Low Noise and Power Metamorphic HEMT Devices and Circuits with X=30% to 60% In_xGaAs Channels on GaAs Substrates

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ABSTRACT

Metamorphic HEMTs (MHEMTs) are becoming the device of choice for low cost millimeter-wave applications, where a high indium content channel is necessary for high performance. This paper will review the material properties, the processing, and the device and amplifier performance of metamorphic HEMTs with 30% to 60% indium channel content, with a focus on work done at Raytheon RF Components.

INTRODUCTION

Recently, GaAs Metamorphic HEMT (MHEMT) technology has emerged as an attractive, low cost alternative to InP HEMTs for high performance low noise and power applications. Previously, only InP HEMT devices could fill this role, but at high costs due to the economies of scale of 2" and 3" wafers. Metamorphic HEMT (MHEMT) technology offers the performance advantage of InP HEMTs and the cost advantage of 4" and 6" GaAs MMICs.

In the MHEMT, the device active layers are grown on a strain relaxed, compositionally graded, metamorphic buffer layer. The buffer layer provides the ability to tailor the lattice constant to any indium (In) content channel desired, and therefore allows the device designer an additional degree of freedom to optimize transistors for high frequency gain, power, linearity and low noise. For example, using a metamorphic buffer layer, InP-based high electron mobility transistors can be grown on GaAs substrates for a substantial cost reduction and manufacturability improvement over a InP-substrate based devices [1]-[5].

In this paper the current status of metamorphic HEMT technology is reviewed, including both low noise and power devices, as well as amplifier fabricated from these components.

High In content $In_xGa_{1-x}As$ channel MHEMTs (x = 53%-60%) have shown impressive results, achieving noise performance comparable to InP HEMTs and excellent linearity. While InP HEMTs and high In content MHEMTs exhibit high gain at millimeter wave frequencies, their low on-state breakdown voltage has limited their use in power applications. Using metamorphic technology to fabricate devices with intermediate (25-45%) In contents, high on- and off-state breakdown voltage, large power densities and 1.4W of output power at 44 GHz have been realized.

MATERIAL PROPERTIES

The metamorphic buffer layer [6]-[8] serves two purposes: to transform the lattice constant from that of the GaAs substrate to that of the high In content device active layers, and to trap dislocations and prevent them from propagating into the device channel. The TEM in Figure 1 illustrates the growth of a high indium content HEMT directly on GaAs using a metamorphic grading layer. The dislocations are indeed trapped in the grading layer and propagate parallel to the substrate's surface. The MHEMT's layer interfaces remain flat despite having twice the indium content and five times the total thickness as a typical GaAs pHEMT.

Figures 2 and 3 illustrate the distinct tradeoff that occurs as one adds In content to the channel of a (metamorphic) HEMT. In Figure 2, the mobility is plotted using measured room temperature Hall data, and the well depth (conduction band discontinuity) is calculated from photoluminescence measurements. The 300K mobility of $In_{0.56}GaAs$ HEMT grown on a GaAs substrate measured within 5% of the mobility of an identical structure on an InP substrate [7], demonstrating the high quality of the MHEMT channel. Channel electron mobility increases with indium in the InGaAs channel, due mainly to a fall in effective mass. This reduction in mass results in higher channel electron velocity, which increases F_t for a fixed 0.15 µm gate length (Figure 4).

Figure 3 shows the drop in on-state breakdown with increasing indium, due to a reduction in channel band gap. Through the use of a strained In(Ga)AlAs Schottky layer with higher Al content and a band gap of greater than 1.7 eV, a larger conduction band discontinuity can be engineered. This provides even better quantum well confinement and less parallel conduction, as well as improved off-state breakdown. (The calculations shown in Figure 2 are using this strained In(Ga)AlAs layer to calculate delta E_c.) The combined effects of improved channel mobility and larger conduction band discontinuity result in lower overall noise figure, especially at higher frequencies.

While GaAs pHEMTs and InP HEMTs are limited to In compositions near their lattice spacing, MHEMTs have a wide range of lattice constants that are available, and therefore enable the customization of the device's properties specific to each application. Although thin strained channels can be grown on InP, these metamorphic devices contain nearly 1000 angstroms of strained material, making their growth impossible without a graded buffer layer. The data points in Figures 2 and 3, some of which lie within the pHEMT's and InP HEMT's forbidden channel indium content regions, are devices grown at Raytheon which exploit this additional degree of freedom.

