the bushes and you didn't know if something that jumped out was a snake or a lizard! Of course since my father was the Managing Director, I had a very good lifestyle, no shortage of any comfort.

In terms of my interest in science and technology it obviously came from the fact that my father was one of the pioneering electronics people in India. He was head of All India Radio after independence and of course BEL. He also founded and was President of the IETE–Institution of Electronics and Telecommunication Engineers. So our house was full of electronics magazines and books, probably better than most libraries I think and I used to read all of them even during high school and that made me very interested in electronics. I pestered my father to let me go to the factory in the summer holidays. So instead of playing like most kids do in the summer, I actually went and worked in the factory. So by the time I went to engineering school, I had already run lathes and milling machines and even made a transistor in the cleanroom at BEL. This was an old mesa transistor. So that was a very unusual opportunity.

HC: You obtained your Bachelor's degree from IIT-Madras in 1969 before the IITs became the brand name that they now are. What was it like?

JB: When I finished high school, I wasn't sure I would get a high enough rank to get into the IITs but of course I tried, and my rank was very good. So I asked my father what would be a good choice of discipline. I was sure he would say electrical engineering and electronics. After all, he spent most of his life doing that. But he asked me to do mechanical engineering! Growing up in India, we listen to our parents right? Of course I'm not sure that's true anymore, but we certainly did when I was growing up! So I had to choose mechanical engineering.

I went for my interview and as my father was so well known, they said to me, "I'm sure your father would want you to be an electrical engineer and that's what we are going to give you"! I was very happy and I said, "Sure, I accept that. Thank you very much" and I came out and my father asked, "Did you get mechanical engineering ?" and I said, "I'm sorry to disappoint you, but I got electrical engineering"! My father was not very disappointed and he accepted that. And that's how I ended up being an electrical engineer.

When I joined IIT it was obvious to me that I was surrounded by students who were much smarter than me. So I decided that I would just have to work harder to be successful. I was very good in my work habits. I lived pretty much a monastic existence and in the end of course I was very successful in my studies and I was pleased to graduate as the valedictorian of my batch.

HC: At RPI you had the chance to work on Indium Gallium Arsenide (InGaAs) alloys with Prof S K Gandhi using the still emergent OMVPE[1] (also called MOCVD[2]) technique. Your thesis must have been among the first in this field. How was the experience?

JB: Based on my performance at IIT, I thought I would easily get into graduate school in the US, but the IIT brand was not there back then. My philosophy was to get into the top schools or don't bother going to the US. So my applications went to Stanford, MIT, and Yale. They all gave me admission but turned me down for financial aid. You may not know this, but I actually joined the Indian Institute of Science to do my Masters' degree. However, by some luck, one of the people that I knew recommended me to Prof S K Gandhi at Rensselaer Polytechnic Institute (RPI). One of Gandhi's students who was supposed to come from China was not able to come. So he sent me a telegram, saying, "if you are interested, I'm willing to give you a research assistantship to come to RPI". So I had a very fortunate experience at the expense of some other student. But in life your fortunes are made by some amount of luck.

After my Masters' degree, Gandhi asked me to come up with some interesting PhD thesis topics. So I looked at the idea of combining Gallium Arsenide (GaAs) and Indium Arsenide (InAs) and found that if I could adjust the composition properly I could get very high mobilities which would allow me to make very high speed transistors. So I went to him and said that this sounds like an interesting thesis and of course his response was that you can't do it unless you grow the material. So I told him that to do this we need to do chloride transport; that's the standard

[1] OMVPE: Organometallic Vapour Phase Epitaxy.

[2] MOCVD: Metal Organic Chemical Vapour Deposition.
This is among the most commonly used techniques to deposit films, especially of compound semiconductor materials like Gallium Arsenide. In this technique volatile chemical species of the reactants, in the form of gases, are introduced into a reaction chamber at elevated temperatures. These then react to form the intended product species on a substrate present in the chamber.

process. He said, “I don’t have the money to build a machine for you. But I have another student who is trying to grow GaAs using a new process where you take an organometallic compound and Arsene gas and combine them.” We had seen a paper on this from Rockwell by Manasevit who had successfully done this to fabricate GaAs layers. No other materials had been grown using this process and this was the only work on OMVPE at the time.

