Performance Capabilities of HBT Devices and Circuits for Satellite Communication

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Abstract—**We have investigated the HBT performance with emphasis on its possible utilization in satellite power amplifiers. After recalling the requirements of satellite power amplifiers the suitability of HBT is discussed in depth including the output power capabilities, the realizable power-added efficiency and linearity, reliability considerations and circuit aspects. Models and simulation tools of HBT in power amplifiers are discussed and the results obtained so far are quoted. A comparison of realized HBT and various FET devices and circuits demonstrates that the HBT is a promising device for applications in satellite power amplifiers. The HBT will be a preferable device for microwave power amplification if the problems concerning the reliability can be solved and further investigations will be performed to obtain larger devices with higher rated output power.**

I. Introduction

THE HIGH maturity reached for semiconductor devices allow their application in satellite solid state power amplifiers (SSPAs). In the past years GaAs-power MESFET became commercially available with excellent power performance at microwave frequencies. Apart from this development new devices raised the interest in spaceborn applications because of the progress in epitaxial growth of heterostructures on GaAs and InP. Based on these new structures High Electron Mobility Transistors (HEMT) and Heterojunction Bipolar Transistors (HBT) were developed. Both structures show excellent performance in the microwave and millimeter-wave range. Another candidate for future use in SSPA's are the MISFET on InP with a semi-insulating AlGaAs layer forming the insulator [1] and the pseudomorphic power HEMT [2] with multiple strained quantum well InGaAs channels.

The field of application for the HBT is still not quite clear. Because of its potential high cutoff frequency, low phase-noise, high linearity and high efficiency the HBT is promoted to be a future device for microwave oscillators and linear amplifiers [3]–[11]. In this study we discuss whether the HBT is also a promising candidate for microwave power amplification, since very high power densities have been reported for this device [12]. Another question is if the HBT will be able to compete with the new developments in MESFET and HEMT design and the InP MISFET. There are several open questions on optimum HBT device operation and technology. The advantages and disadvantages of the different material systems are also not clear yet.

This study concentrates on AlGaAs/GaAs as the most advanced system. The best results regarding output power have been published using this material.

II. Basic Requirements of Satellite Power Amplifiers

The special requirements of solid state power amplifiers (SSPAs) for satellite applications are as follows [13], [14]:

The linear microwave output power has to be up to 30 W at 2 GHz; 10 W at 12 GHz; 5 W at 20 GHz; 1 W at 26 GHz. These data imply that the single chip HBT has to exhibit an output power as high as possible since a complicated power combining results in reduced power added efficiency and reduced bandwidth.

Because a satellite is a system where the generated heat can be removed only by radiation, and because the dc-power supply is costly and weight-extensive the power added efficiency of the SSPA has to be as high as possible.

The input-output characteristic has to be linear in the operation range. This includes low AM/AM and AM/PM conversion and low 3rd order intermodulation distortion. This feature is important to meet the requirements of TDMA and FDMA operation with the related capacity increase.

A proven reliability is a key factor for the application of HBT's in satellite SSPA's.

It is advantageous when the active element can be inserted easily into the circuit. This includes an easy matching of input and output impedances to 50 Ω.

Further aspects are cost, size, weight, availability, radiation hardness and the dc-power requirements.

III. Suitability of the HBT for Satellite Power Amplifiers

In this section the suitability of HBT's for satellite power amplifiers will be investigated according to the requirements listed above.

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A. Output Power

The HBT is considered to be ideal for high power amplification because of its high power density of about 3.8 W/mm [15]. This feature enables the achievement of high output powers with of a multi finger HBT on a single chip without circuit combining techniques [16], because only a small chip area is required for a given power output. The largest distance between the emitter fingers can be kept small thus avoiding phase differences of input and output signals, which degrade the performance of the whole device. Therefore the performance of an HBT is not degraded if the number of emitter fingers is increased typically up to 20 [15]. Although a high output power density helps to avoid problems in connection with combining several devices, the user of HBT's is interested only in the maximum power which has been reported to be 5.3 W at 10 GHz [15].

