Trends in Solid-State Microwave and Millimeter-Wave Technology

The authors explore the next decade from the perspective of Navy requirements as they apply to vacuum tube and solid state technologies, especially power sources, in the microwave and millimeter-wave bands.

K. J. Sleger
R. H. Abrams, Jr.
R. K. Parker
Electronics Science and Technology Division
U.S. Naval Research Laboratory
Washington, D.C.

Recent geopolitical developments and their impact on civil and military economies are expected to play a major role in charting the course of the entire microwave components industry – both solid state and vacuum electronics – during the 1990's. For several decades the Department of Defense (DoD) has provided development funding to this industry in addition to purchasing its finished products. Today, DoD is currently in the process of adjusting future weapons needs to accommodate a rapidly changing world environment. As a result, the future health and well-being of the microwave components industry will require a well-grounded understanding of doing business in the 1990's because technology investment in the military sector is facing major uncertainties.

Recent geopolitical developments are expected to play a major role in charting the course of the entire microwave industry.

The purpose of this paper is to suggest several answers to the all-important question for the solid-state microwave components community – "What lies beyond for the rapidly-changing microwave technologies in silicon, GaAs, and InP?" – based on forecasts and several observations of the relationship between the microwave industry and DoD over the past 15 years.

1990 Microwave/Millimeter Wave Technology

In the broadest sense the major changes that have driven the military microwave industry are based on a few devices: the Gunn diode, the silicon mixer diode, the silicon bipolar transistor, and the GaAs FET (field effect transistor) on the solid-state side and, on the vacuum-electronics side, the TWT (traveling wave tube), and the crossed-field amplifier (CFA).

medium power in the frequency range from 1 to 100 GHz .

Figures 2 and 3 show the current limits for solid-state power devices along with equivalent vacuum electronic device limits.[1] Note that vacuum electronics technology meets the power needs for many military systems. In certain parts of the power-frequency regime there is overlap with solid-state approaches, but solid-state technology has definite

Today the military microwave and millimeter business is dominated by three technologies: the TWT, the Silicon Bipolar, and the GaAs FET.

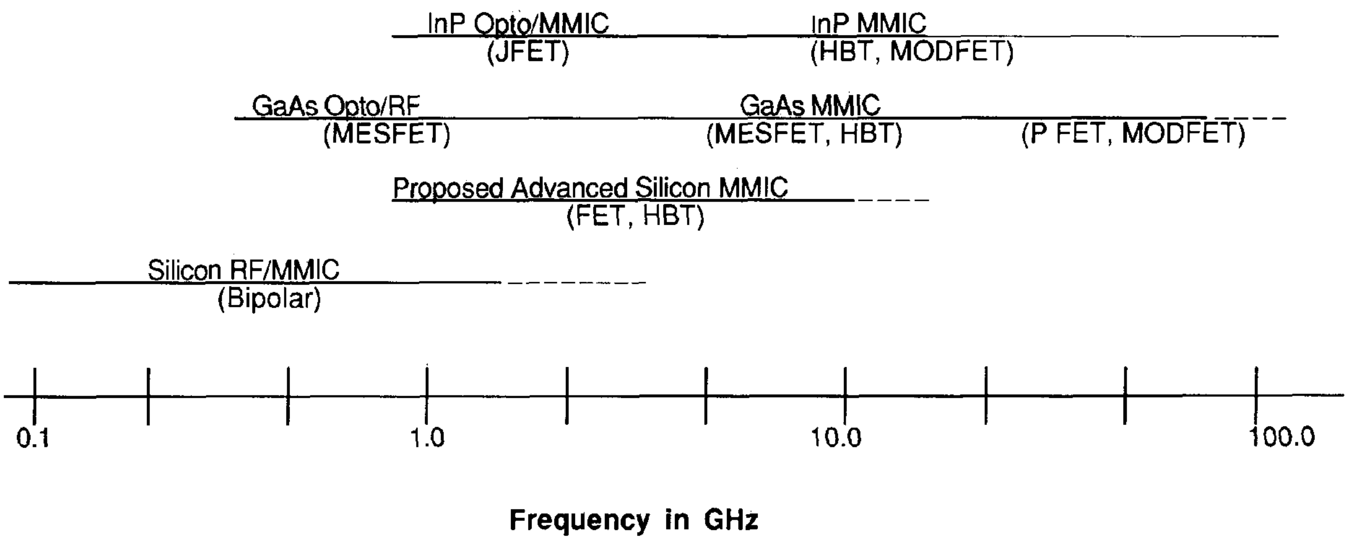

Figure 1. 1990 view of dominant solid-state MMIC technologies as a function of frequency.