So I had to figure out how to grow InAs and I found that there is a compound that can be used to mix with Arsene. Of course nobody had done that before and I wanted to find out some more information about it .What I found is that these metal organic compounds detonate on exposure to air! He (Gandhi) was asking me to take something that was basically an explosive and mix it with one of the most poisonous gases, Arsene. I went back to him and I said, “Is this a good idea? I could kill everybody in the building!”

I spent about a year building this reactor with the other student and we ensured there were no leaks. We spent a lot of time going about it and then it took me another year or so to figure out how to grow this material. There are so many variables when you try and grow a material and unless you obtain some optimal conditions, you will get nothing. So for a while we were not getting any films and finally I figured out the secret of how to make this grow. Once I did that, I started getting all these good films and I characterized them and there were a whole lot of pioneering papers that we published at the time. Not only that, I proposed to Gandhi that we grow oxides with this technique which nobody had done earlier. I worked on various oxides – aluminum oxide, zinc oxide, tin oxide, etc. Unfortunately all that is forgotten in the literature. When people talk about MOCVD they don’t even refer back to that work.

So I think Gandhi doesn’t get enough credit and I too don’t get enough credit for that early work. Anyway I was very excited about this process and I wanted to continue to work on it in the industry because it was much better than the other processes, but everybody (like Bell Labs and IBM) turned me down. I should tell you one more interesting fact–after I left RPI, about a year and a half later, Gandhi called me and asked me if anybody had approached me to tell them how to grow these materials. I said no and he said, “In that case if somebody approaches you, please don’t tell them because people are now writing papers that it’s not possible to grow it. I’m getting a lot of money from the government because I’m the only one who knows how to grow this!” The fact that people were writing papers saying this was not possible demonstrates how hard it was to do what we achieved. But now of course as you know, it has become the most popular technique for growing films.

HC: The IGBT has become synonymous with you and it completely revolutionized the field of power electronics. Tell us how you came to invent it.

JB: In 1974 GE was creating a new group to work on power devices in their research labs, which is quite strange because they had been manufacturing power devices for about 25 years. But the research had mostly stopped. So it was a field that all of us considered to be very mature, something that had been around for a long time and not much innovation was being done. But what GE found was that companies like Siemens were making progress in thyristors and taking the market away from them.

So they put together a new group and hired 3 of us – myself, Adler and Temple. That nucleus started the GE power research activity and fortunately we made many innovations including my invention and development of the IGBT. We all went on to receive quite a lot of recognition for our work.

Before doing the IGBT I worked for about 5 years on other things and one of them was called the Field Control Diode. That work came about because a famous professor from Japan, Prof. Nishizawa (there is an IEEE medal now named in his honor) came up with the SIT, the static induction transistor and we thought we better take a hard look at it because it might be an important innovation and we don't want to be blindsided by something new. The basic problem with the SIT was that it is a 'normally on' device[3] (a depletion mode device) and all the power electronics applications people I spoke to said we cannot run our circuits on such a device and we need an enhancement mode device. This was because when you start the system, you got 'shoot through currents'[4] with depletion mode devices. So when I was trying to make that device into an enhancement mode device, I got this idea of merging the MOS structure together with the bipolar structure to actually create this whole series of devices. But the most interesting among them was the IGBT.

HC: The IGBT was one of those very few inventions that was put into mainstream production almost immediately while many, many innovations exist just on paper. How did that come about?

JB: Our mission at GE was not just innovation on paper. We wanted to do something that GE could use. Around the time that all this happened, coincidentally, the vice president of one of the divisions that wanted to build heat pump drives at GE came to the research labs and he said, "I'm trying to do this using bipolar transistors and it's getting very, very hard to make manufacturable

[3] A normally on device is a device that needs an external signal to be turned off. Normally off devices need external signals to turn them on. Normally on devices use up a lot more power than normally off devices.

