An Ultra-Low-Power MMIC Amplifier Using 50-nm δ-Doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ Metamorphic HEMT

Chi-Jeon Hwang, *Student Member, IEEE*, Lai Bun Lok, *Member, IEEE*, Harold M. H. Chong,
Martin Holland, Iain G. Thayne, and Khaled Elgaid, *Member, IEEE*

***Abstract*—An ultra-low-power monolithic amplifier using 50-nm gate-length GaAs metamorphic high-electron-mobility transistor (MHEMT) has been designed and fabricated by a coplanar waveguide monolithic microwave integrated circuit process. A double δ-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ MHEMT technology with optimal doping profiles was used to achieve both ultra-low dc power consumption and good dynamic-range performance. The single-stage amplifier operates in the 24-GHz band and shows typical gain of 7.2 dB, ±0.5 dB bandwidth of 1.2 GHz, return losses better than 9 dB, and input IP_3 (IIP_3) of +3 dBm while consuming only 0.9 mW of dc power. These experimental results demonstrate the outstanding potential of MHEMT technology for ultra-low-power applications such as wireless sensor networks.**

***Index Terms*—Coplanar waveguide, metamorphic high-electron-mobility transistor (MHEMT), monolithic microwave integrated circuit (MMIC), ultra-low power consumption, δ-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$.**

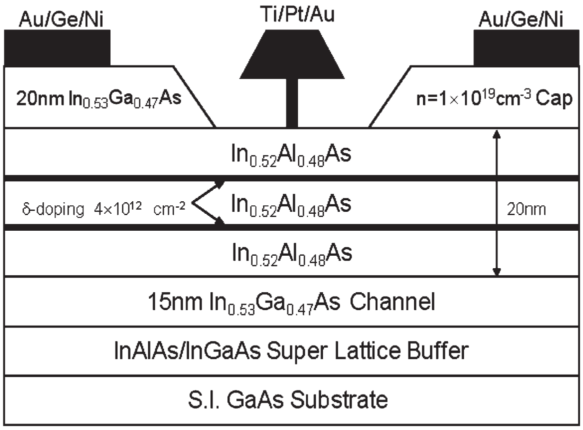

Fig. 1. Device cross section of the 50-nm gate-length δ-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ MHEMT.

I. INTRODUCTION

ULTRA-LOW-power monolithic amplifiers are critical building blocks in wireless sensor networks which are widely predicted to have major growth opportunities in the forthcoming years in numerous imaging, safety, biomedical, and environmental applications. For wireless sensor networks, ultra-low dc power consumption is an important issue because of the limited capacity of small-size battery source [1]. Thus, a device technology is required to optimally utilize the available battery power for internode communication. In recent years, GaAs metamorphic high-electron-mobility transistor (MHEMT) device technology has been widely studied for low-noise and high-gain applications as well as low-power applications.

The GaAs MHEMT has an advantage in that it can incorporate a high indium content channel, with indium composition ranging from 30% to 100%, which results in higher $f_{\max}$ and f_T and lower noise than GaAs PHEMT, and is comparable with InP devices. Therefore, the GaAs MHEMT provides a low-cost alternative to the high performing but more expensive InP HEMT [2]. It also has the property of inherent low operating voltage which can reduce dc power consumption by high indium contents [3], [4]. In addition, the δ-doped strategy can be tailored to ensure good device linearity performance.

In this letter, we report on a single-stage monolithic microwave integrated circuit (MMIC) amplifier with good dynamic-range performance and ultra-low dc power consumption using the double δ-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ 50-nm GaAs MHEMT technology. The amplifier design is targeted for ultra-low-power wireless sensor network applications in the industrial, scientific, and medical band at 24 GHz.

II. DEVICE DESCRIPTION

Our 50-nm gate-length MHEMT device technology is based on an aggressively scaled double δ-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ MHEMT layer structure, as shown in Fig. 1 [5]. The double δ-doped strategy was used to increase transconductance, reduce access resistance, and enhance device linearity [6]. The 1200-nm metamorphic buffer is graded linearly from GaAs to $In_{0.53}Ga_{0.47}As$ and followed by a 72-nm-thick $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ superlattice prior to the growth of the device layers. The relatively low

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C.-J. Hwang is with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576, Singapore (e-mail: hcjpk@hotmail.com).

L. B. Lok, M. Holland, I. G. Thayne, and K. Elgaid are with the School of Engineering, University of Glasgow, G12 8LT Glasgow, U.K.

H. M. H. Chong is with the School of Electronics and Computer Science, University of Southampton, SO17 1BJ Southampton, U.K.