Today, the military microwave/millimeter-wave business situation is dominated by three well-developed device technologies: the TWT (accounting for about two-thirds of power tube sales to the military), and the silicon bipolar transistor and GaAs MESFET, both of which can be monolithically integrated to form a variety of useful circuit functions.

Figure 1 shows the frequency range expectation of the well-known monolithic solid-state circuit technologies of most interest today based on their low noise, wide bandwidth, or power performance. In addition, silicon, GaAs, and InP discrete devices provide both two- and three-terminal sources of power limitations and is taxed by low efficiency in meeting system power needs.

Future solid-state devices using SiC and Diamond may alleviate the efficiency problem.

Future higher-power solid-state devices, such as those envisioned from silicon carbide and diamond, offer some possibility of alleviating the efficiency problem. On the other hand, some form of vacuum

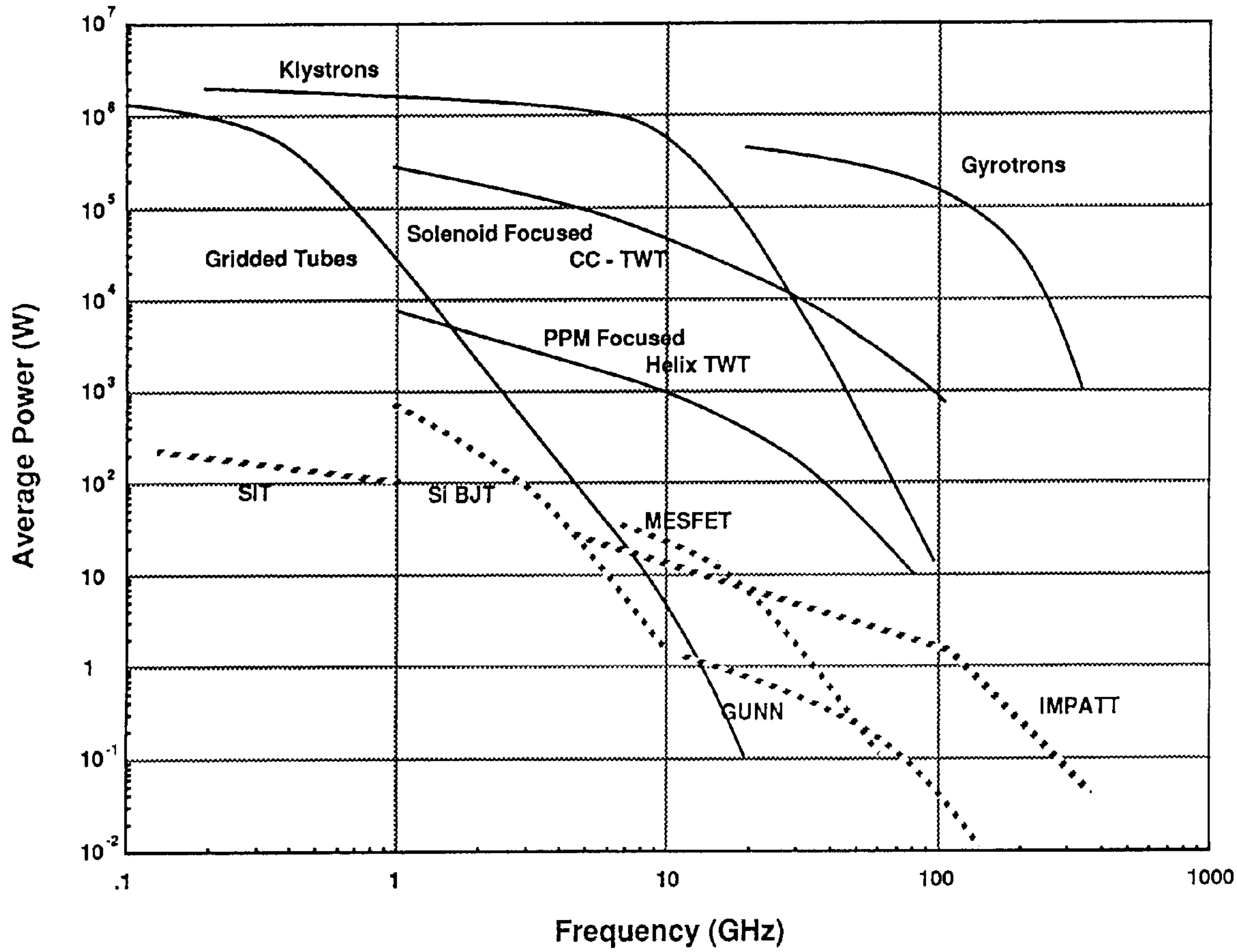

Figure 2a. 1990 view of dominant vacuum and solid state power source technologies

