A Survey of Recent Progress on HEMT and HBT Power Transistors for Ka Band

by
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Table of Contents

1. Introduction ............................................................................................................... 2
2. Figures of Merit for power HEMTs, pHEMTs, and HBTs............................................................. 3
3. Power Generation at Ka Band: Main Problems ........................................................................... 4
4. HEMTs and HBTs for Ka Band Power Generation ................................................................. 5
   4.1 HEMTs and pHEMTs .......................................................................................................... 5
   4.2 HBTs ................................................................................................................................ 6
5. Alternatives for Ka Band Solid-State Power Devices ............................................................ 7
   5.1 InP Materials ................................................................................................................... 7
   5.2 SiGe Materials ................................................................................................................ 11
   5.3 Different Geometries ..................................................................................................... 11
6. Thermal analysis and advanced heatsinking ........................................................................... 11
   6.1 Thermal Analysis ........................................................................................................... 12
      6.1.1 GaAs HBTs ................................................................................................................. 12
      6.1.2 GaAs pHEMTs ........................................................................................................... 13
      6.1.3 InP HBTs ................................................................................................................... 15
      6.1.4 InP HEMTs and pHEMTs ............................................................................................ 16
   6.2 Advanced Heatsinking ...................................................................................................... 17
      6.2.1 NEC, Japan, HBT ...................................................................................................... 19
      6.2.2 TRW, USA, pHEMT .................................................................................................. 24
      6.2.3 Other Groups .......................................................................................................... 27
7. Commercial Products Available ............................................................................................ 27
8. Space and Network Power Combining/Splitting ..................................................................... 29
9. Conclusions ......................................................................................................................... 30
REFERENCES ..................................................................................................................... 31

This work was sponsored by The Research Council of Norway – The Basic Telecommunication Research Programme.

This document was prepared using GetARef reference handling software.
1. Introduction

This work is part of the Sarepta project at SINTEF and the WIRAC project at the Institutt for teleteknikk at NTNU. The Sarepta Project is a planning pre-project funded by Norwegian Industry to develop capabilities in Ka Band Multi-Media Satellite Communications. Ka-Band is from 26.5 to 40 GHz and K-Band is 18-26.5 GHz. The uplink is at Ka-Band and the down link is at K-Band for these services. Norwegian Industry is looking ahead to prepare for design of earth terminals for the K-Ka frequency band. Since the power output requirement for an earth terminal at Ka-Band is greater than is easily obtainable, examination of methods for obtaining high power output earth terminals at Ka-Band is needed. The WIRAC project is funded by the Norwegian Research Council and is to cover Broadband MultiMedia Satellite Communications in the Ka-Band, as well as terrestrial based communications. Since both projects need study in the Ka-Band, it was decided to combine the two projects. The work that is needed for the Sarepta Project is more immediate and development is required to give guidance about possible methods of design. The work that is needed for the WIRAC project is more long term and of a research nature.

Hughes (1996) states that the commercial potential for the Ka-Band “will be limited only to the imagination of the service provider and to market demand.” This article also mentions the NASA ACTS (Advanced Communications Technology Satellite) program, which “has operated a Ka-band satellite since 1992 as a demonstration test bed for U.S. companies and institutions experimenting with advanced communications concepts”. The ACTS Ka Band demonstration project has shown that Ka Band Satellites are feasible technologically. The only thing needed is inexpensive and compact technology for satellite ground stations. This report addresses the power transistor technology issues that currently stand in the way of achieving these ground stations economically using only solid state components. The goals of this report, as previously stated in Hanson (1998d), are: (1) to prepare for future projects at Ka Band for Multi-Media with a 30GHz Ka-band uplink with a 1 to 10W power requirement and with a 20 GHz K-band downlink, (2) to see why costs are so high for 1W to 10 W solid state amplifiers at 30GHz, and (3) to examine the current state of the art in solid state power generation at Ka Band.

A brief search of the INSPEC databases for 1996 and 1997 was done to find the typical reported output powers of devices in the 30GHz range. The results of this search were found to be in two categories: solid state and TWT or klystron devices. The tube devices could get power output from 10KW to 1MW in the 30 GHz range. In the TWT category, Liu, Deng, van Meter, Dressman, McDermott and Luhmann (1997) report on a TWT at 35 GHz which gives 2MW output power and Mita (1996) reports on a TWT at 27.5 to 31.0 GHz with over 100-W CW output power. The solid-state devices are the only devices considered further here. The solid state devices reported power outputs between 0.5 W and 6 W continuous. In the solid state case, Texas Instruments and others have high power solid state devices in the experimental stages right now, but the highest power devices found were from TRW for pHEMTs and from NEC for HBTs with output powers between 2W and 6W. The NEC and TRW results will be covered in detail in Sections 6.2.1 and 6.2.2, respectively. Other related results will be presented in Section 6.2.3.

This report includes many of the details that were left out of the presentation, Hanson (1998d), of the same name given at the COST 260 meeting on Smart Antennas, June 4, 1998. It is a continuation of work reported in the Feb. 5, 1998 report Hanson (1998b). It is complementary to the report Hanson (1998a).
The approach taken to achieve these goals was to perform literature searches, as described in Hanson (1998c), using the INSPEC database available through the internet at NTNU to find articles and references relating to work being done in this frequency band at these power levels. The papers that were “hits” in these searches concentrated on HEMTs (High Electron Mobility Transistors) and pHEMTs (Pseudomorphic HEMTs) which are FETs, and on HBTs which are Heterojunction Bipolar Transistors. For these devices, it was found that junction temperature control is the main issue for power devices. Since the characteristic curves for HBTs are a function of junction temperature and the reliability of both HBTs and pHEMTs is an exponential function of junction/channel temperature, it was found that electro-thermal simulation was a must for accurate and reliable design. In addition to these literature searches, some of the device fundamentals in this report are from three books. These are Anholt (1995), Liou (1996), and Ross, Svensson and Lugli (1996). Rodrigues (1998) and Gonzalez (1984) are two books that were also useful for design fundamentals.

2. Figures of Merit for power HEMTs, pHEMTs and HBTs

In our discussion in this report, several figures of merit are needed. Among these are $h_{21}$, $f_T$, $G_{T\text{,max}}$, $f_{\text{max}}$, $P_{\text{out}}$, and $\eta$. The $h$-parameter short circuit current transfer ratios, $h_{21}$ and $h_{fe}$, are used for HEMTs and HBTs, respectively. $f_T$ is the gain–bandwidth frequency Gonzalez (1984) where $|h_{fe}(f)| \approx 1$. The Maximum Transducer Power Gain, Conjugate Matched, $G_{T\text{,max}}$, which is sometimes called MAG, the Maximum Available Gain, is given in terms of Scattering parameters $S_{ij}$ by Gonzalez (1984)

$$G_{T\text{,max}} = \frac{|S_{21}|}{|S_{12}|} \left( k - \sqrt{k^2 - 1} \right)$$

where

$$k = \frac{1}{2 |S_{12}S_{21}|} \left( S_{11}S_{22} - |S_{12}|^2 - |S_{21}|^2 \right)$$

The figure of merit, $f_{\text{max}}$, is defined Gonzalez (1984) to be where $G_{T\text{,max}}(f)|_f = f_{\text{max}} = \text{MAG} \approx 1$.

The Power Output, the Power Added Efficiency $\eta$, and the Power dissipated in heat are also important. The power balance equation [Gui, Gao and Morkoc (1992)] can be written,

$$P_{\text{out}} + P_{\text{heat}} = P_{\text{in}} + P_{\text{DC}},$$

where $P_{\text{out}}$ and $P_{\text{in}}$ are signal powers and $P_{\text{DC}}$ and $P_{\text{heat}}$ are the DC input power and power dissipated in heat. The power added efficiency $\eta$, sometimes called PAE, is given by

$$\eta = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{DC}}} = \frac{P_{\text{out}}}{P_{\text{DC}}} \left( 1 - \frac{1}{G_a} \right) = \text{PAE}$$

where $0% < \eta < 100%$. The theoretical limit for class A operation when $G_a$ is infinite is 50% [Ross, Svensson and Lugli (1996), p. 57]. The power dissipated in heat is $P_{\text{heat}} = (1-\eta)P_{\text{DC}}$. From this, we can see that the smaller that $\eta$ is, the more power is dissipated in heat, which has to be removed in some way. Another factor is the Mean Time To Failure (MTTF) which is related to the junction or
channel temperature $T$ of the devices. Hotter devices fail faster than cooler devices (See Figure 3 on page 10 of this report.)

3. Power Generation at Ka Band: Main Problems

Conventional devices, BJTs and FETs, have poor performance at Ka-Band, although progress is being made in certain areas to improve their HF performance. GaAs-based pHEMTs, InP-based HEMTs and pHEMTs, and HBTs have better Ka-Band performance and have the highest $\eta$. $P_{\text{out}}$ and $\eta$ are both Q-point dependent. This results in relationships where $P_{\text{out}}$ and $\eta$ usually cannot simultaneously be maximized. With low power added efficiency $\eta$, for example, $\eta = 0.2$, and if $P_{\text{out}} = 10\text{W}$, then $P_{\text{heat}} = 40\text{W}$ which must be removed from the device’s active region. Since GaAs has lower thermal conductivity than Si, this creates a problem in heat control. In particular, in HBTs self-heating causes current gain collapse, as shown in Figure 1, which is from McAndrew (1992), and possible current hogging, which may lead to thermal runaway. Therefore, the devices and the heat sinking must be properly designed. At this time, the literature contains much basic research to get better $f_T$, $f_{\text{max}}$, $\eta$, and $P_{\text{out}}$. This basic research examines different materials, different devices, for example, double-heterojunction devices, and substrate thinning and heat sinking methods.

From Figure 1, it is easy to see the effect of self-heating due to power dissipation, which is sometimes called “Current Gain Collapse” for HBTs. For larger $V_{\text{CE}}$, it is easy to see that there is greater tilt in the characteristics. When both $V_{\text{CE}}$ and $I_C$ are large, giving the greatest power dissipation and self-heating, the difference between the curves with no self-heating and with self-heating are the greatest. For accurate results, this means that an electro-thermal model must be used for HBTs and electro-thermal simulation is needed for accurate and reliable designs. Otherwise, the results are inaccurate, as this curve shows the current gain collapse that occurs with self-heating that

![Figure 1. GaAs HBT Output Characteristics with and without self-heating, from McAndrew (1992).](image)
electrical simulation only will not account for. In addition, since MTTF is exponentially related to temperature, temperature control by heatsinking greatly improves the reliability of these devices.