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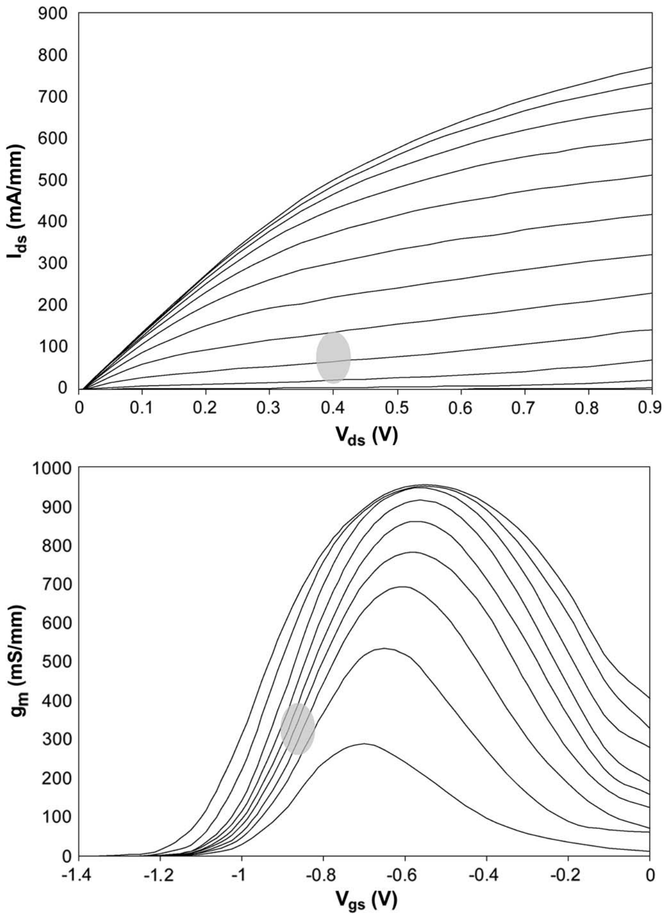

Fig. 2. I–V and transconductance characteristics of a two-finger 50-μm-gate-width GaAs MHEMT (V_{ds}: from 0.1 to 0.9 V; V_{gs}: from 0 to -1.4 V; 0.1 V step).

value of mobility of 6470 $\mathrm{cm}^2/\mathrm{Vs}$ is due to the double δ-doping strategy which increases ionized impurity scattering. Ohmic contact resistances of as low as 0.06 $\Omega \cdot$ mm are obtained using an annealed 150-nm-thick Au:Ge:Ni-based metallization. The devices are realized with 1.1-μm source-to-drain separation between which the 50-nm T-gates are formed using electron beam lithography. Wet chemical etching is subsequently used to form a single-gate recess prior to the deposition of 200-nm-thick Ti:Pt:Au gate metallization for the Schottky contact [5]. The fabrication process further includes 50-Ω/sq thin-film NiCr resistors and 0.4 fF/$\mu\mathrm{m}^2$ SiN metal–insulator–metal capacitors. Two levels of metal interconnects are used, and the MMIC process is completed with a 2-μm-thick electroplated gold metallization airbridge technology.

To enable the amplifier design, an array of MHEMT devices were fabricated on a test wafer mask and characterized at dc and RF. As shown in Fig. 2, the devices exhibit good pinch-off and output conductance characteristics. The typical drain saturation current (I_{dss}) and maximum transconductance ($g_{m,\max}$) for the two-finger 50-μm gate-width device are 770 mA/mm and 950 mS/mm, respectively. The gate-to-drain breakdown voltage is 2.25 V at $I_g = 1$ mA/mm. On-wafer RF measurement on the devices were performed from 100 MHz to 110 GHz for a matrix of low-power biasing conditions. The effect of the input–output feeding probe pads leading to the device were de-embedded from the measurement data to obtain the pure S-parameters of the device. At the bias condition of V_{ds} of 0.4 V and I_{ds} of 2.2 mA, the two-finger 50-μm gate-width MHEMT device has a cutoff frequency (f_T) of 56 GHz and a maximum oscillation frequency ($f_{\max}$) of 109 GHz, respectively. It has a maximum associated gain of 10 dB at 24 GHz, which suggests that this device geometry is capable of meeting the gain and ultra-low dc power consumption requirements within the band of interest. However, to meet the aggressive dc power specification, the device is biased around a highly nonlinear point in the operating curve, as shown in Fig. 2. An accurate large-signal model of the device at these limits has therefore been extracted to facilitate the amplifier design [7]. As a result, an amplifier design with good dynamic-range performance has been achieved, which will be shown in the next section.

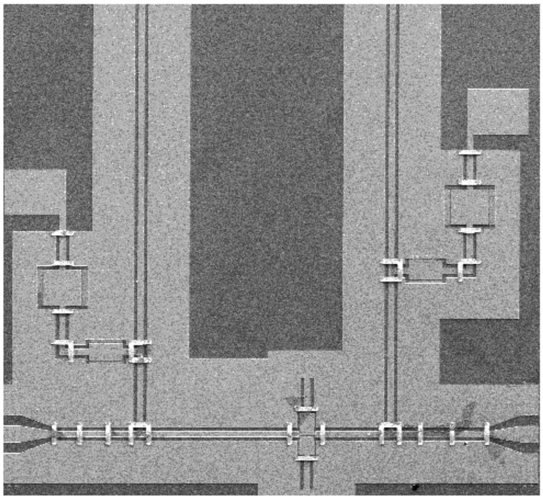

Fig. 3. Microphotograph of the fabricated single-stage MMIC amplifier.

