

# An Ultra-Low Power InAs/AlSb HEMT W-Band Low-Noise Amplifier

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**Abstract**—An antimonide-based compound semiconductor (ABCS) microstrip MMIC, a W-Band low-noise amplifier using 0.2- $\mu\text{m}$  gate length InAs/AlSb metamorphic HEMTs, has been fabricated and characterized on a 50  $\mu\text{m}$  GaAs substrate. The compact 1.2 mm<sup>2</sup> five-stage W-band LNA demonstrated a 3.9 dB noise-figure at 94 GHz with an associated gain of 20.5 dB. The measured dc power dissipation of the ABCS LNA was an ultra-low 1.2mW per stage, or 6.0 mW total which is less than one-tenth the dc power dissipation of a typical equivalent InGaAs/AlGaAs/GaAs HEMT LNA. Operation with degraded gain and noise figure at 3.5 mW total dc power dissipation is also verified. These results demonstrate the outstanding potential of ABCS HEMT technology for mobile and space-based millimeter-wave applications.

**Index Terms**—low noise amplifier, antimonide-based compound semiconductor (ABCS) HEMT, InAs/AlSb HFET, millimeter-waves.

## I. INTRODUCTION

ULTRA-LOW power millimeter-wave low-noise amplifiers (LP-LNAs) represent a critical component for emerging systems applications such as handheld millimeter-wave (94 to 220 GHz) passive imagers and active-array space-based radar. For such applications, antimonide-based compound semiconductor (ABCS) InAs/AlSb HEMTs are particularly promising because of their combination of high electron mobility and peak velocity, along with high electron concentration in the 2DEG that results in unparalleled speed-power performance [1–4]. The InAs/AlSb HEMT device's inherent low-voltage operation, with  $V_{ds}$  below 0.5V, can reduce dc power dissipation by an order of magnitude compared with a GaAs PHEMT device of equivalent performance [5,6], and by a factor of three to four compared to an equivalent InP HEMT device [7,8]. In the case of mobile or handheld imagers, ABCS LP-LNAs are a system enabler

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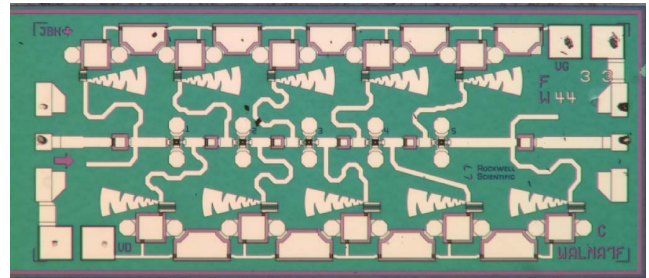


Fig. 1. A photomicrograph of the five-stage ABCS HEMT MMIC W-band LNA. The compact die measures 1.75mm by 0.7 mm with a thickness of 50  $\mu\text{m}$ .

because they eliminate the need for liquid cooling, and permit a substantial reduction in the imager dc power consumption and corresponding weight and cost [9].

Only recently have InAs channel devices reached sufficient maturity to permit the realization of multi-stage MMIC amplifiers. To date, only a 3-stage Ka-Band amplifier [10] and a 3-stage W-Band CPW amplifier [11] have been reported. We report here a five-stage W-band microstrip ABCS MMIC with record gain and noise figure (Fig. 1). The ultra-low power LP-LNA operates from 92 to 102 GHz and uses 0.2- $\mu\text{m}$ -gate-length ABCS HEMT devices. The first pass success for this design is due primarily to a stable ABCS HEMT MMIC technology, high-quality ABCS epitaxial material, accurate active and passive models, and a proven design approach.

## II. DEVICE DESIGN AND CHARACTERIZATION

The ABCS InAs/AlSb HEMT structure is grown using molecular beam epitaxy on two-inch and four-inch semi-insulating GaAs substrates using an AlSb buffer to accommodate the lattice mismatch. Hall measurements show sheet carrier concentration and mobility to be  $3.7 \times 10^{12} \text{ cm}^{-2}$  and  $19,000 \text{ cm}^2/\text{Vs}$  at 295K. The device is capped with a strained InAlAs layer to provide a chemically stable surface layer and minimize gate leakage effects [1,2].

