SOLID STATE MICROWAVE POWER AMPLIFIERS - AN OVERVIEW

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ABSTRACT

This paper summarizes results that have been achieved with various types of microwave solid state power amplifying devices and presents some projections of advances that can be expected within approximately a five year period. The frequency band surveyed extends from 1 to 100 GHz. The emphasis is on CW or high duty cycle pulse applications, where long life is of great importance, such as in a satellite communication system. The types of devices considered include the gallium arsenide field-effect transistor (GaAs FET), IMPATT diodes, bipolar transistors, Gunn diodes, TRAPATT diodes and electron bombarded semiconductor (EBS) devices. An overview of the technology of microwave power combiners is also included.

INTRODUCTION

The purpose of this paper is to highlight some of the recent noteworthy results that have been obtained with solid state microwave power amplifiers, and to present some projections for the near term future. By “near term future” we mean performance that may be expected from devices and amplifiers that can be in the marketplace within the next five years. Earlier this year The Aerospace Corporation was tasked by the NASA Goddard Space Flight Center to assess the present state of the art of transmitters for advanced communications systems in space, and to project where the state of the art is heading. This paper draws, in part, on the findings of that study.

This year marks the 30th anniversary of the invention of the solid state amplifier. In 1948, Bardeen, Brattain and Schockley of Bell Telephone Laboratories announced the point contact transistor. Early transistors were fragile and temperamental. It was not until junction transistors became commercially available several years later that transistors began to be widely applied. With succeeding years, understanding of the basic solid state physics and process technologies continued to advance, and these advances were reflected in the increasing variety and capability of solid state devices. From today's vantage point it is clear that 1948 marks the beginning of a complete revolution in the scope and practice of electronic engineering. Vacuum tubes have been relegated to a few highly specialized applications. As amplifiers, solid state devices are now in use for all purposes except high power applications at high frequencies. Specifically, in spacecraft and communications satellites traveling wave tube amplifiers are still almost universally used in the output stages of microwave transmitters. Now, however, this last frontier is yielding to solid state technology.

There are a variety of solid state devices capable of power amplification at microwave and millimeter wave frequencies. As shown in Figure 1, these may be broadly divided into two terminal and three terminal groupings, and further subdivided into various specific kinds of devices. There is usually a choice of materials from which the active portion of the device can be fabricated.

Some of the devices shown in Figure 1 remain little more than laboratory curiosities. The device which appears to offer greatest future potential for many applications is the gallium arsenide field effect transistor (GaAs FET). IMPATT diodes are an older device which still have an undeveloped potential. These and several other devices which will be reviewed in this paper are listed in Table I. In addition, the status of power combining techniques will also be reviewed.

Throughout this paper the emphasis will be placed on space communications applications: CW or high duty cycle pulse operation.

TABLE I

Solid State Devices Capable of Microwave Power Amplification

Type of Device	Upper Useful Frequency as CW Power Amplifier
Bipolar Silicon Transistors	4-10 GHz
GaAs FETs	20 -25 GHz
IMPATT Diodes	200 - 300 GHz
Gunn Diodes	~ 100 GHz
TRAPATT Diodes	~ 10 GHz.
EBS Devices	~ 4 GHz

GaAs FET POWER AMPLIFIERS

The field-effect transistor (FET) is a three terminal device (see Figure 2) in which a voltage imposed on a “gate” electrode enhances or impedes the flow of current in an underlying conductive channel terminated by a “source” and “drain” electrode. The variation of channel current is accomplished by the effect of the electric field beneath the gate electrode, which accounts for the term “field-effect transistor”.

Gallium arsenide microwave field-effect transistors (GaAs FETs) became a practical reality during the early 1970s. Within a few years development had progressed to the point where GaAs FETs were replacing uncooled paramps in earth stations at 4 and 7 GHz as low noise devices. Space applications came shortly thereafter, initially as low noise devices in the Communications Technology Satellite (CTS) and the Japanese CS Satellite. Now the list of applications for GaAs FETs in space is expanding to include its role as a power amplifier. Interest in extending the application of GaAs FETs in this manner is particularly keen in view of its potential for replacing the traveling wave tube amplifier. Historically, it has been observed that solid state devices offer orders of magnitude advantages over tubes in terms of reliability, size and weight requirements. The interest in GaAs FETs as a replacement of TWTAs is largely based on the premise that similar benefits will thereby accrue.

The state of the art of power GaAs FETs is depicted in Figure 3. Three curves of power output versus frequency are shown. One curve corresponds to actual performance achieved in the laboratory today. The other two curves represent the bounds of predictions for 1983. It must be borne in mind that today’s most spectacular laboratory results are embodied in products that are not suitable for a space mission. They are obtained from devices that are overstressed and therefore have limited life.

Curves similar to Figure 3 were constructed to correspond with the status of GaAs FET development at earlier instants in time. In conjunction with today’s status and the 1983 range of predictions, a family of curves showing GaAs FET power output versus time was constructed. This family of curves is shown in Figure 4.

In reviewing the efficiency obtainable from power GaAs FETs, no consistent trend was found in present day devices. The efficiency decreases with increasing frequency, although the extent to which this degradation occurs is a function of the gate dimensions and the device packaging. At any one frequency the efficiency of commercial GaAs FETs varies widely. This is shown in Table II for a variety of devices at 8 GHz. Note that power added efficiencies (at saturation) range from 15% to 30%. It should be emphasized that the overall amplifier efficiency is considerably less than the power added efficiency of the output stage. This is due principally to the low gain of the power GaAs FET, necessitating a substantial driver chain, and to a lesser extent, to the losses in the power conversion equipment. Typically, the overall efficiency of a GaAs FET amplifier chain having gain equivalent to a TWTA would be less than half the efficiency of the output stage.