III. AMPLIFIER DESIGN AND PERFORMANCE

The single-stage MMIC amplifier has been designed and fabricated using a two-finger 50-μm device. Fig. 3 shows a microphotograph of the fabricated MMIC amplifier chip which occupies a total area of 1.9×2.3 mm^2. To improve the in-band and outband stability, shunt resistor with series capacitor was used in the bias networks [8]. The MMIC amplifier was measured on-wafer using LRRM calibration. Fig. 4 shows the measured amplifier S-parameters, which are in good agreement with simulations. Typically, the gain is 7.2 dB, and the return losses are better than 9 dB for a bias point V_{ds} of 0.4 V and I_{ds} of 2.2 mA. Fig. 5 shows the output power 1-dB compression and the input third-order intercept point (IIP_3) characteristics. The $P_{1\,\mathrm{dB}}$ is -5.8 dBm, and the IIP_3 is $+3$ dBm for a dc power consumption of only 0.9 mW. Finally, the amplifier noise figure was measured to be 1.9 dB at 24 GHz. The performance of the amplifier in this letter is compared with the current state of the art of various technologies as listed in Table I [9]–[14]. Compared with previously reported amplifiers with some other technologies, the proposed MHEMT-based amplifier has shown good performances as well as lower dc power consumption.

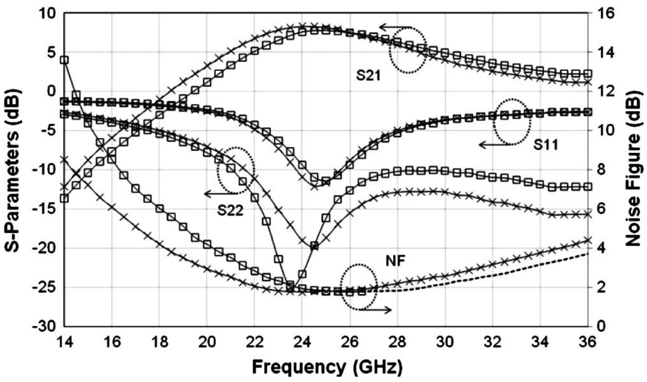

Fig. 4. Gain, return loss, and noise figure at $V_{\rm ds} = 0.4$ V and $I_{\rm ds} = 2.2$ mA: (×) simulation; (□) measurement.

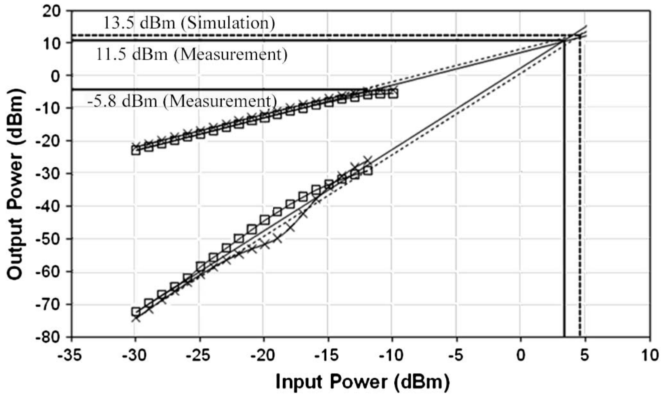

Fig. 5. $P_{1\,\rm dB}$ and IP_3 characteristics at 24 GHz. $V_{\rm ds} = 0.4$ V and $I_{\rm ds} = 2.2$ mA: (×) simulation; (□) measurement.

TABLE I
PERFORMANCE COMPARISON WITH STATE OF THE ART LOW-POWER LNA IN DIFFERENT TECHNOLOGIES

Ref.	Process	No. of TR	Freq. (GHz)	Gain (dB)	NF (dB)	IIP3 (dBm)	PDC (mW)
[9]	90nm CMOS	1	24	7.5	3.2	NA	10.6
[10]	130nm CMOS	4	24	14.7	4.3	NA	20.2
[11]	180nm CMOS	2	22	10.1	4.3	-1	7.2
[12]	180nm SiGe HBT	2	23	9.3	4.3	-8.2	1.5
[13]	100nm ABCS HEMT	NA	12	16.78	1.7	NA	1.5
[14]	150nm PHEMT	2	3.1-10	12.5	3.4-4.0	NA	12.9
This work	50nm MHEMT	1	24	7.2	1.9	+3	0.9

IV. CONCLUSION

An MMIC amplifier using the 50-nm gate-length GaAs MHEMT with double δ-doped In$_{0.52}$Al$_{0.48}$As/In$_{0.53}$Ga$_{0.47}$As has been demonstrated at 24 GHz with good dynamic-range performance while consuming only 0.9 mW of dc power. These results demonstrate the outstanding potential of 50-nm MHEMT devices with double δ-doping strategy for ultra-low power applications such as wireless sensor networks.

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