High Performance MMICs with Submillimeter Wave InP-based HEMTs

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ABSTRACT

This paper presents some recently developed MMICs based on a 0.1-µm gate-length InAlAs/InGaAs/InP HEMT process with an f_{max} above 600 GHz. InP-based HEMTs provide more power gain and lower noise at higher frequencies than any other transistor, including GaAs-based pHEMTs. A number of state-of-the-art InP HEMT MMICs will be presented. This includes a 150-205 GHz amplifier with 15 dB of gain, a broadband 60-140 GHz amplifier with 25mW output power at 140 GHz, a high gain Ka-band LNA and static frequency-divider circuits operating at clock rates above 45 GHz. The high frequency performance of a next-generation 0.08-µm-gate InAlAsSb/InAlAs/InGaAs/InP HEMT technology will also be presented.

INTRODUCTION

Spurred by demanding millimeter-wave applications, InP-based HEMT technology has progressed to the point where 200-GHz active integrated circuits are now practical. The unmatched high-frequency performance of these devices, harnessed by advanced MMIC designs, makes them an outstanding choice for numerous emerging systems such as Ka-band satellites, high-speed fiber optic links and millimeter-wave imagers and sensors. The advantage of the InP-based HEMT stems directly from lattice compatibility between the InAlAs/InGaAs heterostructure and the InP substrate, which allows higher indium content in the channel (53-80%) for increased electron mobility and saturation velocity. The large conduction band discontinuity at the AlInAs/InGaAs interface produces a high sheet charge density and strong confinement of electrons in the channel. This superior electron transport results in higher transconductance, higher gain-bandwidth and lower noise figure than comparable GaAs-based HEMTs [1]. InP HEMTs also exhibit excellent low-voltage operation, which allows them to equal the RF performance of the best GaAs device with one fourth of the dc power dissipation.

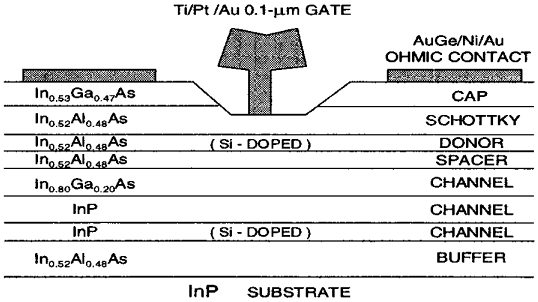

Fig. 1. Material profile for the 0.1-µm-gate InP HEMT.

InP HEMT TECHNOLOGY AND MMIC EXAMPLES

This paper presents several MMICs that demonstrate the unique capabilities of submillimeter-wave InP HEMT devices in numerous applications spanning the range of 1-200 GHz. The HEMT technology employs the material shown in Fig. 1, which is an InAlAs/InGaAs heterostructure grown by MBE on a 3" InP substrate. The composite $In_{0.80}Ga_{0.20}As$/InP channel is psuedomorphic due to the high indium mole fraction, and is silicon-doped on both sides to achieve an electron density of 4×10^{12} cm^{-2} and mobility greater than 10,000 cm^2/V·s. The high-resistivity $In_{0.52}Al_{0.48}As$ buffer layer reduces the output conductance and results in HEMTs with both high f_T and f_{max} values. The HEMTs are fabricated using a planar process with boron ion implantation for device isolation. AuGe/Ni/Au alloy is used for the source and drain ohmic contacts, which have a typical resistance of 0.1Ω mm. T-gates with either 0.1- or 0.12-µm length are formed by Ti/Pt/Au metallization and the exposed device is passivated with a 500-Å layer of Si_3N_4. Airbridge interconnections and plated transmission lines use a 1.5-µm layer of gold fabricated by a liftoff process.

The HEMT devices exhibit typical dc transconductance of 950 mS/mm with a full channel current of 700 mA/mm and gate-drain breakdown voltage of 5 V. RF transconductance is greater than 1100 mS/mm with an extrinsic current gain cutoff frequency f_T above 250 GHz. On-wafer measurement of a 150-µm-wide device from 1-110 GHz suggests a maximum frequency of oscillation f_{max} in excess of 600 GHz [2]. This figure of merit is further confirmed by MMIC amplifiers that have demonstrated 10-dB of gain per stage at 142 GHz [3]. With smaller gate peripheries, broadband gain can be realized at very high frequencies as demonstrated by the 150-205 GHz amplifier in Fig. 2. This G-band MMIC uses eight stages with a *total* gate periphery of 144 µm, and achieves a flat 17±2 dB gain response (Fig. 3) drawing 59 mA dc from a 1.5V supply.