TABLE II

Efficiency and Power Output of Commercial
GaAs FETs at 8 Ghz

Manufacturer	Type No.	Output Power @ saturation mW	Output Power @ 1 dB comp. mW	Power Added Efficiency &
Texas I nst.	MSX801	250		30
Texas Inst.	MSX802	500		30
Texas Inst.	MSX803	1000		30
NEC	V868A		250	24
NEC	V868B		500	20
NEC	V868C		1000	10
MSC	88001	310	260	25
MSC	88002	600	515	21
MSC	88004	1100	940	19
MSC	88010	2800	2500	19
Dexcel	3630A-CR	700	500	15
Dexcel	3615A-P200	300	250	16
Plessey	GAT4/020		100	10

Present development trends in GaAs FETs are oriented toward producing devices having higher power output and improved reliability. Efficiency, gain and bandwidth are receiving less attention, although it is clear that all parameters are interdependent. There is no present basis for projecting major improvements beyond the efficiencies realizable in the better GaAs FET devices available today. There may not be much incentive to design GaAs FET power amplifiers with high efficiency as the major design goal. The need for highest efficiency results in considerable measure from limitations in present spacecraft payloads, and from an application where the solid state amplifier is to function as a plug-in replacement to an existing TWTA. For future spacecraft designs, these considerations are secondary.

Bandwidth is related to power output. Higher output power would tend to imply higher device operating temperatures, which would tend to reduce reliability. To relieve thermal stresses, the power generating surfaces can be dispersed by paralleling several elementary devices within one device package, or by using a wider gate within one GaAs FET device. Either way, the parasitic elements (chiefly shunt capacitance) that limit device bandwidth become more significant. To some extent the effect of shunt capacitance can be relieved by using internal matching sections between discrete elementary devices. This is an approach that would generally be applied insofar as manufacturing technology permits. A more advanced approach, which has been suggested but not yet acted upon, is to design a distributed amplifier using many elementary devices within one package. The latter goal would appear to be beyond near-term attainment, in view of the lack of work in this area.

Figure 5 shows percentage bandwidth as a function of power output for X-band GaAs FETs. The solid region of the curve represents a region that has already been achieved or can be achieved by 1983 without major difficulty. The dotted region represents extrapolations that would require considerably more effort. To achieve 10 watts output would result in an amplifier with about 250 MHz bandwidth at X-band. This would be entirely adequate for any present communications satellite system requirements, but wider bandwidth would be desirable for future systems. To some extent bandwidth limitations will be relieved without any special effort when these devices are scaled to higher frequencies.

In discussing GaAs FET development with leading device designers, a fairly uniform consensus was noted concerning what must be done to achieve future goals. The principal area of uncertainty is the reliability of power GaAs FETs for long life missions. Extensive testing of significant numbers of devices under actual RF conditions is needed. Such tests are expensive. Simpler d-c tests tend to be substituted with less conclusive results.

There is broad recognition of the need for full scale reliability demonstrations. Equally important is the development of accelerated life test methods that would stimulate failure modes that may be encountered during normal operation without provoking irrelevant failure modes. It is not practical to conduct real time life tests on devices having mean times to failure measured in many years.

There is some belief that device designs may not yet be sufficiently mature to warrant the required investment in full scale testing programs. More work should be done in developing improved methods for obtaining high quality substrate material. Alternative metallization schemes must be further developed and evaluated. Device packages offering reduced thermal resistance should be designed. Improvements are needed in device processing to obtain increased uniformity and yield.

The relationship between needed technology programs and development goals is depicted schematically in Figure 6.

IMPATT DIODE AMPLIFIERS

An IMPATT diode exhibits negative resistance at microwave frequencies. It can therefore be used as an oscillator or as an RF amplifier. The frequency at which the device is useful can be as low as 1-2 GHz or as high as several hundred gigahertz (although any given IMPATT diode will be usable over only a small portion of that range).

The IMPATT diode derives its negative resistance properties from a combination of carrier generation by impact ionization and transit time effects. It employs a p-n junction or Schottky barrier, biased in the avalanche region of its volt-ampere characteristic. The doping profile provides the desired combination of carrier generation and transit time delay.

IMPATT diodes most commonly are made using silicon or gallium arsenide. Single drift and double drift devices are available. The latter are generally more efficient and capable of higher power output. A double drift IMPATT diode is roughly equivalent to a series connected pair of single drift devices. It has a drift region on both sides of the junction, one for holes and the other for electrons. The resultant increase in impedance levels relative to single drift devices facilitates matching into microwave circuits. The tendency toward parametric instability is also reduced by the double drift structure.

IMPATT diodes were first introduced about 10 years ago. Within a relatively short time they were hailed as the obvious replacement for the TWT. For a combination of reasons they never assumed that role. Although their potential reliability was thought to be comparable to most solid state devices, it is only recently that their reliability has begun to approach values that would be required for long life in space. One reason for the difficulty in achieving reliability is the nature of the avalanche phenomenon upon which IMPATT diodes depend. Efficient charge carrier multiplication requires a relatively high current density across the junction, which in turn raises the junction temperature. As a result the current densities required for reasonable efficiencies produced junction temperatures that were too high for reliable long life operation. It was characteristic of IMPATT diodes that they seemed to operate best at the point where they were just below burnout. Now, with designs employing efficient diamond heat sinks, good reliability may be obtainable. However, it is still true that these devices tend to be used by amplifier designers in a manner that results in excessive junction temperatures.

A second difficulty with IMPATT diodes is common to most negative resistance devices. There is no inherent isolation between input and output, so that a complete amplifier must include low loss, low VSWR circulators between stages. Careful design is required to achieve broadband characteristics. It is extremely important to control the load presented to the diodes. Certain kinds of mismatches may result in near instantaneous burnout.