The output power of such one chip device is limited by the problem of the realization of a good heat sink. Because of the HBT's high current density of about 10^5 A/cm^2 the peak temperature control in the individual emitter finger is an essential design parameter. If one allows a maximum device temperature increase of 140°C for a 10 finger AlGaAs HBT the output power density has to be limited to 3.8 W/mm [15]. This special 10 finger HBT has a substrate thickness of 75 μm and a plated airbridge for the collector. With this configuration a thermal resistance, normalized to the emitter finger length, of 35°C mm/W was obtained. The result of the calculation of the temperature distribution across this device is shown in Fig. 1. It can be inferred from this figure that there are very high temperature peaks in the emitter fingers while a reduction of the substrate thickness does not improve the thermal resistance significantly. It is obvious that the high power density is accompanied by the penalty of a reduced reliability caused by the high operation temperature.

The limitation of the maximum output power by the thermal resistance is demonstrated clearly by Adlerstein *et al.* [12] who surpassed this limitation by pulsed operation (33% duty cycle). They achieved 18.7 W/mm output power density at 10 GHz. The efficiency was 46% with 5 dB gain. Similar results were obtained by others [6], [17].

Pulse operation and class B are the key features to reduce the power dissipation in the transistor and concurrently reduce the junction temperature of operation.

Due to the limited junction temperature for space applications the maximum power density has to be recalculated. For the geometry of the most advanced device regarding output power [15] the thermal resistance will improve to about 25°C mm/W because the thermal conductivity will be better at the peak device temperature of 110°C. With $\eta = 40\%$ for this device a RF output power density of only 1.35 W/mm is realistic (Fig. 2), which is still a factor of 2 higher compared to FET devices. For a MESFET an output power density of about 0.7 W/mm is state of the art and pseudomorphic HEMT's exhibit power densities in the range of 0.6–0.9 W/mm [2].

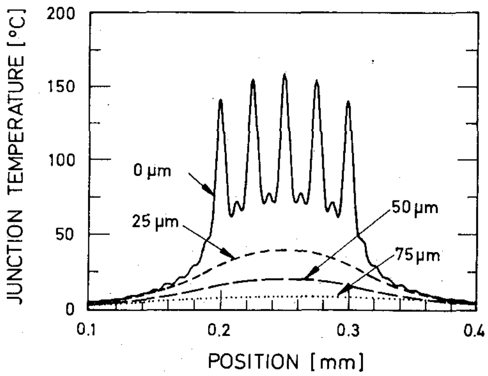

Fig. 1. Temperature profile across one row (= 5 emitter fingers) of a 10 finger sub-cell with the depth into the wafer as a parameter. Power dissipation is 4 W/mm of emitter finger length. After [15].

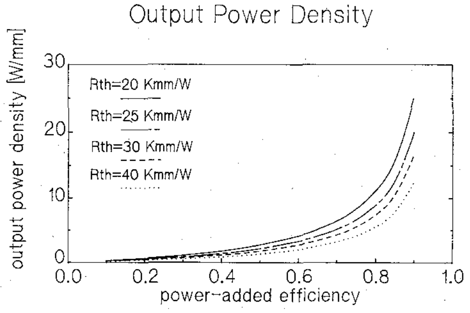

Fig. 2. Output power density P'_{out} versus power-added efficiency with the thermal resistance normalized to the emitter periphery R_{th} as parameter. (gain $G = 10$ dB, heatsink temperature $T_{\mathrm{sink}} = 60$°C, junction temperature $T_j = 110$°C.

Clearly, the high values of power density reported for HBT's do not account for space application, but a significant advantage remains for the HBT which is therefore an interesting candidate for SSPA's.

As calculated in [18] HBT's on GaAs and InP substrates show junction temperatures of 180°C and 140°C respectively at the same power dissipation. This indicates that the better thermal conductivity of InP may result in better power performance of InP-based HBT's, with improved fabrication process.

One additional disadvantage of an increased device temperature is the reduction of f_T. Chen *et al.* [19] demonstrate that the collector space-charge-layer delay time τ_{CBsc} is the dominating factor in the transit frequency f_T at low current densities. At higher collector currents τ_{CBsc} increases, as a result of decreasing drift velocity due to thermal heating. If the collector current density exceeds 75 kA/cm^2 base widening occurs, τ_{CBsc} drops and the time constant of the current induced base width becomes dominant. Chen *et al.* show that these thermal effects cause a 30% reduction for the maximum f_T which should be obtained from a HBT.

