Metamorphic InAlAs/InGaAs HEMT MMIC Technology on GaAs Substrate : From Promise to Reality

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Abstract

We report on fabrication, performance and reliability of metamorphic InAlAs/InGaAs high electron mobility transistors on GaAs substrates (MHEMTs). The MHEMT shows an measured maximum stable gain of 12 dB at 118 GHz, giving an extrapolated f_{max} of 480 GHz. Two stage W-band amplifiers with 18 dB gain and 30 GHz bandwidth are demonstrated. The robustness of our MMICs technology with MHEMTs is demonstrated by high temperature stress at 250 °C for 2000 hours. DC accelerated life tests were made on devices with 0. 25 µm gate length at different temperatures and 1 V drain bias. From an Arrhenius plot an activation energy of 2 eV and MTTF of $2\cdot10^6$ hours at a channel temperature of 150 °C was obtained.

Furthermore a 0.5 µm low cost high performance metamorphic HEMT process on 4-inch GaAs substrates is demonstrated. Excellent uniformity of DC and HF characteristics were obtained across 4" GaAs substrates. An f_T of 53 GHz and a f_{max} of 200 GHz was obtained for 0.5 µm gate length passivated and a with 300 nm SiN. The standard deviation of the threshold voltage is 23 to 35 mV from wafer to wafer. These results show the potential of a low cost technology to manufacture in high volume production MMICs with MHEMTs on 4" GaAs substrates using an i-line stepper for applications from 2 to 77 GHz.

Introduction

Lattice matched InAlAs/InGaAs HEMTs have performance advantages over more commonly used GaAs PHEMTs due to the higher electron velocity and carrier density. However, manufacturing these devices in high production volume is difficult due to limited size, high cost, and brittle nature of InP substrate. Growing InAlAs/InGaAs structures metamorphically on GaAs substrates can eliminate these substrate issues. Unfortunately, the highest performance of a device is of little use if the reliability fails to meet systems requirements. In this paper, we will demonstrate highly reliable metamorphic HEMTs with excellent thermal stability. Moreover, the cost advantage of MHEMTs compared to PHEMTs and MESFETs for some applications will be discussed and demonstrated.

Device Structure and Fabrication

The metamorphic buffer is grown at 450 °C on GaAs substrates using MBE. The composition of the buffer is graded from $Al_{0.48}Ga_{0.52}As$ to $Al_{0.48}In_{0.52}As$ over 1 µm by increasing the In flux, while simultaneously decreasing the Ga flux. A 250 nm $Al_{0.48}In_{0.52}As$ layer is subsequently grown on this metamorphic buffer. The MHEMT structure consists of a double heterojunction epitaxial layer structure, in which Si planar doping is placed both above ($4\cdot10^{12}\,cm^{-3}$) and below ($2\cdot10^{12}\,cm^{-3}$) the undoped InGaAs channel. The Schottky layer consists of 10 nm InAlAs with aluminium content of 0.48 topped by a 10 nm undoped InGaAs cap-layer. The process flow for W-band MMIC fabrication is described in ref. [1]. The LMHEMT (lattice matched) and MHEMT MMIC technology have common process steps. 0.15 µm and 0.25 µm Y-shaped gates were fabricated using direct e-beam lithography. The ohmic contacts were formed using AuGeAu alloy and rapid thermal annealing giving a typical contact resistance of 0.15 Ω·mm. A source resistance of 0.3 Ω·mm and a drain resistance of 0.5 Ω·mm was obtained. The gate was formed using Ti-Pt-Au metal after the selective gate recess with succinic acid. The devices were passivated with 50 nm PECVD SiN. The 0.5 µm gate length pattern was defined using an i-line stepper, and the devices were passivated with 300 nm SiN.

