Status of InP HEMT Technology for Microwave Receiver Applications

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(Invited Paper)

Abstract—**The current status of InP-based high electron mobility transistor (HEMT) technology for low noise amplification at frequencies up to more than 100 GHz is presented. Following a review of recent advances industry-wide in both device and circuit performance, two issues which will pace the rate at which this new technology can be inserted into microwave systems—material/process maturity and long-term reliability—are discussed.**

I. Introduction

InP-BASED HEMT's have demonstrated high-frequency characteristics superior to those of any other transistor, including the highest $f_{\max}$ (600 GHz, as reported in [1]), the highest f_t (340 GHz, as reported in [2]), the lowest noise figure of any room-temperature receiver technology [3], [4], and the highest efficiency at millimeter wave frequencies [1], [5]. Consequently, much effort is being directed toward the insertion of circuitry based on InP HEMT's into a variety of microwave and millimeter wave applications that can benefit from their enhanced performance.

Although the earliest microwave HEMT's were based on the GaAs/AlGaAs material system, it became clear by 1986 that GaAs-based HEMT's with pseudomorphic InGaAs channels provided improved millimeter wave performance, including reduced noise figure and increased power-added efficiency [6]. These GaAs pseudomorphic HEMT's, or PHEMT's, typically contain InGaAs channels with indium content ranging from 15 to 25%. Also in 1986, Aksun *et al.* reported a 1 μm gate-length HEMT with a 53% indium content InGaAs channel, *fabricated on an InP substrate*, that exhibited 50% higher $f_{\max}$ and f_t than a GaAs-based PHEMT of similar geometry [7]. In 1988, the superior noise performance of InP-based HEMT's was demonstrated convincingly at millimeter wave frequencies using short-gate devices [8].

The unequaled performance of the InP-based HEMT arises directly from the intrinsic properties of the InAlAs/InGaAs material system, where the high indium content (typically 53–80%) InGaAs channel possesses high electron mobility and velocity, and the large conduction band discontinuity at the InGaAs/InAlAs heterojunction permits high two-dimensional electron gas (2DEG) densities to be obtained, resulting in high current and transconductance. It is the high transconductance of the InP HEMT which is most directly responsible for its increased operating frequency and excellent gain-bandwidth properties. Transconductance values as high as 1500–1700 mS/mm have been reported [2], [9], and typical 0.1 μm InP low noise HEMT's exhibit g_m of 800–1000 mS/mm, compared with 600 mS/mm for comparable GaAs PHEMT's.

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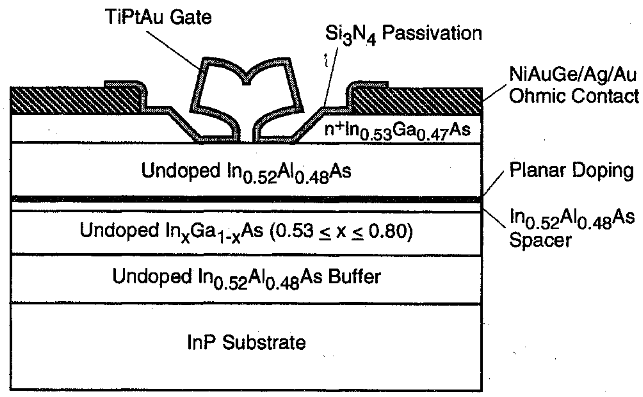

Fig. 1. Cross section of typical InP-based low noise HEMT.

The cross section of a typical InP-based HEMT is shown in Fig. 1. As is the case with GaAs-based FET's and HEMT's, T-shaped TiPtAu gates and silicon nitride passivation have become more or less the industry standards. For high-performance receiver applications, a gate length of 0.1 μm is now typical, although one can find longer gates being used at lower frequencies [10], [11] and research continues on devices with gates as short as 0.05 μm [2].

