HBT vs. PHEMT vs. MESFET: What's best and why

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ABSTRACT

The properties of HBTs, HEMTs, PHEMTs and MESFETs are reviewed and discussed in the context of their suitability for various applications. Noise, power and high frequency performance is reviewed and the physical mechanisms dictating their values are discussed. The reliability characteristics of the devices are discussed and system applications are reported.

INTRODUCTION

GaAs-based devices and circuits have a well-defined place in commercial and defense applications as evidenced by their use in a variety of products and systems. Applications extend from the low-frequency spectrum of several hundred MHz to the millimeter-wave range. The choice of a device is influenced by its maturity in terms of manufacturing but also by other criteria, which are related to fundamental operation mechanisms and determine the performance. Although MESFETs have for long been considered the most mature components, HEMT and HBT technology made significant advances due to the lessons learnt from both III-V and Si manufacturing approaches. This paper presents basic considerations regarding the properties of HBTs, HEMTs/PHEMTs and MESFETs and addresses the relative merits of each technology

LOW-NOISE APPLICATIONS

For low-noise amplifier applications, the PHEMT is generally recognized as the best choice followed up by the MESFET. The main source of noise in FETs is thermal-diffusion type, as a result of random variations in carrier speed in the device channel. The latter leads to current variations and thus noise. Of particular importance is the presence of capacitive coupling between the gate and the channel, which results in the overall noise being determined by subtracting part of the gate noise from the drain noise. This is a unique property of FETs, which leads to very low-noise performance.

Best noise performance is obtained by minimizing the source access resistance and maximizing the current gain cutoff frequency, f_t. The latter necessitates device design for maximum transconductance g_m and minimum gate capacitance C_{gs}, conditions that can to some extend also be controlled by proper bias choice. As a general rule, minimum noise (F_{min}) is obtained under ~I_{dss}/10 conditions. There is, however, a difference in the bias range necessary for this purpose in MESFETs and HEMTs; HEMTs appear to have a broader range of I_{ds} values than MESFETs over which F_{min} is achieved. This provides a larger margin in LNA circuit design. Since high gain is in general desired from the amplifier, and bias for F_{min} does not often coincide with bias for maximum gain, a trade-off is often made in gain vs. noise. This turns out to be less severe in HEMTs due to their broader range of bias for F_{min}. Large gain also requires device designs with a heterojunction or other type of buffer below the channel to minimize carrier injection and reduce the output conductance.

The possibility of high base doping opens new opportunities for HBTs, which could be of interest for wide bandwidth, low-noise operation. An analysis of noise characteristics also shows that PHEMTs offer smaller bias sensitivity of noise performance than MESFETs. InP-based HEMTs offer the ultimate solution to low-noise operation. They are also the best choice for optoelectronic applications, which require compatibility with InP-based optical devices and operation speeds of 40Gbit and above. Fig.1 summarizes the noise performance of various device types as a function of frequency. One observes excellent performance from InP-based HEMTs up to millimeter-wave frequencies i.e., NF of 1.2dB at 94GHz using lattice-matched or strained designs.

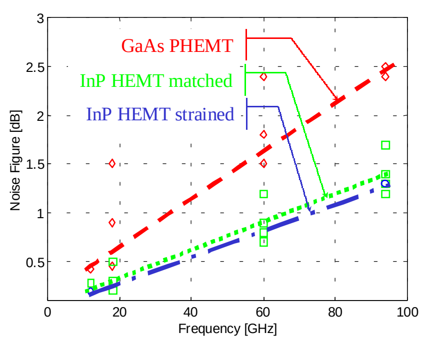

Fig. 1 Noise performance of GaAs- and InP-based HEMTs as a function of frequency

Low-frequency noise is in general smaller in HBTs. With proper circuit design for reduced influence of nonlinearities and thus small noise upconversion, HBT oscillators can be designed with very small phase-noise performance [1].