[4] Shoot through currents occur when the positive and the negative side of the power supply are shorted briefly while the transistor elements in the circuit are being switched from one state to the other.

power electronics because the transistors need costly snubber circuits, expensive and bulky base drive circuits, the cost is not contained, the manufacturing is too complex...”

So he challenged us to come up with something better and within a month I actually came up with the IGBT. As soon as I created the IGBT we realized that it had a lot of nice favorable characteristics to project. We realized we could use this device not just for the heat pump drives but for lighting and many other applications in GE.

When this vice president came back and I presented this idea to him, he got super excited and said, “This has saved my business. I need to get you all the support to make this commercially viable.” And without my knowledge, he went straight to the Chairman of GE, Jack Welch, and briefed him about it and he convinced Jack Welch that this is going to have a huge impact across GE . So Jack Welch called the head of our research lab and said, “I’m going to come down in 2 weeks and this is such a big innovation that I need to hear about this.” Welch, of course had this reputation of being Neutron Jack, which meant that if he didn’t like what he heard he would leave the building behind and dismiss everybody in it just like when a neutron bomb goes off and only the people are gone but the buildings remain!

So careers were at stake and I had the responsibility to convince Jack Welch that this was a sound idea and that I could make it and be successful. I gave a presentation and fortunately he was very impressed and one of the things he said was: “This is so important that we want to capitalise on it in all our divisions like drives, medical, lighting, etc., and we don’t want our competitors to get this device. We don’t want this to be published or talked about.”

So I had to hold back announcing the IGBT for quite a while – a year and a half to 2 years and this is not good for a scientist if you want to get credit for something! So that was tough. But of course within GE, it was highly recognized and I was made Coolidge Fellow (the highest scientific rank at GE) at the age of 35 when most Coolidge Fellows were in their late 50s or 60s. So they recognized that what I had done was extremely significant.

I was then given the resources to develop the IGBT. The normal course of events in developing an innovation in a research lab is to create a process, build the innovation in the lab, test it out and if it looks good, then you work on transferring it out to a product division’s manufacturing line. But the big hurdle when you do this is that the product division may not have the equipment and the processes. It takes millions of dollars to set up the production line and it takes a lot of time and effort. So I said that I can make this innovation directly on our manufacturing line in California where we were making our power MOSFET products and I did not even try to make this in my research lab.

I designed the mask set and the process sequence and then went up to California to convince them that with my mask set, and one additional process step, they can make my device. Usually they would not have allowed me there because they were running product in the lines and wouldn't want that to be disturbed. But because I said, "Do you want to hear from Jack Welch or are you going to let me do it?" and they said, "No, no we'll do it!" Within six months, I had the device coming out of the product line which is unheard of for a new innovation and all these products were uniform in performance with high yield. I then developed a process to control the switching speed so I could tailor the IGBT characteristics for lots of different applications.

The IGBT got distributed to many power electronics engineers at GE and they all ran wild with it and started running space heaters, toaster ovens, steam irons and also fluorescent lamps. Now you should know that everybody was not convinced this is going to work. My colleague Temple had come up with a device called the MOS Controlled Thyristor (MCT) and convinced a lot of people that that is much superior to the IGBT. But you don't see the MCT in the market today. It is more of a thyristor whereas the IGBT is a true transistor. I tried to convince him of this but he would not listen. So he convinced a lot of people that the IGBT was not a good idea or that it would be a temporary solution. If I had given up then, I wouldn't be where I am today. Fortunately that did not happen and everything worked under my supervision and in 2 years we announced our IGBT product.

HC: The IGBT is used extensively in making efficient power switches and systems saving customers millions of dollars and making the world a greener place. How does this make you feel?

JB: That's one of the highlights of my career I think. Innovation in power devices has always been driven by reducing power dissipation in the system. If you have to propose a new power device you have to prove that it would have less power dissipation than existing devices and it could be controlled easily and that the cost of the final product would be low. That all came together with the IGBT. It had all the right things in terms of low on state losses, low switching losses, easy manufacturability, good safe-operating-area[5], and ruggedness. Of course in the market it was all driven by cost more than anything else. Fortunately the chip size of the IGBT was so much smaller than that of power MOSFETs, it was way ahead in terms of cost. It won in every way and people adopted it. But the energy savings were never given that much importance in the 80s and even the 90s.

