Are We There Yet ? – A Metamorphic HEMT and HBT Perspective

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Abstract — **Metamorphic epitaxy technique offers the possibility of combining the advantages of low-cost and manufacturability of GaAs substrates and the high performance of InP-based devices. This paper will present the recent development of metamorphic HEMTs and HBTs and discuss their readiness for commercialization.**

I. Introduction

To-date, GaAs and InP substrates are the most widely used substrates for realizing III-V compound semiconductor devices. As illustrated in Fig. 1, each of these categories of devices has its pros and cons and has niche applications in different frequency ranges. For GaAs-based devices, the cheaper substrate cost and the availability of larger substrate size (6” diameter) results in lower cost per chip. However, their performances are often limited by the amount of indium composition (<25%) one can use in the $In_xGa_{1-x}As$ beyond which severe lattice-mismatched occurs. On the other hand, InP-based devices can offer better performance at higher frequency as they can incorporate indium composition higher than 53%. Unfortunately, InP substrates are more costly, fragile and limited in size (4” diameter) which in turn has resulted in higher cost per chip. As one can see, the performance limitation in the GaAs-based devices and the price limitation in the InP-based devices have put a constraint on the performance-to-price ratio that each technology can achieve.

With the advent of the metamorphic growth technique, this constraint has been alleviated. By incorporating a metamorphic transitional buffer layer between the GaAs substrate and the high indium content active device layers, one can combine the advantages of low-cost and manufacturability of GaAs substrates and the high performance of InP-based devices. Furthermore, the use of metamorphic technique has enabled one to use a wide range of indium composition in the device structure design without limitation on the substrate choice. Hence, as indicated in Fig. 1, the forbidden zone of indium composition between 25%-53% due to substrate constraint is of no more concern. With the metamorphic technique, device engineers can now have more freedom to design the required device structure to suit the target specifications with any indium composition. This also allows one to have the best compromise between the relatively high voltage operation capability of GaAs

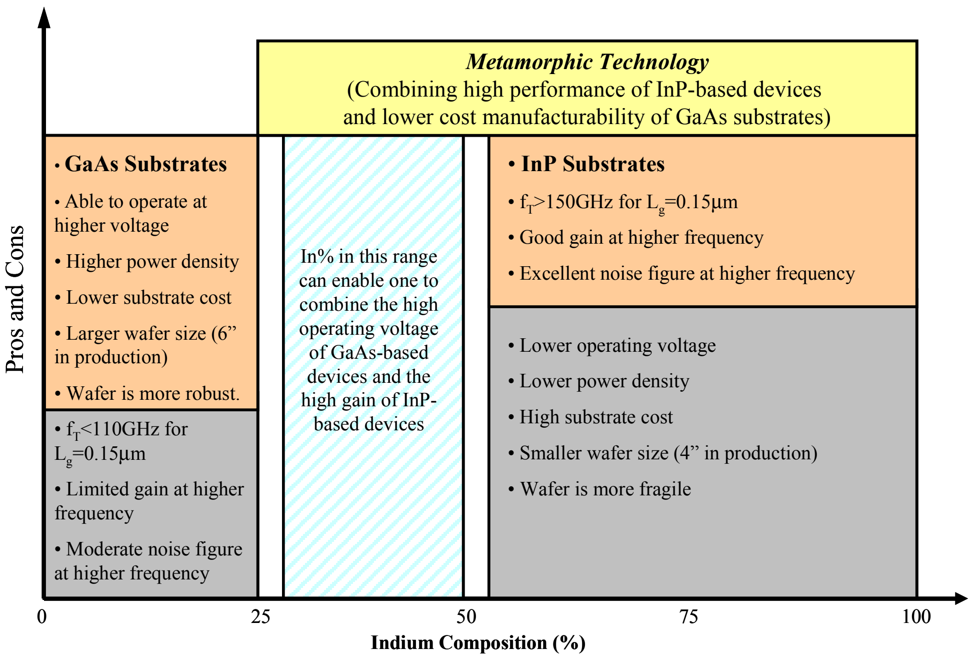

Fig.1 Pros and cons of III-V devices based on GaAs and InP substrates and the advantages of metamorphic devices.