Device and MMIC Characteristics

Maximum stable gain at drain bias 1 V and 2 V against frequency is plotted in fig.1 for a 0.15 µm passivated MHEMT. The MSG measured at V_{DS}= 2 V is extremely high, 12 dB at 118 GHz, resulting in an extrapolated maximum frequency of oscillation of 480 GHz, while the f_T obtained at drain bias of 1 V is 130 GHz. In order to determine the thermal stability of MHEMTs, we have stressed the devices at a high temperature of 270°C in nitrogen ambient for 1000 hours. Figure 2, shows the excellent thermal stability of MHEMT after high temperature stress (HTS), the decrease in the

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drain current is mainly related to gate sinking, as shown in fig.3. Despite the increase in R_{on} (20%), the transconductance did not decrease, as shown in fig.3. These results prove the excellent thermal stability of electrical properties of AlInAs/GaInAs/AlInAs HEMTs on GaAs substrates. The device shows channel breadown voltage of 6 V, as shown in fig.4.

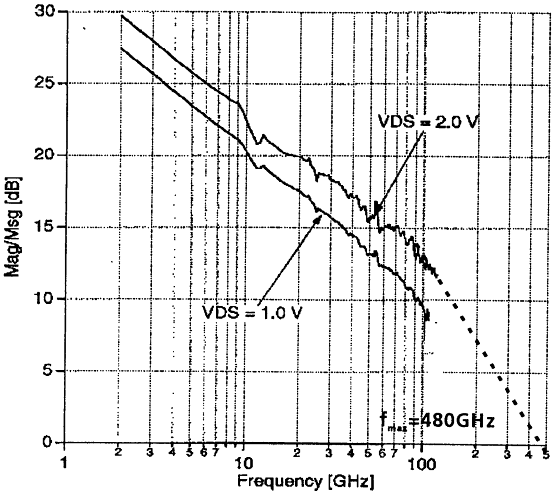

Fig.1: Measured gains of 0.15 μm passivated metamorphic HEMT at peak-g_m (W_g=2x45 μm).

Two stage amplifiers designed for high gain were stored in a nitrogen purged oven at 250 °C for 2000 hours. The S-parameters of the amplifier were monitored at room temperature to investigate their thermal stability. As shown in fig.5, the amplifier shows an extremely high gain of 19 dB at 90 GHz (9.5 dB/stage). After 2000 hours thermal stress at 250 °C, we have only 1.5 dB gain degradation (less then 8%) without degradation of input and output matching.This result proves the robustness of both InP-based HEMT MMIC technology and metamorphic buffer growth. The MMIC yield was typically 80 % over a 2" GaAs substrate.

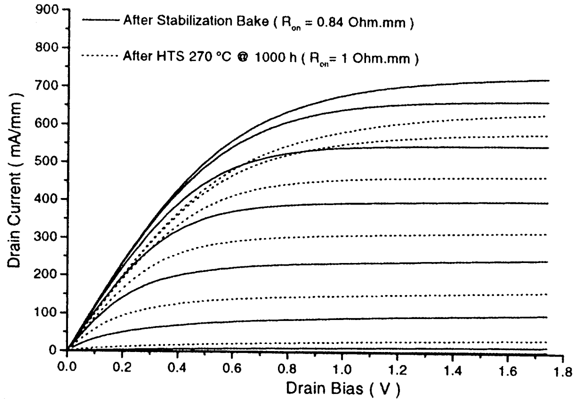

Fig.2: I-V characteristics of 0.15 μm MHEMT on GaAs substrate before (solid lines) and after high temperature stress (dotted lines).

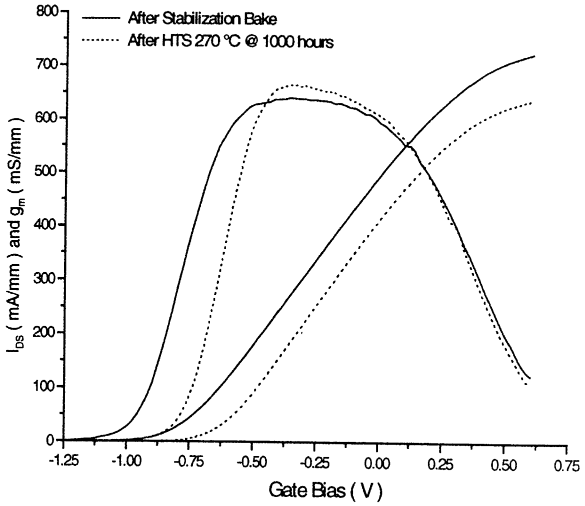

Fig.3: Transfer characteristics of 0.15 μm MHEMT before (solid lines) and after temperature stress (dotted lines).