It's only recently that the world has suddenly become aware that we have a finite source of

[5] Safe operating area denotes the current and voltage conditions under which the device can operate without damage.

energy that is mostly at the detriment of the environment because of all the carbon dioxide emissions from the coal- and the gas-fired electricity generating power plants. Also the large amount of gasoline consumption produces a huge amount of carbon dioxide. I have, since about 2000, asked myself – ok this has had tremendous impact in terms of people benefiting from air conditioning, refrigeration and so on, but what is the impact on the environment?

So I started analyzing it and even to my surprise I found that the benefits have been just enormous. The IGBT is used to make electronic ignition systems for gasoline powered cars. The electronic ignition system replaced the old Kettering system based on mechanical parts. The old system could not be tuned very well and the mechanical parts would start drifting which produced poor fuel efficiency. By going to the electronic system they could very precisely control the spark using the IGBT and they could actually use a leaner fuel mixture as a consequence. There are documented studies that show that fuel efficiency in automobiles improved by at least 10% and with the huge amount of gasoline being consumed, 10% provided enormous savings. When I added that, I was shocked to find the electronic ignition has produced savings that adds up to over a trillion gallons of gasoline not being consumed. That's just a huge amount of savings to consumers and reduction of carbon dioxide emission.

The other place it had a huge impact was motor control because two-thirds of the electricity in the world is used for motors. Going from the old system where we used dampers to control them to adjustable speed drives, you can get an efficiency enhancement of at least 40%. So if you take two-thirds of all the electrical energy being produced and factor in the energy savings, it adds up to a huge amount – 42,000 TWh of electrical energy savings in the world.

Twenty percent of the electricity in the world is used for lighting. IGBTs allowed making the electronic ballast[6] for CFLs fit in the base making them compatible with existing screw-in sockets for incandescent bulbs. Replacing incandescent bulbs with CFLs reduces energy consumption by 75%. This has saved consumers 9,000 Terra-Watt-hours of electricity. The IGBT was used to develop the electronic ignition system for automobiles in 1989. This has reduced gasoline consumption by 10 percent saving over 1 trillion gallons of gasoline saving consumers over $ 5 trillion.

All of this results in cost savings for consumers of over 15 trillion dollars which is just amazing. It has also reduced carbon dioxide emissions by over 75 trillion pounds which is more than what the entire earth produces from all sources in a year!

So how does it make me feel? It makes me feel wonderful! I never dreamt that something I

[6] Electronic ballasts are solid state devices that limit currents flowing through a circuit.

developed would have so much impact in creating a sustainable society.

HC: Baliga's 'figure of merit' has to be among the most quoted numerical values used to quantitatively compare semiconductor materials. Could you explain the rationale behind developing these figures? What kind of impact do you think your work on wide bandgap semiconductors have had?

JB: The equation that I derived was back in the 1979 time frame. At that time everybody was making power devices out of silicon and were quite happy doing so. It seemed like there was plenty of room to make improvements like better MOSFETs or IGBTs so nobody used to worry about what would happen if you change the material. But out of pure intellectual curiosity, I asked myself that question one day and from first principles I derived a very simple equation. Based on that equation I got the relationship that is now named after me, called Baliga's figure of merit. The equation predicted that GaAs is 13 times better than silicon. Not 13% but 13 times better! GE gave me a group of 15 people to try and prove that. So I was responsible for simultaneously trying to develop an IGBT product and a GaAs power product. We were successful in making the first high voltage GaAs Schottky rectifier which became a product. This work certainly kept me very busy!

When I put the available numbers for Silicon Carbide (SiC) into my equation, I found that I could improve things by 200x; this was something worth pursuing. Usually in industry if you get a 2x improvement it is considered significant enough to pursue but I was predicting 13x and 200x and these are game changing, revolutionary innovations.