The indium mole fraction employed in the channel is normally 53%, allowing the InGaAs to be lattice-matched to the underlying material, but pseudomorphic InGaAs channels with up to 80% indium content continue to be investigated for the further improvement in performance expected based on theoretical considerations. In practice, the best noise performance has been obtained for devices with indium content of 53-60% [3], [4], [8], [12], [13]. The highest values of current gain cutoff frequency f_t have been observed with 80% indium InGaAs channels [2], [14], but these devices have failed to exhibit improved noise performance. Maximum frequency of oscillation $f_{\max}$ is a more relevant figure of merit for a microwave transistor than f_t because it relates to power gain, the gain of interest in a high frequency amplifier. We have observed the highest $f_{\max}$, a record 600 GHz, with a 68% indium pseudomorphic InGaAs channel [1].

TABLE I
BEST REPORTED InP LOW NOISE HEMT'S. IN ALL CASES, PERFORMANCE SHOWN IS DEVICE PERFORMANCE, CORRECTED APPROPRIATELY FOR FIXTURE AND SETUP LOSSES

Ref.	Year Reported	Freq. (GHz)	Gate Length (μm)	Passivation	Noise Figure (dB)	Associated Gain (dB)
[15]	1990	18	0.15	—	0.3	17.1
[8]	1988	60	0.2	—	0.9	8.7
[3]	1994	60	0.1	—	0.7	8.6
[3]	1994	60	0.1	Si_3N_4	0.8	7.6
[13]	1994	60	0.15	SiON	0.9	7.0
[4]	1991	94	0.1	—	1.2	7.2
[12]	1992	94	0.1	—	1.3	8.2

II. DEVICE NOISE PROPERTIES

Table I summarizes the best reported noise performance measured for InP HEMT devices at frequencies from 18 to 94 GHz, and with gate lengths ranging from 0.1 to 0.2 μm. As seen in the table, there have now been several reports of InP HEMT's with noise figure less than 1 dB at 60 GHz, including two reports of devices passivated successfully with minimal degradation in noise figure [3], [13]. In general, we find that measured device minimum noise figures in the 18–94 GHz range follow the frequency dependence proposed by Fukui, that is

$$F_{\min}\,(\text{dB}) = 10\log(1 + cf)$$

where c is a constant and f is the frequency [16]. It is unclear how low in frequency this expression is valid, but the low frequency noise performance is known to be limited by $1/f$ noise, the onset of which is defined in terms of a corner frequency. This corner frequency is known to be materials-technology dependent and inversely related to gate length. The 0.15 μm InP HEMT 2–18 GHz $F_{\min}$ data [10] suggest a $1/f$ noise contribution to noise figure at 2 GHz of approximately 0.2 dB.

As compared with GaAs-based PHEMT's, InP HEMT's offer significantly lower noise figure, where the difference increases with frequency, from 0.2 dB at 18 GHz to approximately 1 dB at 94 GHz. Associated gain of InP HEMT's is also typically 1–2 dB higher than that of GaAs PHEMT's, helping to further improve amplifier noise figure by reducing second stage noise contribution. Minimum noise figure is obtained at a much lower drain bias of 1.0 V, compared with 2.0–2.5 V for a typical GaAs PHEMT. As a result of the lower drain bias, both dc power consumption and 1 dB gain compression point are significantly lower for InP HEMT's than for PHEMT's (as reported in [17], $P_{1\,\text{dB}}$ was found to be 5–6 dB lower for a W-band InP HEMT). However, this reduction in $P_{1\,\text{dB}}$ (and therefore third-order intercept point) of a multistage amplifier can be mitigated by increasing the drain voltage or gate periphery of the output stage device or by adopting a double heterojunction device structure with improved power-handling properties [1].

III. LOW NOISE AMPLIFIERS

A variety of high performance InP HEMT low noise amplifiers (LNA's) have been reported at frequencies ranging from

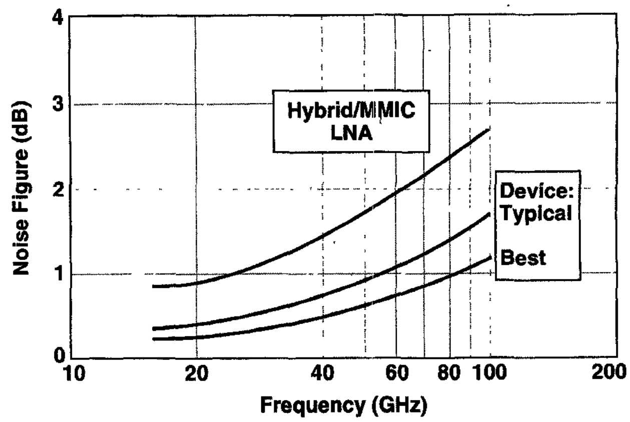

Fig. 2. Noise figure achievable in multistage, narrow-band LNA's using typical passivated 0.1 μm InP HEMT's. Single-device noise figure is also shown.