4. HEMTs and HBTs for Ka Band Power Generation

The requirements for the Astrolink and SPACEWAY projects [see Hanson (1998a)] state that a maximum of 10W and 2W, respectively, are needed for earth stations. Since both Astrolink and SPACEWAY use geo-stationary satellites, only a fixed feed is required. For the Sarepta planning pre-project, this means that a maximum of 10W is required “at the feed point”. No “smart antenna” is needed, as is the case for the WIRAC project. Therefore, we need to find solid-state devices that will generate up to 10W at 30 GHz. The devices found in the current literature that have the potential to provide this kind of power for Ka Band, excluding TWTs, are GaAs-based pHEMTs, InP-based HEMTs and pHEMTs, and HBTs. A book which discusses the electrical and thermal modeling of MESFETs, HEMTs, and HBTs is Anholt (1995). This book includes modeling techniques applicable to circuit simulators.

At present, either circuit power combining or spatial power combining can be used to provide higher output powers than are obtained from single devices. Spatial power combining is discussed in Hanson (1998b) and Hanson (1998a). Those who are successful in attaining power outputs on the order of Watts use some kind of power combining with HEMTs or HBTs. Here we will describe some fundamental background on these devices. Figure 2 shows GaAs-based HBT and GaAs-based pHEMT cross-sections.

4.1 HEMTs and pHEMTs

In the HEMT family, there are lattice-matched HEMTs and pseudomorphic HEMTs, which are called HEMTs and pHEMTs, respectively. The notation \{p\}HEMT will be used to refer to either HEMT or pHEMT devices. The discussion here follows Ross, Svensson and Lugli (1996). For GaAs substrates, typical devices are AlGaAs/GaAs HEMTs (GaAs-based HEMTs) and AlGaAs/InGaAs/GaAs pHEMTs (GaAs-based pHEMTs). For InP substrates, typical devices are AllnAs/GaInAs/InP HEMTs (InP-based HEMTs) and AllnAs/GaInAs/InP pHEMTs (InP-based pHEMTs). Conventional HEMTs use lattice-matching for all layers, which just means that the lattice constants for all layers are designed to be very close to the same. Pseudomorphic HEMTs (pHEMTs), on the other hand, use one or two layers in which the lattice constants are designed to be
different, but by not too much. As long as the thickness of the mismatched layer(s) is below a critical limit, quality layer growth is possible. The first HEMTs were lattice-matched AlGaAs/GaAs HEMTs. However, the current confinement in the channel was poor by today’s standards. It was then found that a barrier between the channel and substrate could improve the situation. This barrier was achieved by the placement of a pseudomorphic InGaAs layer between the GaAs Buffer and the AlGaAs spacer (see Figure 2b), thereby making a pseudomorphic HEMT or pHEMT on a semi-insulating (SI) GaAs substrate. This is also sometimes referred to as a Single Heterojunction pHEMT (SH-pHEMT). In addition, the development of a double heterojunction pHEMT (DH-pHEMT) was important for power applications. In this device, n-type AlGaAs spacer layers are placed on either side of the pseudomorphic InGaAs channel. This is more difficult to grow. The GaAs-based DH-pHEMT is superior for power applications to the GaAs-based SH-pHEMT (page 58). These devices are all based on GaAs substrates.

The other important substrate material in use at present for HEMTs is InP. InP-based HEMTs are fabricated using two InAlAs barrier layers lattice-matched to the InP substrate grown above and below a lattice-matched (HEMT) or pseudomorphic (pHEMT) InGaAs channel. InP-based lattice-matched HEMTs and InP-based pHEMTs share the same layer sequences and often result in very similar performance. GaAs-based lattice-matched HEMTs and GaAs-based pHEMTs have different layer sequences and performance, with GaAs-based pHEMTs having superior performance.

From Ross, Svensson and Lugli (1996), we find that GaAs-based pHEMTs have different DC and pulsed I-V curves and that the pulsed I-V curves most closely resemble the RF behavior of the devices (p. 205). pHEMTs have higher Power Added Efficiency $\eta$, as high as 68%, and power output capability [Chau, Hill, Yarborough and Kim (1996)]. In addition to their uses in Multi-media Satellite applications, Ross, Svensson and Lugli (1996) foresee that application of this device will give vehicles new capabilities, including collision avoidance systems. They give a pHEMT large signal model (pp. 218-221) for Ka-band medium-power amplifiers developed by SIEMENS in Sweden. Professor Ilcho Angelov of the Department of Microwave Technology at Chalmers University of Technology (CTH) in Göteborg, Sweden, whom I visited with recently, is first author of this model [Reference 24, p. 248]. This model includes thermal effects due to power dissipation. Also from CTH, Karlsson (1996) reports on research into GaAs-based and InP-based HEMTs. This thesis contains some interesting process details that are hard to find elsewhere.

4.2 HBTs

HBTs are covered in the book Liou (1996). This book focuses on AlGaAs/GaAs HBTs. As mentioned previously, the author says the main problem that is faced at present with HBTs is the “self-heating effect”, which is due to the poor thermal conductivity of GaAs, which “consequently confines the HBT performance considerably below its electronic limitation” and which distorts the V-I characteristics of the devices as a function of junction temperature. The self-heating effect degrades both the current gain and the cutoff frequency as a function of current density $I_C$. For current density $I_C (A/\mu m)$, where $\mu m$ is the width of the emitter finger, above 100$\mu A/\mu m$, the current gain and the cutoff frequency are all noticeably degraded [Fig. 7.9, p. 177]. He gives an example for a 4x10 $\mu m^2$ emitter finger area. For this emitter finger, the degradation occurs above 1mA. In order to get more current, multifinger HBTs have been used. For a three finger HBT, it is found that “the middle finger is hotter than the outer fingers due to the thermal coupling among the fingers.” In fact, he gives one example [page 110], at high $V_{CE}$, where “the results show a drastic difference between the center and outer fingers; ... The center finger will eventually conduct the most current, and the
other two fingers become nearly inactive. This leads to a sharp decrease in the collector current, which is a phenomenon called thermal runaway.” The use of an external ballast resistor can help, but even with a ballast resistor, he says that thermal runaway can still occur if $V_{CE}$ is sufficiently large. Two other important materials for HBTs are InP and SiGe.

5. Alternatives for Ka Band Solid-State Power Devices

In order to find solutions for Ka Band solid-state power devices, a number of different alternatives are being actively researched at present. This research can be categorized into two areas: (1) different materials and geometries and (2) heat removal and advanced heatsinking. In the first category, different materials, such as InP and SiGe, instead of GaAs are being studied. Companies, such as M/A-COM, TRW, and Hughes, are investigating the advantages of using InP based devices. Among the advantages of InP are high electron velocity and high electric field breakdown voltage, better thermal conductivity than GaAs, and higher $f_T$ and $f_{max}$ than GaAs. These advantages make InP a promising material for millimeter wave devices and optical devices. Companies, such as IBM and Daimler-Benz, are investigating the advantages of using SiGe-based HBT devices. The advantages of this technology are better thermal conductivity than GaAs, more industry experience in Si and Ge devices, and no backside processing is required for heatsinking. Companies, among them Texas Instruments, are experimenting with double-heterojunction HBTs (DHBTs). This is an example of a different geometry than standard HBTs. In the second category, heat removal and advanced heatsinking are being experimented with. There are multiple factors that need to be considered when trying to optimize the performance of HEMT power transistors. These factors often require complex tradeoffs to be made. Via holes from one side of the chip to the other are used to improve grounding inductance and air bridges can be used for heatsinking. Mechanical and chemical thinning of materials in selected areas under the active devices is now a standard practice to obtain a successful design. At Ka Band, in particular, the use of advanced heatsinking with vias and bridges can obtain improved device performance due to lowering of junction temperatures. Electro-thermal simulation is required to obtain optimum results.

5.1 InP Materials

Indium Phosphide, InP, is a promising material for millimeter-wave and optical devices. A very good summary website for InP is Macom (1998b). There are many sublinks from this webpage to other sites. Two examples of sublinks are InP HBT technology with $f_T$ of 170GHz and InP HBT A/D Converters operating at 10 Gsamples/sec representing the state-of-the-art in monolithic semiconductor A/D Converters. In Scandinavia, this website mentions a sublink to the Laboratory of Photonics and Microwave Engineering, Department of Electronics, KTH-Electrum, Electrum 229, SE-164 40 Kista, Sweden. KTH is the Royal Institute of Technology at Kista, which is near Stockholm. They are experimenting with InP Optoelectronic Integrated Circuits. In addition to these, the web page also gives links to Hughes, TI, University of Michigan, and Wright Laboratory, among others.

A large conference on InP and related materials is held yearly; InP (1997) is the Conference Proceedings for 1997. This was the 9th year this conference has been held and the Conference Proceedings have been larger and larger every year, indicating the amount of effort that is going into this material at present. A survey of recent advances and thermal properties of InP-based HBTs is
by Chau, Liu and Beam (1996) of Corp. Res. & Dev., Texas Instrum. Inc., Dallas, TX, USA. Smith (1995) of Martin Marietta Labs., Syracuse, NY, USA discuss their experiences with design and fabrication of InP-based HEMTs. Sawdai, Plouchart, Pavlidis, Samelis and Hong (1996) study the use of SHBTs for power applications, instead of DHBTs, which have higher voltage breakdown and are known to be better for power applications. Elliott, Tran, Lai, Block, Cowles, Tran, Jones, Chen, Oki and Streit (1997) discuss the TRW foundry capabilities for InP-based MMICs using InP HEMTs and HBTs.

M/A-COM [Macom (1998a)] has received a Title III InP Award “to improve the availability of high-quality, large surface area semi-insulating InP”. It also maintains the summary website mentioned above. This M/A-COM web page [Macom (1998a)] states the advantages of InP which are quoted below:

“InP HEMTs exhibit lower noise and higher gain than their GaAs counterparts, especially at higher frequencies. They can have an $f_T$ and $f_{max}$ as much as 100 GHz higher than GaAs-based HEMTs, and a 1dB lower noise figure at 94 GHz.