The 0.2- $\mu\text{m}$ -gate-length ABCS HEMT has measured dc transconductance of 1.5 S/mm and 2.0 S/mm at  $V_{ds}$  of 0.3 V and 0.4 V respectively. For a  $2 \times 20 \mu\text{m}$  device, on-wafer  $s$ -parameter measurements show a cutoff frequency,  $f_t$ , of 142 GHz and a maximum oscillation frequency,  $f_{max}$ , of 178 GHz. Further details on the ABCS HEMT structure and performance used in this MMIC have been reported elsewhere [2, 3].

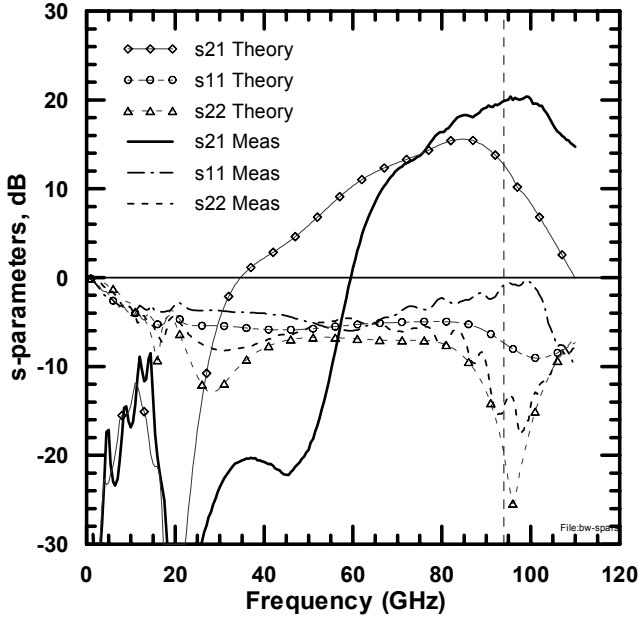


Fig. 2. Measured insertion gain (s21) and input (s11) and output (s22) return loss of the ABCS LP-LNA compared with the theoretical prediction from circuit model. The LP-LNA gain is  $20 \pm 0.5$  dB from 92 to 102 GHz.

### III. AMPLIFIER DESIGN AND FABRICATION

The five-stage W-band LP-LNA was designed using  $0.2\mu\text{m}$  gate length two-finger,  $40\text{-}\mu\text{m}$  total gate width ABCS HEMTs. The linear small-signal model used for the design was based on small-signal  $s$ -parameter measurements to 110 GHz, and noise parameter measurements to 26 GHz. Device pad parasitics were carefully deembedded from the raw measurements. The noise model parameters are obtained by fitting to the measured noise parameters from 2 to 26 GHz, and then extrapolating the model to W-band. The effect of impact ionization must be included in the model to achieve a good fit to the measured data. The devices are dc biased at a nominal drain voltage of 0.35 V and 3.5 mA of drain current. At 94 GHz, the modeled device noise parameters are  $\text{NF}_{\min}=3.3$  dB,  $\Gamma_{\text{opt}}=0.455 \angle 150.4^\circ$  and  $R_n=10.0 \Omega$ .

The  $2 \times 20 \mu\text{m}$  ABCS HEMTs used in the amplifier are interconnected with microstrip matching networks. Air-bridges were used for the device source connections. A full-wave 2.5D electromagnetic solver was used to model layout-induced effects. Several iterations of design and EM simulation were needed to obtain good simulated amplifier performance. Due to uncertainties in the extrapolated noise parameters, a design of experiments consisting of six different amplifier designs with systematic variations in the device input noise-matching impedance was employed. Epitaxial resistors and SiN MIM capacitors were used for the bias network and interstage dc blocks. Novel serrated radial stubs that are 12% smaller than orthodox radial stubs were used in the amplifier dc decoupling circuitry to save die space. The resulting  $1.2 \text{ mm}^2$  die size is believed to be the smallest 5-stage W-band MMIC ever

fabricated. The semi-insulating GaAs substrate was thinned to  $50 \mu\text{m}$  and through-substrate vias were dry etched from the back.