PHEMTs and the high gain of InP HEMTs.

Although the metamorphic techniques have been employed for different types of device applications such as photodiodes [1,2], tunnel diodes [3], VCSELs [4], quantum dot lasers [5] and solar cells [6] etc., this paper only attempts to give a global update of the recent progress in metamorphic HEMTs and HBTs. A personal view on the readiness for the deployment of these devices in the market place is presented through their performance, reliability and application perspectives.

II. Overview Of The MHEMT Technology

A. *MHEMT Development and Progress*

In the late 1980s, the use of metamorphic technique had already been investigated in order to incorporate higher indium composition (x>25%) in the $In_xGa_{1-x}As$ channel to boost the performance of HEMT grown on GaAs substrates. G. Wang et. al. from the Cornell University successfully fabricated a 0.12µm MHEMT using a 1.8µm thick InAlAs/InGaAs superlattice buffer layer [7]. However, due to the poor buffer layer quality, the performance of the device is limited. Despite this early setback, R&D activities in this area have continued to generate great interests globally particularly in the last decade.

In the USA, although some R&D efforts exist in the universities and research laboratories [8]-[9], most efforts are conducted by major companies such as Raytheon [10], BAE Systems [11], TriQuint Semiconductors [12], Motorola [13] and IQE [14] etc.. Raytheon has been a strong advocate for the MHEMT technology and has successfully brought this technology from the R&D test beds to full production. Since September 2001, it has started offering its 4-inch MHEMT foundry process [15].

In Europe, several research groups have extensive R&D efforts on MHEMTs. These include the Fraunhofer Institute for Applied Solid-State Physics (IAF) [16] and Daimler Chrysler AG [17] in Germany, the Institu d'Electronique et de Micrelectronique du Nord (IEMN) in France [18], and the IMEC in Belgium [19]. Both IAF and IEMN have also extended the MHEMT performance by reducing the gate-lengths to ~50-60nm [20]-[21]. At the university level, MHEMT R&D are equally active [22]-[24] and a record-high f_T~440GHz using a 50nm T-gate has been recently reported by the University of Glasgow [22]. In the commercial front, OMMIC in France also started to offer MHEMT foundry services since September 2001 [15].

In Asia, the reported MHEMT R&D activities mainly are carried out by the commercial companies, research institutes and universities from Japan [25]-[28], Taiwan [29]-[31], Korea [32]-[34] and Singapore [35]. In 2003, WIN Semiconductors announced the first 0.15µm MHEMT 6-inch GaAs foundry service [36] with superior low-noise and power performance compared to their PHEMT counterparts. At 29GHz, the MHEMT shows 130mW/mm higher in power density, 6% higher in power-added-efficiency and 1.6dB higher in linear gain compared to the PHEMT [37]. These results are very encouraging and serve to demonstrate the feasibility of exploiting the manufacturing superiority of larger GaAs wafer substrates.

B. *Microwave Performance*

MHEMTs have made significant progress in cutoff frequencies, low-noise and power performance which could rival their PHEMT and InP HEMT counterparts. Fig.2 shows the recent reported state-of-the-art cutoff frequency performance of MHEMTs as well as InP-based HEMTs and GaAs-based PHEMTs. Typical f_T and f_{max} values of MHEMTs achievable by commercial production foundries are f_T> 120GH and f_{max}>200GHz using 0.15µm gate-length technology. f_T value as high as 440GHz [22] and f_{max}~490GHz [38] have also been reported recently using 50-60nm T-gate MHEMTs. The MHEMTs compared favorably with InP-based HEMTs and are better than GaAs-based PHEMTs. It should be noted that the cutoff frequency values of the MHEMTs are affected by both L_g and In%. Nevertheless, Fig.2 illustrates the excellent microwave performance and potential of MHEMTs.