Another problem one has to face designing a HBT for optimum output power is the maximization of its breakdown voltage. If the HBT is properly designed the breakdown voltage is essentially the same as the base-collector junction reverse breakdown voltage BV_{CB0} [4]. Technologically this voltage is determined by the collector doping and width, because the base is usually highly doped [5]. Since the design of the collector does not affect the input E-B diode, high frequency devices can be constructed with large breakdown voltage. However, a large and low doped collector will result in an increased base-collector transit time and consequently reduce f_T [20]. Since the common base breakdown voltage $BV_{CB0} \approx 20$ V is higher than $BV_{CE0} \approx 13$ V a higher power density can be obtained in the common base configuration [17]. If, as usual, the power density limitation is dominated by the quality of the heat sink the common emitter configuration may be prefered for power amplification.

Combining different HBT devices as well as feeding a number of emitter fingers is critically determined by the matching of the input resistances of the individual emitter fingers. Good matching will ensure a homogeneous distribution of the power and will avoid hot spots with the related reliability problems because of the thermal positive feedback mechanism [21], [22]. Basically, the input resistance across a wafer (not necessarily from wafer to wafer) matches well because this value depends on the material energy gap which is easy to control by the epitaxial process [5]. In contrast to homojunction transistors a HBT can be designed such that the current gain h_{fe} exhibits a negative temperature coefficient [23], [18].

For a further improvement of the matching of the input resistance, a ballasting resistor is proposed [24] which is realized by introducing a n^-GaAs layer of 0.2 μm thickness and highly controlled sheet resistance into the emitter. The ballasting resistor will obviously have the disadvantage of degrading the power gain of the device, and therefore a trade-off between optimum matching and maximum gain has to be envisaged.

B. Efficiency

Amplifiers with HBT's are capable of very high power added efficiencies. For instance at 10 GHz 67% power added efficiency was reported [17]. At 18 GHz an efficiency of 48.5% is possible [25]. These results can only be obtained if a bias point near class B has been chosen.

HBT's are well suited for class B operation as opposed to FET and HEMT devices which exhibit serious reliability problems, due to increased drain-gate avalanche current, in class B operation:

A HBT shows no parasitic collector current during the "off"-period of the class B operation. MESFET and HEMT cannot be reliable operated in class B due to increased gate current in the off period. However, in some applications MESFET's were used in class B operation at the cost of reduced operating voltage and output power in order to avoid reliability problems.

The breakdown voltage (BV_{CEO}) is not depending on the input voltage in contrast to MESFET and HEMT devices. This disadvantage for FET devices reduces significantly the useable output voltage swing of these devices.

The complementary p-n-p HBT can be realized with reasonable performance [26], [27]. In the future complementary pairs of HBT's may be used to fabricate push-pull amplifiers with high efficiency. However, as shown in [26], [27] the power performances of p-n-p HBT's are still behind those of the more established and more promising n-p-n HBT's.

HBTs exhibit high power gain even at low current level. It can be shown that the small signal gain β is constant over 6 decades of collector current (Fig. 3).

The HBT has a low value of the reactive elements at the transistor output. This is important in order to avoid current and/or voltage overshoot as commonly encountered in MESFET's at large power levels.

Because the power added efficiency is defined by $\eta = P_{\text{out}}/P_{\text{DC}}(1 - 1/G)$ a gain G in the order of 10 dB is required for good power added efficiencies.

C. Linearity

HBT's are considered to have the capability of a very linear operation although careful investigations of the major contributions to the overall IMD are still missing. It has been pointed out in [4], [5], [8] that the figure of merit for linear performance, P_{lin}, given by the ratio of the third-order intercept point IP_3 to the dissipated dc power P_{dc}, $P_{\text{lin}} = IP_3/P_{\text{dc}}$, is usually larger than 10, which is a factor of 2–3 higher than for MESFET and HEMT indicating the superior linearity of the HBT. However, it has to be kept in mind that the value of the third-order intercept point is sometimes misleading, especially for MESFET's, because it assumes an ideal third-order nonlinear element. A more sophisticated analysis utilizing harmonic-balance and/or Volterra series approach is required for clarity.

