GaAs Metamorphic HEMT (MHEMT): The Ideal Candidate for High Performance, Millimeter Wave Low Noise and Power Applications

C. S. Whelan, P. F. Marsh, W. E. Hoke, T. E. Kazior

Raytheon RF Components, 362 Lowell Street, Andover MA 01810
Phone: 978-470-9456, e-mail: colin_s_whelan@rrfc.raytheon.com

ABSTRACT

GaAs metamorphic HEMTs promise to be the next generation of transistor technology to fill the emerging demand for high performance millimeter-wave devices. 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

As the microwave frequency spectrum becomes more crowded and as the demand for more bandwidth grows, high performance millimeter-wave low noise and power devices are critical for a wide range of commercial and military 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, 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.

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 voltages and large power densities 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 a MHEMT structure on GaAs, where an InAlGaAs buffer layer is used to grade the lattice constant to that of InP. The $Al_{0.48}InAs/In_{0.53}GaAs$ MHEMT interfaces remain flat despite having twice the indium content and nearly twice the total channel thickness as a typical GaAs pHEMT. No threading dislocations nor thickness undulations are apparent.

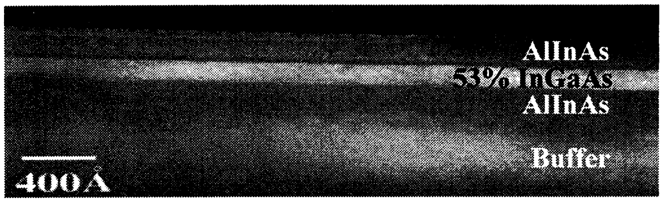

Figure 1. Cross section TEM of a 53% In MHEMT on GaAs.

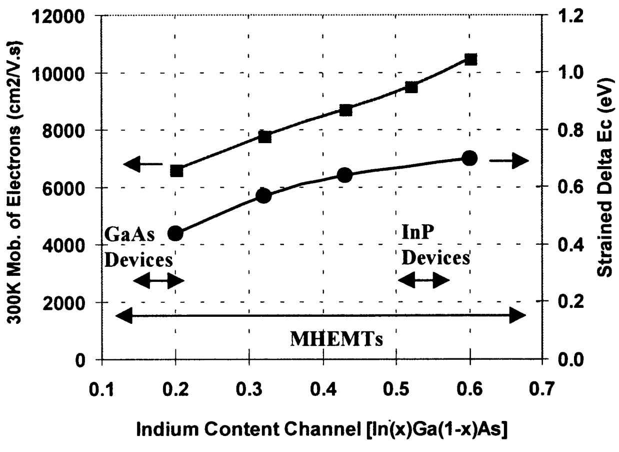

Figure 2. As indium is added to the channel, both the mobility and well depth increase (when a strained InAlAs layer is used).

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, demonstrating the high quality of the MHEMT channel. Channel electron mobility increases with indium in the InGaAs the 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, 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.

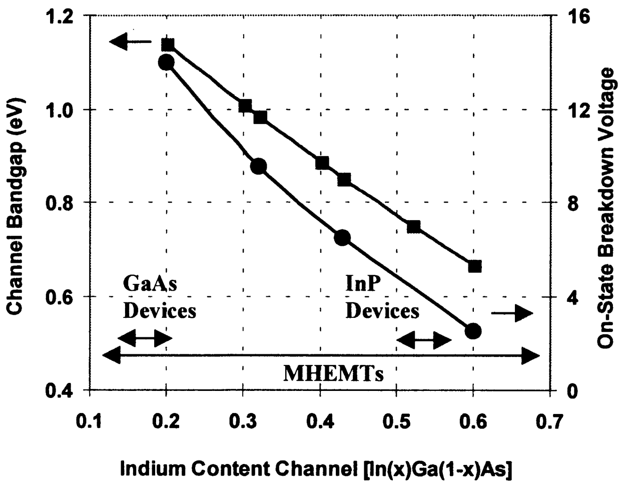

Figure 3. As indium is added to the channel, the channel band gap falls, reducing breakdown voltage.

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. 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.

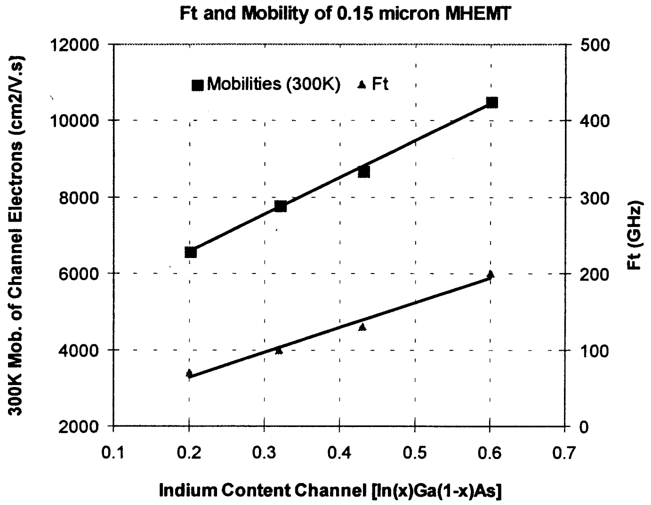

Figure 4. For a fixed gate length, the additional In content in the channel increases the mobility and therefore the F_t (extrapolated at -6 dB/octave from measured data).

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 InAlAs 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.

TABLE 1

A TABLE SHOWING THE EXCELLENT MATERIAL QUALITY AND UNIFORMITY OF MHEMT DEVICES PROCESSED ON A 3" WAFER.