The ABCS HEMT MMIC fabrication process was derived from Rockwell Scientific's production GaAs PHEMT process [5]. Following this approach minimized development risk and allowed the mature PHEMT passive devices to be carried over unchanged to the ABCS MMIC. The main differences between the two processes are in the isolation and ohmic contact steps, and the electron-beam lithography process for defining the gate.

### IV. AMPLIFIER CHARACTERIZATION

Performance of the five-stage amplifier was measured on-wafer with GGB Picoprobe rf probes. The measured  $s$ -parameters are shown in Fig. 2 where they are compared with simulated results. The agreement between theory and measurement is close, with a 12 GHz shift upwards observed in frequency of the measured gain bandwidth. The shift is also observed in the input match and resulted in a poor input match at the design frequency of 94 GHz. This suggested that the fabricated devices had shorter gate lengths, hence smaller gate capacitance, than the modeled devices. Further evidence for this is shown by the higher measured gain and lower noise figure compared with simulation, both indicative of a device with higher  $f_\tau$  and  $f_{\max}$ . Over the band from 92 to 102 GHz, the measured gain is  $20.0 \pm 0.5$  dB, and the output return loss is better than 13 dB. Due to the shorter gate length device, the measured amplifier is not unconditionally stable, with  $K < 1$  from 90 to 105 GHz, although no oscillations were observed during measurement. Noise figure measurements and simulated results are shown in Fig. 3. The measured amplifier

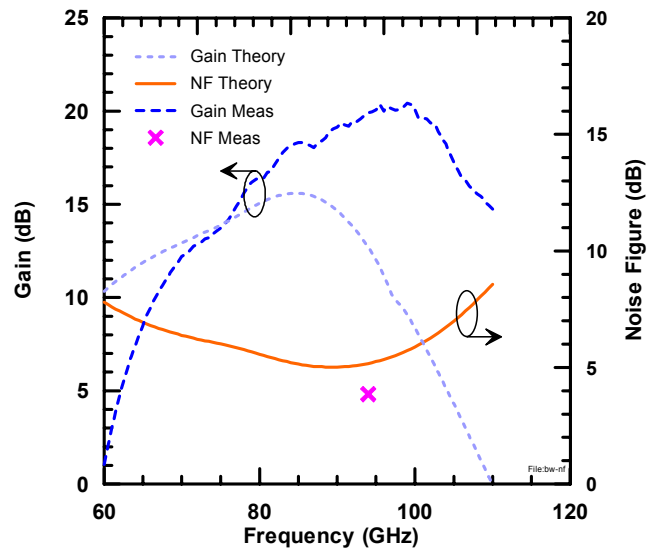


Fig. 3. Measured noise figure and associated gain of the ABCS LP-LNA compared with the theoretical prediction from circuit model. The measured LNA shows higher gain and lower noise figure than the simulated amplifier, most likely due to shorter gate lengths.

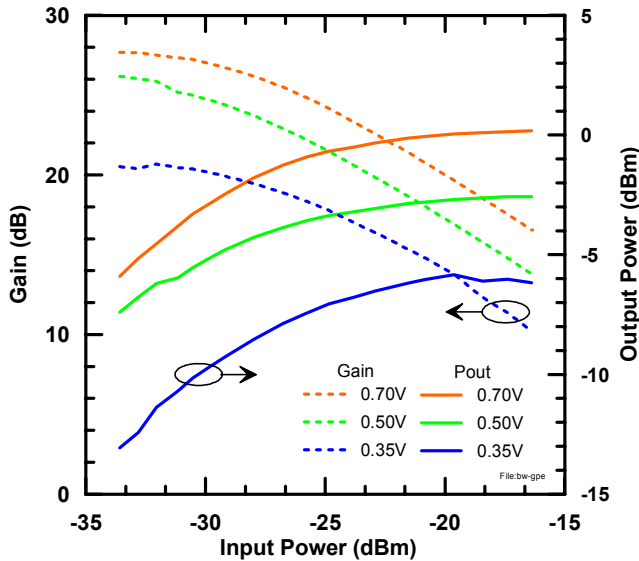


Fig. 4. Plot of measured gain and output power at 94 GHz versus input power for LNA drain voltages of 0.35, 0.5, and 0.7 V. Output power at 1dB gain compression is -8.5 dBm at  $V_{dd}=0.35V$ , and -2.5 dBm at  $V_{dd}=0.7V$ .