2 to 140 GHz. These include both hybrid microwave integrated circuit (MIC) amplifiers based on discrete transistors as well as monolithic microwave integrated circuits (MMIC's). In general, the hybrid circuit implementation is used for applications requiring the lowest noise figure and limited in volume, while MMIC's are preferred for applications requiring small size (e.g., phased arrays), low production cost in moderate to high volume, and/or excellent repeatability (unit-to-unit tracking).

Fig. 2 shows the noise figure achievable in both hybrid and MMIC LNA's over relatively narrow bandwidths (5–10%) using typical passivated 0.1 μm InP HEMT's. Although the hybrid and MMIC LNA's would appear to have identical noise figures (since only one curve is shown for both), the hybrid LNA noise figure is in fact lower since it is referred to the input connector, and therefore includes transition and isolator losses, while the MMIC noise figure shown represents only chip-level performance.

We have reported hybrid LNA's at V- and W-band [4], [17], [18], [19], including a two-stage amplifier with 1.7 dB noise figure and 17 dB gain at 62 GHz and a three-stage design with 3.2 dB noise figure and 17 dB gain at 94 GHz. Additional InP HEMT hybrid amplifiers have been reported by others at V-, W-, and D-band [20], [21].

A summary of low noise InP HEMT MMIC's reported over the past six years is presented in Table II. MMIC noise figures presently range from less than 0.5 dB at 2 GHz to approximately 3 dB at 94 GHz, and continue to improve. Of particular significance is the W-band MMIC, shown in Fig. 3, which exhibited 3.3 dB minimum noise figure at 92 GHz and less than 5.0 dB noise figure across the full 75–110 GHz band (a 35 GHz bandwidth). Also of significance is the 142 GHz MMIC shown in Fig. 4; this MMIC represents the highest frequency amplifier demonstrated to date with any transistor technology. In general, one can expect to see continued progress toward further reduction in MMIC noise figures and increased operating frequencies.

IV. BROAD-BAND DISTRIBUTED AMPLIFIERS

Because of their excellent high frequency gain, InP HEMT's have enabled the realization of MMIC distributed amplifiers

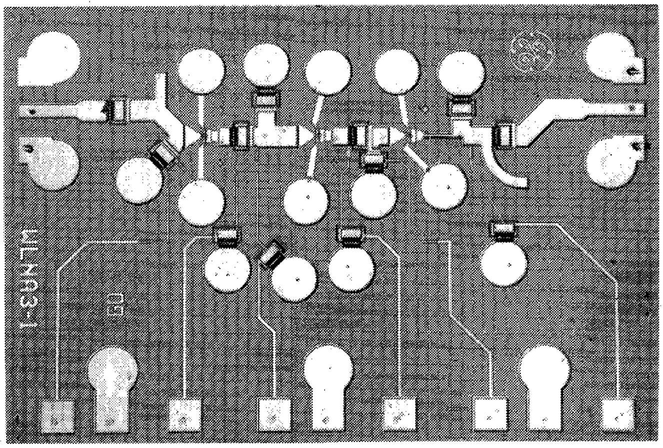

Fig. 3. Three-stage 75–110 GHz MMIC [28].