electronics device miniaturization could prove equally attractive for systems which are size, volume, and efficiency intensive. Systems of the future potentially could be made more affordable and effective by using a hybrid approach that involves both solid-state and vacuum electronic technologies.

From the Past into the Future

Several projected trends that may impact the industry's future should be highlighted. Sales of both vacuum electronic power devices and solid-state amplifiers to DoD are shown in Figures 4 and 5 for the period 1950-1993.[1] The years 1990-1993 are projections which estimate a shrinking DoD market as the result of recent occurrences in eastern Europe.[1,2] Note that vacuum electronics sales as a percentage of the DoD procurement budget has varied by only a factor of about two (0.6% to 1.2%) over a four-decade period, which includes the Korean and Vietnam conflicts.

Vacuum device sales have varied by only a factor of 2 as a fraction of DoD spending over the last 40 years.

Solid-state sales began about 1970, with the steep rise in the 1980's representing, for the most part, the insertion of GaAs FET technology. Figure 5 forecasts that the 1990's ratio of solid-state sales to DoD procurement levels out at about 0.5%, not much different than that of the 1950-1990 period for power tube technology.

If flat sales continue into the 1990's, the inference is that technologies such as GaAs MMIC may

Growth Rates for Average Power Production at Frequency

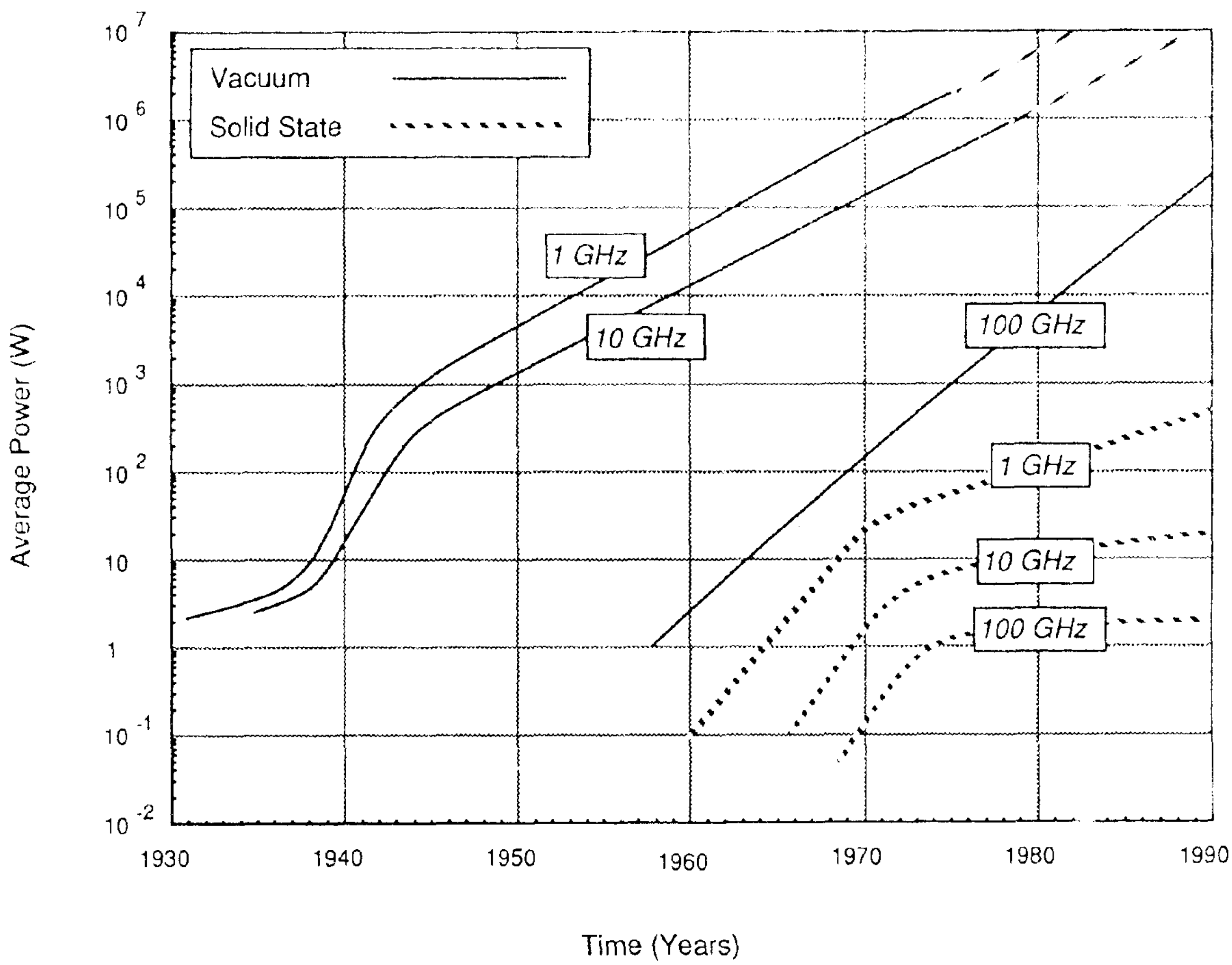

Figure 2b. The historical growth of solid state and tube average power.

not have a drastic impact on the overall sales of solid-state components to DoD. This situation could change if, for instance, (1) DoD invests in sufficient new systems that exploit advanced vacuum or solid-state devices or (2) a commercial-volume market emerges for new microwave technologies. The former possibility is not expected; the latter possibility is considered below.

High-volume markets represent a new direction for the military microwave industry, the MMIC being a case in point. Some people in the microwave solid-state industry believe that the need for high volume will occur automatically as soon as MMICs are fabricated. But the reality is that the industry may not be able to cope with MMIC insertion demands of the 1990's which tend to impose short lead times on component manufacturers.

The IC industry may not be able to cope with the short military lead times of the 1990s.

Another area of potential misunderstanding surrounds the often-cited $75.00-or-less military MMIC chip. Some industry representatives cite the projected availability of this chip with confidence. In reality volume needs to reach 10 million chips/year/line to comfortably reach the $50-$75 chip price level. The commercial world can reach this