IMPATT diode amplifiers can operate in a negative resistance mode or in an injection locked mode. Because the injection locked mode has significantly higher efficiency, IMPATT diode power amplifier developments have concentrated in this area. The injection locked amplifier is highly nonlinear, with characteristics approaching that of a hard limiter. It is therefore usable with angle modulated systems (such as FM or QPSK) where only one carrier at a time is present. With multiple carriers intermodulation would generally be considered excessive. Hence, frequency division multiple access (FDMA) systems cannot usually share a single IMPATT diode power amplifier.

A lock-in bandwidth of about 3% is the approximate limit for the injection locked mode when the amplifier is driven by an unmodulated carrier. For a fixed carrier frequency near band center, modulated by a digital bit stream, the limited data suggest that the bit error rate becomes significant as the width of the RF spectrum approaches the steady-state CW lock-in range.

Because of these special peculiarities of IMPATT diode amplifiers, they never assumed the role of a TWTA replacement. Nor is it likely that they will assume such a role in the future, except for special cases. Although IMPATT diodes and associated amplifier circuitry are now relatively well understood, other solid state devices, principally GaAs FETs, have more desirable characteristics as a TWT replacement at frequencies up to about 20 GHz. The IMPATT diode is capable of significantly higher power output than the GaAs FET. (At 10 GHz, by a factor of six to one in laboratory devices). However, the development of power combining technology, together with the more rapid growth in GaAs FET capability largely nullify the advantage of IMPATT diodes. The outstanding example of IMPATT diode application in a space mission was their use in the COMSTAR beacons. However, they were used as oscillators rather than amplifiers in this application.

The IMPATT diode amplifier appears to have a significant future role in space at frequencies above 15-20 GHz -- not as a TWTA replacement, but in systems that can be designed to accommodate their more restrictive characteristics. Digital systems employing TDMA clearly represent a future trend. For these applications the IMPATT diode amplifier is well suited. Power combining techniques suitable for use with IMPATT diodes have been developed at frequencies up to 40 GHz. These techniques appear to be extendable to 60 GHz in the relatively near term. With more intensive development effort, extrapolations to 90 GHz appear reasonable.

In some applications the cost advantage of IMPATT diodes over GaAs FETs may be significant. In the frequency region below 15-20 GHz, as much as a tenfold advantage in watts per dollar has been estimated for IMPATT diodes in pulsed oscillator service. The main applications in this mode would be in areas other than for communications. For CW service the IMPATT diode cost advantage does not appear great enough to compensate for their otherwise less desirable characteristics relative to GaAs FETs.

The present state of the art of IMPATT diodes, in terms of CW power output versus frequency, is shown in Figure 7. A projection of what can be accomplished by 1983 is also included. By means of similar curves constructed at particular instants in past time, a trend of power output versus time was established. A family of curves for different frequencies was derived in this way, as shown in Figure 8. Note that these curves level off and show little growth compared to the corresponding GaAs FET curves. This is in part the result of IMPATT diodes being a more mature technology. Additionally, the GaAs FET is of more interest to a wide range of users, and hence its growth is being expedited by substantial commercial funding of development programs. It appears that in this country advances in IMPATT diode technology will require support by the defense agencies and by NASA. Japan has a vigorous program of development work in IMPATT diodes, principally because of their strong commitment to Ku-band space systems.

BIPOLAR TRANSISTORS

Historically, the first solid state device usable as a practical amplifier at microwave frequencies was the silicon bipolar transistor. Its useful upper frequency limit for power amplification is approximately 10 GHz, but other devices, particularly the GaAs FET, offer superior performance at frequencies above about 4 GHz. Devices providing power outputs of the order of 40 watts at 1.0 GHz and 5 watts at 4.2 GHz are typical of the performance of commercially available “off the shelf” units now. Microwave bipolar power transistor development has been active at frequencies up to about 3 GHz. In this region power output has doubled in the past four years and it appears that this growth rate will be sustained for the near term.

Typically, a microwave bipolar power transistor combines several chips in one package. The power gain may run from 4 to 6 dB and the device power added efficiency is generally less than 50%. The efficiency of a complete amplifier chain is usually no more than half the device efficiency.

The success of microwave bipolar transistors is largely due to the mature silicon technology developed for lower frequency units. Likewise, their future growth seems limited by this material. The microwave bipolar transistor offers demonstrated reliability. It appears to have carved out a durable place for itself. However, interest in developing it further for frequencies above 4 CHz is lacking because of the more promising future of the GaAs FET in this region.

MISCELLANEOUS DEVICES

Gunn Diodes

Gunn diodes have been used as oscillators for more than 10 years. Commercial microwave radios now utilize Gunn diodes both as receiver local oscillators and as power amplifiers. The rapid development of IMPATT diodes has, however, displaced Gunn devices for most applications. IMPATT diodes can now provide higher power output at lower cost in dollars per watt than Gunn devices. The area in which the Gunn diode remains clearly unsurpassed is as a generator of low noise microwave power above about 6 GHz. Because of this characteristic and its relatively low cost, the Gunn diode appears likely to dominate the receiver local oscillator market in this frequency range. As a power amplifier in a transmitter, its low noise characteristic is generally of no importance.

Gunn diodes for use at frequencies below 30 GHz are generally made of gallium arsenide. At higher frequencies indium phosphide Gunn devices have been shown to offer superior performance.

TRAPATT Diodes

The TRAPATT (Trapped Plasma Avalanche Triggered Transit) diode has a structure similar to an IMPATT diode except that in the TRAPATT diode the avalanche region is not in a fixed position. CW operation has been obtained at frequencies up to about 10 GHz. In the pulsed mode the TRAPATT diode has produced higher peak power than any other solid state device at frequencies up to 100 GHz. Nevertheless, the TRAPATT has had few if any practical uses to date, because it has acquired the reputation of being a difficult, unstable device. The development of IMPATT diodes with comparable power and efficiency will probably further reduce future interest in TRAPATTs.

