Proving They Can Take the Heat

by Jo Ann McDonald, US Correspondent

A technology update on the progress and promises of high temperature electronics, highlighting unprecedented international cooperation, and featuring two major U.S. catalyst agencies, NASA's Lewis Research Center and the US Air Force's Wright Laboratory.

Excellent work is being done on high temperature electronics (HTE) in a growing number of international laboratories, especially on wide bandgap (WBG) materials, and more specifically, silicon carbide (SiC). Never before has the semiconductor industry experienced such open cooperation and rapid communication between researchers in America, Eastern and Western Europe, and Asia. Each year, investigators have become more closely knit through key meetings and the HTE community is now linked through an entire online network, HITEN, <http://www.hiten.com> which is dedicated to keeping international HTE researchers, developers, and systems designers in virtual touch on a daily basis.

No matter how exciting the field, of the many commonalities among these researchers, adequate R&D funding remains everyone's biggest hurdle. Due largely to government/industry dual use philosophies (where mil/aero development mirrors commercial to more rapidly produce the volumes necessary to sustain business interests), industry is emerging as the commercial driver. International teaming of industry, government, and universities is stronger and more effective than ever before.

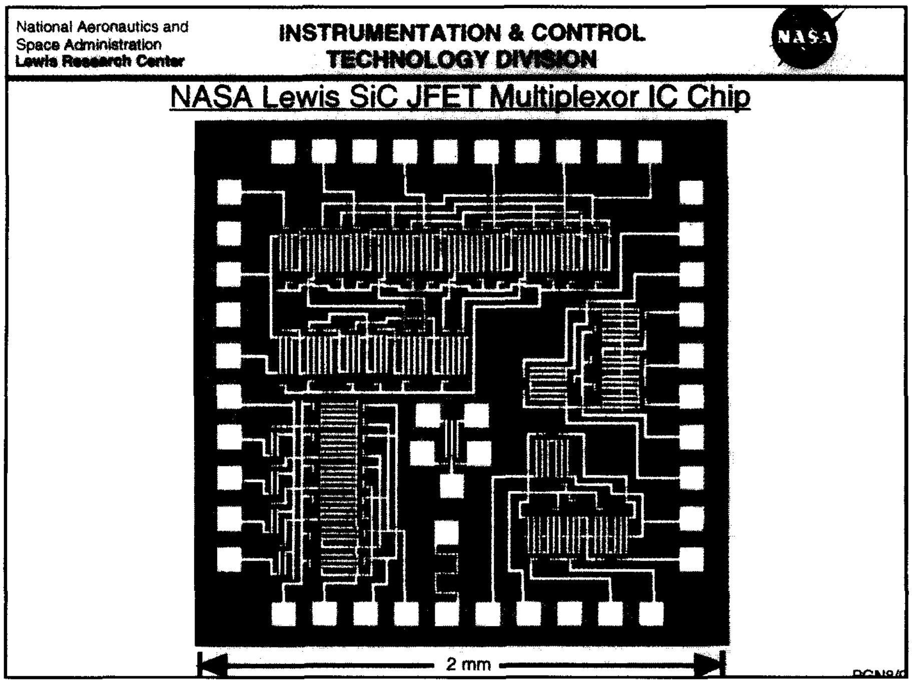
Hot topic within the applications sector HTE development is being driven by industry's need to improve efficiency and reduce the production costs and physical weight of their end systems. It has been effectively proven that the overall cost of electronics in automobiles and airplanes can be remarkably reduced if electronic devices can function directly in the hot areas of, for example, engines of automobiles and airplanes, or down the well holes in petroleum engineering.

NASA's High Speed Civil Transport: Beyond the Concorde .... and affordable! NASA's High Speed Civil Transport would be an excellent application for SiC-based technology.

At the speed of heat

By way of illustration, the U.S. Air Force has estimated that advanced electronic flight control, stores management, power management and distribution, and propulsion control systems implemented on an F-16 fighter jet would allow the aircraft to shed as much as 800 pounds of valuable weight by eliminating mechanical, hydraulic, and pneumatic systems presently in use, as well as their maintenance support requirements.