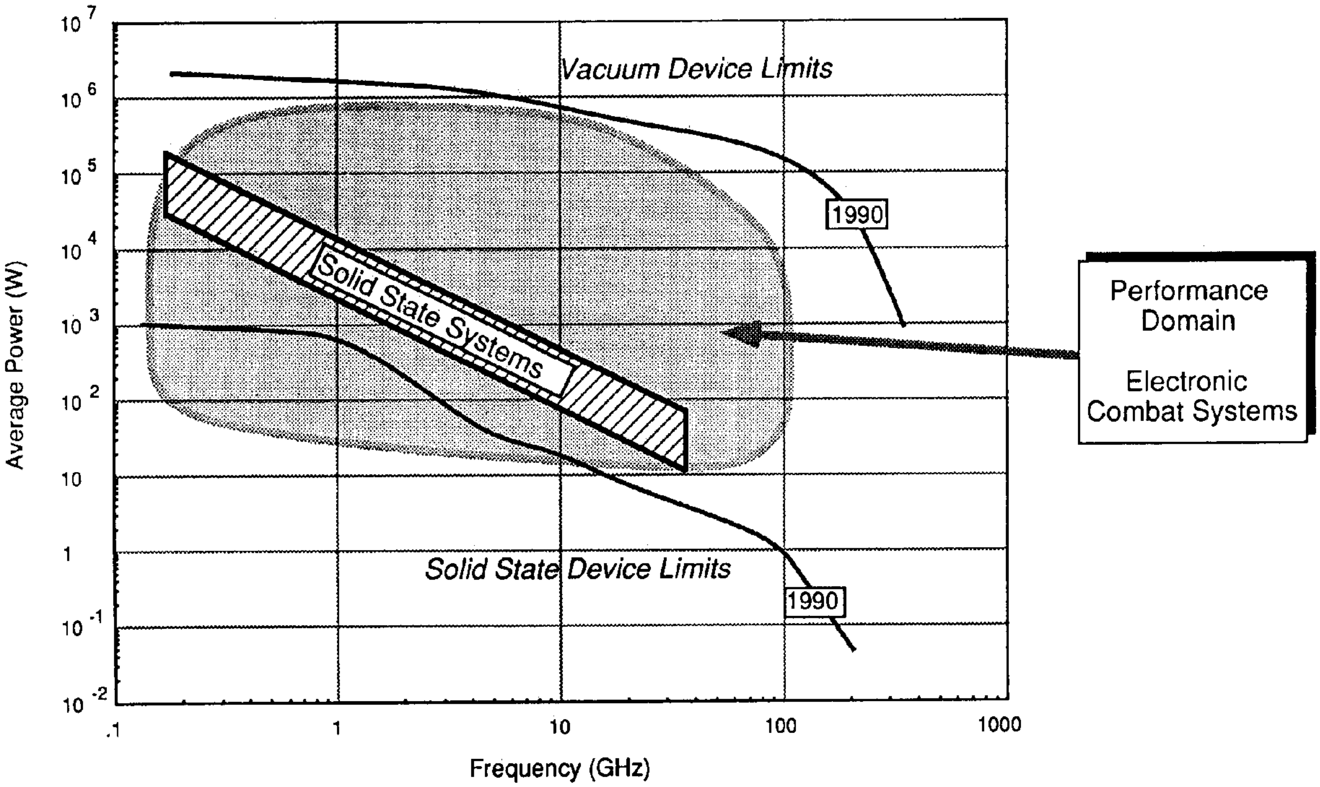

Figure 3. Performance requirements for military systems: Limits of device and combined performance [1].

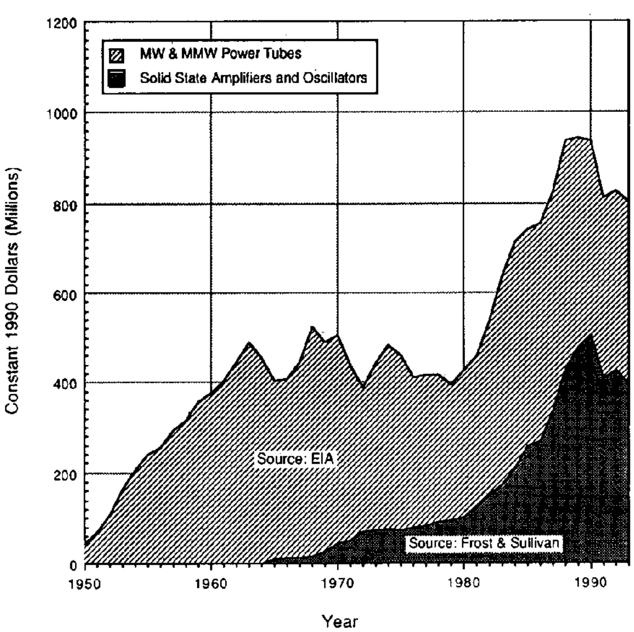

Figure 4. Military sales of microwave and millimeter wave amplifiers and oscillators [1].