EBS Devices

Electron bombarded semiconductor (EBS) devices represent an interesting hybrid combining a semiconductor in a vacuum tube. A focused electron beam bombards a target diode or group of diodes. Hole-electron pairs are generated, and charge multiplication takes place in the semiconductor material. The resultant current is delivered to the output circuit by means of a biasing potential applied to the diode. As an RF amplifier EBS devices are useful from VHF to about 4 GHz. They are uniquely useful when a very linear amplifier is needed. As a microwave amplifier its other performance characteristics can generally be achieved more effectively with bipolar transistors. At 2 GHz, 50 to 100 watts CW should be an attainable goal.

POWER COMBINERS

Interest in developing efficient power combiners stems from the power limitations of solid state amplifiers. Power combining can take place within the device package or it can be accomplished by external circuitry. In-package combining was previously mentioned as a means of increasing the power output of GaAs FETs. Although in-package combining can also be accomplished with IMPATT diodes, there is usually little incentive to do so, as it is difficult to obtain proper load sharing between multiple negative resistance devices in one package. Moreover, the additional parasitic reactances introduced by in-package combining would degrade the outstanding high frequency performance of IMPATT diodes.

There are several ways to implement circuit combiners. Major types are identified in Figure 9. Concatenations of multiple combiners are evidently also possible, although at this point in time none such appear to have been developed.

Resonant combiners sum the power of several devices in a single cavity. Coupling between the devices is obtained directly through the electromagnetic field. Cavity combiners are used with two terminal devices. Thus, they can be applied to combine the power produced by several IMPATT diodes, but they cannot be used with GaAs FETs. Resonant combiners have been built at frequencies ranging from 5.0 GHz to 40 GHz.

Among the nonresonant combiners the binary tree approach is the simplest. A cascade of 3 dB hybrids is used as a power splitter at the input port. After amplification in individual two terminal or three terminal active devices, the output power is summed in a second cascade of 3 dB hybrids. A three level, eight device power combiner of this sort is illustrated in Figure 10. Since the losses in the cascaded hybrids are cumulative, there is a practical limit to the number of combining levels that can be advantageously employed in the binary tree approach. Up to 4 levels (16 devices) appears to be reasonable.

The N-way power combiner avoids the cumulative losses that accompany the binary tree approach. The input power is split in an N-way hybrid or radial line and applied to the individual active devices. The output power is summed in a second N-way hybrid or radial line structure. Raytheon has designed N-way power combiners for use with IMPATT diodes. Westinghouse has designed such combiners for use with GaAs FETs. Simulation studies are said to show that up to 40 -way combining may be feasible.

The limit on performance of the N-way power combiner may be a thermal one rather than an electrical limit. As more devices of higher power are added, it becomes increasingly difficult to dispose of the heat generated in the active devices. The geometry of the N-way combiner does not favor good heat sinking.

An important requirement for any combiner is so-called “graceful degradation”. Failure of one (or more) devices whose power is being combined should not cause complete failure of the combiner. Circuit combiners of the hybrid tree or radial line type inherently possess a graceful degradation characteristic. Cavity combiners, which are often used with IMPATT diodes, will degrade gracefully if the diode fails in some specified manner. For example, if it is known that an IMPATT diode forms a short circuit upon failure, a coupling circuit to the cavity can be designed so that if a short is substituted for the diode, little degradation occurs. However, if the diode fails in an atypical manner, the complete amplifier may be disabled.

Table III shows the performance achieved by representative types of power combiners. In comparing these results it must be emphasized that the development goals and conditions of operation of the active devices were often not the same. For example, the 120 watts achieved by Ratheon was said to represent an optimized tuning condition with the junction temperatures of the individual diodes ranging from 220° to 240° C. While this may be a satisfactory operating condition for some applications, the power levels would have to be scaled down for a long life application in space.

TABLE III

Representative Power Combiner Results

Developer	Freq (GHz)	Max CW Output Power (watts)	Combiner Type	No. of Active Devices, Type	Combining Circuit Efficiency (Percent)
Raytheon	5	120	Cavity, TM_{010}	6 GaAs IMPATT (single drift)	87
TRW	37	5	Cavity, TM_{010}	8 Si IMPATT (double drift)	63
Ford Aerospace	8	6.5	Binary Tree	8 GaAs FET (RCA, T. I.)	65
Westinghouse	9	4.4	Radial Line	12 GaAs FET (Fujitsu)	95

Looking toward the future, the power output obtainable from solid state transmitters will increase because of the twofold effect of more effective power combiners and the availability of higher power devices. In order to utilize higher power devices, improved thermal designs will be needed. The radial line combiner built by Westinghouse employs water cooling. For some purposes this would not be an acceptable method. The use of miniature heat pipes may be a feasible alternative. Changes in the radial line structure to increase isolation and bandwidth would then permit power combining of a larger number of GaAs FET devices.

Good thermal design is equally important with cavity combiners employing IMPATT diodes. The IMPATT diodes themselves may employ diamond heat sinks to reduce the thermal spreading resistance to the mounting surface. This approach is effective to the extent that a good heat sink is available close to the point of mounting.

At the higher frequencies, the small dimensions of the cavity limits the number of devices that can be combined. One approach toward relieving this problem is to develop combiners using higher order modes. Other developments would be needed to scale techniques that have been successfully employed at the lower frequencies upward to the higher frequency regions. Better manufacturing tolerances would be required, which are not easily achieved.

Figure 11 is a projection of what can be achieved, given sufficient interest, in increasing the power output obtainable at various frequencies. These curves factor in the twofold improvements that may be expected from improved devices and improvements in circuit combiners. It must be emphasized that while attainment of these results appears technically feasible, a level of funding support is presumed which is in some cases lacking.

CONCLUSIONS

The bipolar transistor using the now mature silicon technology appears to have established a durable role for itself as a power amplifier at frequencies up to 4 GHz. At the upper end of this range, competitive inroads from GaAs FETs may erode the dominance of bipolar devices. Within the frequency band from 4 to approximately 20 GHz, GaAs FETs are likely to become the preferred device for use as solid state CW power amplifiers. However, for those applications where linearity is of no importance, the IMPATT diode may offer a more economical alternative, particularly in pulse service.