In the following the inherent advantages of the HBT structure and the special design considerations are listed which facilitate a linear operation at microwave frequencies.

The high base doping, basically required to achieve a low base resistance, results in a low base width modulation. Therefore, the parameters of the emitter-base junction are not very sensitive to the input power [16], [5]. The high base doping results in a low output conductance which is manifested by a high Early-voltage or by a high g_m/g_o ratio which both should be high for maximum linear operation.

Especially for an amplifier in class B operation a constant gain of the device over a large range of input power is essential to obtain a good linearity. Common-emitter HBT's show a current gain which is nearly constant over six decades of base current [28] as it is shown in Fig. 3 in contrast to HEMT and MESFET devices which provide no power gain near the pinch-off region.

The major contribution to the nonlinearities of an HBT is originating from the modulation of the base-collector

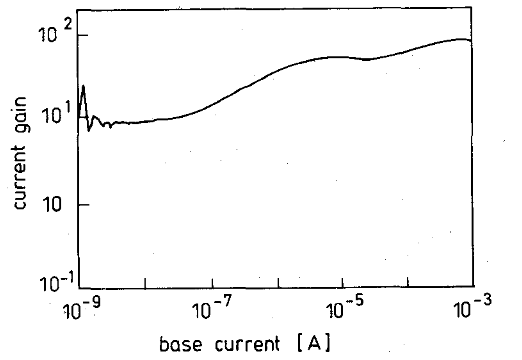

Fig. 3. Current gain β versus base current I_B for a 40 μm wide HBT. After [75].

capacitance and resistance [29] and the recombination current in the base. The influence of this capacitance can be reduced or even suppressed by either reducing the thickness of the collector [30] or properly adjusting its doping [31].

A high gain is favorable to reduce the required input signal amplitude on the nonlinear input E-B diode.

D. Reliability

Microwave power HBTs generally require high emitter current densities, exceeding 10^5 A/cm^2 to optimize the power added efficiency and to minimize the influence of the collector base junction capacitance on the carrier transit time. A number of possible degradation mechanisms are directly or indirectly associated with these typical operation conditions.

Interconnection lines contacting the emitter fingers are particularly susceptible to *electromigration damage*. It can be shown that the medium time to failure for electromigration exponentially depends on current density and temperature [32], [33]. It is therefore very important to keep the current density of interconnection lines within safe limits ($\leq 1 \cdot 10^5$ A/cm^2). With regard to power HBT's this requires either a large number of short emitter fingers in parallel or a very sophisticated method of contacting the emitter fingers (for example wide airbridges).

Vertical electromigration of the emitter metal into the emitter epitaxial layers due to the combination of high current densities and high temperatures is supposed to be one on the most dominating failure mechanisms (see Fig. 4). Vertical electromigration is always triggered by a high density filamentary current originating from protrusions of intermetallic phases or buried oxides at a metal/semiconductor interface or from threading dislocations in the semiconductor itself. This generates local hot spots and thus leads to material migration in the direction of the electron flow. [5], [32].

Reverse breakdown is a significant limiting factor for the microwave output power of HBTs. Very important is the question whether devices can be accidentally driven into breakdown conditions for example by certain environmental conditions (radiation pulses, electrostatic discharges etc.) [34], [35], because this may result in severe degradation or even complete device destruction. Especially current induced breakdown mechanisms have to be eliminated by a proper design of the epitaxial layers in the emitter-collector region as shown by [35]. Catastrophic breakdown preferably takes place at very exposed areas on the devices such as sharp corners, protusions etc. (see also Fig. 4) where a local concentration of the current can be expected [34].

The very flat base ohmic contact accessing the thin p^+-base region is considered to be very sensitive to any interdiffusion effects.