When I came to NCSU, I started working with Prof Davis in the Materials Science Department to make the first silicon carbide devices because he was growing 3C SiC on Silicon. But the quality was just terrible to make devices and we couldn't get anything from them. Fortunately Davis's students founded a spin-off company from NCSU called CREE which started making 6H SiC material available. I was able to purchase that material and make the first SiC power devices using it.

I always believed that my work should be impactful in the main stream commercial domain. I don't like to work on very niche products; so what I was trying to prove to people is that what I had made could be used for a lot of applications like in inverters for motor drives for example. I had seen statements from CREE saying they were pursuing only the high temperature and radiation resistant applications. But once I proved that you could make an extremely high performance device for commercial applications, it completely changed the thinking in the industry as well as by the funding agencies. So suddenly a huge number of people began working on solving the SiC processing problems and that made this material successful. So although I can claim the impetus for doing it and for contributing many innovative ideas, of course I can't claim all the success for it.

By 2010 there were 4 companies marketing Schottky diodes and MOSFET based on SiC. The Schottky diode they are manufacturing is called the Junction Barrier Schottky (JBS) diode, based on a concept I proposed for silicon devices in the 1980s without which the SiC device won't work very well. So I think there's no longer any doubt that they can be commercialized. The question is how much of a market penetration they obtain and that depends on the cost. So people are working hard on it. The wafer size is a big determinant of the cost and they have recently increased the wafer size to 4" if not bigger and completely got rid of the defects such as micro pipes and reduced the defect densities. So it's a matter of time I think before it starts having more and more market penetration. But of course most power electronic applications are very cost sensitive so it's not easy to make the transition. You have to justify it based on the lifecycle of the product, the efficiencies you gain and the energy savings and these actually can make it pretty good. So I think they're having some luck doing that in the case of inverters. If you go back to the papers I authored (based on my thesis) some time ago, you will see that we replace bipolar silicon devices like the IGBT (my own baby) with unipolar SiC devices. We replace silicon power rectifiers, which have terrible switching behavior, with SiC Schottky rectifiers and replace IGBTs with SiC MOSFETs. That's how I was positioning this material and that's how the industry has gone also. In recent years we are moving to extremely high voltage applications–utility scale applications for which we are envisioning doing some bipolar devices like IGBTs on SiC.

HC:. Do you think that the superior properties of wide bandgap materials for power electronics make their device structures and thus their subsequent manufacturing simpler or is this more than offset by difficulties in fabricating these materials to begin with?

JB: In terms of structural simplicity the answer is actually no. Some of the early work on SiC was misguided in the sense that people blindly used the silicon structure to make SiC devices and they failed to take note of the high electric field that can exist in the material. This causes problems with dielectrics and in other places that I have pointed out and have created innovative variations that solve these problems. And with these solutions people are now having good success I think. The JBS structure for example is used to reduce the electric field at the Schottky contact without which the leakages would be huge in these devices.

Then for MOSFETs I have proposed what we call the accumulation channel field effect transistors (ACCUFETs) where we use shielding of the gate oxide to prevent its rupture and reliability problems. These ideas are now utilized to make products. So in terms of structure they aren't simple, but not too complex and the process for fabrication is not much worse than silicon itself except that you need some very high temperature steps with special equipment. The main problem is and has been the starting material. Without solving that problem no matter how much you innovate on the device structural side, you won't get too far.

HC: Could you tell us briefly about the current research being undertaken by your group?

JB: My current research is directed more to utility applications We are developing a solid state transformer which is a very smart transformer. It can do power factor correction, it has bi-directional power flow, and is very small in size and weight compared with the conventional transformer. On the primary side we need 15-kV SiC devices and on the secondary side we need devices that are much better than silicon devices so we're doing that with materials like Gallium Nitride based High Electron Mobility Transistors (HEMTs). This is what I am now working on.

HC: As an entrepreneur you have founded 3 companies. Please tell us something about these companies and your involvement in them. What does it take to be a successful entrepreneur especially in the highly competitive semiconductor industry?