At frequencies higher than approximately 20 GHz, the IMPATT diode amplifier is the most promising solid state device for use as a power amplifier. Gunn diodes will continue to retain their present role as low noise, low power signal devices.

To replace traveling wave tube amplifiers, power combining circuitry appears necessary, and several promising alternatives for their design are available. However, the increased power handling capability of solid state devices, coupled with new directions in system architecture, may limit the future role of power combining circuitry.

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At least a dozen major companies in this country and abroad are active in developing various types of solid state amplifying devices and amplifier circuits. Several universities and government laboratories have programs underway in materials and process technology. There are also systems houses and user organizations that are building amplifiers and designing novel system architecture that will take advantage of the unique opportunities offered by this new technology. The result has been an outpouring of literature whose volume has seldom been equaled in one relatively specialized field. The following bibliography includes a small sample of the pertinent material. The interested reader will easily find much more.

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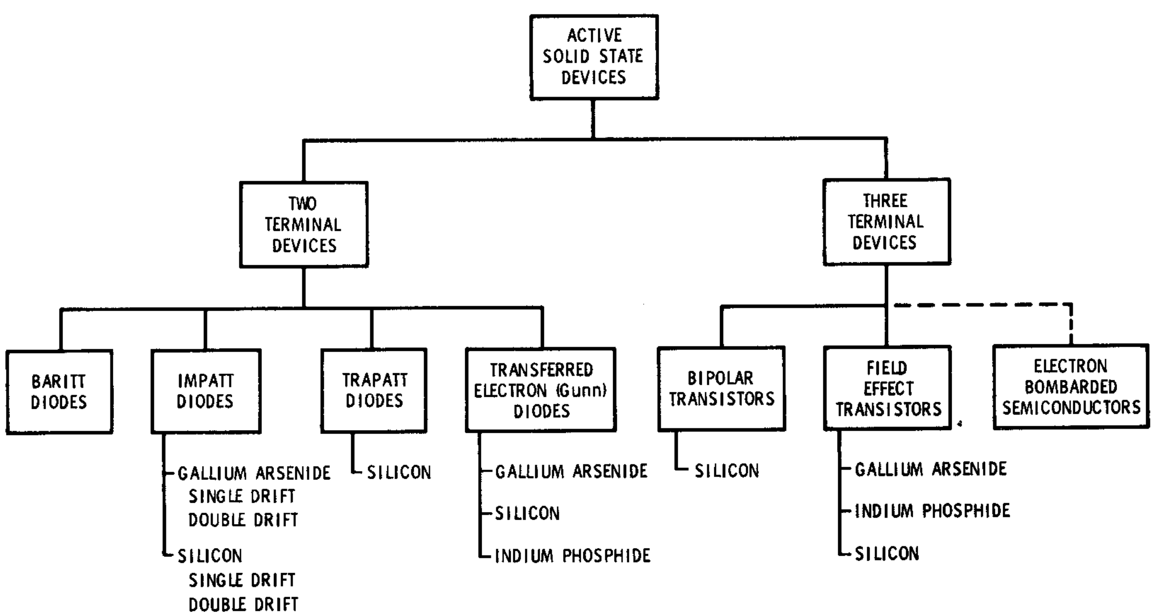