Diffusion of the base dopants into the emitter or collector region severely degrades the electrical performance. Materials for p^+ doping of the base that gained technological importance are Be, Mg, Zn and C [36]–[39]. The different doping materials show significant differences with respect to the diffusion behavior and the maximum doping concentration that can be achieved [38]–[41]. Dopant diffusion and therefore also the reliability of the complete device depends on the growth conditions of the base and of the subsequent emitter layers. It has been recognized that stable dopant profiles can be obtained when the growth process *substitutionally* places the dopants into the GaAs lattice [42]. Often the as grown highly doped base layer *dictates* the growth conditions of the subsequent layers in order to avoid dopant interdiffusion during the growth process itself or to avoid strong memory effects as in the case of Zn and Mg doping [38], [40]. Be and Zn doping is considered to be more problematic with regard to interdiffusional effects than C or Mg [36]–[39]. At the current state of the technology carbon doping of the p^+-base seems to be the best choice [36], [37].

In the following the *surface recombination effects in the extrinsic base region* (see Fig. 4) will be discussed that is typical for HBTs and is not necessarily associated with the operation at high power levels. This mechanism reduces the current gain of HBTs and is stronger for small emitter structures (emitter size effect) [43]–[45]. Because of Fermi level pinning in connection with a high surface defect density of GaAs a significant amount of the carriers (electrons) that are injected from the emitter into the base region can easily move along the base surface, recombine there, thus producing a parasitic base-emitter current. Thin layers of *depleted* AlGaAs, of the order of 50 nm [45], have been successfully used for base surface passivation of GaAs/AlGaAs microwave HBTs [44]–[46]. Since AlGaAs is quite reactive to oxygen, AlGaAs passivation layers have to be encapsulated properly to avoid reliability problems during long term operation. Unfortunately, no comprehensive reliability evaluation has been published on this topic so far. A possible solution could be a thin semiinsulating GaAs layer of thickness less than 50 nm instead of the AlGaAs cap layer.

Considerable further research efforts have been undertaken to reduce the surface recombination by utilizing a suitable passivation of the extrinsic base region. This is accomplished by saturating the dangling bonds on the GaAs surface using a *sulphur based* passivation [47], [48].

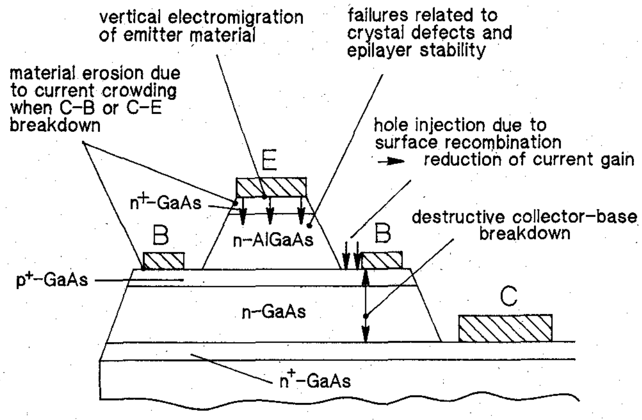

Fig. 4. Important degradation mechanisms in HBT's.

However, it has not yet been possible to develop a long term stable sulphur based passivation process. Another possibility to reduce base surface recombination effects is the realization of collector up HBT's where the emitter base junction is buried and the AlGaAs layer is never exposed during the device fabrication process [36] and/or utilization of base semiconductor materials with lower surface recombination velocities (for example Ge [49]).

All the above reliability problems that are associated with HBT applications in space-borne microwave power amplifiers can only be reduced when the actual device is specially constructed for reliable operation. This means that in the design process all reliability hazards, that are known so far, have to be considered. In detail a reliable design for power HBT's should meet the following requirements:

Only semiconductor material with a *very low dislocation density* should be used to avoid defect induced migration mechanisms and the degradation in the collector-emitter breakdown voltage. In this connection problems might occur if additional dislocations are introduced particularly into the emitter region during device fabrication or by severe mechanical treatment of the already completed devices.

An interconnection metallization with a *high activation energy for electromigration* should be used for contacting particularly the emitter fingers.

Refractory ohmic contact metallizations, specially designed and optimized to guarantee a homogeneous current flow together with a very low contact resistivity are to be used for all ohmic contacts to the device.

A suitable passivation of the extrinsic base region possibly by using a *depleted* AlGaAs layer has to be applied to prevent excessive recombination currents.

Carbon doping of the base is recommended to avoid dopant diffusion.

Current induced destructive breakdown effects at high power levels should be eliminated by *proper epilayer design rules*.