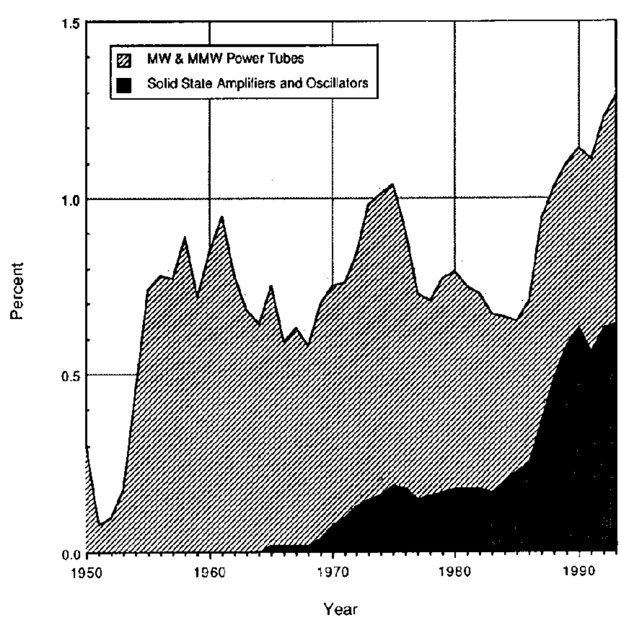

Figure 5. Military sales divided by total DoD system procurement [1]

volume level, for example, with automotive radars (collision avoidance, traffic control, etc.), VSATs (Very Small Aperture Terminals) and DBS (the Direct Broadcast Satellite for television).