The gain per stage of InP is 50% greater than the gain per stage of GaAs amplifiers, and the DC power consumption per stage is 33% lower. Their operating voltage is half that of GaAs amplifiers.

InP HBTs offer similar performance improvements plus higher operating frequencies. ICs based on InP HBTs have set numerous speed and bandwidth records in recent years.

InP-based HBTs have an $f_T$ and $f_{max}$ that are 40 GHz higher than GaAs HBTs at higher current densities. They have lower microwave noise figure at higher frequencies than GaAs. They have comparable third-order intercept to GaAs at higher frequencies for the same DC power. They have lower 1/f noise and corner frequencies than GaAs PIN diodes constructed from their collector-base junction make excellent photo-detectors.

OEICs Optoelectronic devices such as photodiodes and lasers can be integrated with electronic components to provide cost-effective optoelectronic integrated circuits (OEICs).

The ability to integrate microwave, digital and photonic functions on the same chip is critical to enabling a number of applications, such as conformal phased arrays.”

This page, Macom (1998a), also gives the current status of Semi-Insulating (SI) InP Wafers:

“The quality of SI InP wafers is still a long way behind GaAs, which is one of the key factors limiting the widespread application of InP devices. The table below {not included here} shows an example of a current industry specification for semi-insulating InP substrates. Note that, except for the mobility specifications, the requirements are very similar to semi-insulating GaAs.”

M/A-COM has received the Title III InP Award “to improve the availability of high-quality, large surface area semi-insulating InP” to overcome the scarcity of semi-insulating InP wafers.
Hughes is working on power InP-based HEMTs, which is of special interest here, as well as other applications of InP. Matloubian and Larson (1996) of Hughes discuss the issues involved in producing power HEMTs. They also have a large reference list. They say that InP-based HEMTs exhibit 67% higher mobility than GaAs-based pHEMTs which have GaInAs channels (GaAs-based pHEMTs). They say that InP-based HEMTs have an $f_T$ approximately 30% higher than the best GaAs-based HEMT or pHEMT materials and have “set record performances for the fastest transistor operating at room temperature with an $f_T$ of 343 GHz”. For power applications InP-based HEMTs have a thermal conductivity 40% higher than GaAs and have higher current densities than GaAs. Despite these advantages, there are a number of problems that must be overcome. A figure giving the interacting factors involved in optimizing the design of power InP HEMTs is given in their Figure 4 on page 281. These include Device Size, Gate Recess, Current Density, Gate Length, Source Vias, Substrate Thermal Conductivity, and Substrate Thickness. They state that the “basic requirements for a good power transistor for microwave and millimeter wave applications are the following: low knee voltage, high gate-to-drain and drain-to-source breakdown voltage, high current density, and high gain.” ... “at millimeter wave frequencies the operating voltage of the device is limited to less than 5V due to the rapid drop of $f_T$ with the drain-to-source bias. Therefore, breakdown voltages of approximately 10V are adequate for most applications and maximizing the power gain (without sacrificing output power) to improve the power-added efficiency typically becomes the most critical parameter.” In particular, this article covers those factors that have to be dealt with to achieve InP power devices. Shealy, Matloubian, Liu, Lam and Ngo (1997) of Hughes describe a high power density, high $\eta$ HEMT at 7GHz.

Hughes has a web site at Hughes (1998). According to M/A-COM’s links website, Hughes Research Microelectronics Laboratory, HRL, “has one of the world’s largest programs on InP electronics. Both HBTs and HEMTs are under investigation and are grown by MBE.” At the Hughes site, they discuss their research and development in HEMT and HBT technology using both InP and GaAs.

**“High Performance, HiRel Device & IC Pilot Line**

To capitalize on the rapid advances in InP technology and maintain its leadership over foreign competitors, HRL has established a pilot line for high performance microwave/millimeterwave InP- and GaAs-based devices and ICs. The facility was designed for cost-effective fabrication of state-of-the-art, HiRel parts. The staff consists of nationally recognized scientists and engineers who are developing advanced devices and ICs. The staff includes a core experienced in design of experiment (DOE) and total quality management (TQM) device fabrication for improved product reliability, improved process controls, reduced product costs, and reduced cycle time. Research and development is performed side-by-side with the fabrication of HiRel parts to provide, as rapidly and cost-effectively as possible, HiRel devices and ICs.”

From the same web page at Hughes (1998), they have graphs of the reliability of HEMTs and HBTs versus device junction temperature. These graphs, included below, clearly indicate the effect of channel or junction temperature on the reliability of the devices. Junction temperature management is obviously a key factor in design of reliable power HEMTs and HBTs. For the HBT shown, the relationship in the graph was found to be

$$\text{MTTF} = 10^{11} \times 10^{-\left(\frac{T-75^\circ C}{12}\right)} \text{ hours}$$
From this, it is easy to see that the higher the temperature, the lower is the MTTF in an exponential relationship. This example underscores the importance of maintaining control of the junction temperature. For the HEMT shown, the relationship in the graph appears to be

\[ \text{MTTF} = 10^{40.15} \times 10^{-16.574 \log_{10} T(\degree C)} \] hours

This appears to be a log-log graph, but it is difficult to read accurately. In any case, as before, the larger the junction temperature, the lower the MTTF.

**InP-based device reliability**

![Figure 3. MTTF vs. Channel Temperature for HEMT and HBT. From Hughes (1998).](image)

The reliability of InP-based HBTs and HEMTs is discussed in an article by Hafizi and Delaney (1994) of Hughes. They say, “The ultimate usefulness of this technology, however, depends on its reliability for system applications. Our extensive experimental data indicates that the reliability performance of millimeterwave InP HBT’s meets stringent system requirements such as flight specifications. Another InP-based technology, high-electron mobility transistors (HEMT) have, in the past five years, moved from the research laboratories to insertion in government and commercial electronic systems. For space payload applications of these two technologies, we have projected mean-time-to-failures in excess of $10^{10}$ hours at 45\(^\circ\)C operating temperature with corresponding activation energies of 1.6 to 1.9 eV. The failure rates are also vanishingly small with dispersions of 0.2 to 0.5 associated with the lognormal failure distribution.” So properly designed for temperature control, both HBT and HEMT technology is reliable.

TRW also has large programs in InP MMICs. As mentioned before, Elliott, Tran, Lai, Block, Cowles, Tran, Jones, Chen, Oki and Streit (1997) discuss the TRW foundary capabilities for InP-based MMICs using InP HEMTs and HBTs. Tran, Cowles, Yang, Block, Grossman, Kobayashi, Wojtowicz, Oki, Steit, Elliott, Callejo, Yen and Rezek (1997) of TRW describe their experiences with manufacturing InP-based HBT technology.
5.2 SiGe Materials

Silicon–Germanium, SiGe, is a promising material for millimeter-wave devices. Companies, such as IBM and Daimler-Benz, are investigating SiGe-based HBT devices. The advantages of this technology are better thermal conductivity than GaAs, more industry experience in Si and Ge devices, and no backside processing is required for heatsinking. Moniz (1997) of IBM gives a review article on the future of SiGe for RF applications in the 800 MHz to 2.5 GHz frequency range. He concludes that GaAs and SiGe will battle for RFIC Power Amplifiers and that LNAs and highly integrated RFICs will be predominantly Si/SiGe and that IBM’s SiGe BiCMOS technology “will be a force in RFIC products” in the future. He compares GaAs to SiGe. Rheinfelder, Strohm, Beisswanger, Gerdes, Schmuckle, Luy and Heinrich (1996) of Daimler-Benz report on Ka-band SiGe HBTs in MMICs. They use a completely coplanar process since it eliminates backside processing and easy access by on-wafer probing. Beilenhoff, Heinrich and Hartnagel (1992) used a 3-D full-wave analysis and finite differences in the frequency domain to model their layout. Finally, Sato, Tezuka, Soda, Hashimoto, Suzuki, Tatsumi, Morikawa and Tashiro (1996) describe development of a 2.4 Gbit/sec receiver using a Super Self-aligned Selectively grown SiGe Base (SSSB) Bipolar transistor. They report that the SSSB transistors have an fT of 60 GHz.

5.3 Different Geometries

Experiments with different geometries are covered in Sections 6.1.1 through 6.1.4. Examples are double-heterojunction HBTs and double-heterojunction pHEMTs. These are often used in practice for power applications because they tend to have higher breakdown voltages.

6. Thermal analysis and advanced heatsinking

Because the temperature issue seemed to be a major factor in preventing the mass production of 30 GHz power amplifiers with 2-10 W output capability, the INSPEC database for recent years was searched for thermal properties. Several searches were carried out; one such search is given below. Each paper in the database contains a Thesaurus Field. “DE(...)” selects those database items with the enclosed expression in the Thesaurus Field. “DE(...)” is the abbreviation for “Thesaurus Terms”.

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<td>DE(TEMPERATURE) or DE(TEMPERATURE CONTROL) or DE(TEMPERATURE DISTRIBUTION)</td>
<td>9200</td>
</tr>
<tr>
<td>#2</td>
<td>DE(THERMAL ANALYSIS) or DE(THERMAL CONDUCTIVITY) or DE(THERMAL CONDUCTIVITY OF SOLIDS) or DE(THERMAL DIFFUSION) or DE(THERMAL STRESS CRACKING) or DE(THERMAL STRESSES) or DE(THERMOELECTRIC EFFECTS IN SEMICONDUCTORS AND INSULATORS) or DE(THERMAL STABILITY)</td>
<td>2636</td>
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<td>#3</td>
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<td>#4</td>
<td>DE(MICROWAVE DEVICES) or DE(MICROWAVE FIELD EFFECT TRANSISTORS) or DE(MICROWAVE INTEGRATED CIRCUITS) or DE(MICROWAVE POWER AMPLIFIERS) or DE(MICROWAVE POWER TRANSISTORS)</td>
<td>938</td>
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<td>#5</td>
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It or similar searches were repeated for each year in the available INSPEC data bases. This process gave a list of “hits”. Promising articles corresponding from the list of “hits” were copied, read and summarized.

As was stated before, since the device’s electrical parameters for \( \{p\}\)HEMTs and HBTs depend on junction or channel temperature \( T \), it is necessary for power devices to use electro-thermal modeling. This results in a requirement to perform thermal modeling along with the electrical modeling of the devices. Advanced heatsinking is also needed to maintain the channel or junction temperatures at levels which result in suitable MTTF (see Figure 3). The papers that were found usually used either some kind of thermal analysis, or some kind of advanced heatsinking. Some used both.