The high *radiation hardness* of HBT's favors their space application. In space, electronic circuits are exposed to neutrons, protons, gamma rays, cosmic rays and electrons. These radiation types induce displacement of atoms from their lattice sites, ionization of atoms (creating excessive carriers) and other effects [50]. Charge creation due to ionizing radiation causes disturbances of the internal potential distribution of an electronic circuit because of an increased overall conductivity across the whole circuit (radiation induced current flow in the semi-insulating substrate). In GaAs FET devices this additionally leads to backgating effects severely disturbing the electrical performance. HBT's in principle exhibit an *increased radiation hardness* as compared to FETs due to the n^+ layers which shield the active regions from the semiinsulating substrate material avoiding long-term radiation-induced transients to which MESFET's are particularly susceptible [5], [50].

E. HBT Circuit Considerations

HBT's are commonly operated in the common-emitter (CE) and common-base (CB) configurations. The CE operation is prefered in power amplifiers because the HBT device can be designed to exhibit intrinsically stable operation at matching conditions for maximum output power. On the other side, in CB configuration HBT's tend to oscillate which is convenient for oscillator design.

Following the results reported in [15], [17], [51], [52] input impedances of approximately $Z_{\text{in}} \approx (1 \sim 6)\Omega + j(-10 \sim 10)\Omega$ and output impedances $Z_{\text{out}} \approx (3 \sim 10)\Omega - j(20 \sim 3)\Omega$ are realistic for small signal excitation for power HBT's with 1 W output power operating at 10 GHz.

With respect to easy power combining the HBT offers the advantage of having a nearly resistive input impedance. This is due to the fact that the emitter-diffusion capacitance is very small because the hole injection into the emitter is suppressed by the heterojunction. Consequently, the HBT has a low input quality factor of about 0.5 in the 2.5 to 10 GHz range [53].

Due to the large variation in collector current with input power level the correct values for power matching should be obtained from large-signal analysis. This leads to a power matching procedure different from the conjugate of S_{22} resulting in higher load resistances [25].

A critical design parameter is the determination of the bias circuit and operating point. HBT's can be biased by applying a constant emitter-base junction voltage V_{BE} or a constant base current I_B [17]. In the case of constant V_{BE} the collector current rises significantly with input power drive, which is highly desirable in power amplifiers, especially for satellite applications because of the lower dc dissipated power at lower drive levels and consequently high power-added efficiency and thermal stability. Such operating conditions are especially beneficial for satellite transponders to meet efficiently various traffic conditions. As pointed out above the suitability of HBT's for class B operation could yield even higher power-added efficiencies with little trade-off between biasing the HBT for maximum output power, maximum linearity and maximum efficiency.

In the case of CB operation and constant emitter voltage the collector and emitter currents also increase strongly with input power level. At very large input powers the collector and emitter currents as well as the output power level coincide with those obtained from biasing the HBT with a constant emitter current for maximum output power operation. However, the slope of the output power characteristic versus input power is different for all biasing conditions. In the case of CE bias the output power increases with a slope factor of 1.4 with input power, whereas the normal slope factor of 1 is observed for a constant emitter current CB bias scheme and finally the slope factor is only 0.65 when the HBT is operated in the CB configuration with a constant bias voltage. The different slope factors probably originate from the changing matching conditions with input power drive due to the large variations in collector current for the CE bias.

With special emphasis on microwave power operation circuits have been proposed in which the single HBT devices are connected in parallel and combined with suitable power combiners and dividers to obtain the required output power [4], [24], [25], [28], [51], [52]. Also monolithically integrated impedance matching and combiner circuits have been realized [4].

The further circuit configurations which could considerably enhance HBT power amplifier performance are:

Darlington circuit to increase the input impedance and the gain of power HBT's while retaining emitter feedback resistors for reliable current distribution over several HBT cells as well as for reliable temperature operation,

series-cascade circuit and push-pull circuits to operate at higher collector-emitter bias voltages which are readily available in satellite applications to reduce the losses in satellite dc power supplies. Also the push-pull configuration enhances the gain and power performance of the overall circuit in class B operation and reduces the power dissipation in each HBT device.

F. HBT Models and Simulation Tools

Modeling of HBT devices is important for advanced circuit design and device performance evaluation. HBT device modeling has mainly concentrated on small-signal models [54], [55], [31], [56]–[63] and SPICE models [64], [65]. Only a few contributions dealt with large-signal physical modeling [66]–[71].

