An Ultra-Low Power InAs/AlSb HEMT X-Band Low-Noise Amplifier and RF Switch

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***Keywords*—low noise amplifier, antimonide-based compound semiconductor (ABCS) HEMT, InAs/AlSb HEMT.**

***Abstract*—Several antimonide-based compound semiconductor (ABCS) microstrip MMICs, an X-Band low-noise amplifier and an rf switch, using 0.1-µm gate length Antimonide Based Compound Semiconductor (ABCS) metamorphic InAs/AlSb HEMTs, have been fabricated and characterized on a 50 µm GaAs substrate. The compact 0.7 mm^2 two-stage X-band LNA demonstrated a 1.25 dB noise-figure at 10 GHz with an associated gain of 22.3 dB. The measured dc power dissipation of the ABCS LNA was an ultra-low 1.6mW per stage, or 3.2 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 0.98 mW total dc power dissipation is also verified. The compact 0.9 mm^2 single-pole double-throw X-band RF switch demonstrated a 0.99 dB on-state insertion loss and an off -state isolation of > 32 dB. These results demonstrate the outstanding potential of the ABCS HEMT technology for low-power X-band applications.**

I. INTRODUCTION

ULTRA-LOW power X-band low-noise amplifiers (LP-LNAs) represent a critical component for emerging systems applications such as stratospheric and space-based active-array radar systems. 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 stratospheric or space-based radar, ABCS LP-LNAs are a system enabler because they reduce the per element power consumption to levels that permit operation of hundreds of thousands of elements while retaining realistic spacecraft prime power size, and hence corresponding weight and cost.

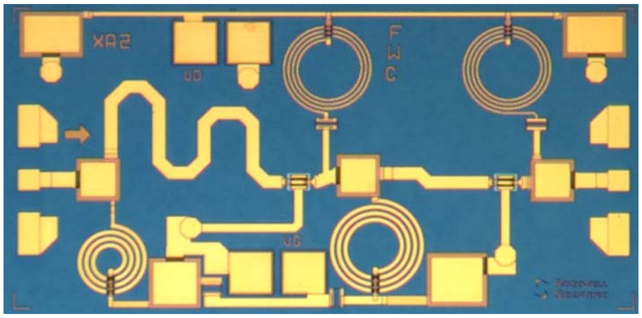

Fig. 1. A photomicrograph of the two-stage ABCS HEMT MMIC X-band LNA. The compact die measures 1.4mm by 0.7 mm with a thickness of 50 µm.

Recently InAs channel devices have reached sufficient maturity to permit the realization of multi-device MMIC circuits. Several demonstrations at Ka-band [9] and W-Band [10,11] have been reported. We report here a two-stage X-band microstrip ABCS LNA MMIC with record low power consumption, gain and noise figure (Fig. 1). The ultra-low power LP-LNA operates from 8 to 12 GHz and uses 0.1-µm-gate-length ABCS HEMT devices. We also report the first ABCS rf-switch with 0.99dB insertion loss and >32 dB isolation at 10 GHz. The first pass success for these designs are due primarily to a stable ABCS HEMT MMIC technology, high-quality ABCS epitaxial material, accurate

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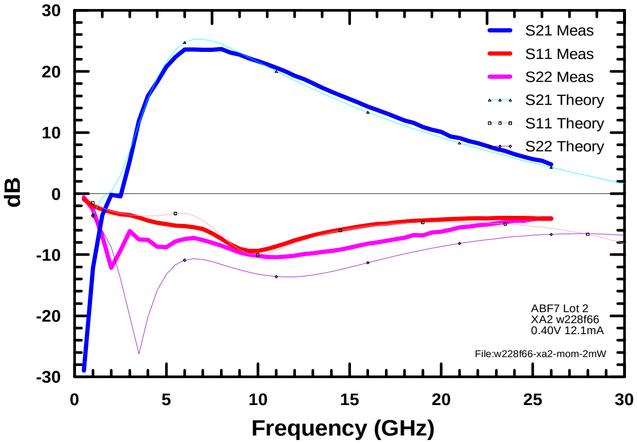


Fig. 2. Measured insertion gain (s21) and input (s11) and output (s22) return loss of the ABCS LP-LNA compared with the theoretical prediction from circuit model. The LP-LNA gain is 22 ± 1 dB from 9.5 to 10.5 GHz.

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. The device is capped with a strained InAlAs layer to provide a chemically stable surface layer and minimize gate leakage effects [1,2].