6.1 Thermal Analysis

The papers that were found were divided into GaAs and InP results and those were further divided into HBTs and \( \{p\}\)HEMTs. A book that also contains thermal analysis information for MESFETs, HEMTs, and HBTs is Anholt (1995). The following Sections, 6.1.1 through 6.1.4, deal with GaAs HBTs, GaAs pHEMTs, InP HBTs, and InP HEMTs and pHEMTs.

6.1.1 GaAs HBTs

Liou (1996) covers GaAs HBTs. Some of the information that is in this book was also found in the published literature, except at an earlier stage of development. Two such papers are Liou, Barlage, Barrette, Bozada, Dettmer, Jenkins, Lee, Mack and Sewell (1995) and Liou and Bayraktaroglu (1994). The first paper has much about the use of a thermal shunt on the emitters of the HBTs to shunt heat away from the junction. More is said about this in the section on advanced heatsinking. The second paper demonstrates the thermal runaway in multi-finger HBTs that are improperly designed. Another paper, which does a careful study of this effect based on a simplified diode equivalent is Lu and Snowden (1996). This gives an excellent description of the problem. Another paper, which is useful is Schneider, Erben and Schumacher (1995). This paper gives “Thermo-Electrical Design Rules” for HBTs. Higgins (1993) gives a good overview of the problem and discusses both topside and bottom-side heat removal. McAndrew (1992) of AT&T Bell Labs gives an analytical electrothermal model for use in circuit simulators. He clearly shows the effect that self-heating has on the characteristic curves (See Figure 1). Marty, Camps, Tasselli, Pulfrey and Bailbe (1993) develop a physics-based model for electrothermal modeling of GaAs HBTs. Dikmen, Dogan and Osman (1994) develop a “high-temperature” physics-based model for HBTs with junction temperatures between 27°C and 300°C. This covers the temperature range which room-temperature devices would be expected to operate. Russell, Webb and Davis (1995) combine a “thermal diffusion simulator based on the TLM (Transmission Line Matrix) method and the standard circuit simulator SPICE.” This paper shows “current hogging in an Eight-Finger Device”. Camnitz, Kofol, Low and Bahl (1996) of Hewlett-Packard develop a Large Signal physics-based model using junction self-heating for the Hewlett-Packard MDS system.

Design issues for GaAs HBTs are discussed in several papers. Corcoran, Poulton and Knudsen (1991) of Hewlett-Packard cover HBTs from the analog circuit design viewpoint and describe a thermal simulation tool that they developed. Gui, Gao and Morkoc (1992) of the University of Illinois study the peak junction temperature and power limitation of GaAs-based HBTs. Poulton, Knudsen, Corcoran, Wang, Pierson, Nubling and Chang (1992) state the need for electrothermal

6.1.2 GaAs pHEMTs

Fewer papers turned up as “hits” in the years searched from 1989-1997 for GaAs pHEMTs than for GaAs HBTs. This probably is because the search emphasized temperature and thermal analysis of microwave devices. A number of papers on thermal modelling of GaAs MESFETs did show up in the search and are included in the second paragraph below that begins with “As mentioned above”. Ross, Svensson and Lugli (1996) is the book referred to earlier about GaAs pHEMTs. Section 4.1 above covers much relevant information from this book. Two other chapters of interest here are on “Accurate Active Device Models for Computer Aided Design of MMICs” and “Advanced CAD Models”. These chapters reference MESFET and HEMT models developed by Dr. Iltcho Angelov and colleagues. In a July 7, 1998 visit I made to Dr. Angelov at the Department of Microwave Technology at Chalmers University of Technology in Sweden, he provided me with two recent reports on HEMT and MESFET Modeling. These are Angelov (1996b) and Angelov (1996a). In these two reports and the numerous papers referenced, he gives large signal models for HEMTs that include the temperature variation. The starting point for deriving this model is a MESFET model. This Chalmers Model has been incorporated into Microwave Circuit Simulators. In Appendix 3 of Angelov (1996b), he gives a procedure for extracting the HEMT model of a power HEMT. This seems to be an invaluable reference for HEMT modeling. Dr. Angelov recommended the Philips foundary in France as a reliable source of HEMTs up to 70 GHz. One interesting paper using this 0.2µm HEMT MMIC technology from Philips Microwave Limeil (PML) is Ribas, Bennouri, Karam and Courtois (1997). They are able to make micro-electro-mechanical systems (MEMS), including suspended microstrip transmission lines and planar suspended spiral inductors using this process. They also describe a CAD engineering kit including the micromachining design rules on the Mentor Graphics framework.

The highest output power reported at 30GHz using power pHEMTs was given by Siddiqui, Sharma, Callejo, Chen, Tan and Yen (1996) of TRW. More will be said about this paper in Section 6.2.2 of this report. Ingram, Stones, Huang, Nishimoto, Wang, Siddiqui, Tamura, Elliott, Lai, Biedenbender, Yen and Allen (1997), also of TRW, report on a 6W Ka-Band Power Amplifier using GaAs-based pHEMT technology at 34.5 GHz. Chou, Li, Leung, Wang, Chen, Lai, Wu, Kono, Liu, Scarpulla and Streit (1997) report on failure mechanisms in thermally stressed power pHEMTs. They give a table summarizing state-of-the-art power performance of GaAs-based pHEMTs.

As mentioned above, a number of papers on GaAs MESFETs turned up as “hits” in the thermal analysis search of microwave devices. These hits are discussed here. Wright, Marks and Decker (1991) describe some analysis methods for determining the GaAs MMIC junction temperatures from the static heat flow equation. They evaluate four different solution methods, including 1) series solution, 2) finite difference method, 3) finite element method, and 4) boundary element method. They discovered that the series solution was easiest. Rizzoli, Lipparini, Costanzo and Frontini (1993) use a Green’s function technique and a three-dimensional numerical approach for the

A number of applications of GaAs pHEMTs were also found in the literature search. Kalayci, Tempel, Lutke, Akpinar and Wolff (1995) give a Ka-band medium power amplifier using MESFET technology. Lai, Nishimoto, Hwang, Biedenbender, Kasody, Geiger, Chen and Zell (1996) of TRW use source vias to fabricate a 59-64 GHz amplifier with 275mW output power at 27% power added efficiency $\eta$. They say, “This is the highest reported combination of output power and power added efficiency reported to date at this frequency band.” Yarborough, Saunier and Tserng (1996) “compare the performance of a three-stage amplifier using both pHEMTs and ion-implanted MESFETs as the active devices. Output power, gain, efficiency, and intermodulation distortion are compared.” The pHEMTs are DH-pHEMTs. Their conclusions are quoted below:

“We have demonstrated 1 watt CW output power, high-gain, three-stage MMIC amplifiers using 0.25 $\mu$m pseudomorphic AlGaAs/InGaAs HEMTs and 0.2 $\mu$m ion-implanted MESFET technologies at Ka-band. The 0.25 $\mu$m pHEMT process achieved the highest gain and power-added efficiency performance, demonstrating greater than 20 dB power gain and an average 35% PAE (37% peak) over a 26.5 to 28 GHz band. An alternate, low-cost solution was demonstrated with direct ion-implanted 0.2 $\mu$m GaAs MESFETs at a penalty of 2 dB lower power gain, and 9 to 13 percentage points lower PAE performance. High carrier to third-order intermodulation ratios at moderate to low signal levels indicate these amplifiers are suitable for wireless communication applications at millimeter-wave frequencies.”

Nash, Platzker, Wohlert and Liss (1997) of Raytheon give a 42 to 45 GHz amplifier with 1.4W output power using GaAs-based pHEMT technology. They describe in detail the design process they went through. Mondal, Dietz, Vu, Peterson, Haubenstricker, McReynolds, Laux, Moghe, Rice and Aina (1997) of Northrup report on research into making MMDAs (Microwave and Millimeterwave Device Arrays). They say, “MMDAs that consist of pHEMTs, diodes, and active layer resistors are developed with the same concept as digital arrays but remain stored on partially processed wafers.” They use GaAs for 20-100 GHz MMIC designs. They present one set for low noise applications and another set for medium power applications. With this, they are able to make a wide variety of different functions. Stenger, Sarantonos, Niehenke, Fudem, Schwerdt, Kuss, Strack, Hall and Masti (1997) give a transmitter design with Ku-band input, processing at Ka-Band and with 1-watt peak output at W-Band. Finally, due to a number of common processing steps, HBTs and pHEMTs can be grown on the same substrate. Kobayashi, Oki, Umemoto, Block and Streit (1996) use GaAs-based pHEMTs for the front-end Low Noise amplifiers and the local oscillator amplifier. “Low noise figure is provided by the HEMTs for receiver sensitivity while ... excellent $V_{th}$ threshold and beta matching is provided by the HBTs enables good active double-balanced mixer performance in a compact area.” The 2-$\mu$m HBTs have $f_T$ of 23 GHz and the 0.2$\mu$m pHEMTs have an $f_T$ of 80GHz. The receiver is designed to operate over the 1.4-2.6 GHz band.
6.1.3 InP HBTs

Jalali and Pearton (1995) covers InP HBTs, but a copy wasn’t found in time for this report. A recent survey paper on InP-based HBTs is Chau, Liu and Beam (1996) from Texas Instruments (TI). They say that “InP-based HBTs have recently emerged as the fastest bipolar transistors in the world.” The advantages of InP-based HBTs over GaAs-based HBTs include “lower power consumption, higher speed, and larger gain” and high current driving capability. They give recent results on both InP-based single-heterojunction bipolar transistors (SHBTs) and double-heterojunction bipolar transistors (DHBTs). As mentioned previously, DHBTs are preferred for power applications. They say that SHBTs have achieved $f_T$ and $f_{max}$ as high as 200 GHz and 236 GHz, respectively, and that DHBTs have achieved $f_T$ and $f_{max}$ as high as 160 GHz and 267 GHz, respectively. They report that the value of $f_T$ for InP-based SHBTs is significantly higher than the best value for GaAs-based HBTs, 171 GHz. They give a number of Figures comparing the InP-based technology figures of merit for the processes of a number of different companies. They also say that it is often assumed that since the thermal conductivity of InP is more than GaAs that the junction temperatures of the InP device is less than the GaAs device, all other factors being the same. They point out, however, that this is not necessarily true, since InGaAs has a very poor thermal conductivity. They use a three-dimensional numerical simulator developed at TI to model the behavior including the InGaAs layer. They give an interesting Figure on the temperature distribution in an eight-finger InP DHBT (their Fig. 3, p. 117). They mention that rise in junction temperature in InP SHBTs will cause a transistor to blow up when $I_{CEO}$ becomes excessive at elevated junction temperatures. They show that a power DHBT can be achieved with only 194Å InGaAs in the collector.