In working within new scenarios for NASA's proposed High Speed Civil Transport, NASA Lewis Research Center engineers estimate that an additional 600 pounds could be saved in the aircraft by using a distributed-architecture system (based on SiC device technology), thus eliminating 90% of the present cabling, connectors, shielding, and environmental control systems (ECS) required by current Si-based centralized-architecture systems. Ignoring the elevated engine compartment temperatures, Si-based electronics with a MIL-STD maximum temperature limit of 125C (typically derated to 100C to ensure reliability) cannot reliably operate anywhere in a supersonic airframe in the absence of active cooling



systems, which reintroduce much of the weight penalty saved by distributed architecture. The most attractive solution would be to distribute uncooled HTE systems directly into these hot areas.

How Hot?

The NASA Lewis Research Center's (NASA-LeRC) High Temperature Integrated Electronics and Sensors (HTIES) team is developing SiC as a material for advanced semiconductor electronic device applications that can operate in very hostile environments, which NASA defines as 600°C, or 1112°F. As Phil Neudeck of the HTIES team puts it prominently on , "That's glowing red hot! Silicon simply can't function under such conditions".

Phil Neudeck (see photo) is a NASA-LeRC research engineer and considered a key US catalysts and especially reliable source regarding current, overall, industry progress. As such he is often asked to present industry overviews at meetings. It is with much appreciation that this reporter relied heavily on him for this article. After we both actively participated in the Third International High Temperature Electronics Conference (HiTEC) in Albuquerque, New Mexico, this June and having assessed progress and performance reports since then, Phil shared the following summary:

"In my personal opinion, Silicon-on-Insulator (SOI) technology clearly fits the bill for non-power applications below 300°C. It's available near-term to high levels of integration, and pretty much ready for use in a variety of low-power applications. But because SOI is incompatible with vertical geometries employed in high-power semiconductor switches, it appears unsuitable for larger power conditioning and motor control systems.

"Therefore, the combination of high power with high temperature is where wide bandgap semiconductors make sense, along with low-power electronics for T > 300°C.

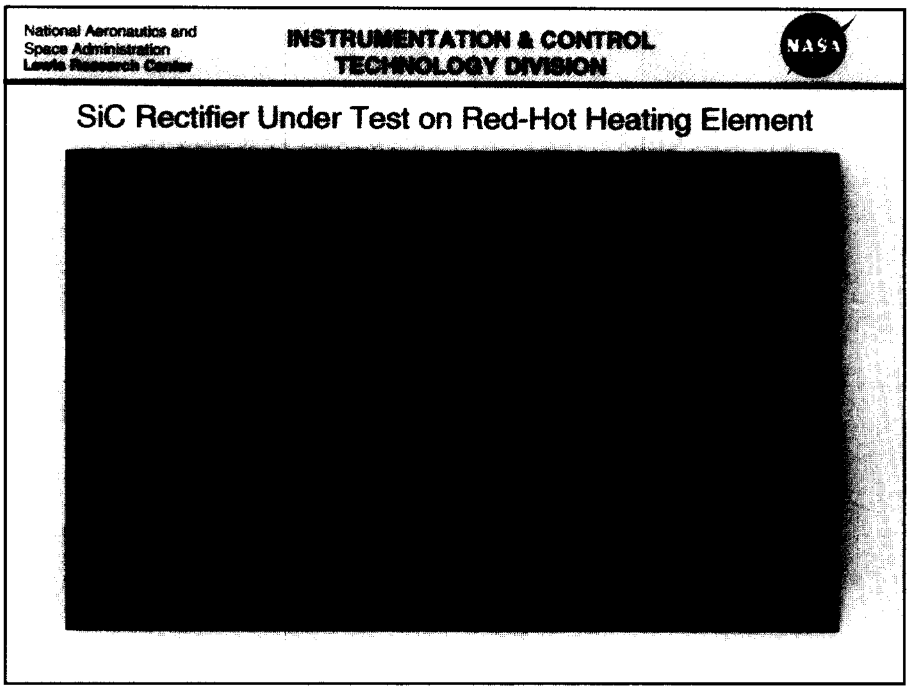
"The III-Nitrides are already impacting optoelectronics. I'm enjoying the competition that's shaping up between SiC and the III-Nitrides in the high-temperature and high-power electronics fields. Its difficult right now for me to ascertain which technology will prevail in the T > 300C low-power HTE market as well as the microwave power market. The bandgap engineering available to the III-Nitrides is an advantage, but it seems to me... right now, that the nitrides have some more difficult thermal management, material quality, and material doping issues to deal with than SiC. I think its going to be tougher for the nitrides to capture the high-power switch market, where vertical device geometries and thermal management issues play towards 4H-SiC's strengths.