But the military market place is much less focussed in any given application area with the result that such volume building by any means becomes a critical issue. In order to build MMIC volume the military microwave industry needs to focus on increasing the necessary learning to reach steady insertion into military systems, not to lower MMIC costs. Cost reduction will come later. The microwave component industry, to remain most viable, needs to consider the slow and careful transition from the handcrafted product to the manufactured product during the 1990's.

What's New and Coming?

Competitive industries of the 1990's need to pay attention to the global economy in which products continuously increase their value-added content. In other words, industries must be flexible in responding to the needs of a changing world by offering products which keep them healthy by building application bases.

The microwave industry must develop manufacturing technologies capable of incorporating small changes to serve the DoD.

The microwave industry is no exception in that it, too, must develop manufacturing technologies capable of incorporating small changes into either standard and/or application specific products. The military market has traditionally sustained small volume, handcrafted parts and has limited success with high volume, application specific parts for reasons that go beyond the scope of this paper.[3]

Commercial vendors can build volume with both standard and application specific silicon digital parts by using flexible manufacturing techniques assisted by computer-aided design. The same opportunity exists to build both commercial and military microwave circuit volume using modern day MMIC foundries and microwave CAD techniques.

Now to address some of the changes projected to impact the microwave industry during the 1990's. These are:

Emergence of volume markets

1) The development of advanced CAD/CAE-/CAM for quick turn-around of parts and first-pass design success

2) The miniaturization of circuit functions requiring massive amounts of space today, such as filters, switches, circulators and multiplexers

3) The merging of microwave and optoelectronic circuits for microwave applications such as phased arrays

4) The availability of high-temperature microwave circuits for aircraft and automobile engine control

5) The availability of many types of MMICs with MSI integration levels

The current Navy initiatives would produce benefits in 1) miniaturization 2) wide dynamic range 3) anti-jam capability 4) shared radar-communications or radar-surveillance.

Candidates for Miniaturization

1) All of the above cited for volume markets are candidates for miniaturization.

2) The emergence of vacuum microelectronic devices for up to 100 watt broadband power requirements and for receiver protection circuits

3) The wafer-scale integration of Si and GaAs MMICs

4) The three-dimensional packaging of circuits for very high MIC integration

5) Miniaturization of conventional vacuum power devices (see microwave power module initiative)

These trends can in turn be reinterpreted in terms of projected supporting activities in materials, devices, and circuits shown below.

Development of Materials

1) Vertical Zone Melt semi-insulating GaAs substrates, 3-in or more in diameter with uniform defect densities less than 10 square centimeters

2) Silicon carbide and diamond electronic-grade thin film technology

3) High-quality, iron-free, InP semi-insulating substrates

4) High-quality SIMOX (silicon) and Si/Ge technology for microwave devices and ICs with performance to 12 GHz or more

5) Wide range of high temperature superconductor films

Device Developments

1) Heterogeneous bipolar transistors (HBTs) using GaAs, InP, and Si/Ge materials

2) SiC and diamond high-temperature RF electronic devices

3) Quantum-based devices for non-linear functions

4) Small, low-voltage vacuum electronic and microelectronic devices

Circuit Developments

1) Miniature filters and circulators

2) Co-planar monolithic microwave integrated circuits with medium scale integration (MSI MMICs) complexity

3) Very broadband MMICs and vacuum devices

4) High-temperature superconductor passive components

5) Wafer-scale integration

6) Very high levels of module integration

7) Shared aperture wideband circuits and modules

Finally, we need to look at some applications, especially commercial ones, which can provide the impetus for all of this activity.

Silicon Semiconductors

Very-low-cost microwave circuits to 18 GHz are the glue for 3D circuits' miniaturization and microwave-digital processors.

GaAs (gallium arsenide) Semiconductors

Commercial MMICs might include engine control, high definition television (HDTV), atmospheric sensing, point-of-contact sales data transmission using very small aperture satellite terminals (VSAT), and personal security systems.

InP (indium phosphide) Semiconductors

Included are millimeter-wave communications, personal security, personal safety, space surveillance/satellite networks, and advanced automobile cruise control systems.

SiC and Diamond Semiconductors

On site, high temperature aircraft/automobile electronics, dc to low microwave ultra-reliable radiation tolerant devices and circuits would exploit these high temperature semiconductors.