The 0.1-µm-gate-length ABCS HEMT has measured dc transconductance of 1.64 S/mm and 1.91 S/mm at Vds of 0.3 V and 0.4 V respectively. For a 2 x 40 mm device, on-wafer s-parameter measurements show a cutoff frequency, f_τ, of 260 GHz and a maximum oscillation frequency, f_{max}, of 225 GHz. Further details on the ABCS HEMT structure and performance used in this MMIC have been reported elsewhere [2, 3]

III. AMPLIFIER DESIGN AND CHARACTERIZATION

The two-stage X-band LP-LNA was designed using 0.1µm gate length two-finger, 80-µm total gate width ABCS HEMTs. The linear small-signal model used for the design was based on small-signal *s*-parameter measurements to 50 GHz, and noise parameter measurements to 26 GHz. Device pad parasitics were carefully deembedded from the raw measurements. 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 0.25 V and 5 mA of drain current. At 10 GHz, the modeled device noise parameters are NF_{min}=0.67 dB, $G_{opt} = 0.683 \angle 14.2^o$ and $R_n = 15.0\ \Omega$.

The 2x40 µm 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. Epitaxial resistors and SiN MIM capacitors were used for the bias network and interstage dc blocks. The resulting 0.7 mm^2 die size is believed to be the smallest 2-stage X-band ABCS MMIC ever fabricated. The semi-insulating GaAs substrate was thinned to 50 µm and through-substrate vias were dry etched from the back.

	Vd	*Id*	*Gain*	*P_{DC}*	*NF*
	(V)	*(mA)*	*(dB)*	*(mW)*	*(dB)*
Low Noise Bias	0.35	9.2	22.3	3.2	1.25
Low Power Bias	0.25	3.93	12.2	0.98	n/a

Table 1. Measured performance of the 2-stage LNA at 10 GHz for low-noise bias and low-power bias.

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.

Performance of the two-stage amplifier MMIC 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

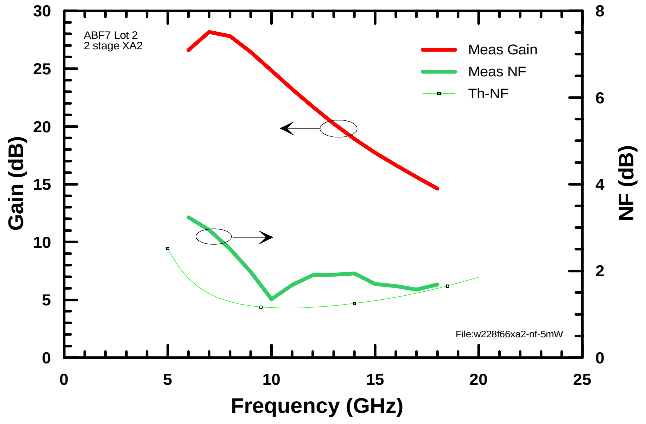


Fig. 3. Measured noise figure and associated gain of the ABCS LP-LNA compared with the theoretical prediction from circuit model. The measured LNA shows higher noise figure than the simulated amplifier, most likely due to gate leakage effects.

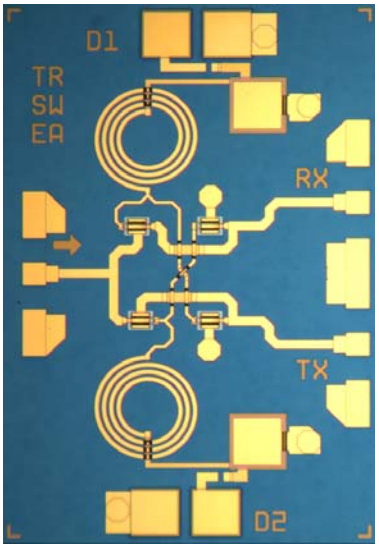


Fig. 4. Fig. 1. A photomicrograph of the SPDT ABCS HEMT MMIC X-band RF switch. The compact die measures 1.15mm by 0.75 mm with a thickness of 50 µm.

theory and measurement is close. Over the band from 9.5 to 10.5 GHz, the measured gain is 22.3 ± 1.0 dB, and the output return loss is better than 10 dB. Noise figure measurements and simulated results are shown in Fig. 3. The measured amplifier noise figure at 10 GHz is 1.25 dB, and is in close agreement with theory.