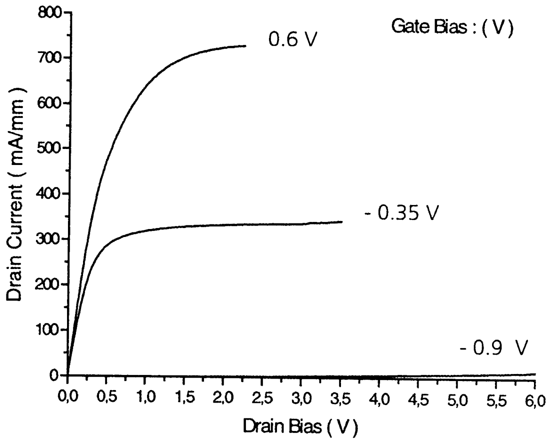

Fig.4: Breakdown voltage characteristics of 0.15 μm passivated MHEMT.

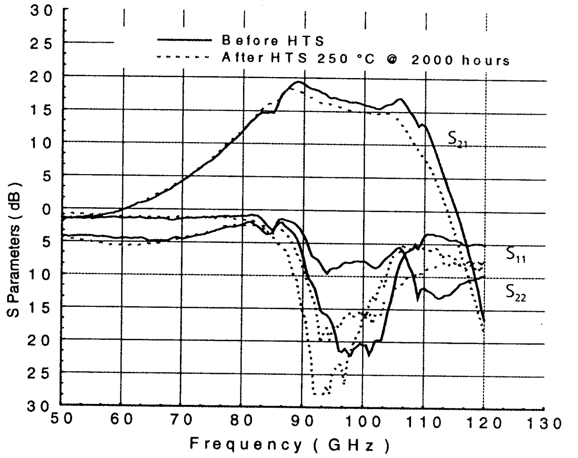

Fig.5: Measured S-parameters of two stage high gain amplifier before (solid lines) and after temperature stress (dotted lines).

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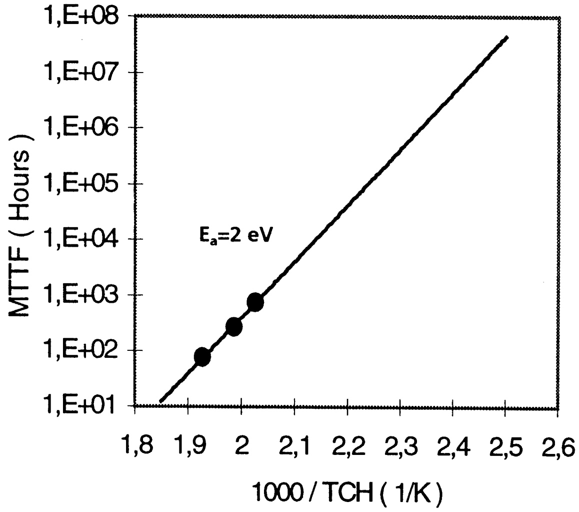
Device Reliability