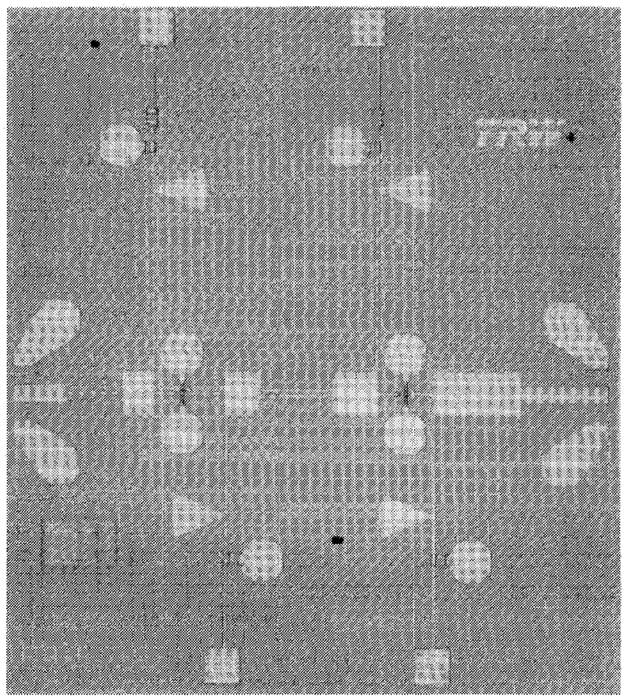

Fig. 4. Two-stage 142 GHz MMIC [32].

TABLE II
SUMMARY OF BEST REPORTED InP HEMT MMIC LNA'S

Ref.	Year Reported	Freq. (GHz)	Number of Stages	Minimum NF (dB)	Gain (dB)	NF over Band (dB)
[10]	1993	2.3-2.5	3	0.4	35	0.5 max.
[11]	1993	7-11	2	1.0	21	1.2 max.
[22]	1995	19-22	3	1.1	38	1.2 max.
[23]	1993	43-46	2	—	25	2.3 ave.
[24]	1995	43-46	3	1.9	22	2.0 ave.
[25]	1994	50	2	2.8	9	—
[19]	1990	63	2	3.0	18	—
[26]	1992	56-60	2	3.2	15	4.2 ave.
[27]	1993	56-64	3	2.7	25	3.0 ave.
[24]	1995	58-62	2	2.2	16	2.3 ave.
[28]	1993	75-110	3	3.3	11	5.0 max.
[29]	1993	75-110	4	6.0	23	—
[30]	1995	92-96	3	3.3	20	4.4 max.
[31]	1994	120-124	2	—	11	—
[32]	1995	142	2	—	9	—

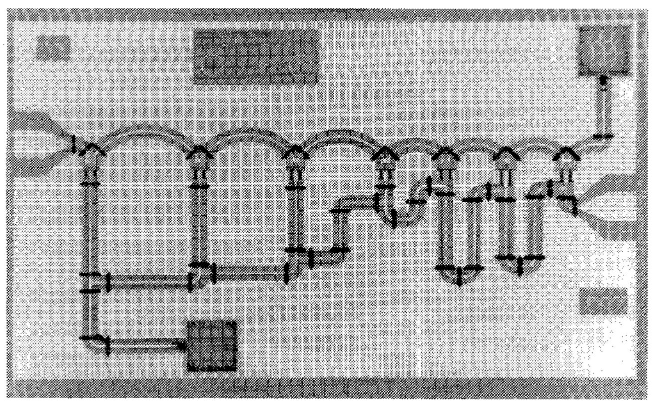

Fig. 5. 5–100 GHz MMIC distributed amplifier [33].

with ultrawide bandwidths and high operating frequencies. This is illustrated most strikingly by the MMIC shown in Fig. 5, which demonstrated 5 dB gain from 5 to 100 GHz, the largest bandwidth of any MMIC reported to date [33]. A number of InP HEMT MMIC distributed amplifiers with operating frequencies extending into the millimeter wave regime have been reported [34]–[37]. Although these MMIC's exhibit greater than decade bandwidths, their noise figure is somewhat higher than that of the conventional reactively-matched MMIC's listed in Table II. Consequently, they remain of interest almost exclusively for broad-band applications such as EW and instrumentation.