MHEMTs have also demonstrated excellent low noise and high power performance [39]. For example, Raytheon has reported a 0.15µm gate length $In_{0.32}(AlGa)_{0.68}As/In_{0.43}Ga_{0.57}As$ MHEMT with P_{out} of 850mW/mm at 35GHz. Similar device exhibited a NF_{min} of 1.18dB and an associated gain of 10.7dB at 25GHz. It is interesting to note that the channel indium composition of 43% employed in these MHEMTs falls in the range of 30-50% which are previously difficult to realize in either GaAs or InP substrates.

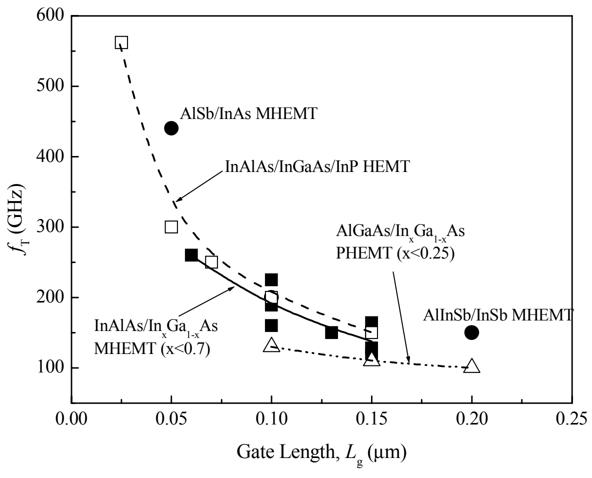

Fig. 2. Current gain cutoff frequency versus gate-length for reported state-of-the-art MHEMTs, InP HEMTs and GaAs PHEMTs.

Another important emerging technology is the Sb-based MHEMTs. These MHEMTs employ very narrow bandgap channel (InAs and InSb) HEMTs which enable them to have very high cutoff frequency at very low applied bias. These include AlInSb/InSb MHEMT [40]-[41] and AlSb/InAs [42]-[44] which are grown metamorphically on GaAs substrates. For example, a 0.2µm gate-length AlInSb/InSb MHEMT has been demonstrated for the first time with a high f_T of 150GHz at V_{ds} of only 0.5V [40]. The power dissipation is 5-10 times lower than state-of-the-art silicon MOSFETs and is hence very attractive for the next generation ultra high-speed and very low power digital and RF applications.

C. MHEMT Reliability

One of the key factors in realizing a high performance MHEMT is the metamorphic buffer layer design and growth. The buffer layer should provide a good transition of the lattice constant from the GaAs substrate to the active epitaxial layers grown on top of the buffer layer. The buffer layer should have tolerable surface roughness (r.m.s. value <20Å based on 5µm ×5µm) and dislocation density (<10^6 cm^{-2}). Several material systems have been successfully employed for the metamorphic buffer layers. These include InAlGaAs [45], AlGaAsSb [11], InAlAs [12] although other types of buffers such as InGaP [35], InGaAs [46] and InAlP [14] have been explored. All these different buffers have shown surface roughness ~13-15Å based on a 5µm ×5µm scan area and an acceptable dislocation density of ~10^6 cm^{-2}. However, it is pointed out in [25], that the reported dislocation density values of ~10^6 cm^{-2} are typically underestimated as a result of the particular technique employed. The actual values could be as high as ~10^7 cm^{-2}. Nevertheless, MHEMTs with these buffer qualities still exhibit good device performance and reliability results.

Device reliability results have been reported by several groups [36][47]-[48]. As summarized in Table 1, these results show that MHEMT with an MTTF>10^6 hrs are reliable enough for most practical applications and even adequate for space qualification. However, it should be noted that the device reliability will be compromised as one increases the In% or/and reduces the gate-length as reported in [49].

Several studies [49]-[50] have been conducted to investigate the effect of the metamorphic buffer on the device reliability. In contrary to what one would expect, the results suggest that the metamorphic buffer does not influence the device reliability. The causes for the reliability issues in MHEMT were primarily attributed to the metal interdiffusion and gate sinking effects [49], hot-hole or hot-electron trapping at the surface etc. [50].