Interestingly, the Ebers–Moll bipolar models incorporated in time domain CAD programs, e.g. SPICE, reveal high accuracy also for HBT devices when some additional parasistic elements and the characteristics of the heterojunction diodes are included. Especially, the distributed characteristics of the base resistance and collector-base capacitance are very important. A modified Ebers–Moll model has also been adopted for bipolar microwave transistors in previous investigations on microwave power amplifier large-signal simulation [72]. However, for HBT device optimization for power amplifiers clearly a physically-oriented method should be used including large-signal effects.

A further major drawback is the lack of accurate HBT models in CAD packages for microwave circuit simulations and for efficient IMD calculations. A Volterra-series based approach, as previously applied to bipolar transistors [72] and MESFET's [73], [74] could yield high efficiency of calculations for these purposes.

IV. COMPARISON OF HBT, MESFET, HEMT, AND MISFET

This section compares the state of the art performance of the different devices. In Fig. 5 the RF output power density of these devices is depicted versus the frequency. It can be inferred from this figure, that the field effect devices, namely MESFET, MISFET and the HEMT, are in the 0.08 W/mm – 1 W/mm range. In this case the periphery is the gate width. For the HBT much higher values up to 18 W/mm output power normalized to the emitter length have been reported. Although this extreme value is obtained for pulses operation, the CW output power density is usually about 4 W/mm demonstrating the high power density performance of this device.

In Fig. 6 the gate width or emitter length can be depicted for MESFET, HEMT, MISFET and for the HBT, respectively, versus the frequency. The large gate widths of the MESFET devices demonstrate that they are the most advanced semiconductor power devices for microwave frequencies. The realized emitter periphery for the HBT's are similar to the fabricated gate periphery in HEMT's and MISFET's although little data is available for HBTs at frequencies above 10 GHz.

By the combination of Fig. 5 with Fig. 6 the microwave output power was obtained in Fig. 7. The largest output powers are achieved with MESFETs indicating their high maturity even for frequencies above 10 GHz. These devices show the predicted $1/f^2$ decrease in contrary to the quoted HBT and MISFET devices which fall faster with frequency. HEMT devices fall with approximately $1/f$, which can be attributed to the narrower fabricated gate length with constant gate width. The realized HBTs exhibit only 10% of the output power of the MESFET.

Very good efficiencies can be obtained with HBTs (Fig. 8) around 10 GHz. However, MESFETs efficiencies approaching 60% at 6 GHz have been reported utilizing harmonic tuning in the matching circuits and class B operation. As discussed above the reliability of commercially available MESFET devices is poor in class B and hence considerably lower operating efficiencies are realistic for MESFET satellite applications.

The gain of the various devices versus frequency is illustrated in Fig. 9. Although high gain can be obtained for HBT's, power devices exhibit about 5 dB gain at 10 GHz. This is comparable with state of the art discrete MESFET power devices.

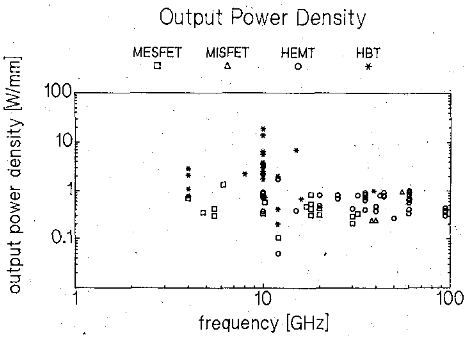

Fig. 5. Power density versus the frequency for realized microwave FET and HBT devices.

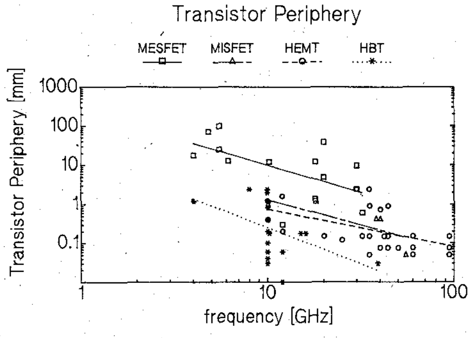

Fig. 6. Gate width and emitter length versus the frequency for realized microwave FET and HBT devices respectively.