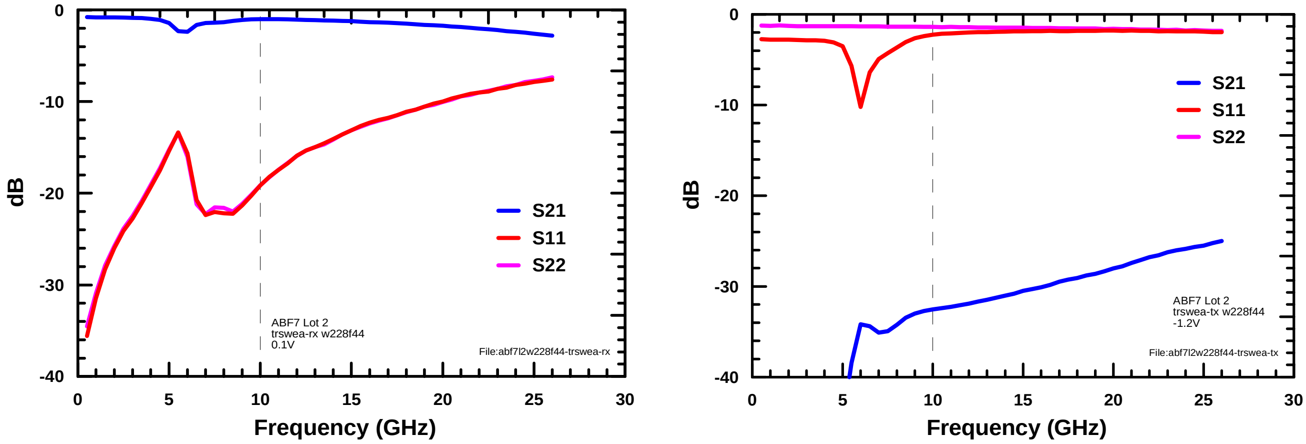
The ABCS HEMT has a very low drain saturation voltage, Vdsat, where electrons in the channel reach peak drift velocity. Consequently, the LP-LNA can be biased at exceptionally low drain voltages where dissipated dc power is extremely small (Table 1). For lowest noise figure, the rf measurements were made with Vdd = 0.35 V and Id = 9.2 mA, corresponding to a dc power of 3.2 mW. This dc power dissipation is less than one-tenth the power consumption of X-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. For some applications where operation with degraded gain and noise figure may be tolerated, operating the amplifier as low as Vdd = 0.25 V leads to a dc power dissipation of only 0.98 mW, which is believed to be the lowest reported dc power dissipation of any X-band low noise amplifier. The output power of the LNA at V_{dd} = 0.35 V is -3.0 dBm at the 3 dB gain compression point.

IV. SWITCH DESIGN AND CHARACTERIZATION

Fig. 4 shows a photograph of a series-shunt X-band MMIC single-pole double-throw (SPDT) rf switch designed into RSC's ABCS process along with measured data. The X-band switch was again designed using 0.1µm gate length two-finger, 80-µm total gate width ABCS HEMTs. The gate bias for the 'off' state devices was –1.0 V, and for the 'on' state was 0.0V. The measured s-parameters for the switch are shown in Fig. 5. Over the band from 9.5 to 10.5 GHz, the measured insertion loss for the 'on' leg is 0.99 ± 0.02 dB, and the output return loss is better than 18 dB. The measured isolation for the 'off' leg is 32.6 ± 0.2 dB.

V. CONCLUSION

A two-stage ABCS HEMT ultra-low-power low-noise amplifier (LP-LNA) designed to operate at X-Band is reported. The amplifier achieved 22.3 dB gain and 1.25 dB average noise figure at 10 GHz with a total dc power dissipation of only 3.2 mW using 0.1 µm gate length devices. A compact 0.9 mm^2 single-pole double-throw X-band RF switch demonstrated a 0.99 dB on-state insertion loss and an off -state isolation of > 32 dB. These results demonstrate the outstanding potential of the ABCS HEMT technology for low-power X-band applications.



(a) **(b)**

Fig. 5. (a) Plot of measured 'on' state insertion loss and return loss versus frequency for the RF SPDT switch. (b) Plot of measured 'off' state isolation and return loss versus frequency for the RF SPDT switch.

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ACRONYMS

HEMT: High Electron Mobility Transistor
ABCS: Antimonide-Based Compound Semiconductor
2DEG: Two-dimensional electron gas
LP-LNAs: Low-power low-noise amplifiers
SPDT: Single-Pole Single-Throw