Some papers on applications of InP-based HBTs were also found. Kobayashi, Cowles, Tran, Block, Oki and Streit (1995) and Kobayashi, Cowles, Tran, Block, Oki and Streit (1996) of TRW report on an InP HBT distributed amplifier for 2-32 GHz and 2-50 GHz, respectively. Kobayashi, Tran, Cowles, Block, Oki and Streit (1996) of TRW report on InP-based HBTs direct coupled amplifiers. They compare this to GaAs and SiGe HBT and BJT performance (their Figure 1). Their InP-based HBTs operated at low supply voltages between 2 and 3 Volts and achieved a record Gain-Bandwidth-Product per DC power of 3.66 GHz/mW. The closest competitor was SiGe from Daimler-Benz. Streit, Gutierrez-Aitken, Cowles, Yang, Kobayashi, Tran, Block and Oki (1997) of TRW describe “an InP-based HBT fabrication line to produce HBT integrated circuit in high volume”. Since InP-based HEMTs and InP-based HBTs have a number of common processing steps, InP-based HBT and HEMT MMICs are “processed together on the same production line using as many common process steps as possible”. They give a low voltage power amplifier produced on this line that gives 2W of power at 950 MHz. They also comment that by combining HBTs and HEMTs on the same MMIC, the next generation of InP HEMT-HBT MMICs will be able to provide op-amp capability at millimeter wave frequencies. Tran, Cowles, Yang, Block, Grossman, Kobayashi, Wojtowicz, Oki, Steit, Elliott, Callejo, Yen and Rezek (1997) of TRW follow up the above paper with this one giving some modeling details of the HBT process, which again achieved new records. Bauknecht and Melchior (1997) report on InP-based DHBTs giving 0.6 W of power at 10 GHz. Nguyen, Liu, Chen, Virk and Chen (1997) of Hughes report on the engineering of InP-based power DHBTs and give details of the experimental results at 2, 9, and 18 GHz. They noted the expected current gain collapse at higher collector voltages. Hong, Song, Bhat, Chough, Hayes, Sugeng, Wei and Hwang (1993) of Bellcore, Red Bank, NJ, also describe their experiences in developing InP-based microwave power DHBTs. Datta, Shi, Roenkher, Cahay and Stanchina (1997) do modeling and design of an InP-based pnp HBT and give curves of figures-of-merit vs. doping levels in the base and collector. Swahn, Lewin, Mokhtari, Tenhunen, Walden and Stanchina (1996)
in a joint venture between Hughes, Ericsson, and KTH describe development of a 40 Gb/s fiberoptic
demonstrator system using InP-based HBTs. Finally, Schaffer, Warren, Bustamante and Kong
(1996) of Hughes report on a 2 GHz 12-bit DAC. The Hughes InP HBT process was used. High
speed ADCs and DACs are needed to provide the all-digital broadband radio, like the WIRAC
project requires. So, this paper is interesting from that perspective.

6.1.4 InP HEMTs and pHEMTs

As mentioned before, Ross, Svensson and Lugli (1996) is the book dealing with GaAs-based
pHEMTs. However, they do have a chapter by Matloubian and Larson (1996), who are from
Hughes, on InP-based power HEMTs at the back of the book. In addition to this reference, relevant
articles were chosen from the InP Conference [see InP (1997)]. From this Conference, Putnam,
Somerville, del Alamo, Chao and Duh (1997) present an experimental and theoretical study of the
temperature dependence of the off-state breakdown voltage of InP-based DH-pHEMTs. This work
is important because breakdown voltage is an important parameter for power pHEMTs. They
present a new model for these effects. Onda, Fujihara, Wakejima, Mizuki, Nakayama, Miyamoto,
Ando and Kanamori (1997) present a new type of InP-based pHEMT, which they call a Channel
Composition Modulated Transistor (CCMT). This is intended to improve electron transport and
confinement in the channel. Chen, Lai, Wang, Yen, Streit, Dia, Jones, Block, Liu, Huang, Chou and
Stamper (1997) of TRW study the effect of the gate recess etch process in DH-pHEMTs for high
power applications at 94 GHz. They demonstrate a MMIC amplifier which has an output power of
130 mW with 13% PAE at 94 GHz when biased at 2.7 Volts. This represents the best output power
of a single InP-based MMIC at this frequency. They show that this InP-based MMIC outperformed
their GaAs-based counterparts in PAE. Migliore, Chavarkar, Yen, Mishra, Fischetti and Laux (1997)
propose a new engineering of the InP-based HEMT to obtain high fT and fmax, and call the new
device a Lateral Bandgap Engineered HEMT (LBE-HEMT). They use a 2-D simulator called
DAMOCLES to generate the needed electron velocity profiles in the InGaAs channel.

In the application area, Daimler–Benz AG is working with InP-based HEMTs. Among their efforts
are Berg, Dickmann, Guehl and Bischof (1996), Berg, Dickmann, Bischof, Kossowski and Narozny
(1995), Berg, Hackbarth, Maile, Dickmann, Guhl, Adelseck and Hartnagel (1996), and Berg,
Hackbarth, Maile, Kossowski, Dickmann, Kother, Hopf and Hartnagel (1996). In addition, Berg,
Hackbarth and Dickmann (1997) use lattice-matched InP-based HEMTs to design a Broadband
Amplifier for the 80-100 GHz range. They used the HP MDS to simulate and optimize the amplifier.
Lai, Wang, Chen, Block, Liu, Streit, Tran, Siegel, Barsky, Jones and Gaier (1997) of TRW report on
the highest frequency solid-state amplifier to date providing 12 dB gain at 155 GHz. This is done with an InP-based HEMT process. They believe that their process can provide InP-based HEMTs with useful gain up to 220 GHz. They used a 0.1 µm InP HEMT MMIC process. As mentioned before, Elliott, Tran, Lai, Block, Cowles, Tran, Jones, Chen, Oki and Streit (1997), also of TRW, report on a 3-inch fabrication line for InP-based HEMT and HBT MMICs. Since HEMT and HBT fabrication have a number of common processes, as mentioned earlier, it is possible to use many of the same steps. This paper also discusses the change from 2 inch to 3 inch wafers. TRW has transitioned the InP MMIC fabrication line from R&D to production. More than 50 different MMICs have been fabricated on this line to date. Cowles, Lai, Tran, Wang, Chen, Kobayashi, Block, Yen, Liu, Oki and Streit (1997), also of TRW, have designed an InP-based process in which HEMTs and HBTs can both be fabricated on the same MMIC. This paper describes the steps that they had to use to do this successfully. They fabricated a number of MMICs that used both HEMTs and HBTs. Hagimoto, Kataoka, Yoneyama and Kobayashi (1997) discuss the impact of InP-based
integrated circuits on lightwave communication systems. This paper is concerned primarily with
digital transmission technology and presents a demonstration of a 40Gbit/s optical transmission
experiment using these integrated circuits. Finally, Walden (1996) of Hughes reviews recent
progress on InP-based receiver front ends.

6.2 Advanced Heatsinking

The papers that were found also included advanced heatsinking technology that removes heat from
the device’s active region. In order to remove heat from the junction or channel, materials are
thinned mechanically and chemically. Electro-thermal analysis and design are required to get
optimum results. Advanced heatsinking, including using vias and bridges for heatsinking, is required
for successful designs. For example, pHEMT performance is enhanced by the gate definition
process and by backside processing [Ross, Svensson and Lugli (1996), pp. 109-124] which thins the
wafer down to a minimum and then heatsink metallization is added to the thinned wafer so as to
improve temperature performance. Under areas of the MMIC device which are used for pHEMT
active devices, the substrate is thinned to 30-50 microns and a “bathtub” is formed to provide for
heatsink metallization under the active devices, which then remove heat quickly from the devices.
They give an example and say a “2 W power transistor on a 200 micron thick substrate held at an
ambient temperature of 70°C has a junction temperature of 230°C. A similar transistor on 100
micron thick substrate with a bath tub heat sink has a junction temperature of 160°C. ... This
technique of selectively heat sinking the transistors in the MMIC also has the benefit of reducing the
wafer breakages as wafers of sub 100 micron thicknesses tend to be very prone to break during
processing.”

![Figure 4. Bathtub heatsinking (a) and selective thinning (b) of regions under active devices. From Ross, Svensson and Lugli (1996).](image)

The fact that HBTs and pHEMTs can be grown on the same substrate leads to the conclusion that
similar heat removal techniques can be used for HBT and pHEMT power devices. The book on
pHEMTs, Ross, Svensson and Lugli (1996), has considerably more detail about how to handle the
“wasted” power dissipated in heat than does the book on HBTs, Liou (1996). In the papers in the literature, similar techniques are used for both devices.

Two figures from Ross, Svensson and Lugli (1996) are given in Figure 4. As shown here, the backside of the substrate is thinned mechanically and then it is further selectively thinned under the active devices using backside processing steps. This also shows that via holes can be used to connect the backside heatsinking with the face of the device. Airbridge – via connections are useful and airbridges are used for heatsinking also. Ross, Svensson and Lugli (1996) show how an airbridge is fabricated in their Figure 6, page 114. Anholt, Bozada, Desalvo, Dettmer, Ebel, Gillespie, Havasy, Ito, Jenkins, Nakano, Pettiford, Quach, Sewell and Via (1996) give the figure shown in Figure 5 below. It shows how airbridges are used for heatsinking HBTs. The details will be discussed in Section 6.2.1. The groups that are being successful at designing and fabricating power amplifiers in the one to six Watt output range at Ka-Band have used electro-thermal design and advanced heatsinking. Two groups who have been successful, TRW in the USA and NEC in Japan, will be featured in the next two Sections, 6.2.1 and 6.2.2.

Figure 5. HBT Airbridge heatsinking. From Anholt, Bozada, Desalvo, Dettmer, Ebel, Gillespie, Havasy, Ito, Jenkins, Nakano, Pettiford, Quach, Sewell and Via (1996).