Figure 1 Active Solid State Microwave Devices

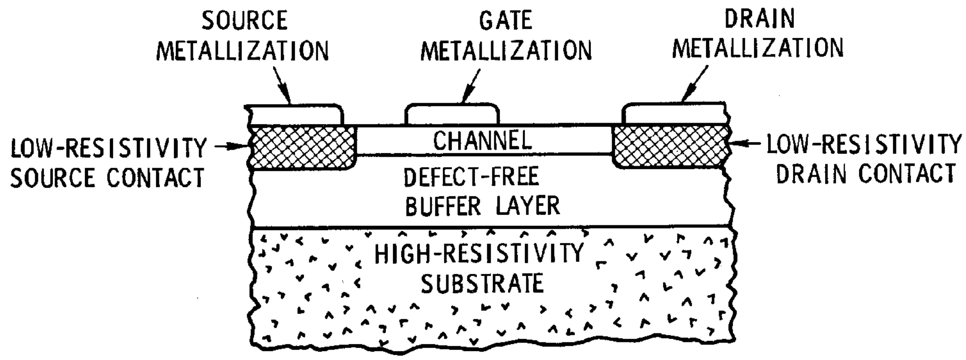

Figure 2 MESFET Device Structure

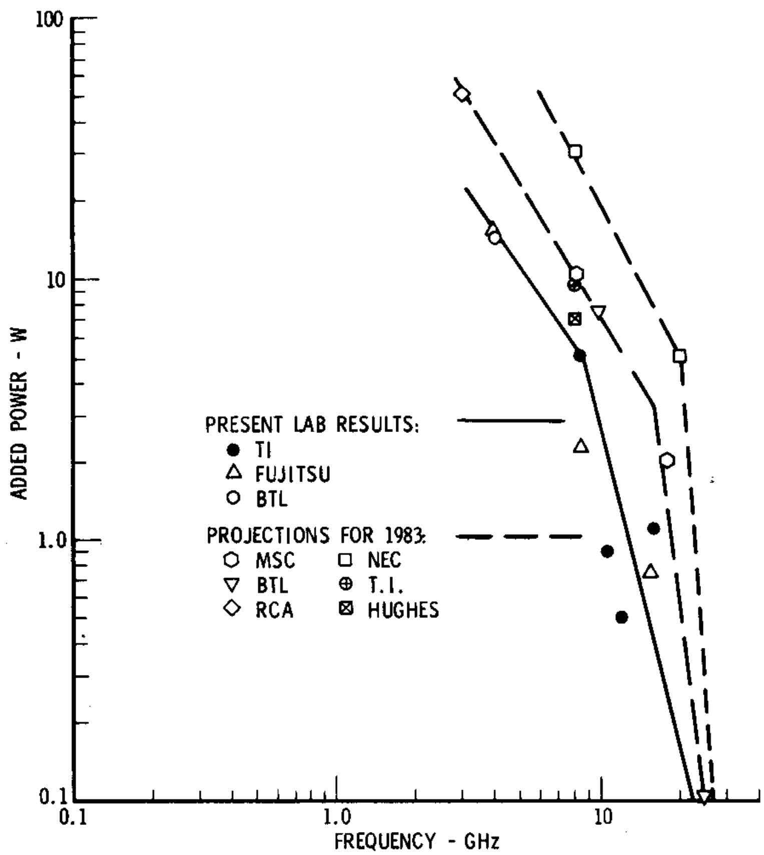

Figure 3 GaAs FET Power Output vs Frequency

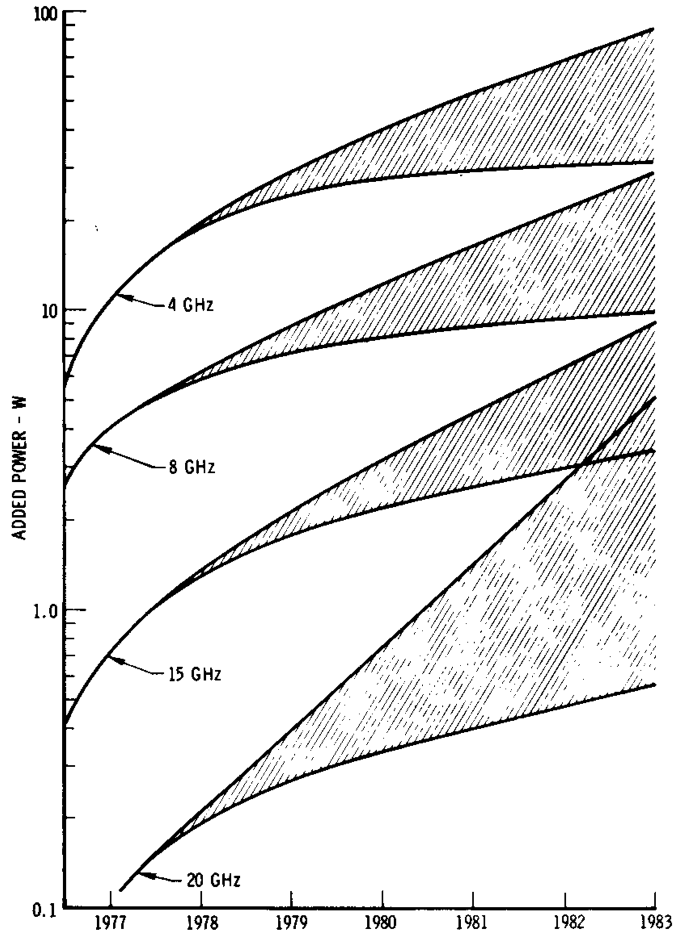

Figure 4 Output Power GaAs FET Device Packages

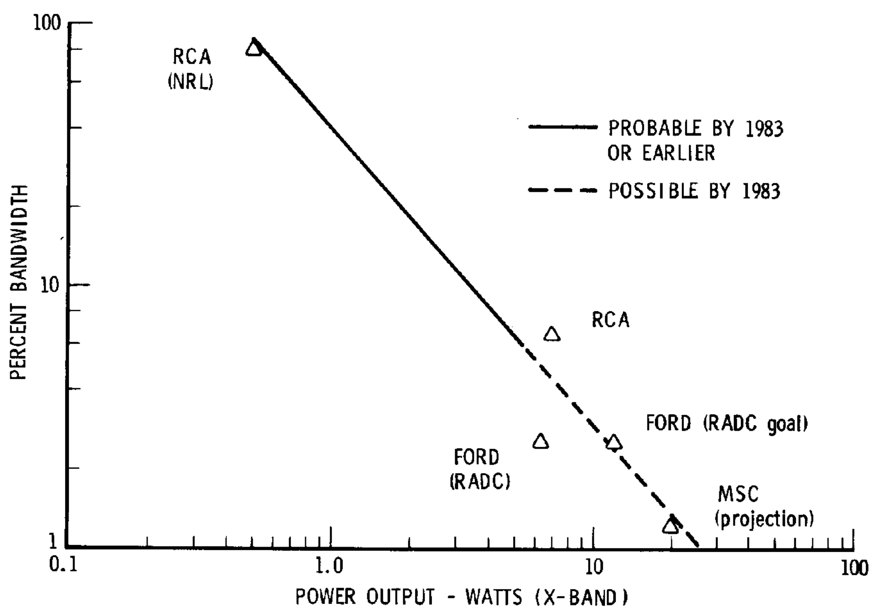