Field Emitter Arrays

This application is for small intermediate-power microwave sources for phased arrays and receiver front-end protection

What's New and Coming?

The Navy has a variety of initiatives that address current needs in its microwave electronics operational capability. Only the most salient initiatives can be mentioned here. They are:

1) Vacuum microelectronics

2) Bulk semiconductor growth

3) Advanced silicon MMICs

4) The high temperature superconductivity space experiment (HTSSE)

5) Miniaturized filters and multiplexers

6) Advanced computational techniques for vacuum electronic devices

7) High-dynamic-range receiver front-ends

8) Advanced phased array antennas

9) Refractory semiconductor devices

10) Microwave power modules

Table 1 provides more details about these initiatives. Note that the principal benefits can be grouped into several major areas: miniaturization; wide dynamic range, anti-jam capability; and shared radar/communications or radar/surveillance functions.

One device, the HBT, is a potential major player in at least five areas and is expected to make a major impact on the next generation of Navy electronic systems beyond the year 2000.

Refractory semiconductors and miniaturized vacuum technology will most probably have an extended impact that continues well after the year 2000.

Other technologies such as advanced silicon and InP MMICs are seen as having an important effect on technology fallout as early as 1995.

InP-based heterostructure technology is expected to supersede much of today's GaAs-MESFET-based technology and certain types of GaAs-based HBT and MODFET technology.

The 1990's and beyond represent a new, uncertain era for the solid-state microwave and millimeter wave components industry. The uncertainty mainly lies in the area of DoD weapon system purchases. The newness of the era stems mostly from the challenges of developing commercial applications, from innovative vacuum-electronics technology, and of developing advanced military compo-

INITIATIVE	OBJECTIVE	BENEFITS
Bulk Semi-conductor Growth	To develop high quality GaAs and InP semi-insulating substrates for the electronics industry	+ Very low dislocation densities + Removal of Cr (GaAs) and Fe (InP) + 3"-6" substrate diameter + Low cost, manufacturable
Vacuum Microelectronics	Develop small efficient low-voltage power devices which exploits the strengths of both solid state and vacuum electronics while avoiding the weaknesses of these technologies	+ High performance, small, affordable millimeter wave power amplifier + Broadband power in the 10-100 watt range + Exceptional radiation hardness + Mass production
Microwave Power Module	Develop small efficient high volume power modules by integrating solid state and vacuum electronics technologies. Power modules respond to needs that tax an all solid state or all vacuum electronics approach	+ Enhanced architectural design flexibility + Reduced size, cost, weight of future system + Improved system noise performance + Mass production
Advanced Computational Techniques for Vacuum Electronic Devices	To develop three-dimensional fully-electromagnetic computer codes and design tools for vacuum electronic device design	+ Reduced design costs + Quick performance optimization + Low noise CFA improvement
Superconductivity Research Program - Space Experiment (HTSSE)	To test and insert high temperature superconductor microwave products for space systems and to develop space uses for high temperature superconductors	+ Radiation hardness + Test results from superconducting materials in space (information) + Stimulate application oriented device development
Refractory Semiconductor Devices	To improve the power output, reliability and high temperature capabilities of current solid state power devices. To grow high quality electronic films of SiC and diamond	+ Radiation hardness (SiC, diamond) + Increased anti-jam capability + Chemical inertness for ruggedness and relaxed packaging requirements
Advanced Silicon MMICs	To extend silicon MMIC technology to X-band or higher. To exploit recent advances in SIMOX technology and Si/GE HBT technology	+ Very low cost MMICs + Single chip integration of digital and MMIC functions + Mass production
High Dynamic Range Front-Ends	To significantly improve the dynamic range of receiver front-ends, mostly with MMIC technology	+ Spur reduction + Increased probability of friend or foe detection + Mass production
Microwave Filters and Multiplexers	To miniaturize and replace many of the bulky filters, circulators and waveguide circuits currently in use, MMIC and ferrite technology	+ Reduced size and weight + Potential for mass production + Wider bandwidth operation + Improved selectivity
Advanced Phased Arrays	To develop the next generation of T/R modules with shared electronic functions (Radar/EW, Radar/Communications, etc.)	+ Increased electronic agility + Low sidelobe emissions + Minimize prime power and system cooling

Table 1. Some Navy initiatives focussed on the microwave and millimeter wave industry.

nents, such as shared-aperture modules and burnout-free wide-dynamic-range receivers.