USAF "MORE ELECTRIC AIRCRAFT" INITIATIVE

Although there are many issues regarding material yet to be worked through, results of prototype WBG devices to date are capturing the attention–and the imagination–of systems designers of next generation autos, aircraft, spacecraft, power, communications and radar sectors. In many cases, applications go well beyond upgrades and replacements of existing analog methods and shielded or remoted silicon devices. The U.S. Air Force's More Electric Aircraft (MEA) initiative is underway in various AF sectors.

Wright Laboratory's Aerospace Power Division (WPAFB, Ohio), for example, is studying the feasibility of using electrical power to drive aircraft subsystems which have historically been driven by hydraulic, pneumatic, and mechanical systems. Hydraulically driven flight control actuators, engine gearbox driven fuel pumps, and air driven environmental control systems would be powered by electric motors. According to Major Michael A. Marciniak, Deputy Division Chief of the Aerospace Power Division, "The MEA concept, which removes the hydraulic subsystems along with their leaky and sometimes toxic fluids, lubricants and cleaning solutions also results in the elimination of required maintenance equipment. This, of course, means big dollar savings because you save in manpower and transport sorties associated with the maintenance, aside from the performance and weight benefits of an electrical subsystem itself." WBG semiconducting materials, are being designed into these high temp, high power systems. The resulting weight savings and performance benefits of replacing hydraulic and pneumatic systems with electronic ones can be multiplied by distributing heat resistant SiC-based electronic systems directly into hot areas, thereby reducing or eliminating the need for ECS to cool electronic compartments to the current MIL STD upper limit of 125°C.

An Air Force ground-based demonstration program titled the Power Management and Distribution for a More Electric Aircraft (MADMEL) will test a hybrid power system's ability to supply power to a variety of simulated MEA loads. Si-based devices will be employed in MADMEL's baseline design which will include ECS cooling to maintain Si junctions below 90°C to ensure reliability. Future MADMEL designs hope to incorporate HTE devices thereby reducing or eliminating the need for ECS cooling.



"It's difficult for me personally to envision where diamond is going to fit into the semiconductor device picture, given the technological lead that SiC and III-N's have, and the possibility that they [SiC and III-Ns] may have filled many applications niches that diamond was originally targeted for. My personal opinions aside, the market and mother nature will sort all of these issues out in time. In the end, the fittest technology for each specific application in terms of cost and performance will win out eventually, perhaps leaving sufficient markets for all the wide bandgaps.

"The largest market for wide bandgap semiconductors will likely lie in room-temperature-ambient applications, keeping in mind that internal junction temperatures could be quite high in some of these applications. If the SiC community sufficiently improves the crystal growth to where large-area SiC power devices become feasible, this could rapidly become the most lucrative application for SiC. As Jay Baliga's studies (at NCSU) have suggested, the performance advantages of SiC over silicon, in terms of reduced parasitics, faster switching speed, and reduced thermal management, could perhaps displace billions of dollars of silicon-based solid-state power business. But SiC micropipe and dislocation densities still need to come down by at least an order of magnitude or two on mass-produced SiC wafers before this can start to happen."

NASA-LeRC and ARL Discover positive temperature coefficient in high quality 4H-SiC pn junctions

Representative of the critical effort being undertaken by NASA-LeRC in regard to tackling those fundamental material problems, in a late paper given this summer at the 54th IEEE Device Research Conference in Santa Barbara, CA, Phil Neudeck and Dave Larkin of NASA-LeRC and Chris Fazi of the Army Research Lab reported the first clear demonstration of positive temperature coefficient breakdown behavior in 4H SiC. According to Phil, "the work demonstrates that robust 4H SiC power devices with the same (if not better) high breakdown reliability of modern silicon power devices should be achievable after SiC technology maturation greatly reduces material defects such as micropipes, dislocations, and deep levels."