noise figure at 94 GHz is 3.9 dB, which is better than the simulated result of 5.2 dB; and is believed to be due to the fabricated devices having shorter gate lengths than the model. Measurements of output power and gain compression are shown in Fig. 4. The output power of the LNA at  $V_{dd} = 0.35 V$  is -7.0 dBm at the 3 dB gain compression point, and increases to 0.8 dBm for  $V_{dd} = 0.7 V$ .

The ABCS HEMT has a very low drain saturation voltage,  $V_{dsat}$ , where electrons in the channel reach peak drift velocity. Consequently, the LP-LNA can be biased at exceptionally low

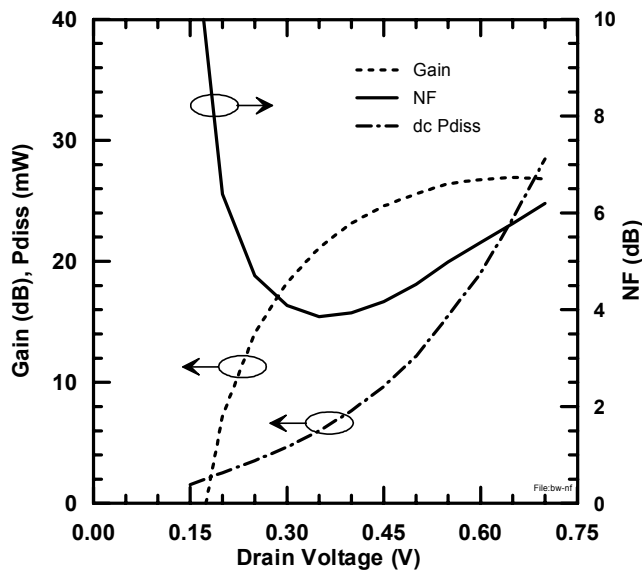


Fig. 5. Plot of measured gain and noise figure at 94 GHz, and total dc power dissipation versus applied LP-LNA drain voltage. Operation with dc power dissipation as low as 3.5 mW is demonstrated with degraded gain and noise figure.

drain voltages where dissipated dc power is extremely small. For lowest noise figure, the rf measurements were made with  $V_{dd} = 0.35 V$  and  $I_d = 17.2 mA$ , corresponding to a dc power of 6.0 mW. This dc power dissipation is less than one-tenth the power consumption of W-band amplifiers using GaAs-based HEMTs that are typically biased at 2 V or more, and one-third that of InP-based HEMTs that are typically biased at 0.75 V or more. Fig. 5 shows the gain, noise figure, and dc power dissipation at 94 GHz for a range of drain voltages from 0.15 to 0.50 V. For some applications where operation with degraded gain and noise figure may be tolerated, operating the amplifier as low as  $V_{dd} = 0.25 V$  leads to a dc power dissipation of only 3.5 mW, which is believed to be the lowest reported dc power dissipation of any W-band low noise amplifier.

## V. CONCLUSION

A five-stage ABCS HEMT ultra-low-power low-noise amplifier (LP-LNA) designed to operate at W-Band is reported. The amplifier achieved 20.5 dB gain and 3.9 dB average noise figure at 94 GHz with a total dc power dissipation of only 6.0 mW using relatively long 0.2  $\mu m$  gate length devices. Simulations and preliminary measurements show that a new generation of ABCS devices with gate lengths reduced to 0.1  $\mu m$  will produce ABCS amplifiers with even lower power dissipation and noise figure by requiring fewer stages of amplification for similar performance at W-band frequencies. These results demonstrate the outstanding potential of ABCS HEMT technology for mobile and space-based millimeter-wave applications.

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