DEVICE PROCESSING AND PERFORMANCE

MHEMT devices are typically mesa etched for isolation using a sulfuric or phosphoric based etchant. A series of metals containing Au/Ge are evaporated and annealed to form an ohmic contact, with contact resistance numbers in the range of 0.08 to 0.2 Ohm-mm. Following ohmic formation, gate etching is performed selectively by removing the InGaAs cap layer and stopping on the InAl(Ga)As barrier layer. Ti/Pt/Au gates are then evaporated. Finally, silicon nitride is used to passivate the device. The device processing is nearly identical to our GaAs pHEMT process, allowing for easy integration into the GaAs production line.

The DC performance data for a $In_{0.60}GaAs$ MHEMT device shows a G_m of 850 mS/mm, an I_{max} of 630 mA/mm, a V_{po} of –0.75V and a $V_{dg\ BRK}$ = 8. An excellent uniformity of less than 3.1% standard deviation for all parameters across a 3" wafer is due to both the high selectivity of the gate etch and the precision of the MBE growth process.

LOW NOISE DEVICES AND CIRCUITS

Raytheon's MHEMT low noise results [9]-[10] rival the best published MHEMTs [11], as well as the best InP HEMTs [12]. A 0.15 µm $In_{0.60}GaAs$ Raytheon MHEMT biased at 1V and 90 mA/mm showed 0.24 dB F_{min} with 16.2 dB associated gain at 12 GHz, and 0.61 dB F_{min} with 13.8 dB G_{assoc} at 26 GHz. Rohdin et al [11] showed 0.25 dB with 15 dB of associated gain at 12 GHz, using a 0.1 µm $In_{0.53}GaAs/InAl_{0.48}As$ MHEMT.

Figure 5 shows the one result of a comprehensive study on noise figure versus the percent of channel In content of MHEMTs. As the channel In content is increased from a pHEMT's 19% In to a substrate-forbidden 33% In MHEMT, the minimum noise figure is reduced from 1.4 dB at 25 GHz to 1.2 dB. Further increasing In content to 43% In results in a substantial drop in minimum noise figure to 0.75 dB. Beyond 43% In, no significant improvement in noise figure is achieved at 25 GHz, as demonstrated by the 53% In MHEMT with a F_{min}= 0.85 dB and the 60% In MHEMT with a F_{min}= 0.65 dB. Devices with shorter unit gate width resulted in lower gate resistance and F_{min}s as low as 0.45 dB with the 43% In MHEMT.

The associated gain at the minimum noise match for the same 300 µm devices is plotted versus drain bias at 25 GHz in Figure 6. The pHEMT shows approximately 8 dB of associated gain near its minimum F_{min}, in contrast to the 33% In MHEMT with 10 dB. The 43% In MHEMT has ~10-11.5 dB of G_{assoc} over the large current range where noise figure remains quite low. The 53% and 60% devices reach their peak associated gain of 12-12.5 dB quickly, demonstrating the clear advantage of high indium channels at very low currents.

Figure 7 plots the noise figure and gain of a 3-stage 60% In MHEMT Ka-band LNA with less than 1.5 dB NF and greater than 23 dB of associated gain from 31-32 GHz [13]. Particularly impressive is the 15 mW of total DC power consumed by this 3-stage LNA.

POWER DEVICES

Drain bias limits of 3.5V have hampered the output power density of some MHEMT devices and most InP HEMTs, predominately due to low on-state breakdown. Even so, output power(s) (densities) of 1W at 950 MHz [14], 509 mW/mm at 20 GHz [15] and 240 mW/mm at 60 GHz [16] have been achieved with 53% In MHEMT devices. Figure 8 compares all the published MHEMT results versus the best InP HEMT power devices (> 150 microns in periphery), most of which consist of composite channels (InGaAs/InP) to improve on-state breakdown. The 30-45% In MHEMT devices lie above the trend line, and show promise as a high power mm-wave device alternative to InP HEMTs. The 43% In device has also demonstrated 1.5 dB improved G_{assoc} at the same power output density as a GaAs pHEMT. Both devices were biased at 5V, class AB and power tuned at 35 GHz.

Exploration of lower indium contents has resulted in higher on-state breakdown, enabling 5V and 6V drain biasing to be used for higher power density. Using a 33% In channel, > 820 mW/mm at 10 GHz [17] and > 640 mW/mm at 35 GHz [18] have been achieved with 6V drain biasing. With a 43% In, 12x50 µm (600 µm) MHEMT over 900 mW/mm was achieved at 35 GHz using a double recess structure for improved breakdown [19]. Interestingly, this same 43% In device (with lower electron sheet density) displayed < 0.6 dB F_{min} at 25 GHz due to its high channel mobility and excellent confinement. Recently, we fabricated a 8.16mm 3-stage 44 GHz power amplifier using our 33% In MHEMT and demonstrated 1.4W output power, 18% PAE with 14 dB of gain. We believe that this is the highest P_{out} achieved on an MHEMT to date.