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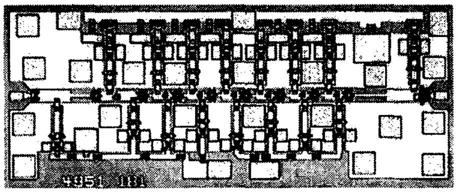

Fig. 2. G-band (150-205 GHz) amplifier using eight stages of $18 \times 0.1\ \mu m^2$ InP HEMTs, die size 1.1 mm^2.

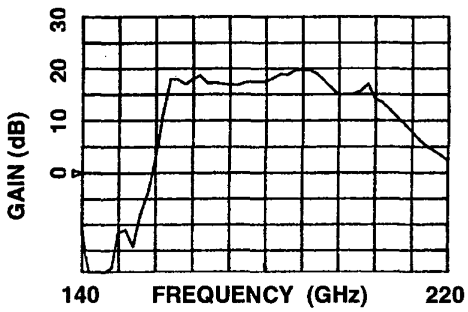

Fig. 3. Gain response of the G-band amplifier: 17±2 dB across 150-205 GHz.

Amplifiers of this type have near-term applications in remote atmospheric sensing as well as emerging automotive radar and ultra wideband communications systems. While the noise figure of this amplifier has not yet been measured, MMIC LNAs fabricated in this HEMT process have demonstrated record low noise performance at W-band. A four stage LNA exhibits an average noise figure of 2.5 dB at room temperature and 30 dB gain across the 76-96 GHz band [4]. W-band LNAs have been produced in significant volume at HRL with an RF yield of approximately 70%. In addition to low noise figures, the high channel current and large breakdown voltage afforded by this HEMT technology allows power amplifiers to be designed for frequencies up to at least 140 GHz, with output drive capability more than double that of comparable InP HEMTs demonstrated in this frequency range [5]. An example is the 60-140 GHz medium power amplifier shown in Fig. 4. This MMIC uses three stages of InP HEMTs and two-device power combining for a broadband response with a total output periphery of 320 µm. Power gain across the whole band is 12±2 dB, with an output power of 25 mW available from 100 to 140 GHz. The total dc supply is 220 mA at $V_{ds} = 2V$.

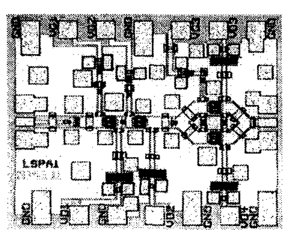

Fig. 4. Broadband InP HEMT medium-power amplifier with 12±2 dB gain from 60-140 GHz.

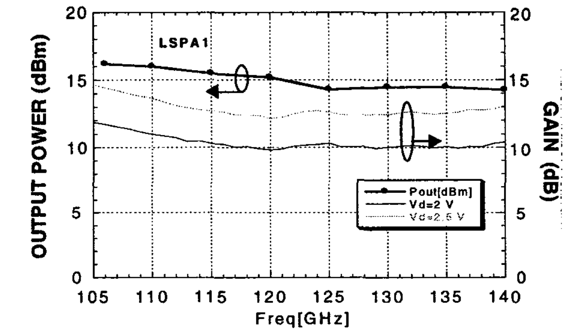

Fig. 5. Large-signal RF performance of the 60-140 GHz amplifier: 25 mW output power from 100 to 140 GHz.

The high transconductance and small resistive parasitics that are critical to achieving high f_{max} also lead to very low noise figures and high gain at lower frequencies. For applications like LEO/GEO satellite systems, LMDS and 24-38 GHz radio links this means that InP HEMT MMICs achieve superior performance with lower power dissipation, fewer amplification stages, smaller size and reduced chip count and assembly costs. This is especially advantageous for dense antenna arrays such as in Ka-band satellite systems and multifunction common apertures (e.g. simultaneous sensing and communications). An example of InP HEMT performance is the Ka-band LNA illustrated in Fig 6. This four-stage tuned amplifier achieves a 1.2±0.2 dB noise figure and 40±4 dB gain over the entire Ka-band from 26 to 40 GHz, using 60 mW dc power [6]. For the same dc power, the InP HEMT LNA attains 20 dB more gain and equal or lower noise figure than the best GaAs-based Ka-band LNAs.