These challenges will require manufacturing and design skills far beyond today's capabilities. It will also require the development of new materials such as SiC, diamond, high temperature superconductors, and structures for vacuum microelectronic devices. There is no question that the challenge is there, the question is, can the industry respond?

References

1 "Microwave Tubes: A National Security Concern", Report of the Department of Defense Advisory Group on Electron Devices, 1990.
2 "The US Military Microwave Components Market", Report A2104, Fall 1989, Frost and Sullivan, NY, NY.
3 "The Self-Destruction of America's Defense Industrial Base", Senator John McCain, (R-AZ), Armed Forces Journal, International, pp 40-45, June 1990.

Disclaimer

Robert K. Parker *received the BS degree in Physics from Allegheny College, Meadville, Pennsylvania in 1964; the MS degree in Space Physics Engineering from the Air Force Institute of Technology, Wright-Patterson AFB, Dayton, Ohio in 1966; and the Ph.D. degree in Nuclear Engineering from the University of Mexico, Albuquerque, in 1973.*

From 1964 to 1972 he served in the U.S. Air Force as a scientific project officer. Since then he has been with the Naval Research Laboratory, Washington, D.C. where he has been actively engaged in a study of the science and technology associated with the generation of coherent radiation in nonneutral plasmas.

He is the author of numerous papers in plasma physics, vacuum electronics and accelerator technology.

In 1981 he formed and is currently the Head of the Vacuum Electronics Branch in the Electronics Science and Technology Division in which topics of interest include such fields as the generation of coherent radiation from UHF to the far infrared, high brightness electron beam optics and computational techniques for modeling electronic devices.

He is also the Navy member of the DoD Advisory Group on Electron Devices and a member of the Executive Board of the Air Force Advanced Thermionics Research Initiative (ATRI) program at the University of California at Los Angeles.

Dr. Parker is a member of the IEEE and has served on the Executive Committee of the Nuclear and Plasma Science Society, Plasma Science and Applications Committee, the Plasma Physics Division of the American Physical Society, and Sigma Xi. He is currently an Associate Editor of the IEEE Transactions on Electron Devices.

Richard H. Abrams, Jr. *received the SBEE degree from Massachusetts Institute of Technology in 1959 and the Ph.D. degree in Plasma Physics from the University of Maryland in 1970.*

His industrial experience includes thermionic energy conversion research at ThermoElectron Engineering Corporation and General Motors Research Laboratory. He has been active in the energy and environmental policy area, and has been a consultant to both government and corporate management on technical strategic planning.

Prior to joining the Naval Reasearch Laboratory, he served as Chief Scientist of B-K Technologies, where he was engaged in assessments of various technologies, including the generation of high power microwaves.

Among his foremost interests since joining NRL in 1988 has been the analysis of policies affecting the vacuum electronics technology. He is currently the Head of the Sources and Fabrication Section of the Vacuum Electronics Branch of NRL's Electronics Science and Technology Division, in which capacity he is responsible for the direction of Navy research programs in vacuum microelectronics and in thermionic and secondary electron emitters. He also serves as the NRL manager of the Ultra-Low-Noise Crossed-Field Amplifier program.

Dr. Abrams is a member of the American Physical Society and the Sigma Xi honorary fraternity.

Kenneth J. Sleger *received the BSEE and MSEE degrees from Case-Western Reserve University, Cleveland, Ohio in 1962 and 1965 and the Ph.D. degree in Electrical Engineering from Carnegie-Mellon University, Pittsburgh, Pennsylvania in 1971.*

Since joining the Naval Research Laboratory, Washington, DC in 1971, he has made contributions to a wide range of technologies and devices including PbS-PbS(1-x)Se(x) heterostructure lasers, GaAs FETs, InP FETs and GaAs MMICs. More recently he is engaged in SiC FET technology and MIMIC CAD activities. He has also worked with GaAs FET process science, GaAs FET reliability and improved metallizations for GaAs and InP FETs.

Dr. Sleger is currently the Head of the High Frequency Devices Section at NRL with responsibility for exploratory investigations of new microwave and millimeter wave devices and ICs. In addition he is Project Manager for a substantial portion of the Office of Naval Technology exploratory device and IC effort in the RF/MW/MMW solid state area. He is a Senior Member of the IEEE and a member of the IEEE Electron Devices Society.