Company	MTTF [hrs]	Ea [eV]	In%	Lg [µm]	Ref
WIN	3×10^7	1.7	40	0.15	[36][37]
Raytheon	2.9×10^6	1.5	60	0.15	[47]
IAF	3×10^7 1×10^6	1.8 1.3	65 80	0.10 0.07	[48]

Table 1. MHEMT reliability results (Accelerated DC life tests based on $\Delta G_{m,max}$ =10% criteria at 125°C in nitrogen ambient).

D. MHEMT Applications and Commercialization

MHEMTs have been successfully implemented in a wide range of integrated circuit applications. Fig. 3 gives a glimpse of these applications which cover a wide frequency range from 10-220 GHz [32][51]-[54].

The metamorphic technology has also made a significant impact on high gigabit OEIC applications at 1.55µm wavelength [55]-[58]. This takes advantage of the fact that devices with the In composition >60% for 1.55µm operation can be realized on GaAs substrates instead of InP substrates. For example, Zhang et. al. [55] have reported the first 40 Gbps OEIC integrating a metamorphic traveling wave amplifier with PIN diodes. This receiver shows 6GHz wider bandwidth and 7dB more gain than the hybrid counterpart.

The commercialization of MHEMT technology is well in place ranging from pure-play epiaxial suppliers such as IQE, Intelliepi and Picogiga, to foundry services such as WIN Semiconductors, Raytheon and OMMIC, to the offering of standard product parts such as LNA, PA and TIA. This has provided the consumers with an alternative to the existing III-V technologies based only on GaAs or InP substrates.

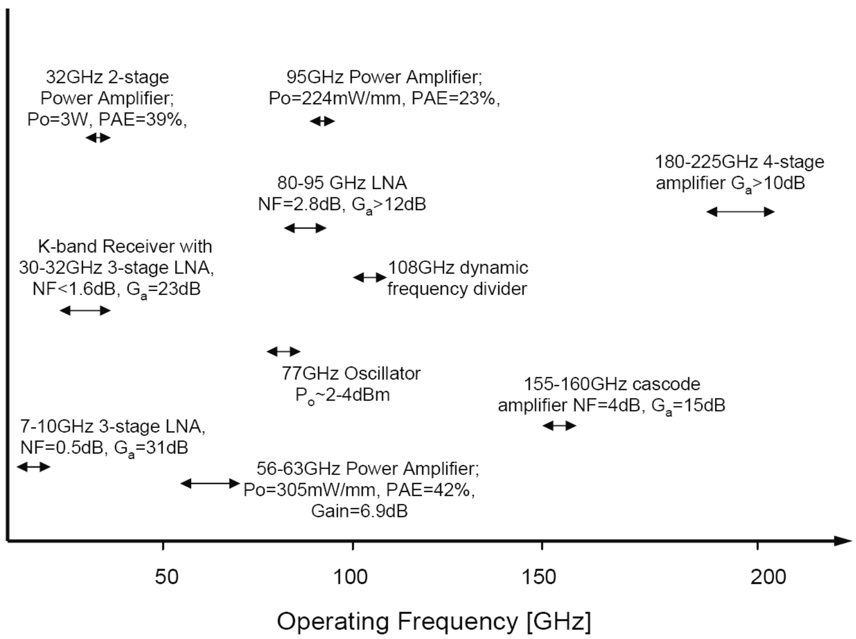

Fig. 3. Types of integrated circuits using MHEMTs.

III. OVERVIEW OF THE MHBT TECHNOLOGY

A. MHBT Development and Progress

With the successful development of MHEMTs, the metamorphic technique has also been explored for HBTs since 2000 by a handful of research groups worldwide [59]-[64]. In comparison to MHEMTs, MHBT technology is still very much in the early developmental stage. Although the recent results [65] have shown very encouraging dc and microwave performance of MHBTs, more investigation in the metamorphic buffer layer and device optimization, reliability studies, and demonstration of integrated circuits would have to be done to bring MHBT at par with the current MHEMT technology status.