CONCLUSION

Metamorphic HEMTs have distinct advantages over the existing GaAs and InP HEMT technology: the freedom to choose virtually any high In content InGaAs channel provides for application specific device optimization and high frequency performance, while the GaAs manufacturing economies of scale (high volume, large wafer size) reduce the cost.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Lisa Aucoin, who is critical to the success of Raytheon's MHEMT program. We also would like to thank S. Lichwala, R. Leoni, N. Pisiello, P. Lyman, P. Lemonias, J. Mosca T. Kennedy and M. Grigas, all members of the MHEMT team.

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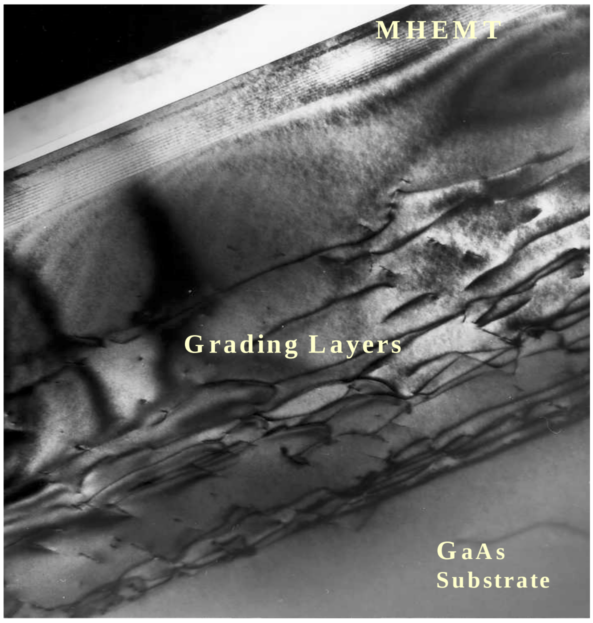

Figure 1. Cross section TEM of a MHEMT on a GaAs substrate.

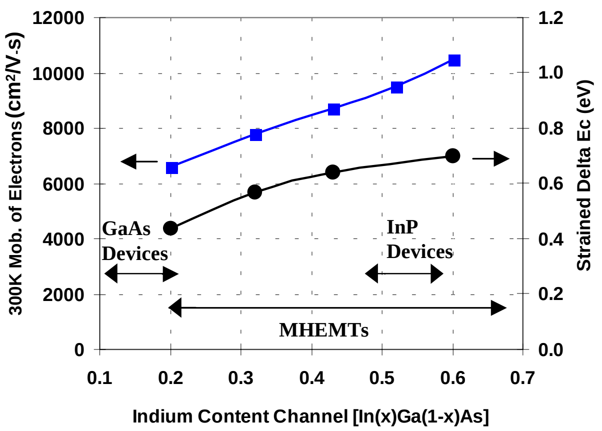

Figure 2. As indium is added to the channel, both the mobility and well depth increase (when a strained InAlAs layer is used).

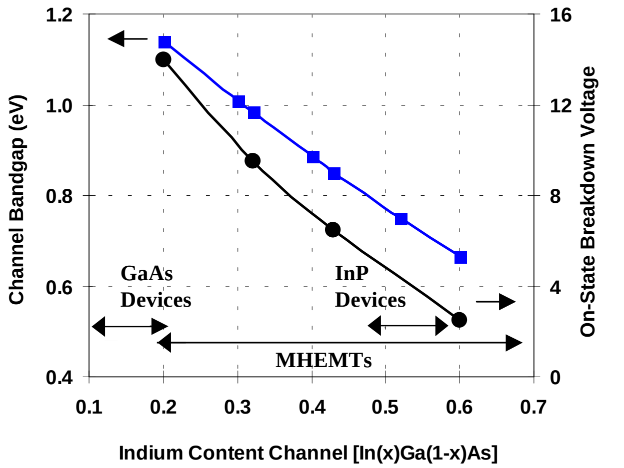

Figure 3. As indium is added to the channel, the channel band gap falls, reducing breakdown voltage.

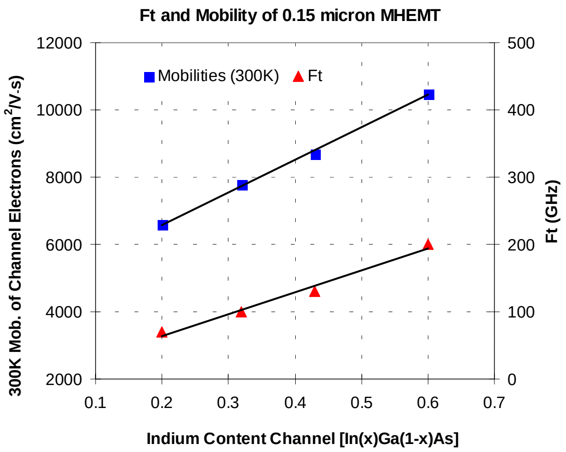

Figure 4. For a fixed gate length, the additional In content in the channel increases the mobility and therefore the F_t (extrapolated at -6 dB/octave from measured data).