POWER APPLICATIONS

Power amplification is characterized by parameters such as power compression, third order intermodulation (IMD), power added efficiency (PAE) which are not normally examined in low-noise amplifiers. The most mature technology for this purpose the MESFETs, is not necessarily the best choice for power, especially when the operation frequency is high. This is due to the requirement of small gate length imposed by the high frequency, which translates to smaller channel thickness. This imposes higher doping in order to conserve the I_{ds} performance and thus smaller breakdown and power. Despite these limitations, reasonable power characteristics of 0.53W/mm have been obtained at 18GHz from a MESFET with 600µm gate periphery [2]. More recently, a 0.3µm long gate MESFET with GaAs channel on Al_2O_3 demonstrated record PAE of 89% at 8GHz with 9.6dB gain, 0,12W/mm-output power and a small V_{ds} bias of 3V [3]; the Al_2O_3 insulating buffer was obtained by wet oxidation of $Al_{0.98}Ga_{0.02}As$ on low-temperature AlGaAs.

Fig. 2 summarizes the power performance of HEMTs, MESFETs and HBTs. The use of heterojunctions opens new possibilities in optimizing device performance. AlGaAs/GaAs HEMTs allow higher frequency of operation than MESFETs. These devices are, however, limited in terms of sheet carrier density n_s (10^{12} cm^{-3}) and thus current and power due to their small conduction band discontinuity ΔE_c. Despite this limitation, 100W of power have been obtained at 2.1GHz using a 86.4mm gate HEMT [4]. Improved performance can be obtained by adding heterojunction channels or increasing ΔE_c. The former leads to higher overall n_s without at the same time compromising in breakdown since the doping of individual channels remains the same. The latter can be realized using the so called pseudomorphic PHEMT approach where the GaAs channel is replaced by $In_xGa_{1-x}As$ where x is usually about 0.2. The channel thickness is in this case of the order of 150Å in order to ensure reasonably good material properties. PHEMTs have n_s values of at least $4 \times 10^{12} cm^{-3}$ and therefore currents exceeding 1A/mm can be achieved. A power exceeding 0.44W/mm has been obtained with this approach at 44.5GHz using a 1800µm gate device [5]. Further n_s and thus I_{ds} improvement can be obtained by fabricating HEMTs on InP substrates. This technology offers the additional advantage of higher thermal conductivity for InP substrates. InP substrates and the related technology is, however, less mature than GaAs. Most popular among all devices for power applications

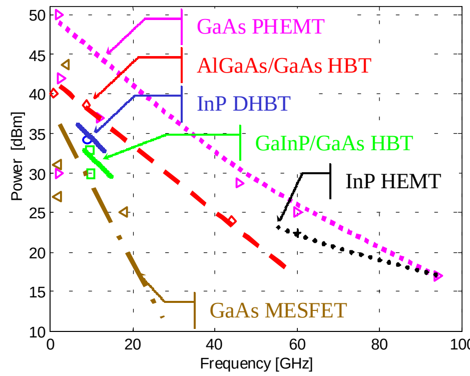

Fig. 2 Power performance of HEMTs, MESFETs and HBTs as a function of frequency.

is the PHEMT. From the technological point of view, further improvements in PHEMT performance can be envisaged by employing double and asymmetric recess. Moreover, for InP-based HEMTs, which are in general limited in breakdown due to their low-bandgap InGaAs channel, some improvement can be envisaged by employing InGaAs/InP composite channels. The use of heterojunction barriers can help by reducing impact ionization generated holes form leaking to the gate.

Power back off is normally required for better linearity performance of PHEMTs. This appears to be a much less demanding requirement in case of HBTs which appear to combine good linearity performance at an input power level which is appropriate for good PAE.

Power applications and development of small size, high efficiency chips have benefited from the availability of HBTs. These devices although less mature in technology than PHEMTs, offer higher breakdown voltage, better threshold voltage uniformity and exponential rather than power-law transfer characteristics. Of major importance is the consideration of thermal issues due to self- and adjacent device heating. This can lead to significant power performance difference in CW vs. pulsed operation which is not so pronounced in devices such as FETs. Large-signal modeling of HBTs including thermal effects has led to very satisfactory results and agreement with experiment [6]. Moreover, thermally stable cascode (TSC) HBT designs have been demonstrated that manifest lower temperature increase than conventional HBTs while at the same time offering higher gain [6]. Other approaches include thermal shunts for heat removal from the top of the chip but these add in general to the cost of technology.