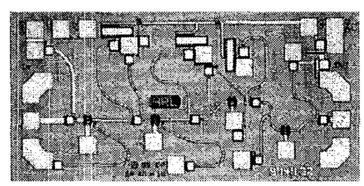

Fig. 6. Four-stage high gain Ka-band LNA using 100-µm InP HEMTs, 1.4 mm^2 die size, 60 mW dc power.

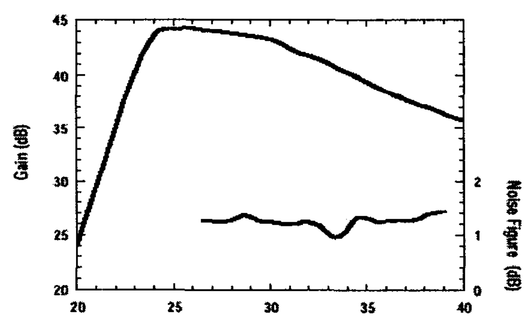

Fig. 7. Full-band performance of the 4-stage Ka LNA.

The high f_T of the InP HEMT device makes it well suited for broadband circuits such as those critical to lightwave interfaces and other high-speed network elements. Fig. 8 illustrates the >200 GHz gain-bandwidth achieved by a simple amplifier comprising two cascaded 50 × 0.12μm^2 InP HEMT devices with inductively-peaked resistive loading [7]. The total dc current is 15 mA at V_{ds} = 1V. With 12 dB gain from 100 MHz to over 50 GHz and a measured Ka-band noise figure of 3-3.8 dB, this circuit equals the performance of HEMT and HBT distributed amplifiers with an order of magnitude lower dc power dissipation.

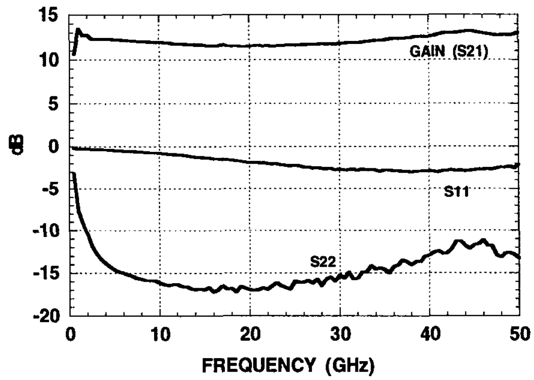

Fig. 8. Broadband, two-stage InP HEMT LNA exhibits distributed-amplifier performance with only 15 mW dc power. Gain is 12 dB from 1 to 50 GHz, Ka-band noise figure 3.5 dB.

High f_T also benefits digital circuits, such as the binary static divider shown in Fig. 9. Static dividers (T flip-flops) are fundamental high-speed logic building blocks, and their performance is an accurate metric for the speed of the device technology. Integrating digital circuits into millimeter-wave MMICs is the next step in improving the performance and lowering the assembly cost of subsystems such as PLL frequency synthesizers. The example divider is fabricated in the same technology as the previous MMICs, and employs small-periphery InP HEMTs in a capacitively-enhanced FET logic scheme [8]. Microwave impedance matching and tuning techniques were used in design for optimum high-speed performance. This 1:2 divider has successfully operated at a clock rate of 47.2 GHz in preliminary testing, which makes it the fastest FET static divider reported to date [9].

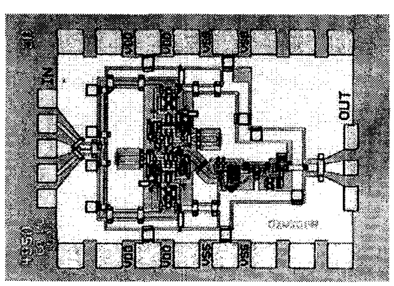

Fig. 9. 47 GHz 1:2 static frequency divider using 0.12-μm InP HEMTs.

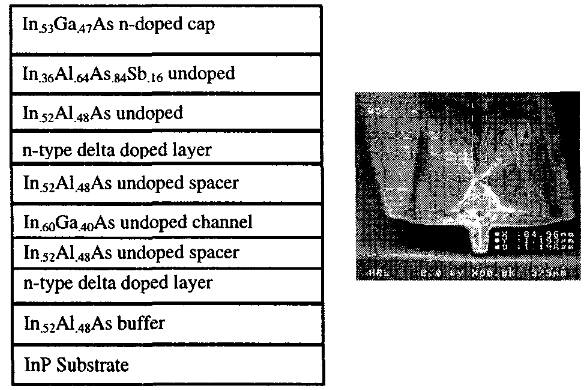

Fig. 10. Next-generation InP HEMT using an AlInAsSb Schottky barrier layer and 0.08-μm T-gate.