Accelerated DC life tests were carried out on metamorphic HEMTs with gate length 0.25 µm and passivated with 200 nm PECVD SiN. These devices had the same performance as 0.15µm PHEMTs. Figure 6 shows the MTTF Arrhenius plot for MHEMTs stressed at V_{DS}= 1 V and I_{DS}= 200 mA/mm at different ambient temperatures (the channel temperature is typically 7 °K higher than the ambient temperature). With a 10% drop in g_m as failure criterion, an activation energy of 2 eV and MTTF extrapolates to 2.10^6 hours at T_{ch}= 150 °C and 4.10^7 hours at T_{ch}=125 °C was obtained. These results meet even stringent life time requirements for commercial, military and space applications. Our 0.15 µm single side doped InP-based HEMTs with 68 % indium content in the channel shows MTTF of 4.10^7 hours at T_{ch}=125 °C with activation energy of 1.8 eV [1]. The main degradation mechanisms observed in our MHEMTs are gate sinking and source and drain resistance degradation. However, the degradation in R_D is higher then in R_S. Thus, the quarternary buffer is highly reliable in accomodating the lattice mismatch between GaAs and InAlAs/InGaAs without degrading the device reliability.



MHEMT stressed at V_{DS}= 1 V and I_{DS}= 200 mA/mm.

MMIC Hydrogen Sensitivity

A major problem concerning the reliability of GaAs and InP-HEMTs MMICs is the issue of hydrogen sensitivity. Many microwave packaging materials outgas hydrogen which attacks devices with Ti and Pt in the gate structure. We have reported on 0.15 µm InP-based HEMT MMICs with Ti-Pt-Au insensitive to hydrogen [1]. Three stage metamorphic low-noise amplifiers were heated up to 270 °C in hydrogen ambient for 3 hours. As shown in fig.7, our MHEMT MMIC technology is insensitive to hydrogen gas. Thus, our MMICs can be packaged in hermetically sealed package without reliability degradation. Note, that our GaAs FETs also are insensitive to hydrogen.

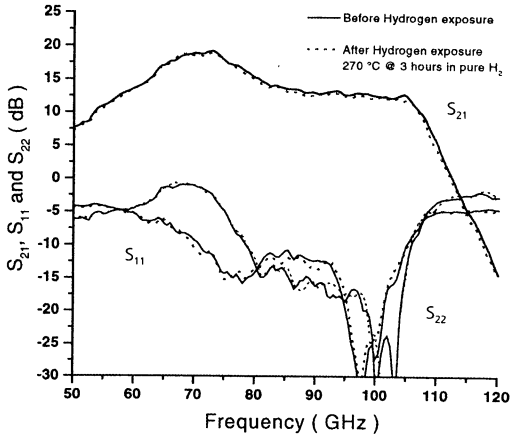


Fig.7: Effect of thermal annealing in H_2 ambient on S-parameters of three stage MHEMT LNA.

Low Cost Process : 0.5 µm MHEMT with i-line stepper on 4 inch GaAs substrate

These highly reliable metamorphic HEMTs were made with e-beam lithography. We started developing a low cost process on 4-inch GaAs substrates with optical lithography using an i-line stepper. The metamorphic HEMT can compete with the conventional GaAs PHEMT if device performance and / or cost advantage can be improved.

Metamorphic HEMTs with l_g= 0.5 µm, for example, are excellent candidates for highly linear power devices at 1.9 GHz for digital cellular phones, with a power supply using a single battery (NiCd, 1.2 V) only. The advantage of the MHEMTs are due to the low open channel resistance (R_{on}< 0.8 Ω.mm). This will provide MHEMTs with higher output power and PAE as compared to MESFETs and PHEMTs with equal gate width.

MHEMTs with gate length of 0.5 µm were made on 4" GaAs substrates and passivated with 300 nm SiN. The open channel resistance is about 0.65 Ω.mm. The wafer average peak-g_m is 750 mS/mm with maximum drain current of 720 mA/mm and output conductance of 15 mS/mm. The standard deviation of DC characteristics across the wafer is less then 5 %. The average threshold voltage is - 820 mV with

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standard deviation of 23 mV to 34 mV from wafer to wafer.