Some other designs using these techniques will be mentioned. Chou, Li, Leung, Wang, Chen, Lai, Wu, Kono, Liu, Scarpulla and Streit (1997) of TRW give a table of state-of-the-art power performance of GaAs pHEMT MMICs at Q-band(33-50.5 GHz), V-band(50-75GHz), and W-band(75-110GHz). They investigate high channel temperature effects in pHEMTs. Simon, Wohlert, Wendler, Aucoin and Vye (1996) describe low, medium, and high power pHEMT amplifiers intended as TWT drivers. Chau, Hill, Yarborough and Kim (1996) give a comparison of K-band power transistors from several different organizations, including MESFET, pHEMT, and HBT technologies. They report on GaAs-based HBTs at 20 GHz. They obtain the highest output power (1.18 W), power density (3.93 W/mm), and close to the highest PAE (57.1%) of those in their comparison. In a paper the next year the same authors, Chau, Hill, Yarborough and Kim (1997), report that “Unlike our baseline collector air-bridge layout configuration, however, the power gain and therefore the power-added efficiency were significantly improved by using an emitter airbridge to connect individual emitter fingers within the unit cell to nearby ground vias to reduce the emitter inductance.” They give a figure that is similar to Figure 5 above. They say that “Compared to MESFETs and pHEMTs, HBTs offer significantly higher output power, power density, and
operating voltage.” They refer to their previous paper, Chau, Hill, Yarborough and Kim (1996). Another paper, which uses thermal shunts and bathtub thermal management techniques, is Bozada, Barlage, Barrette, Dettmer, Mack, Sewell, Via, Yang, Helms and Komiak (1995). This group has many of the same members as the group that presented Figure 5 above. They show both Common-Emitter and Common-Base thermal shunted power cells in GaAs-based MMIC power amplifiers. They go into detail about the “successful integration of the ... thermal shunt HBT with the ... bathtub technology”. They comment that this produced a record combination of efficiency, gain, and linearity at Ku-Band (12.4-18.0 GHz). They say, “We attribute these highly linear/efficient characteristics to the thermally stable HBT operation which allows the high peak current during rf large-signal swing.” Another paper from this same group is Liou, Barlage, Barrette, Bozada, Dettmer, Jenkins, Lee, Mack and Sewell (1995). This is a thermal analysis paper for their thermal shunting techniques for HBTs. We can reasonably say that thermally stable operation at Ka-Band requires advanced heatsinking techniques, such as those shown here. In the following two Sections, we will look at the NEC and TRW groups. Both have been successful in making R&D power amplifiers with around 5W output at Ka-Band. NEC of Japan used HBT technology, while TRW of USA used pHEMT technology, so this also gives a look at solutions in these two technologies.

6.2.1 NEC, Japan, HBT

The NEC group used a very methodical approach. This comes across in their papers and so it is interesting to track their progress. They have given detailed accounts of the design and development of their power HBTs. Their first paper in this series is Amamiya, Kim, Goto, Tanaka, Furuhata, Shimawaki and Honjo (1994), which shall be called [NEC1] here for convenience. In this paper, they use an ultra-high Carbon doping in the regrown extrinsic base region to obtain an extremely low base resistance. They develop both Common Emitter (CE) and Common Base (CB) versions of six-emitter HBT power transistors. These are shown in Figure 6a and Figure 6b, respectively. They report on a three dimensional TLM thermal simulation that they performed to design the emitter fingers. The emitter fingers in their designs were 1.6µm x 6.1µm in size. The Table on page 20 summarizes their results. From this data, they conclude that the CB structure is preferred over the CE structure since the CB structure has the highest gain and PAE and close to the same power output. They conclude “Further improvement in the power performance can be expected by revised

![Figure 6a. Six finger common emitter structure. From [NEC1].](image1)

![Figure 6b. Six finger common base structure. From [NEC1].](image2)
layout to reduce grounding inductances.” Therefore, all of their following papers use the CB structure.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Gain</th>
<th>Output Power</th>
<th>PAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE</td>
<td>2.5dB</td>
<td>404mW</td>
<td>16%</td>
</tr>
<tr>
<td>CB</td>
<td>9.1dB</td>
<td>365mW</td>
<td>23%</td>
</tr>
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</table>

They follow up [NEC1] with Kim, Tanaka, Amamiya, Furuhata, Shimawaki, Miyoshi, Goto and Honjo (1995), which shall be called [NEC2]. They use the Common-Base GaAs-based HBT technology at 26.85 GHz and obtain 0.65W and PAE of 16%. One thing that they say in this paper that is a critical piece of information is that SSPAs (Solid-State Power Amplifiers) “operated in the near-millimeterwave frequency band should be designed within a physical length of (~400 µm at 26 GHz, is a wavelength on GaAs substrates) to avoid phase difference of input signals among the fingers.” They also comment that, as we have seen here, the electrical performance of HBTs is limited by thermal instability. They say, “we designed power cells in a common-base (CB) configuration for operation in the 26 GHz band. Each power unit cell had 12 unit fingers (total junction area = 480 µm²) and each unit finger consisted of four emitters (1.6µm × 6.1µm × 4 emitters).” Thus, each emitter in their design was 1.6µm × 6.1µm in size, which is the same size as in [NEC1]. Figure 7 shows this design. One can see the similarity to Figure 6. They say, “We determined the geometries of the emitter fingers and the chip by a three-dimensional thermal analysis (that) considered the local-temperature dependence of the collector current. From the analysis results, we determined the emitter finger spacing and the chip thickness to be 15 µm and 30 µm, respectively. We also used a thick metal bridge and a plated heat sink (PHS) structure to improve the thermal stability. A 10-µm-thick Au bridge was metallized to connect all emitters. This bridge can achieve thermal stabilization without the use of emitter ballasting resistors resulting in degradation in RF characteristics. The substrate was lapped and etched down to 30 µm, and a 30-µm-thick Au plate was metallized for a PHS structure to reduce the junction temperature (thermal resistance).”

![Figure 7. 12 finger HBT with 4 emitters per finger and side vias. From [NEC2], Kim, Tanaka, Amamiya, Furuhata, Shimawaki, Miyoshi, Goto and Honjo (1995).](image-url)
They add, “In multi-finger devices, power gains, i.e., and MSG/MAG, are significantly decreased with increasing an active device area (the number of fingers) because of an increase in parasitic inductance to ground. To reduce the severe degradation in the power gains, we used multiple through-wafer via holes. The via holes were made larger and closer from the fingers to ground than those fabricated in previous work.”

They show infrared camera images of devices with and without the thick Au thermal bridge, while maintaining power dissipation at 0.71 W. Peak temperatures were 70°C and 110°C, respectively. They say, “Due to the thick Au bridge, the developed HBT exhibited uniform temperature distribution among the emitter fingers, resulting in significant reduction in the junction peak temperature. From this result, it is easy to see that the thick Au bridge is very effective in improving thermal stability.” They conclude their paper by saying, “We believe that more output power can be produced by connecting several power cells in parallel with well-designed matching and divider/combiner networks.”

In the next paper in the series, Tanaka, Murakami, Amamiya, Shimawaki, Furuhata, Goto, Honjo, Ishida, Saito, Yamamoto, Yajima, Temino and Hisada (1996), which shall be called [NEC3], they experiment with this. They report that “The for 1.6µm × 6.5µm size emitter was 142 GHz and 238 GHz for a uniform base and graded base HBT, respectively.” They take an input signal and with a power divider circuit, split the power into six signal paths. For each signal path, they use a power cell consisting of one such as shown in Figure 7 that is capable of producing 650 mW of output power. They then power combine the outputs of the six signal paths together with a power combining circuit. Doing some simple arithmetic, ideally, this would provide an amplifier with a power output of 3.9W. They say, “The 6-chip combination produced 2.2W with 5 dB associated gain and 19% PAE (corrected for fixture loss) at 24 GHz. Considering the potential power output for each cell, greater power (>3W) should be obtained by optimizing the power combining circuit (note that the power output is not saturated).” This illustrates some of the difficulties in producing power transistors at this frequency by power combining.

In [NEC3], from which Figure 2a was taken, they also study the design of new unit-cell chips and report on three different designs, called designs A, B, and C by the authors. The original paper had 12 fingers and 4 emitters per finger. Each emitter was 1.6 µm × 6.1 µm, giving a total junction area of 480 µm², a power of 0.65 W and a power density of 1.35 mW/µm² at 16% η. The new unit-cell designs are shown in the following table:

<table>
<thead>
<tr>
<th>Design</th>
<th>Each Emitter</th>
<th>Emitters/finger</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.6µm × 9.6µm</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1.6µm × 9.6µm</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>1.6µm × 19.6µm</td>
<td>1</td>
</tr>
</tbody>
</table>

Design A has only one emitter per finger, design B has two emitters per finger, and design C has one emitter per finger, but it is more than twice as long as those in designs A and B. They note that “A long emitter (> 20 µm) is preferred at X-band, but is not suited to higher bands where the emitter behaves more like a lossy transmission line due to internal capacitances and resistances. This can be seen by the type-C cell ... which suffers in both power density and PAE (< 15%). The device with
short length, double emitter (type-B cell) showed reasonable power density (>1mW/\mu m^2) and PAE (>20%). However, this particular type of cell showed a nonlinear relation between input and output power, probably due to thermally unstable operation. The best power performance was obtained for the type-A cell (12-finger), which showed maximum output power of 480 and 740 mW for devices with a uniform and graded base, respectively.” Their type-A cell (12-finger) is shown in Figure 8a and my sketch of one of the subcells of a 4 finger HBT with two emitters per finger is in Figure 8b.

Power added efficiency \( \eta \) varies as a function of input power. They show that the maximum \( \eta \) for the 12-finger type-A cell with graded based is 42%. Referring to this record high \( \eta \) for HBTs, they say, “The record high PAE for power HBTs in the near mmWave band (> 25GHz) is 20% improvement over that of conventional HBTs.” Here they refer to their 1995 paper [NEC2], which had PAE of 16%. They continue, “The difference is attributed to the via hole layout, which provides equal grounding conditions for each sub-cell ..., as compared to the side-via design used in our previous work... The reduced grounding inductance was more beneficial for the common emitter (CE) cell which showed about 10% improvement over that of the CB cell. Nevertheless, the CE cell was discarded because much higher gain was obtained by using the CB cell..., particularly for large cells.”