60% In MHEMT	Imax (mA/ mm)	Idss (mA/ mm)	Vpo (V)	Gm (mS/mm)	Off-state V_{BRK} (1mA/mm)	R_s (Ohm-mm)
DC Param.	630	520	-0.76	800	8.3	0.37
%Stdev	3.0	2.3	3.1	1.9	2.8	2.9

DC performance data for a $In_{0.60}GaAs$ MHEMT device is shown in Table 1, normalized to a gate width of 1 mm. When the channel to gate distance is taken into account (represented by V_{po}), the G_m of 800 mS/mm is indeed quite good, demonstrating the excellent channel transport properties that can be achieved with metamorphic HEMTs. The high off-state breakdown is achieved through the use of a strained high Al content Schottky layer which improves the barrier height and a selective cap layer recess. The 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] and 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. Both these results compare favorably to state-of-the-art low noise InP HEMT results.

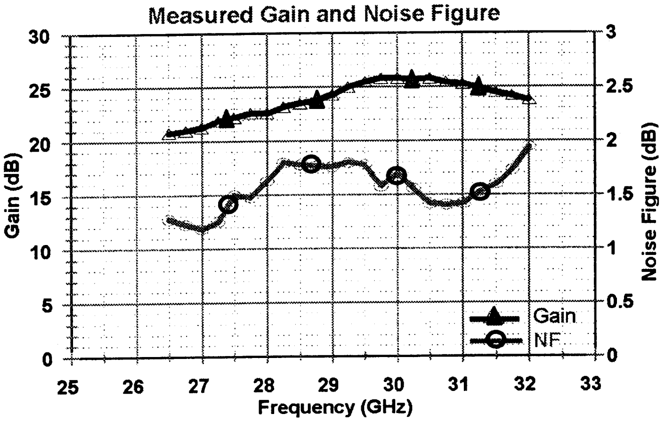

Figure 5. The 3-stage MHEMT LNA shows 1.6 dB noise figure and 25 dB of associated gain from 30-31 GHz.

Low noise amplifiers with state-of-the-art performance have been demonstrated for a variety of military and commercial applications utilizing MHEMT technology.

Figure 5 plots the noise figure and gain of a 3-stage 60% In MHEMT Ka-band LNA with less than 1.6 dB NF and greater than 25 dB of associated gain from 30-31 GHz [13]. Particularly impressive is the 31 mW of total DC power consumed by this 3-stage LNA. MHEMTs demonstrate the same high gain and low noise at low (current) biases as InP HEMTs due to their higher channel mobilities and velocities.

Figure 6 shows an ultra-wide band 2-stage MHEMT LNA which displays less than 3 dB of noise figure and approximately 30 dBm of third order intercept (TOI) from 4.5 to 18 GHz. Few amplifiers, regardless of the device technology used, have simultaneously demonstrated such high linearity and bandwidth. Gain flatness, because of its somewhat lower importance in this particular application, was traded for improving TOI and noise figure across the band. The simultaneous realization of low noise, high bandwidth and linearity are a unique achievement of the MHEMT technology.

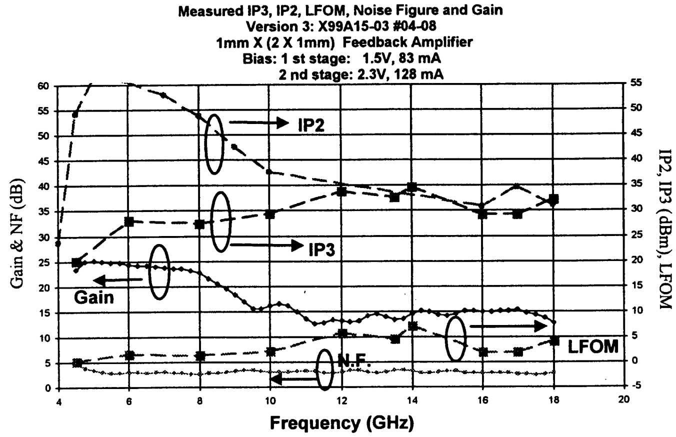

Figure 6. A 4.5 to 18 GHz 2-stage LNA which combines low noise and high linearity using a 60% In MHEMT.

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 7 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.

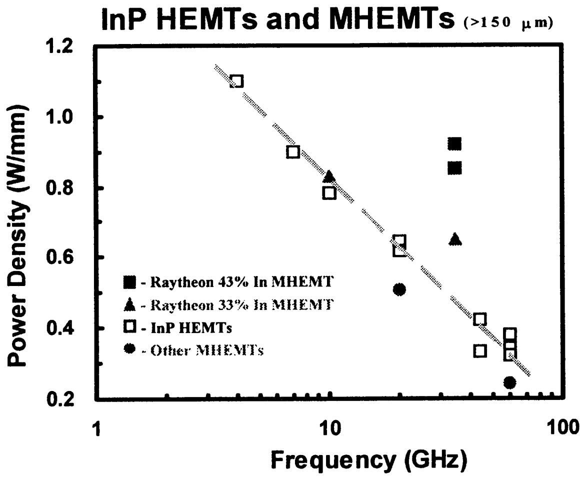

Figure 7. Power density of InP HEMTs and MHEMTs versus frequency.

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. These devices are being used as building blocks for MMIC power amplifiers.

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. MHEMTs have demonstrated state-of-the-art mm-wave low noise, high power, high linearity and low DC power consumption. Clearly, MHEMTs show promise as the next generation millimeter-wave device.

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