B. Buffer Layer and Thermal Considerations

The design and growth of metamorphic buffer layer for MHBT is more challenging as compared to that for MHEMT. The reasons are two folds. Firstly, HBT operation involves both the majority and minority carriers in the epitaxial layers. It is much more sensitive to the defects density in the metamorphic buffer layers and the surface roughness [59] particularly in large scale integrated circuits applications. Secondly, HBTs are typically used in applications which required them to operate at much higher power densities [59]. As such, the thermal conductivity of the buffer layer has to be taken into consideration when choosing the material system.

Buffer Material	Thermal Conductivity [W/m.K]	Surface Roughness [nm]	Ref
InP	35	9.5	[68]
InGaP	16	6.5	[67]
InAlAs	9.9	4	[65][67]
InAlP	8	3.6	[68]
InGaAs	4.4	--	[67]
AlGaAsSb	8.4	4.0	[66]

Table. 2 Reported thermal conductivity and surface roughness of different material system used for MHBT metamorphic buffer layers.

Table 2 summarized the different types of material systems developed for the metamorphic buffer layers of MHBTs. Among these, buffer layers using ternary compounds such as InAlAs [61][65] and quaternary compounds such InAlGaAs [62] and AlGaAsSb [66] have shown better surface roughness and lower defect density. On the other hand, the metamorphic buffer using binary compounds such as InP [66] have shown to have the highest thermal conductivity. One possibility of overcoming these shortcomings is by using a linearly graded InGaP metamorphic buffer as suggested in [67]. This buffer scheme provides more freedom in the metamorphic buffer layer growth with higher thermal conductivity compared to those using InAlAs and AlGaAsSb [66].

Detailed studies of the thermal resistance for MHBTs have been reported by [66]-[68]. As shown in Fig. 4, the thermal resistance due to the metamorphic buffer layer is higher in the InAlAs buffer than in the GaInP buffer as reported by H. Wang et. al. [67]. However, for the $In_xGa_{1-x}P$ buffer, the composition is linearly graded from x~0.52 (near the GaAs substrate) to x~1 (near the HBT collector). As pointed out by Kim et. al., [68], this has resulted in the upper portion of the InGaP metamorphic buffer layer comprising of material which is almost InP-liked and hence in the overall lowering of the thermal resistance.

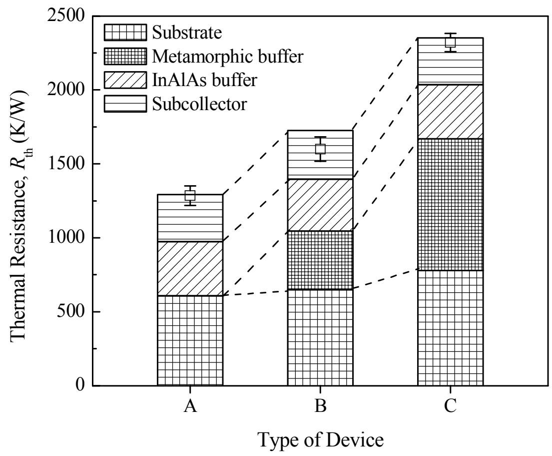

Fig.4. Calculations of contributions from the different layers in MHBTs and LHBT (from subcollector to substrate) to the total thermal resistances. The open symbols with error bar are the experimental data. (Device A: LHBT, Device B: MHBT with InGaP metamorphic buffer, and Device C: MHBT with InAlAs metamorphic buffer).

C. Microwave Performance

The first microwave characteristics of MHBTs were reported in 2000 [59]. The device with a 5×5 μm^2 emitter exhibited f_T of 48GHz and f_{max} of 42GHz. Since then, excellent progress has been made through the improvement in the fabrication process and aggressive device scaling. To date, record values of f_T~268GHz and f_{max}~339GHz have been achieved for a MHBT with the emitter size of 0.5×7 μm^2 [60]. However, reports on the microwave noise and power performance of MHBTs have been lacking. To the best of the authors' knowledge, the only reports on such performance were given by Halder et. al. [69] and Wang et. al. [59]. For a 5×20 μm^2 emitter MHBT, the measured output power is ~18dBm (64mW) and 40% power-added efficiency at 2.5GHz. For a similar lattice-matched InP HBT (LM-HBT) fabricated at the same laboratory and under the same biased conditions, the measured output power is ~20dBm (100mW) and 42% power-added efficiency. The lower power performance of the MHBT is attributed to the self-heating mechanism caused by the poorer thermal conductivity of the MHBT grown on GaAs substrate. Microwave noise measurements were also evaluated on several 5×5 μm^2 emitter MHBTs. At 2GHz, the typical NF_{min} value is ~2dB for MHBTs and ~1dB for LHBTs. Finally, the low-frequency noise characteristics of MHBTs have also been reported [70]. The noise spectra of MHBTs exhibit only 1/f noise behavior with no visible Lorentzians characteristics. The noise level of the MHBTs is comparable to the corresponding LHBTs. Although these are preliminary results, they suggest that the superior performance of InP HBTs can be exploited through the use of MHBT with continued improvement through the metamorphic growth technique and proper heat dissipation mechanism.