Prior to achieving this important milestone, experimental 4H and 6H SiC pn junction rectifiers have exhibited negative temperature coefficient of breakdown voltage, a property that leads to unacceptably low power device reliability. Without the assurance of high reliability offered by positive temperature coefficient breakdown behaviour, SiC power device commercialization would be extremely difficult. Within the SiC research community, this has been considered a "hot potato" issue because the inability of SiC to get reliable positive temperature coefficient of breakdown voltage has been one of the fundamental barriers that had to be overcome before SiC power devices could be taken as a serious, viable option to silicon power devices in most applications.

"Considering the importance of stable breakdown properties to power device reliability, it was crucial to ascertain whether unstable breakdown is a fundamental property of SiC that would not be solved by crystal growth improvements. By studying higher quality junctions with minimum crystal imperfections, we have been observing much better breakdown properties in the case of 4H-SiC," explains Phil. While the work represents an important "existence proof" that reliably stable breakdown behavior is realizable in 4H-SiC, he cautions that, "we're just turning the corner on this issue.

Much important work remains to be done in quantifying and understanding the true nature of the SiC breakdown process."

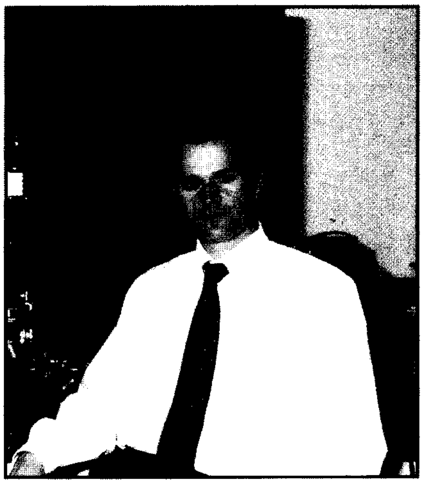
Leadership in the US HTE community

There are many centers of excellence within the growing HTE community. Within the U.S. government, DARPA, the Office of Naval Research (ONR) and Naval Research Lab (NRL) the Ballistic Missile Defense Organization (BMDO) and Army Research Lab (ARL) have been especially stanch supporters over the years. In this HTE update, I've highlighted two additional US government research laboratories because they have been extraordinarily helpful and cooperative, and because their efforts stand out as exemplary cases as to why industry and government must continue to invest in the development of high temperature electronics. Those two centers are the NASA/Lewis Research Center in Cleveland, Ohio, and the U.S. Air Force's Wright Laboratory at Wright Patterson AFB, Ohio.

The NASA/Lewis Research Center's SiC team always tells it like it is..." and "ought to be" (as one can see from the above, from Phil Neudeck), and

NASA LEWIS' CATALYST ROLE IN HTE DEVELOPMENT

The NASA Lewis Research Center was one of the first U.S. entities to recognize the importance of wide-bandgap electronics when it re-initiated its SiC research program in the early 1980's. "Our early success in obtaining large-area 3C-SiC epilayers helped spark renewed interest in silicon carbide. Since then, NASA Lewis has been one of the leading technology conduits for SiC research, attracting new players to the field in addition to providing key technology information to existing programs," says Phil Neudeck, research electronics engineer, whose respected work and evaluations are often credited in the literature. As one who keeps closely up to date on developments, Phil often finds himself thrust in the catalyst role as industry spokesperson. The primary goal of the NASA Lewis program throughout has been to develop the base technology of silicon carbide electronics and sensors for high temperature and high power aerospace environments. "However, we are excited about the tremendous benefits SiC electronics technology offers to non-aerospace applications, particularly in power distribution, ground transportation, and communications systems," says Phil. NASA Lewis works with other government agencies to jointly further U.S. SiC technology development while avoiding duplicative research. "We work particularly closely with our Ohio cousins at the USAF Wright Laboratory, who are pursuing SiC for the same aerospace reasons that we are. But we each emphasize our own pieces of the SiC technology puzzle, which when solved can be joined to enable SiC electronics useful to commercial and governmental aerospace interests. The aerospace interest in SiC is very broad-based in government and industry, ranging from subsonic and supersonic aircraft to launch vehicles and satellites, all the way to interplanetary space probes."