Good power performance has been achieved with GaAs HBTs such as 10mW/µm^2 at 10GHz and 4mW/µm^2 at 25GHz [7]. InP DHBTs have also been reported with 3.6mW/µm^2 at 9GHz, while InP SHBTs from the University of Michigan led to record for this type performance with 1.4mW/µm^2, and a PAE of 43%. The InP-based design offers an attractive solution in terms of gain and high frequency of operation. These devices are also the best choice for high linearity operation due to the cancellation of currents at high harmonics, which takes place at the internal nodes of the HBT.

HIGH-FREQUENCY OPERATION

If high frequency operation is required, PHEMTs offer the best choice due to their high gain up to millimeter-wavelengths and their good noise and power performance. Fig. 3 summarizes the frequency performance of various types of FETs. Although applications at very high (mm-wave) frequency cover a smaller part of the market than systems at microwave frequencies, the potential exists for use of PHEMTs in commercial systems such as for example, the automotive anti-collision radar system. Space applications are also in demand of PHEMT technology at continuously higher frequencies.

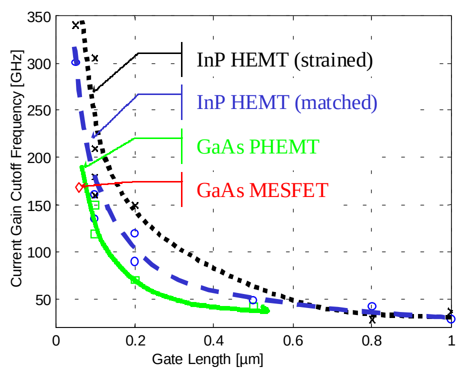

Fig. 3 High frequency performance of HEMTs and MESFETs as a function of frequency

InP-based HEMT technology offers the best choice for millimeter-wave systems. It offers excellent low-noise operation up to millimeter-wave frequency and allows high gain values. HBTs based on GaAs and InP have also shown good high frequency characteristics and a record performance (f_{max} = 250GHz) has recently been reported by NEC. Their maximum frequency of operation is, however, lower than that of HEMTs.

RELIABILITY

Reliability is also an important factor intervening in the choice of device. MESFETs and PHEMTs have demonstrated good reliability characteristics and significant progress has been made in improving the reliability of HBTs. Current issues related to device reliability include hydrogen diffusion upon packaging of FETs which results in threshold voltage V_{th} variation. Gate sinking due to the interdiffusion of the Schottky gate metal such as Ti/Pt/Au in the semiconductor channel also leads to V_{th} shift and can be controlled to some degree by insertion of metals such as Mo. The reliability of PHEMTs is considered to be acceptable for many applications but InP-based HEMTs lack by about an order of magnitude in performance. Thermal stability related to donor material changes has been suggested as a possible reason but more work is needed to fully analyze these effects.

Base-emitter junction variations have been observed in HBTs due to base dopant diffusion and defect formation at this critical for device operation region. These result in gain variations with time and are the subject of current investigations. AlGaAs/GaAs HBTs showed lifetimes that are almost inverse-square related to the operation current density. Activation energy E_A values obtained from temperature dependent tests showed relatively low values of 1.5eV. This implies at first the need for reducing the operation current density and controlling the device temperature, either of which would handicap device use in circuits. Compensation of such effects by employing larger device size is not desirable since this would reduce the device impedance and risks to make matching challenging. Material and processing improvements have led to better reliability that extends up to 10^9 hours for a junction temperature of 120°C and a current density that can exceed 25kA/cm^2 [8]. The use of In co-doping in the base and GaInP instead of AlGaAs in the emitter has also led to