V. CYROGENIC OPERATION

HEMT low noise amplifiers operating at physical temperatures of 10–20 K continue to be of great interest for radio astronomy applications because they provide excellent sensitivity and simplified receiver implementations as compared with masers and SIS receivers, both of which operate at 4 K. InP HEMT's have to date provided the lowest cryogenic noise temperatures of any transistor type; amplifiers based on devices produced in three different laboratories (Lockheed Martin, TRW, and Hughes) have at 18 K exhibited 40 GHz minimum noise temperature $T_{\min}$ of 10 K (corresponding to 0.15 dB noise figure) [38]–[40]. Hybrid amplifiers have been developed at frequencies of 26–36 GHz, 38–45 GHz, 40–50 GHz, and 60–80 GHz, and as shown in Fig. 6, InP HEMT-based receivers are expected to be competitive with SIS receivers for frequencies up to about 100 GHz.

Many additional applications could benefit from the dramatic improvement in InP HEMT noise performance possible with even modest cooling. A typical cooling curve (plot of $T_{\min}$ versus physical temperature) can be found in [40] and

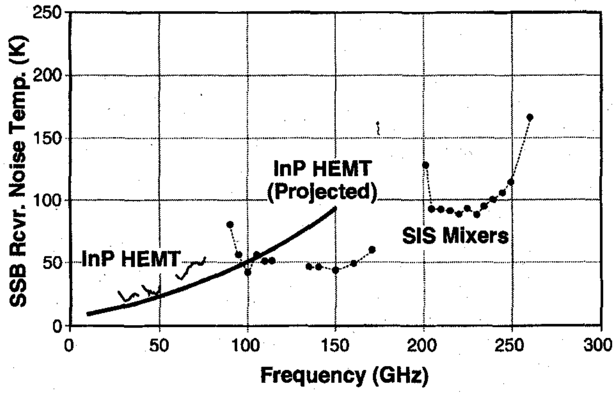

Fig. 6. Comparison of noise performance of InP HEMT and SIS mixer receivers [41].

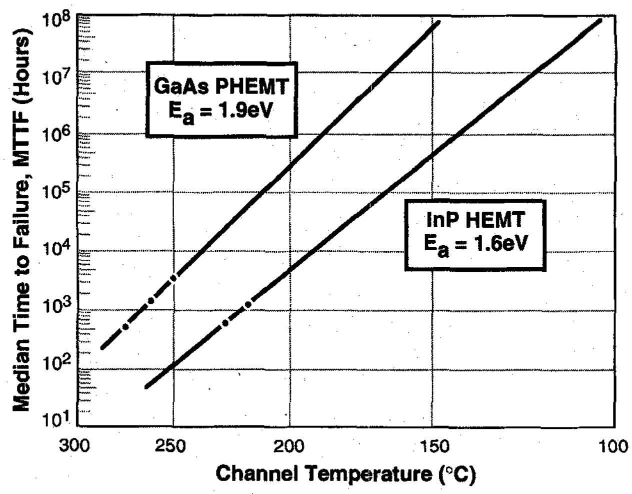

Fig. 7. Accelerated dc life test results for low noise HEMT's [46]. Each data point corresponds to 8–10 samples.

indicates that the steepest portion of the cooling curve occurs in the vicinity of room temperature, where a 4% change in noise temperature arises from each 10°C change in physical temperature.

VI. Material and Process Maturity

For a variety of reasons, InP HEMT MMIC's currently cost more than GaAs-based MMIC's. First, InP substrates are smaller: 2- and 3-in wafers are available, as compared with 3-, 4-, and 6-in for GaAs. Most InP HEMT and optoelectronic device fabrication (including production) is now carried out on 2-in wafers [9], [42], but there is effort underway to scale these processes up for application to 3-in wafers. Three-inch InP substrates currently cost $750–1000 versus $130–160 for GaAs substrates. Moreover, because InP wafers are more fragile, wafer breakage is higher, lowering line yield.

InP MMIC dc and RF yields are today generally lower than those obtained for GaAs due to less mature processing technology, but this is improving. Probably the single most important process parameter controlling yield and uniformity across large wafers is the gate recess depth. Several workers have recently reported the use of selective gate recess etching techniques that significantly improve InP HEMT process uniformity [9], [13], [43]. In [43], for example, Enoki *et al.* report a threshold voltage standard deviation of 16 mV across a 2-in wafer, corresponding to a gate recess depth variation of only a few angstroms.