Phil Neudeck, NASA, Lewis.

The SiC program at NASA Lewis is somewhat different from other government labs in that the majority of the research is done internally. Rather than funding large outside research efforts, NASA Lewis' program primarily focuses on partnering their internal epitaxial growth and device research with universities and U.S. industries. "This approach allows us to attack both near term obstacles as well as novel high-risk/high-payoff innovations," says Phil. "Our hands-on SiC research gives us technological insights and expertise that are unique within the U.S. Government."

The direct URL to NASA-LeRC's website is: http://www.lerc.nasa.gov/WWW/SiC

"NASA-LeRC" can always be depended on to succinctly convey the basic fundamental problems yet to overcome. "Wright Lab" is a focal point for similar reasons, and also because they are a primary administering agency for key WBG programs in the US, and their More Electric Aircraft (MEA) concept (see sidebar on Wright LANS) appears to be the most likely vehicle for initial insertions of SiC Schottky diodes, a important building block for future successful HTE systems. Both laboratories house some of the leading names in the field. Among those who have continually helped this author better understand the real work involved are: Phil Neudeck, Tony Powell and Dave Larkin at LeRC; Bill Mitchel, Jim Scolfield and Matt Roth at Wright, and especially two people at Wright that keep the fires lit under the various HTE programs: Major Mike Marciniak, who is now Deputy Division Chief of the Aerospace Power Division and Laura Rea, primary point of contact for HTE Materials at the Materials Directorate. Together, these fine people, and their colleagues and counterparts around the world, are proving how and why HTE can take the heat, and why HTE development is in everyone's vital interest.

An especially noteworthy program from Wright Lab, for example, has been to get the major US has been to get the major US industrial partners to rally around a common cause, tackling some of those shared fundamental problems in SiC substrate development. The SiC Consortium, managed by Wright Laboratory Materials Directorate, is now in full swing. According Laura Rea, point of contact for the Consortium, three research projects are well underway at universities, with the integrated participation of the Consortium's industrial partners: ATMI, Cree Research and Northrop Grumman.

"The first effort is at Georgia Tech, under Professor Ajeet Rohatgi, to characterize defects and minority carrier lifetime in SiC. The second effort at Purdue, led by Professor Jim Cooper, is to investigate the high field electron transport in 6H and 4H SiC. The third project is at Case

"Western Reserve University under Professor Pirouz, and will study the temperature and doping dependence of the critical resolved shear stress of SiC," says Laura. The SiC Consortium effort is complimentary to other materials research efforts sponsored by Wright Lab and DARPA. "We have our core research effort, which includes in-house materials characterization, as well as our contractual development efforts. In addition, we manage three significant SiC materials programs for DARPA."

For more information about Wright Lab's Materials Directorate, their direct URL code on the web is: http://picard.ml.wpafb.af.mil/kensky/MLO-PO/docs/mlpo.html

The international corps of wide bandgap researchers is, indeed, a tight knit group, despite the fact that many of the technologies within their realm are quickly entering the commercial sector. Group III nitrides and the various substrates that support it, such as SiC and sapphire (and the list is growing) are the darlings of the LED and laser diode worlds as they produce the necessary blue to round out the primary colors in the spectrum. (See "Optoelectronic Update" in CSID, and in next TFR issue for more details). This huge commercial marketplace for outdoor displays, traffic and auto lights, and eventually white lights and increased capacity CD-ROMs helps further the development of WBG semiconductors in general, thus helping fuel the development of WBG materials and devices for HTE applications.