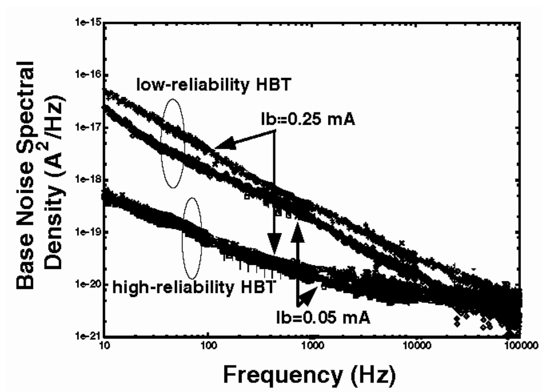

Fig. 4 Comparison of low frequency base current noise of high and low reliability HBTs.

reliability improvement; E_A values of 1.8eV can for example be achieved with GaInP with more than 10^8 hours at the same junction temperature but lower current density.

Techniques have been recently introduced to screen HBT reliability by evaluating the low frequency noise characteristics [8]. This technique allows also identification of the source and nature of the mechanisms that lead to current gain degradation. The base current noise spectral density was found to be much smaller and with a weaker dependence on bias in higher reliability devices (see Fig. 4).

APPLICATIONS

There is a large variety of applications for all three device types discussed. GaAs MESFETs are for example, used in a wide range of analog-digital cellular applications. Digital cordless telephones also employ power MESFETs. The handset size imposes, however, a need for low voltage, single power supply and high PAE. Biasing in MESFETs used in such applications is therefore arranged by employing a source resistor, which leads to the required negative gate bias. This approach results, however, in high frequency gain degradation and PAE reduction. The alternative approach is HBTs, which can be operated using a single power, supply and have a low knee voltage in their I-Vs. The change from analog to digital cellular phone systems using for example a π/4-shifted QPSK signal, imposes a requirement of much higher output power for even lower supply voltage. The adjacent channel leakage power should also be maintained low in this application with less than -48dBc at 50KHz off-center frequency. Performance within these specifications and with 1W output power at 950MHz using 1.5V supply has been demonstrated with PHEMTs [9]. High PAE is also important for long battery life in wireless applications and in satellite applications where the available power is limited. The demand for high PAE devices in satellite systems becomes increasingly higher as phased arrays are introduced to produce multiple beam spots and improve communications performance.

InP-based HEMTs and other InP-based components such as PIN diodes are particularly suitable for millimeter-wave applications such as mobile satellite communication systems and collision avoidance (CAS) systems.

HBTs are attractive at cellular radio frequencies for power amplification. This can range from the Watt level for handsets to 150W or more for base stations. The advantages offered are high gain per amplification stage and competitive if not better linearity and PAE. An important advantage of HBTs is the fact that it offers good linearity properties without necessarily backing up the power as is often done in FETs. This leads to good linearity properties combined with high PAE. On the other hand, the smaller operating voltage imposed by handset applications leads to difficulty in achieving high PAE. The V_{CE} offset voltage of the HBT and the collector, emitter resistance, determines the on-state voltage, which limits the output signal. Reduction of V_{be} is also often sought despite the fact that a high value can be useful for power down of an amplifier. The use of GaAs Double-HBTs and InP-based technology can be attractive for this purpose. High-speed, low power applications using small area devices also benefit from GaInP designs due to their large ΔE_v which increases injection efficiency and thus enables higher based doping and speed, while the low surface recombination velocity of InGaP leads to reduced base leakage. The use of small emitter area HBTs is the most effective way for reducing power consumption while keeping the current density high. Although the latter guarantees high-speed performance, the small emitter size compensates the speed improvement by increased emitter resistance R_E. Graded emitter designs have been proposed for this purpose [10].

HBTs have also been introduced in fiber optic transmission systems operating at 10Gbit /sec rates and higher speed systems are currently envisaged. Although the actual operation speeds can be satisfied using GaAs technology, InP HBTs are the preferred solution for future generations that are envisaged up to 80Gbit/sec.

Overall, the properties of HBTs, PHEMTs and MESFETs are reviewed and discussed in the context of their suitability for various applications.

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