NEXT-GENERATION InP HEMTs

New HEMT material systems are also being developed at HRL to push the f_T and f_{max} beyond the limits of the InAlAs/ InGaAs technology. One such improvement is the InAlAsSb Schottky layer, which has a wider bandgap (1.9eV vs. 1.5eV) than the conventional InAlAs. This creates a larger channel conduction band discontinuity and a higher Schottky barrier at the gate, resulting in a device that can achieve higher current density and transconductance and sustain higher breakdown voltage. Short-channel effects (e.g., weak pinch-off, high output conductance) are also alleviated, allowing the gate length to be scaled down even further to obtain higher f_T without degrading f_{max}. Figure 10 illustrates a HEMT with a composite $In_{0.36}Al_{0.64}As_{0.84}Sb_{0.16}/In_{0.52}Al_{0.48}As$ Schottky layer on an InGaAs channel with 60% indium content. Devices with 0.12-μm and 0.08-μm gate lengths have been fabricated on this structure with promising results. Figure 11 illustrates the dc transconductance characteristics of a 100 × 0.12 μm^2 HEMT, which achieves a maximum current density of 850 mA/mm and a peak transconductance of 1220 mS/mm at 1V drain-source bias. These figures are, respectively, 20 and 10% higher that the best values obtained for similar HEMTs with InAlAs Schottky barriers [10].

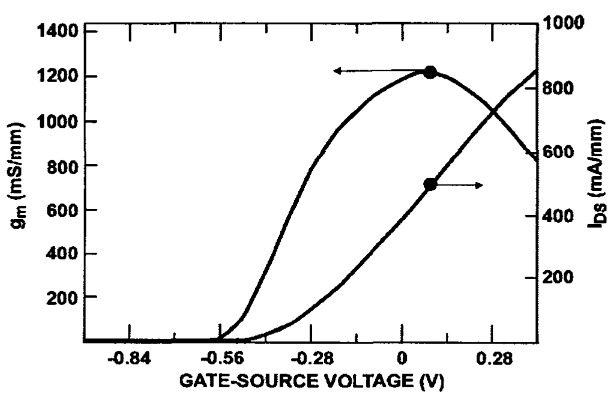

Fig. 11. DC transconductance of the InAlAsSb/InAlAs/ InGaAs/InP HEMT.

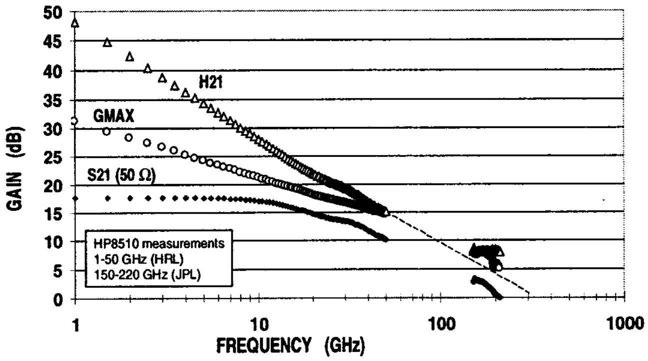

Fig. 12. High-frequency performance of a 100 x 0.08 μm^2 InAlAsSb/InAlAs/InGaAs/InP HEMT at Vds = 1.5 V, Ids = 500 mA/mm. Preliminary data from 140-220 GHz predicts f_T and f_{max} in excess of 300 GHz.

High frequency measurements have been made on 0.08-µm-gate devices which confirm that the RF performance of the device is not significantly degraded by short channel effects. Figure 12 shows the maximum stable gain (MSG/MAG), current gain h_{21} and 50Ω transducer gain S_{21} for a device with 100 × 0.08 μm^2 gate biased at V_{ds}=1V, I_{ds}=200mA/mm. Calibrated measurements were made on-wafer using two HP 8510 network analyzers, one operating up to 50 GHz and the other from 140-220 GHz. The extrapolated gain and high-frequency data indicate that both f_T and f_{max} of the device exceed 300 GHz, the combination of which is among the highest reported values for any three-terminal device [11].

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