JB: I had a very successful research program at NCSU and I had an industrial consortium (PSRC) that I started in 1991 with membership of over 20 companies and they gave me the financial resources to hire a lot of students. We came up with lots of ideas and at last count I ended up with 47 patents based on the PSRC work. Patents are of little value unless you transform them into products and that is not an easy process. A lot of things have to come together to make a product. So once I had all these patents, I had some venture capitalists come in 2000 asking me if I would be interested in starting a company based on my work. The first company I started was based on a licensing model where I was the only employee. I partnered with several companies who licensed the technology from us and that was very successful. The device we made was called the Trench MOS Barrier Schottky (TMBS) rectifier and it was commercialized by a company called Vishay Siliconix in 2000. A year ago, Vishay announced that this has been the most successful rectifier product in the last twenty years. So that's a good feeling. However it pales in comparison with the IGBT, so nobody talks about it!

The VCs (venture capitalist) also wanted to start a company where we could build the product and sell it. So I looked around and I found that in RF base stations, people are using lateral diffused MOSFETs (LD-MOSFETs) and they have all kinds of non linearity problems. They were spending $1000 buying the Motorola transistors, and another $2000 to remove the nonlinearity. I thought maybe I could come up with some way of getting rid of this nonlinearity. That would be a really unique and phenomenal product. So I sat down and worked out some new physics and I created what are called as super linear (SL) MOSFETs. My first reaction when I derived that new physics was that, after 50 years of work on MOSFETs by thousands of people, somebody must have come up with this! But I couldn't find it anywhere. Not in any books nor publications. So I filed for a patent and it was issued to me. So, I was very fortunate to discover another very fundamental idea. Next, I had to create practical structures that exhibit the correct physics I had discovered. There's no use having the physics if you can't build the structure that makes the physics work. But I was fortunate to be able to come up with how the structure should look and the processes to make it. And with that much knowledge, never having made the device I told the VCs if we are successful in doing this we can corner the whole wireless base station market which is about a billion dollars a year. So they got very excited and I founded a company called Silicon Wireless. After that they asked me how we would go about making it? And I said, "Well we have a big problem. There is no facility in the US. They are all in Taiwan and other places. Also I need to have a facility that we could collaborate with to make the structures." I suggested we approach Fairchild Semiconductor, one of my sponsors and see if we could partner with them. With one power point presentation, they gave me 10 million dollars and that was pretty impressive. Using that money we were then able to start hiring people. They also allowed me to use their manufacturing line in Salt Lake City, Utah. I had a dozen people working for me over there and within one year we had created the super linear transistor which was amazing. That was fortunate and we introduced the product in the market in 2002.

Then I asked myself if I can do something in terms of transistors for powering microprocessors for use in the voltage regulator modules (VRM) which are used to convert the power from the 19V back-plane power supply to the 1 volt required to run the processor. So I developed a chipset for this application in a company called Silicon Semiconductor that I founded. That was also very successful and we found ourselves years ahead of the rest of the world meaning big companies like Siliconix, Hitachi and Philips.

After evaluating our products, Intel gave us a design win for providing power to their microprocessors. Since they have 80% of the microprocessor market we were very pleased in getting them to use our product. This product is very successful. We licensed it to several companies and it is now available in the market. And that was my successful diversion into entrepreneurship.

What you have to do when you innovate is to create something that's so outstanding that your customers would feel attracted enough that they can tolerate the risk of taking a product coming from a small enterprise. If you are a startup company you are a very small uncertain enterprise. You may go belly up and if companies design their product based on your product, they jeopardize their product line. So you have to show them that you are solving a huge pain for them. This was true in the base station case for example. With the super linear product, my customers could save $2000 out of $3000. So that's a good business proposition for them to switch from Motorola to a small company. As for the VRMs, they were having huge problems with heat inside servers and laptops so reducing the heat by 30–40% was the big deal.