Figure 5 Percentage Bandwidth of GaAs FET Power Amplifiers

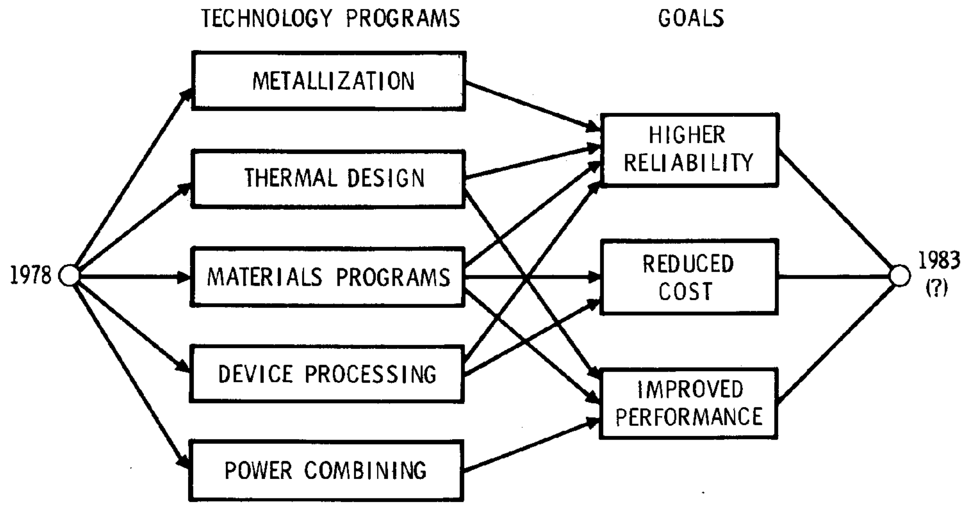

Figure 6 Advancing the State of the Art of Power GaAs FETs

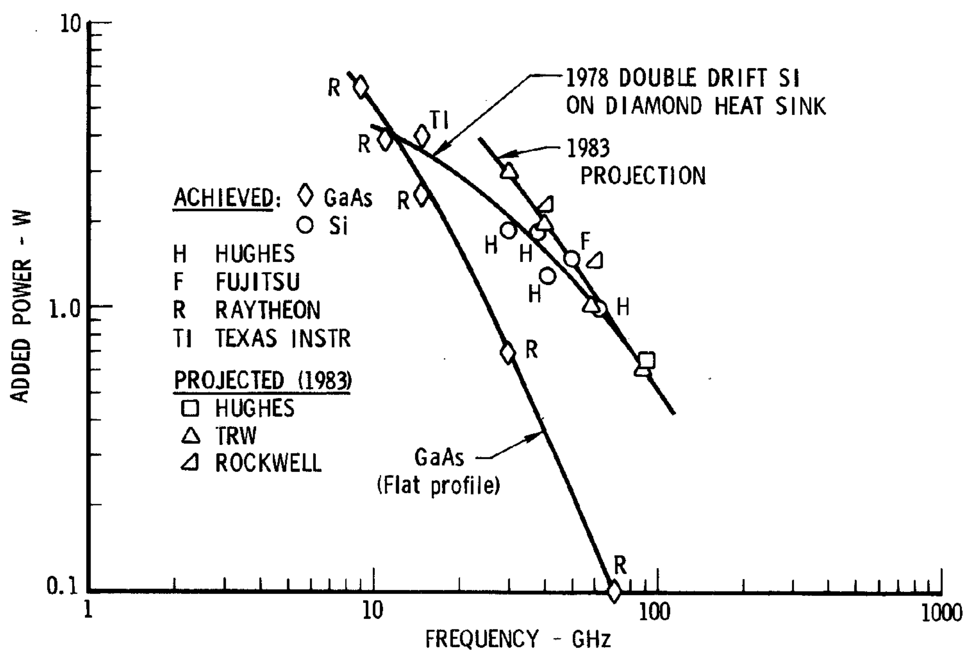

Figure 7 Impatt Diode Device Achievements and Projections

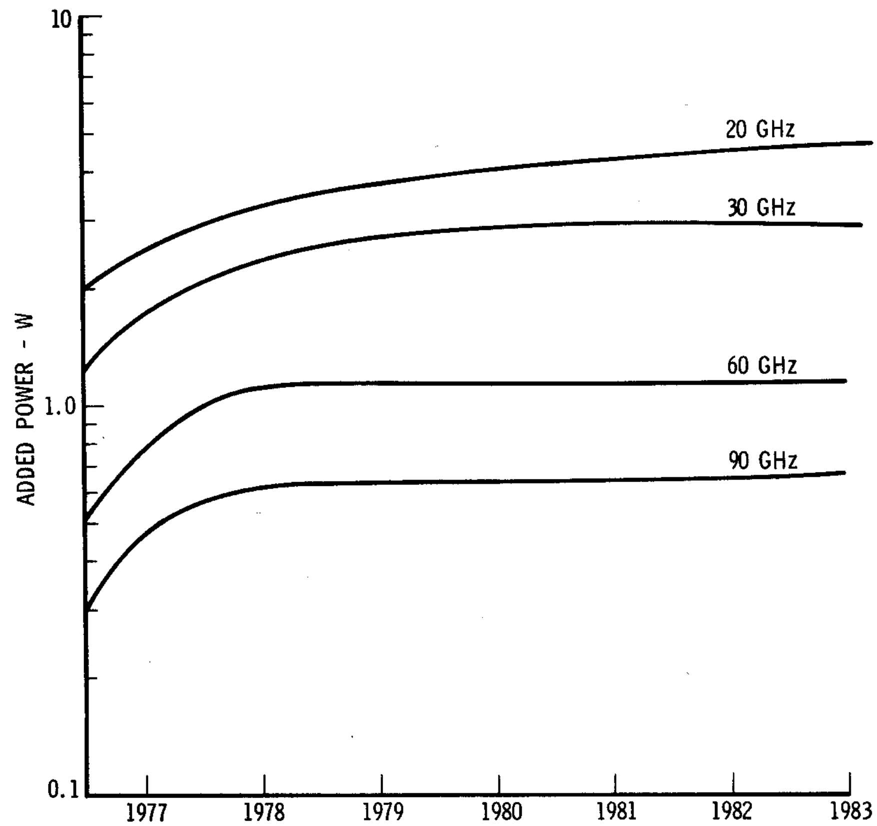

Figure 8 output Power Projections, Impatt Diode Devices ($\Delta T = 200°C$, Diamond Heat Sink)