For the type-A unit-cell of Figure 8a with a graded base, each emitter was 1.6 \( \mu \)m \( \times \) 9.6 \( \mu \)m, giving a total junction area of 184 \( \mu \)m^2, an output power of 0.74 W and a power density of 4.0 mW/\mu m^2 at 42% \( \eta \)(PAE). They show that the power density and the PAE were dramatically increased from the conventional design of Figure 7 when they used the new design shown in Figure 8a.

In the last paper in the series, Murakami, Tanaka, Amamiya, Shimawaki, Goto, Honjo, Ishida, Saitoh, Yajima and Hisada (1996), which shall be called [NEC4], they report on the “Unit cell” given in Figure 8a. At 23.5 GHz, they say that the power output is 940 mW, PAE is 46%, and gain is 7.8dB. They also give Figure 9 on the next page which gives the power out and PAE at 23.5 GHz as a function of input power for a unit-cell amplifier as shown in Figure 8a.

![Figure 8. (a) 12 finger HBT with one emitter per finger and vias with equal grounding conditions. From [NEC3] (b) Sketch of a 4 finger HBT with two emitters per finger. (Hanson)](image)
In [NEC4] they report on the results of fabricating and testing a four input–four output version of the design in Figure 8a from [NEC3]. This is shown in Figure 10 on the facing page. Note that they call the cells “fish-bone-type” cells. From this Figure, one can see that they have taken four “Unit-cells” of the type shown in Figure 8a and placed them side by side. This results in a four input–four output chip. They then take two of these chips and, using the emitters as inputs and the collectors as outputs, they then have an eight input–eight output transistor. They take an input signal and using a power divider circuit, they split the input signal into eight signal paths. They apply each signal path to an emitter lead. Then at the collector, they take the eight outputs and using a power combiner circuit, power combine the eight collector signals into a single output. They say in conclusion, “an AlGaAs/GaAs HBT power amplifier composed of CB-HBT chips has achieved an output power of 3.63 W (35.6 dBm), PAE of 21.2%, and linear gain of 6.2 dB with a 1-dB bandwidth between 25.5 and 26.5 GHz. ... This work shows great potential for higher power (> 5W), higher efficiency (> 30%) HBT amplifiers at 26-GHz band and higher frequencies.”

Some simple arithmetic is worth doing. Since the individual “Unit-cells” obtained 740 mW in the 25–26 GHz band (see [NEC3]), and 8 times 0.74 is 5.92 W, then with ideal matching, divider and combiner networks the output power would be 5.92 W. Since 3.63 W was obtained, then this means that the matching, divider and combiner networks are not ideal and could probably be improved. This shows, however, that the main problem of thermal instability has been solved using the “Advanced Heatsinking” methods described and a significantly greater output power was obtained.

Two other papers by this same group at NEC are also of interest. First, Suzuki, Shimawaki, Amamiya, Nagano, Niwa, Yano and Honjo (1997) report on 50-GHz bandwidth base-band amplifiers using GaAs-based HBT’s. This is interesting since they used their HBT process to design direct-coupled amplifiers that can be used from baseband to 50 GHz. They obtained peak and of more than 100 GHz and 250 GHz, respectively. They say, “This value is larger than that for InP-based HBTs.” They conclude that “These are the widest bandwidths yet reported for lumped-amplifiers and are comparable to those of distributed amplifiers. These results show the great potential that these amplifiers have for use in future optical communication applications and millimeter-wave applications.” Second, Hayama, Kim, Takahashi, Goto and Honjo (1997) report...
on an L-band power HBT. Although it is at a lower frequency (L-Band) than we are interested in, this paper shows similar design procedures as were used above applied to a commercial use. They conclude, “The developed power HBT with 60 fingers of $2 \times 30 \mu m$ emitter exhibited 31.4 dBm output power and 61% power added efficiency... These results satisfy Japan’s PDC standard in a chip area that is less than 20% of that needed for a conventional GaAs power MESFET. Also, this is the highest PAE of an L-band GaAs power transistor reported to date for low-voltage digital cellular applications.”

![Figure 10. Front view of a CB-HBT chip consisting of 4 fish-bone-type cells composed of twelve 1.6 $\mu$m x 9.6 $\mu$m single emitter subcells. From [NEC4].](image)

### 6.2.2 TRW, USA, pHEMT

The TRW group obtained the best power results with the pHEMT technology, so it is interesting to track their progress in this area. They have given accounts of the design and development of their power pHEMTs. The papers that were found on power pHEMTs were in the 1996, 1997, and 1998 IEEE MTT-S Digests. One paper was found on Ka-Band power amplifiers in each year. In addition, there were three papers in the 1997 Digest from TRW reporting on power pHEMTs at higher frequency bands, the Q, V, and W bands. Since our focus for this report is the Ka Band, and explicitly for 30 GHz uplink, we will focus on the three papers found in the Ka Band. These are Siddiqui, Sharma, Callejo, Chen, Tan and Yen (1996), which will be called [TRW1], Ingram, Stones, Huang, Nishimoto, Wang, Siddiqui, Tamura, Elliott, Lai, Biedenbender, Yen and Allen (1997), which will be called [TRW2], and Siddiqui, Sharma, Callejo and Lai (1998), which will be called [TRW3]. GaAs-based devices are used in all cases. Three substrate thicknesses are reported: 1.2 mil, 2 mil, and 4 mil. Since there are 25.4 $\mu$m/mil, this translates to 30 $\mu$m, 51 $\mu$m, and 102 $\mu$m, respectively. Consequently, 30 micron, 50 micron, and 100 micron substrates, respectively, are the closest even metric equivalents.

In the first paper [TRW1], they report on a pHEMT power amplifier for the 27.5 to 29.5 GHz band LDMS (local multipoint distribution service) system. They use a GaAs-based pHEMT process “engineered to provide high breakdown voltage and high current densities.” The basic power amplifier is a 0.2 $\mu$m $\times$ 1600 $\mu$m device, which is designed with sixteen 100 $\mu$m wide gate fingers with each gate 0.2 $\mu$m in length. So, their basic power amplifier can be viewed as a 1.6mm-wide pHEMT.

They use four of these 1.6mm-wide pHEMTs together with input and output matching circuits to lay out a hybrid power amplifier design using power dividing/combining. The input is power divided into four signal paths using a 10 mil Quartz substrate. This is followed by a 2 mil or 50.8 $\mu$m GaAs substrate containing the four signal paths and designed to provide input conjugate matching to the measured S-parameters. The input matching networks are followed by four of the 1.6mm-wide
pHEMTs described above. They report, “in order to reduce the thermal resistance of the basic cell, the active area below the device is thinned to about 30 µm for improved thermal resistance.” They say, “The output network consists of two cascaded sections of quarter-wave transmission lines. It presents a power match to the devices as well as serving as a power combiner.”

Their hybrid power amplifier “provides unconditional stability under all load conditions.” They fabricated several hybrid power amplifiers using the 1.6mm power pHEMT devices. They report that at 28 GHz, “The average small signal gain was 8.75 dB.” The power amplifiers “attained a power gain of 5 dB and output power of 37 dBm (5W) with 39.6% power-added-efficiency from 27.5 to 29.5 GHz.” Dividing 5W by 4 × 1.6mm they say, “this translates to greater than 780 mW/mm”, including output circuit losses. In conclusion, they say, “This definitely represents the highest output power, power density and efficiency ever reported at Ka-band from a single amplifier.”

In the second paper chosen [TRW2], Ingram, Stones, Huang, Nishimoto, Wang, Siddiqui, Tamura, Elliott, Lai, Biedenbender, Yen and Allen (1997) demonstrate a 6-Watt 24% PAE Ka-band power module with 21.5 dB power gain. They say, “The power module consists of a driver amplifier (chip) and two power amplifier chips.” TRW processes GaAs-based devices on 4-mil, 2-mil, and 1.2-mil substrates. They report that “Based on our past experience with 4-mil substrate designs, the power density delivered by 2-mil device(s) is at least 25-35% better than the 4-mil device of similar periphery.” They also say that “2-mil GaAs wafer offers the advantages of providing shorter thermal path and smaller via hole pattern to the back side, thus allowing multiple via holes to be inserted between gate fingers without increasing the pitch of the gate fingers. This multiple via holes to ground lowers the overall source inductance of the device. ... These multiple vias to ground also substantially improve the thermal dissipation of the heat generated per such small device area.”

The measured performance of the Ka-band power module was reported at 34.5 GHz. They give the figures for the performance of the driver amplifier alone and of the power amplifiers alone. A single power amplifier gave 3.5 W at 28% PAE. The entire Ka-band power module, including the Wilkinson dividers/combiners, one driver chip and two power chips, was measured to have “an output power of 37.5 dBm (> 6W) and PAE of 24% and an associated gain of 21.5 dB at 34.5 GHz.”

In the third paper chosen, [TRW3], which is by the same group as [TRW1], the application is again the local multipoint distribution service (LMDS) as in [TRW1]. They give the power requirement
for this application as 1 Watt. It is interesting to note that the title of [TRW3] is the same as [TRW1], except the word “MONOLITHIC” is added to [TRW3]. Their previous paper for LMDS used a hybrid approach. In this new paper, they use a monolithic approach instead of a hybrid approach. They give a Table comparing Ka-band power amplifiers. Referring to this Table, they comment on their earlier work in [TRW1], “It is clearly seen that the power density of 780 mW/mm, presented in [TRW1], is still the best power density achieved by a hybrid MIC amplifier.” In [TRW3], they demonstrate a monolithic power amplifier for the 27.5 to 29 GHz band. They report that the amplifier “attained peak output power of 33.9 dBm (2.4 W) and peak power added efficiency of 37%.”

They compare the hybrid MIC approach of their earlier work with the current MMIC approach. They say, “The large periphery devices used in high power amplifiers present very low impedance levels. The variations in assembly fabrication process invariably require extensive assembly, test and tune operations, which result in modules with high cost. The power MMICs, on the other hand, offer small size, reproducible performance, and high reliability. They are also highly cost effective due to minimum or no tuning requirements in module fabrication process.”