The S-parameters of 2x30 µm wide MHEMT were measured from 2-120 GHz. An f_T of 53 GHz and f_{max} of 200 GHz were obtained for a 0.5 µm gate length device, biased at peak-g_m and 2 V drain bias, as shown in fig.8. A f_{max}/f_T ratio of 3.7 and $f_T.l_g$ product of 27 GHz.µm was obtained. The high f_{max} is mainly related to the low feed-back capacitance of 60 fF/mm giving a C_{gs}/C_{gd} ratio of 35 and to the high voltage gain (g_m/g_o) of 50. Despite the thick passivation layer (300 nm), the C_{gd} related to the SiN is very low. This is related to the triangular shape of the 0.5 µm gate, which allow low gate resistance with low parasitic capacitance compared to 0.25 µm T-gate.The 0.5 µm MHEMTs show very high maximum available gain of 8 dB at 77 GHz, as shown in fig.8. Such high gain makes the 0.5 µm MHEMTs technology very promising for low-cost production of MMICs for collision avoidance radar at 77 GHz. For example, FMCW radar sensors at 77 GHz with 0.5 µm InP-based HEMTs on InP substrates have been demonstrated [2].

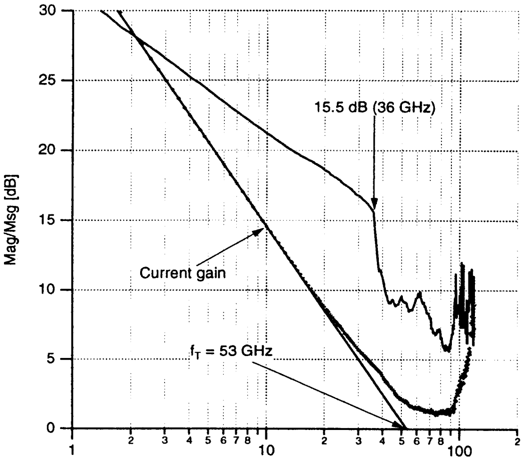

Fig.8: Measured gain of 0.5 µm MHEMTs (W_g=2x30 µm at V_{DS}= 2 V)

At 36 GHz, the 0.5 µm MHEMT shows 15.5 dB gain, which is about 4-5 dB higher than with our 0.15 µm passivated GaAs PHEMTs. The potential of 0.5 µm MHEMTs for power applications is shown in fig.9.A channel breakdown voltage of 12 V, maximum drain current of 700 mA/mm combined with maximum available gain of 14 dB were obtained at 40 GHz. This makes 0.5 µm MHEMT technology very promising for power applications in the frequency range 28 to 40 GHz.

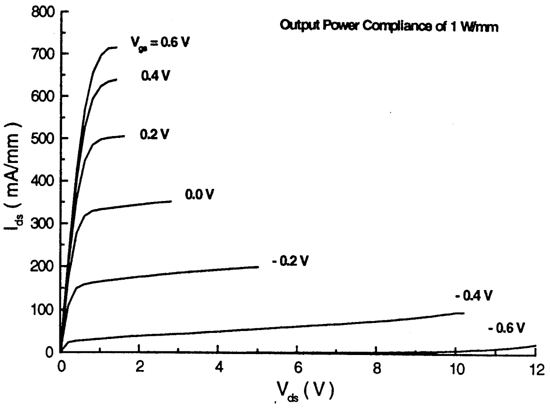

Fig.9: Breakdown voltage characteristics of 0.5 µm MHEMTs passivated with 300 nm SiN.

Summary and Future Trends : We have demonstrated high performance metamorphic devices and MMICs with excellent device reliability. W-band two stage high gain amplifiers with excellent thermal stability has been demonstrated with 0.15 µm MHEMT technology. The amplifiers were stressed at 250 °C for 2000 hours. High reliability of 0.25 µm MHEMTs was found with activation energy of 2 eV and MTTF of 4.10^7 hours at 150°C channel temperature. Finally, costs and potential of metamorphic HEMT technology with 0.5 µm gate length on 4-inch GaAs substrate can compete with 0.25 µm GaAs PHEMT for applications from 2 to 77 GHz. Thus, at IAF MHEMT MMIC technology on 4 inch substrates with 0.5 µm gate length defined with i-line stepper is under development, with the promise of high performance and low fabrication cost of MMICs.

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