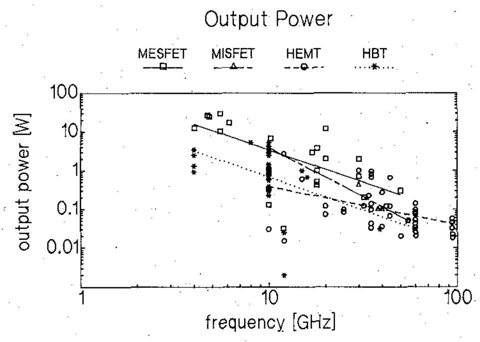

Fig. 7. Power versus the frequency for realized microwave FET and HBT devices.

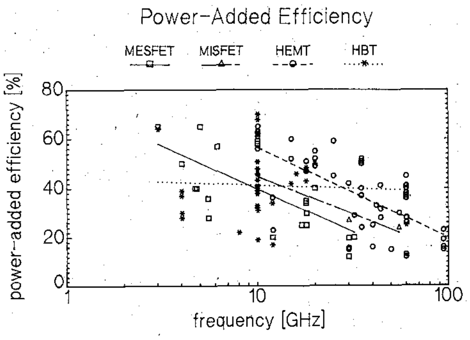

Fig. 8. Power added efficiency versus the frequency for realized microwave FET and HBT devices.

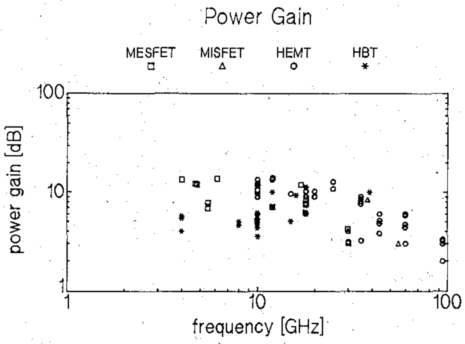

Fig. 9. Gain versus the frequency for realized microwave FET and HBT devices.

V. Conclusion

From the previous discussion it can be concluded that the HBT is potentially capable of replacing FET's in high efficiency SSPA's for the following reasons:

For space application an output power density of around 1.3 W/mm is realistic at a maximum device temperature of 110°C. This is twice the value of FET devices. Improved heat sinks will allow operation at still higher power densities.

The absolute output power of state of the art devices is low because of missing experience in forming larger devices. In principle the HBT exhibits superior capabilities for high output power. Realization of larger devices could be facilitated by the restricted maximum operating temperature.

The HBT is ideal for linear and high efficiency operation.

The HBT is well suited for class B operation. It offers comparable matching problems as the FET devices considered. An advantage may be that the input impedance is nearly frequency independent.

The gain achieved so far is comparable to state of the art FET devices.

The HBT exhibits superior radiation hardness as compared to FET devices.

Reliability considerations have necessarily to be included into the HBT design process. At the current state of research the reliability of HBT devices has to be investigated in more detail.

The GaAlAs/GaAs HBT will be a preferable device for microwave power amplification in satellites when the problems concerning the reliability will be solved and further investigations will enhance the formation of larger devices.

HBT's based on other compound semiconductor materials, like InGaAs/InP, are also investigated systematically by many research institutions. However, because of the minor quality of the epitaxial layers, especially the collector, and the technological problems encountered, the output powers achieved are far less compared to those obtained from the GaAlAs/GaAs HBT structures.

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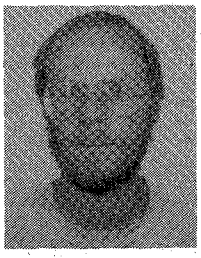

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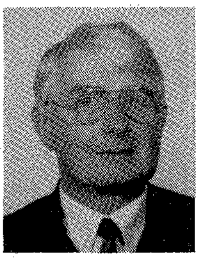
Giuliano Gatti, for a photograph and biography, see this issue, p. 1158.



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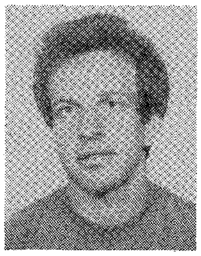

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