D. Reliability Issues

In contrast to MHEMTs, there is no report of life test conducted on MHBTs. Only some studies on the current and temperature stress tests have been reported [71]-[72]. In these studies, to investigate the impact of optimization of the metamorphic buffer layer on the device bias-temperature stability, the stress tests were conducted on MHBT-A (surface roughness ~2nm), MHBT-B (surface roughness ~10nm), and LHBT. The results in Fig.5 show that MHBT-B degrades faster than the MHBT-A and LHBT due to the degradation of the device junction quality probably caused by the increase in trap-related recombination. It is interesting to note that similar stress test has been performed on MHEMTs grown on the buffer which is same as the one for MHBT-B. However, no significant degradation was observed during the bias-temperature stress tests. This result suggests that compared to MHEMTs, growth of high quality metamorphic buffer is more critical for the stability of MHBTs. On the contrary, a different investigation has found no impact of the defect density from the InP metamorphic buffer on the device performance and yield [65]. Clearly, more studies are required to understand the impact of metamorphic buffer layer on MHBT device performance and long term stability.

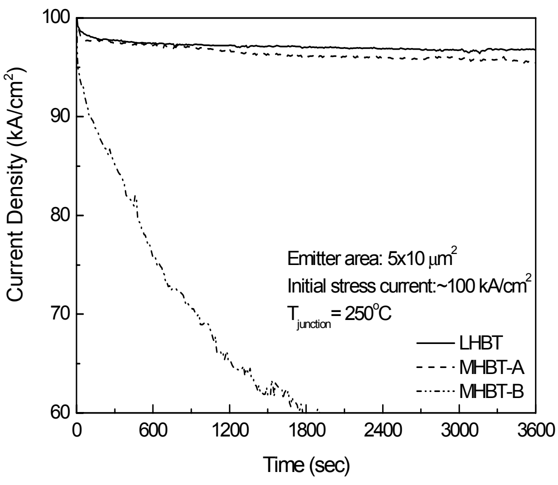

Fig.5 Degradation of MHBTs and an LHBT under high junction temperature ($T_j = 250^oC$) and high current density (100 kA/cm^2) stress.

IV. CONCLUSION

The metamorphic epitaxy technique has enabled the possibility of combining the advantages of low-cost and manufacturability of GaAs substrates and the high performance of InP-based devices. In this paper, we have presented the recent development of metamorphic HEMTs and HBTs and discussed their readiness for commercialization.

MHEMTs have shown excellent device and reliability performances which rival their lattice-matched HEMT counterparts. Commercialization of this technology has already taken place. In the authors' opinion, for MHEMT technology, the answer to the question "Are we there yet?" is a resounding Yes. It is in good standing to compete with GaAs PHEMTs and InP HEMTs and may eventually replace them for large-volume commercial applications in agreement with the projection by the ITRS 2003 Roadmap [73].

As for MHBT technology, it is still in its infancy as compared to the MHEMT technology. Although the results thus far have shown encouraging performance, it is too premature to see any clear trend as of now. More studies and developmental work will have to take place before MHBTs can be at par with their lattice-matched HBT counterparts. Furthermore, there must be a demand from the commercial sector in order to accelerate and drive the furthermore development of MHBT technology as in the case for MHEMT technology.

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