They continue, “In general, it is possible to attain high efficiency and high power density with smaller periphery devices. However, the power amplifier design challenge is to achieve high efficiency at high output power levels. An additional challenge in the design of monolithic power amplifier is to achieve power densities somewhat closer to that achieved by MIC power amplifiers which are usually tuned to get the best performance from devices.”

They use the TRW GaAs-based pHEMT process engineered to “provide high breakdown voltage and high current densities.” The substrate is 4-mil GaAs. This is interesting since they used 1.2 mil and 2 mil substrates in the previous works. They use both 0.15 µm gate length × 320 µm gate width devices and 0.15 µm gate length × 480 µm gate width devices as basic cells. The first stage of the two stage power amplifier uses 1.28 mm periphery devices. These drive the second stage. The second stage uses 3.84 mm periphery output stage devices. They used a Curtice nonlinear model to design the amplifier. Figure 11 shows a photograph of the 28 GHz monolithic power amplifier.

![Figure 11. Photograph of 28 GHz monolithic power amplifier. From [TRW3].](image)

They obtained an RF functional yield greater than 70%. They conclude, “To our knowledge this is the first time that the performance of monolithic power amplifier in terms of power density is close
to that achieved by hybrid MIC amplifiers and is approaching that of HEMT devices. The results are consistent since our 2 mil and 4 mil GaAs MMICs, and 1.2 mil GaAs discrete devices use the same process and device structure.”

Three other papers on power amplifiers by TRW are also of interest. These are the Q, V, and W band power amplifiers referred to before. First, Lester, Chi, Lai, Biedenbender, Garske, Rordan and Chow (1997) report on a 3 Watt Q-Band pHEMT MMIC power amplifier at 44.5 GHz. They say, “The waveguide power amplifier module features the use of thinned 2-mil GaAs MMICs with off-chip output matching and combining on a 5-mil alumina substrate.” They use TRW’s pHEMT 0.15 µm process. The power module is designed for WR-22 waveguide. Second, Hwang, Lester, Schreyer, Zell, Schrier, Yamauchi, Onak, Kasody, Kono, Chen and Lai (1997) report on a V-band (59 - 64 GHz) MMIC chip set for use as building blocks to create high power solid state power amplifiers with output power in the range from 1 W to 50 W. A 4-mil thick gain stage MMIC and a 2-mil thick power stage with 300 mW output power at 22% PAE were developed. Both are fully matched with 50Ω input and output impedances. They use a 0.15µm double heterojunction pHEMT process. The key change that they report making is the use of the 2-mil (50µm) thick substrates, which have the known advantages with low source inductance and lower thermal resistance. 3.5 µm thick gold was sputtered and plated on the backside of the wafer. Finally, Huang, Lin, Lai, Biedenbender, Huang, Wang, Geiger, Block and Liu (1997) report on a two-stage monolithic W-band power amplifier using a 0.1 µm GaAs-based pHEMT power process. They use a 2-mil thick substrate and obtain a maximum output power of 300mW with 10.5% peak PAE. They conclude, “To our knowledge, the 300-mW output power represents the highest output power for a single W-band power amplifier chip at this frequency.” They add, “This performance represents a breakthrough in monolithic millimeter wave PA design and demonstrates the maturity of power HEMT process capability.” These three papers, while not in the Ka-Band, demonstrate the advances that TRW is making with power pHEMTs.

6.2.3 Other Groups

Other groups are worth mentioning that aren’t covered elsewhere in this report. Of these, Lee (1997) reports on a 28 GHz transceiver with 0.5 W output using power combining. Saunier (1996) reports on progress in HFET and PHEMT amplifiers and says that they have designed and fabricated a pHEMT amplifier with 1.15 W output power, 20 dB gain and 37% efficiency at 27 GHz. Yarborough, Saunier and Tserng (1996) of Corporate Res. & Dev., Texas Instrum. Inc., Dallas, TX, USA, have ‘demonstrated a high-gain, high-efficiency Ka band three-stage MMIC power amplifier providing >1 watt CW output power, >20 dB power gain, with an average 35% power-added efficiency (378 peak) over a 26.5 to 28 GHz band using 0.25 µm AlGaAs/InGaAs pseudomorphic HEMT (pHEMT) process technology”. Chau, Hill, Yarborough and Kim (1997) of Texas Instruments report on an HBT that achieved 1.04 W CW output power and 65.7% power-added efficiency with 6.3 dB associated gain at 20 GHz.

7. Commercial Products Available

The web was searched for commercial devices available now, and except for one from DBS Microwave and one from Quinstar Technology, it was found that at 30 GHz the maximum power output was about 160mW for a commercial product. This is the TRW product shown in the data
APH238C
K-Band Power HEMT Amplifier

Features
- RF frequency: 23 to 32 GHz
- Balanced design for excellent return loss
- Pout max of 25 dBm
- Gain = 14 dB
- Unconditionally stable
- Compact size
- Biasable from either side

Description and Applications
The APH238C monolithic HEMT amplifier, a broadband, two-stage power device, is designed for use in commercial digital microwave radios, wireless LANs, and military high-reliability applications. The balanced design provides unconditional stability as well as excellent input and output VSWR. To ensure rugged and reliable operation, HEMT devices are fully passivated. Both bond pad and backside metallization are Ti/Au, which is compatible with eutectic die attach, thermocompression, and thermosonic wire bonding assembly techniques.

Design Goals

<table>
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<th>Specifications</th>
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</table>
QPN-2930-AA Solid State Power Amplifier with 1W output in the range 27.5-30 GHz. The retail price is US$16,900.

There were three more companies that were found that provided products in this frequency range. These are HP, MITEQ, and CTT. At the MITEQ webpage at Miteq (1998), a part AMF-6B-275300-19P was found that gave 19dBm of power at 27.5-30GHz. These were priced at US$3,315 each in quantities of 125. 125 of the devices would be needed to power combine to get 10W (assuming no losses!). This would cost US$415,000 just for the devices. At the CTT website CTT (1998), some millimeter wave amplifiers were found, for example, the ASW/400-1814, from 26.5-40 GHz, which has 18 dBm output power saturated. At the HP website at Hewlett-Packard (1998), HP had a 2 – 50 GHz Distributed Amplifier, the HMMC-5025, which has 12dBm power at 40GHz. HP also had a 20– 40 GHz Amplifier, the HMMC-5040, which has about 18dBm of output power. In conclusion, except for the ones from DBS Microwave and Quinstar Technology that offered 2W and 1W at 28GHz, the largest output power was on the order of 0.16 W. We need 40 dBm, DBS and Quinstar offer 33 and 30 dBm, and the others offer between 10 and 22 dBm.

8. Space and Network Power Combining/Splitting

All of the successful approaches to obtaining power in excess of 1W at 30 GHz used network, or circuit, power combining and network, or circuit, power splitting inherent in the approach. As we have seen, typically the input is split into 2, 4, or 8 signal paths using a power divider/splitter/combiner. Then each signal path is taken through one of a number of power amplifiers each of typically 1W or less. Then the amplified signal outputs are power combined using 2, 4, or 8-way Wilkinson power combiners. This is the approach that we have seen in the papers referenced in this report. They all use a network power combining scheme. At this time, the largest commercial solid state power output device is the one from DBS Microwave at 2W and 28GHz. Since we need 10W, if we used these devices, then we would need 5 of them and would have to use some power combining scheme. If we used the TRW chip, then we would need something like 60 of them if losses were neglected.

There is another possibility to achieving this power combining when it is desired to radiate the output power from the power amplifier. This approach is called Spatial Power Combining [See Hanson (1998b)]. In this approach, instead of using circuit power combining and one feed, spatial power combining uses multiple radiating antennas to handle the power combining. This is another way to radiate 10W, but have lower power amplifier output stages. For an ideal Spatial Power combiner, 8 radiators each radiating 1.25 W in phase would result in 10W radiated.

Two recent books on Spatial Power Combining were found. These are Navarro and Chang (1996) and York and Popovic (1997). These books appear to incorporate many of the ideas that were found in individual papers found by searching the INSPEC database. Time didn’t permit to finish the review of spatial power combining for Sarepta and WIRAC.
9. Conclusions

There is promising work in the manufacturing of solid state devices that are in the lab coming close to seeing output powers of 10W realized. It should be noted, however, that all of the successful approaches use circuit, or network, power combining of smaller powers to attain these levels. This fact leads to the conclusion that for attaining 10W of radiated power, an approach using *spatial power combining* and lower power units is feasible, and needs further exploration.

All the successful approaches required use of electro-thermal modeling and advanced heatsinking. The careful thinning of the brittle substrates and/or the application of bathtub heatsinking on the rear side of the wafer and of bridge heatsinking on the face of the wafer is required to obtain a successful design at present. There were many references found on thermal design, which could be the subject of another report, if time had permitted. This is an interesting subject in itself. The design of power amplifiers at 30GHz seems to be a job requiring many diverse skills, including thermal design of heatsinking. We have seen in Figure 3 that MTTF is exponentially related to channel or junction temperature. This reinforces the need to keep the devices cool for greatest reliability.

The largest powers found in the literature for pHEMT solutions come from the work by [TRW1] with 5W and by [TRW2] with 6W, and that for HBT solutions comes from the work by [NEC4] with 3.6W. Note that these are all using GaAs-based devices. [TRW1] obtain 37 dBm (5.0 W) from 27.5 to 29.5 GHz using a pseudomorphic HEMT (pHEMT) device. This is only 3dBm off of what we are wanting. The authors say that “This represents the highest output power and efficiency ever reported at Ka-band using MIC amplifiers. This was attained by combining the outputs of 4 pHEMTs on a chip carrier to realize this power level. Therefore, it appears that they have been successful in achieving a power output of about 1.25W from each pHEMT. So in theory, we would need only eight of these pHEMT devices, power combined, to get the needed 10 W power output. Similar comments could be said about the results of [NEC4] and [TRW2].

So at this point, there are promising results coming out of the laboratories. Planning needs to be done to decide how the Norwegian industry can utilize these research results reported here. Possibilities are to obtain power amplifiers on the order of 1W and do some sort of power combining, either network or spatial, to attain the needed output radiated power levels. This is applicable to both the Sarepta and the WIRAC projects at NTNU and SINTEF.

We have also seen that much research is being carried out in alternative materials to GaAs. InP is the other material that is at the forefront of research now and that many companies are active in InP research. These alternatives, presented in Section 6.1, are most applicable to the WIRAC project at NTNU and SINTEF.
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