However, all the developers worldwide share the same fundamental material and device problems that must be overcome if yields are to reach acceptable levels. Applications for the WBG semiconductors in high temperature applications is still in the future, for the cold hard facts in the high temperature game are the same as they were for GaAs as it struggled for niches silicon couldn't fill. If you can do your design with silicon, you'd be crazy not to. But just imagine what you could do with SiC ICs when they become available, affordable, and reliable...off high volume fab lines?

SILICON CARBIDE's TOUGH STUFF!

SiC has various attributes that sets it apart from the field. First and foremost, it has a decent supply of commercial wafers already moving through the initial marketplace, by more than one supplier. More importantly, those wafers are made from usable single crystal material–a basic requirement for commercial success. Although the starting material has not yet lived up to its potential, and is still pricy, the positive technical attributes of those wafers makes SiC desirable for HTE applications. As Chris Harris of the SiC Group at Industriellt MikroelektronikCentrum AB (IMC in Kista, Sweden) so eloquently puts it, "above all, it is the physical properties of SiC that ring to its merit and excite even the dullest to its potential."

WBG semiconductors are inherently less sensitive to increased temperatures. "The thermal conductivity exceeds even that of copper; any heat produced by a device is therefore quickly dissipated. The inertness of SiC to chemical reaction implies that devices have the potential to operate even in the most caustic of environments. It is extremely hard," IMC's Chris Harris goes on to explain. "Of importance to our nuclear and space age is the fact that SiC is extremely radiation hard and can be used close to reactors or for space electronic hardware. Less transparent are the properties of particular importance to the device design engineer, high electric field strength and high saturation drift velocity." Those inherent qualities mean that devices can be made smaller and more efficient. "SiC is a material with which it is possible to stretch the limits of conventional technology to its extremes," he explains. Those are precisely the attributes that major customers, such as engine manufacturers in automotive and mil/aero sector are looking for. An excellent source for details of SiC makeup and polytypes are available on IMC's website: < http://www.imc.kth.se/kraft/whysic.htm >

WHERE IS THE MARKET HEADED?

As reported last issue in my report from the HiTEC meeting in Albuquerque, AEA Technology of Oxfordshire and Magus Research of London, presented preliminary findings from the first market study of its kind for HTE. The researchers estimate that the actual market for HTE in 1994 is estimated to have reached a definitive level of $140.1 million, and forecast the HTE sector to grow, in US terms, to $1.3 billion by 2005. According to AEA and Magus, well logging equipment, aerospace, and automotive will provide the key drivers, with a wide range of niche applications in several other industries accounting for the rest. The market researchers go on to cite that, "by temperature range, it was found that operation up to 200°C currently satisfies most requirements. However, as the technology matures, applications at higher temperatures will be enabled, around the year 2000, and are expected to account for 19% of the actual (total available) market by 2005. Silicon-based technologies are expected to dominate applications up to 200-250°C. GaAs and wide bandgap semiconductors (WBS) which include SiC, diamond, and Group III nitrides (III-N) will play critical roles beyond 250C, accounting for 16% of the high temperature electronics demand by 2005."

In attendance when these preliminary figures were presented by keynote speaker, Simon Lande, Director of Magus Research, Phil Neudeck's adds that "HiTEC in Albuquerque last June offered some interesting perspectives on technologies competing for the HTE market. The market survey paper presented at the opening session predicted that 5% of the HTE market would go to wide bandgap semiconductors in the year 2005, amounting to a somewhat small, by semiconductor industry standards, $50 million market. However, the paper included only those electronics whose atmospheric operational ambients exceed 125°C, thereby excluding the largest potential markets for wide bandgap semiconductors which lie in optoelectronics, power conditioning, and high-power microwave applications operating at room temperature atmospheric ambients with high internal junction temperatures. Furthermore, the survey was limited to totaling values for HTE semiconductor components without regard to the cost savings and performance enhancements those parts offer to larger systems. I think it's important to keep in mind that much of the value of high temperature electronics lies not in the parts themselves, but rather in the large system enhancements that these parts will enable." Simon Lande totally concurs. "Phil has provided a very perceptive analysis and his comments are absolutely right. However, the survey DID look at these aspects. In the presentation, the focus was on the component markets." The entire study is available through HITEN: http://www.hiten.com