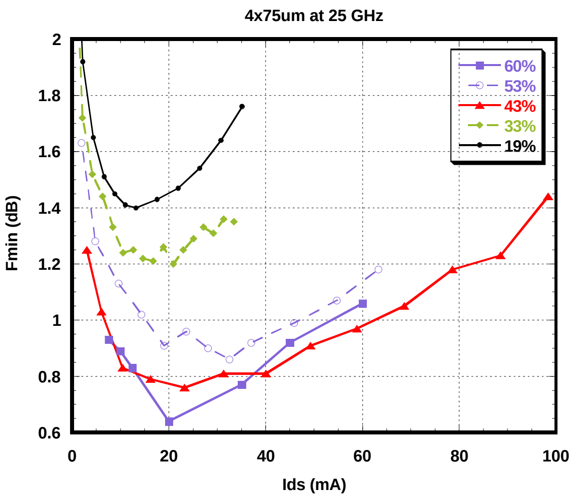

Figure 5. F_{min} versus drain current at 25 GHz for 0.15 µm gate length, 4x75 µm periphery, devices.

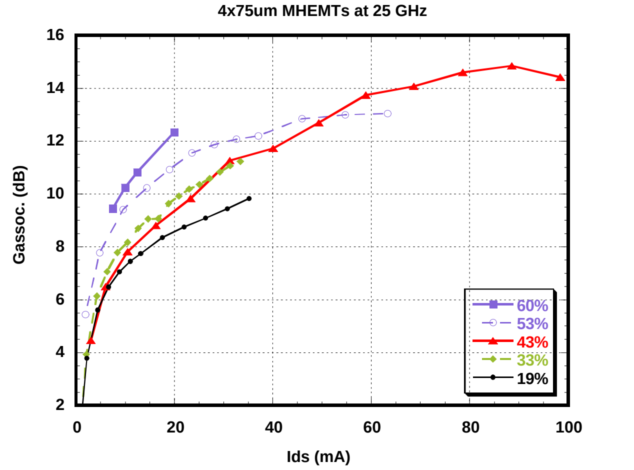

Figure 6. Associated gain versus drain current at 25 GHz for 0.15 µm gate length, 4x75 µm periphery, devices.

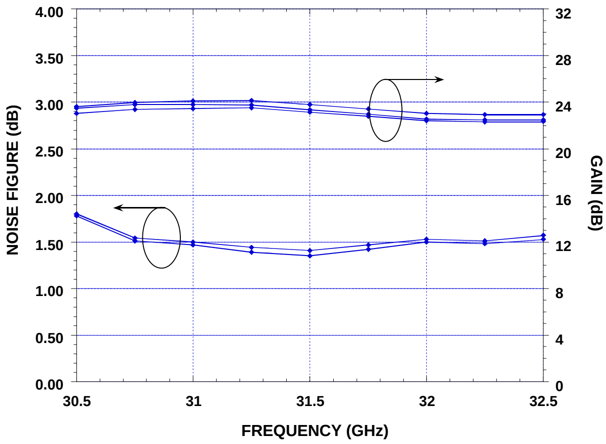

Figure 7. The 3-stage MHEMT LNAs show 1.5 dB noise figure and 23 dB of associated gain from 31-32 GHz.

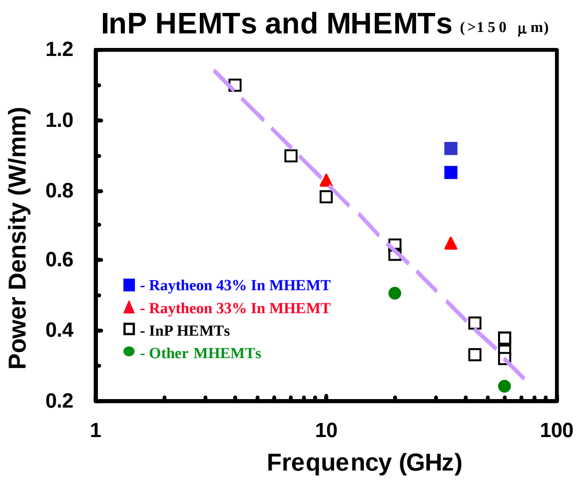

Figure 8. Power density of InP HEMTs and MHEMTs versus frequency for devices of greater than 150 microns total periphery.