This then is what you need – some compelling reason that solves a problem the customers have and it has to be done with a technology that they feel comfortable with. I was doing everything using silicon in a mainstream fab so that there was no exotic material with unknown problems. That has been my approach to successful innovation in a start-up company.

HC: You are a prolific author, having written and edited 18 books and more than 500 papers.

JB: I used to joke when I first came to NCSU that at GE I had to write papers on weekends and evenings because that was not my job and I had to write papers whenever I could because I felt compelled to do so. But by the time I came to NCSU, I had already written about 150 papers, and several books that made it easier for me to be an academic. But once you are at a university, your business is writing papers and books and so I accomplished that. Now of course when you are writing papers its generally done with students and it's always fun to see a young student learn the ropes and become more and more proficient. Unfortunately just as they get really good, we have to graduate them! This is the worst possible way to do a business – to get rid of your best people but that's the way it works and then you start again! But it's always fun to work with young people. What I've been doing in the last few years since 2005 is to write a whole series of books and the idea was to take all this knowledge I have gathered over the years and put it down in the form of books that benefit students and maybe even people doing research in the industry. There is a tendency for people to re-discover old things because they don't have the experience and they have not seen it before.

So I've been trying to do this in more of a tutorial format. I wrote this 1000-page textbook *Fundamentals of Power Semiconductor Devices* that came out in 2008. In fact it became a best seller on Amazon in the field of microelectronics which surprised me because it was such a specialized book. That feels good. It takes a lot of intense long term work to write a book and there is no money in it. So it's more the satisfaction of sharing knowledge with other people.

HC: You received the National Medal of Technology and Innovation, the highest honor granted to an engineer in the US, in 2010 from President Obama; one more recognition in a series of awards that have come your way. How was the experience?

JB: That is just an amazing thing. You never dream of such a thing. It's wonderful in many ways. The most important one probably is that it gives the limelight to the IGBT and its impact on society. The IGBT is an embedded technology in the sense that consumers don't really see it. I mean, they use a CFL, but they don't know the electronics inside. They use cars but they don't know what's in the ignition system. They run air conditioners but don't see the electronics running the motor. So it's all hidden and gives all these benefits. So it's nice to get this recognition.

Jayant Baliga receiving the National Medal of Technology and Innovation from Barack Obama.

Of course personally, I'd say it's a great vindication because I couldn't publish the work on the IGBT for several years because of Jack Welch putting an embargo and what happened is, at the time I was developing it there were all these skeptics who said it could not be done, that it would latch up and burn and destroy itself and all that stuff. But as soon as I was successful they all started claiming they were the ones who came up with the idea. So this now gives the stamp of approval to that from the President himself that I'm the one who is acknowledged having developed it. So that felt good.

Then of course there is the whole ceremonial aspect of it. You have to go to the White House and meet the President and this is an award that he personally puts around your neck. It's quite an amazing thing to be feted by the President so I think I'll cherish that forever. Of course I received it with my family there to enjoy that moment. After the ceremony they ask the laureates to go to the blue room and the President had a photograph taken with each of us. After 2 months the White House sent it to me and he has autographed it saying, "Congratulations" So I have a photograph on my desk with the President that has been signed by him!

HC: What is your research philosophy? What advice would you give to young researchers the world over?

JB: What I tell young people whenever I get the chance to speak to them is that ,whatever you want to do, you should feel passionate about it. If you're passionate about it, really excited about it, you will be in a position to make the best contribution. It doesn't matter what exactly it is. It could be research or something else but you should feel very passionate about it and that will make you enjoy every moment. So for me, whenever I think of something I want to do I really find myself being passionate about it. For example when I'm writing books I feel passionate about writing the book and I try to do my best and make it as thorough and approachable for people reading it.

So when doing research, come up with an idea that would not just be an idea that you can write a paper, but might come in handy for use by people in the future. That gives a lot of satisfaction – the fact that whatever I've done has impacted society. So I guess that's the other aspect of doing something that you feel has some end impact. But having the impact that the IGBT has had is a rarity. It's just a matter of circumstances and some amount of luck that it happened. I'm grateful for that and the fact that I could add some amount of value to society.

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