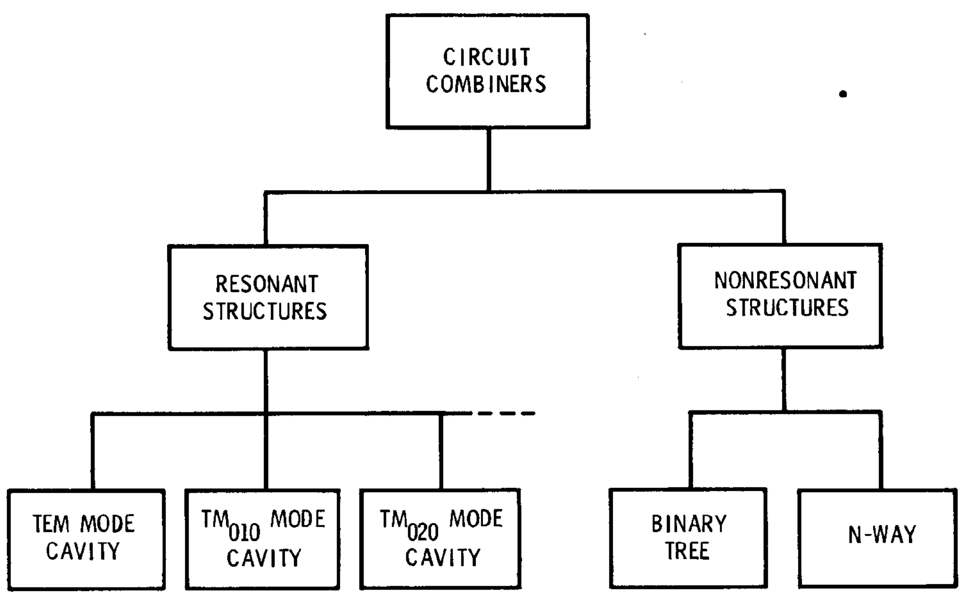

Figure 9 Circuit Combiner Classification Chart

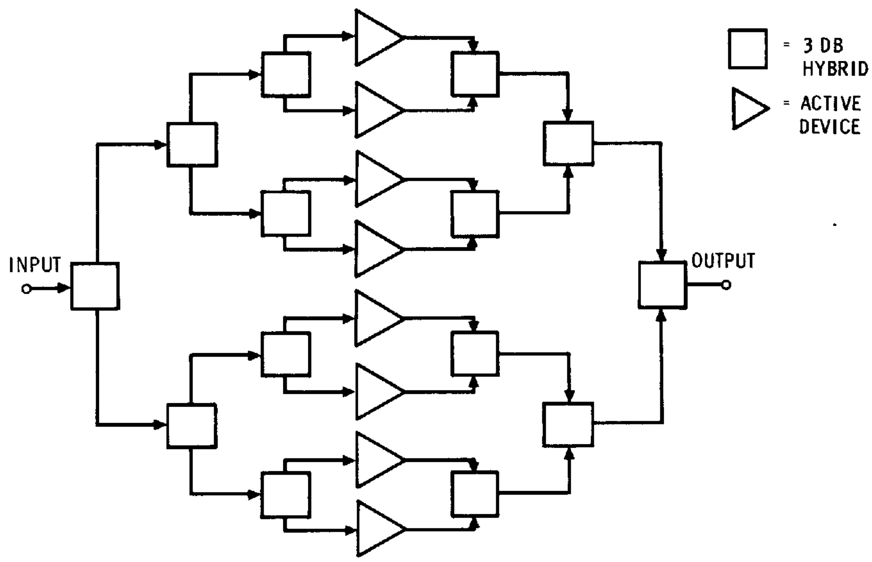

Figure 10 Illustrative Hybrid Tree Combiner

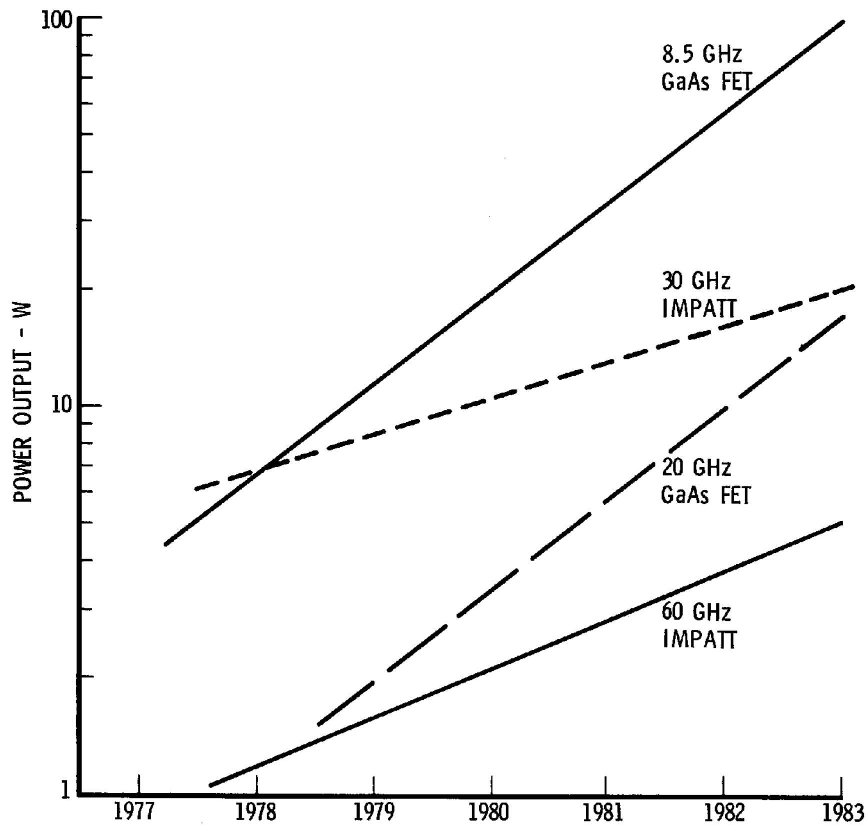

Figure 11 Circuit Combiner Power Output Projections