Even though InP HEMT process yields are expected to reach levels comparable to GaAs, MMIC's produced on InP substrates will almost certainly always be higher in cost than GaAs MMIC's due to the smaller wafer sizes, and will therefore be used only where performance requirements mandate their use. A promising new development that could allow the production of InP HEMT MMIC's at essentially the same cost as GaAs MMIC's is the metamorphic InAlAs/InGaAs HEMT, in which the InP HEMT epitaxial layers are grown directly on GaAs substrates using special buffer layer structures to accommodate the large lattice mismatch. Recently, metamorphic InAlAs/InGaAs HEMT's have demonstrated both dc transconductance [44] and 12 GHz noise figure [45] comparable to that achieved on InP substrates. However, neither the impact on MMIC yield nor the long-term reliability of metamorphic material structures with increased lattice strain and defects have yet been determined.

VII. Reliability

Even the highest performance device is of little use if its reliability fails to meet application requirements. Satellite applications are perhaps the most demanding in terms of required operating lifetime, with a typical minimum MTTF requirement of 10^7 h at a channel temperature of 80°C. As shown in Fig. 7, InP HEMT MTTF as determined from accelerated dc life testing is significantly shorter than that of GaAs PHEMT's, but still meets even stringent satellite lifetime requirements.

Passivation is desirable to reduce InP HEMT sensitivity to environmental effects (particularly humidity). Thin layers (typically 500 Å) of silicon nitride and SiON have been found to produce minimal degradation in the performance of millimeter wave InP low noise HEMT's [3], [13], [30], but these layers are probably too thin to be pinhole-free and so thicker passivation layers are likely to be needed for nonhermetic applications. In addition, it has been reported that InP HEMT's with TiPtAu gate metallization degrade more rapidly than GaAs PHEMT's in the presence of hydrogen which can accumulate within hermetically sealed packages [47], and work is progressing throughout the industry both to modify the device structure to minimize its hydrogen sensitivity and to reduce the hydrogen partial pressure within the package [48].

VIII. Future Trends and Summary

InP HEMT's have demonstrated the best high frequency characteristics of any transistor produced to date, and possess significant potential for further improvement. As shown in Fig. 8, the 600 GHz $f_{\max}$ device reported in [1] exhibits useful gain at frequencies up to 200–300 GHz. With additional optimization of the device design, an $f_{\max}$ of 1 THz should be attainable, enabling for the first time a number of military

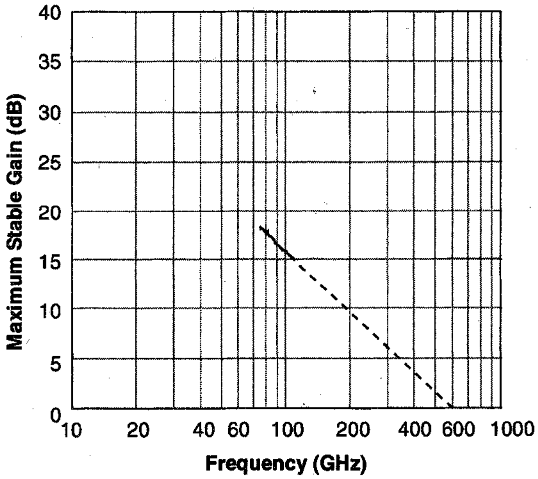

Fig. 8. Maximum stable gain of 0.1 μm InP HEMT, calculated from 75–110 GHz S-parameters. An $f_{\max}$ of 600 GHz is obtained by extrapolating at −6 dB/octave [1].

and commercial MMIC-based systems at frequencies beyond 100 GHz.

Below 100 GHz, InP HEMT's will find widespread use in a number of receiver applications, their insertion being limited only by the speed with which their manufacturability can be improved.

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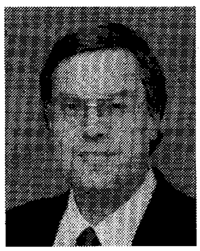

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