Broadband AlGaN/GaN HEMT MMIC Attenuators with High Dynamic Range

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Abstract — GaN-based HEMT Microwave Monolithic Integrated Circuit (MMIC) attenuators were realized for the first time. The MMICs employed AlGaN/GaN HEMTs fabricated by optical contact lithography (L_g=*1μm*) with high current gain (f_T) and maximum power gain (f_{MAX}) cutoff frequencies of *17* and *24GHz*, respectively. The MMIC attenuators employing three *100μm*-wide AlGaN/GaN HEMTs in π-configuration had minimum insertion of *4dB*, high dynamic range (*>30dB*), and broadband operation (up to *18GHz*). On-wafer power characterization at *8GHz* confirmed successful operation of the GaN-based attenuator MMICs at power density exceeding *15W/mm*.

I. INTRODUCTION

GaAs MESFETs [1] as well as GaAs- and InP-based HEMTs have been successfully used as switching and variable attenuation elements and demonstrated excellent high frequency characteristics, small DC power dissipation, and high switching speed [2,34]. However, power-handling capabilities of MMICs made using conventional III-V compounds are limited by modest electrical strength of these materials (F_B=*0.4-0.5MV/cm*).

Recent advances in wide bandgap semiconductor technology suggest a possibility of using GaN-based HEMT MMICs for realization of microwave signal control and amplification functions [5]. The use of devices with high breakdown allows improved power handling of attenuators as discussed in [6]. By employing AlGaN/GaN HEMTs one can therefore expect increased power handling while preserving the high-frequency and wide dynamic range characteristics due to the high electric strength of GaN (F_B>*2MV/cm*) and good electron transport properties [5].

In this work, we report the first demonstration of GaN-based MMIC attenuators using AlGaN/GaN HEMTs with broadband and high-dynamic range characteristics and excellent power handling.

II. FABRICATION AND PERFORMANCE OF DISCRETE AlGaN/GaN HEMTs

AlGaN/GaN heterostructure layers were grown by MOCVD on sapphire substrates. The layers consisted of (starting from the top) *3nm*-thick *nid* $Al_{0.25}Ga_{0.75}N$ barrier, *25nm*-thick $Al_{0.25}Ga_{0.75}N$ donor doped at $2\times10^{18}cm^{-3}$, 3nm-thick *nid* $Al_{0.25}Ga_{0.75}N$ spacer, and a *nid* GaN channel. The HEMTs were fabricated on rectangular mesas using optical contact lithography and the SEM photograph of a fabricated device is shown in Fig.1. Dry etching was performed by CCl_2F_2-based RIE using photoresist mask to create outward sloped walls for improved step coverage. Ti/Al/Au/Pt metals were used for source and drain ohmic contacts. Rapid thermal annealing at *900°C* in N_2-atmosphere was used to reduce contact resistance to *1Ωmm*. *1μm*-long gates were defined by optical contact lithography as shown in Fig.1. Pt/Ti/Au metal layers were used for gate metallization.

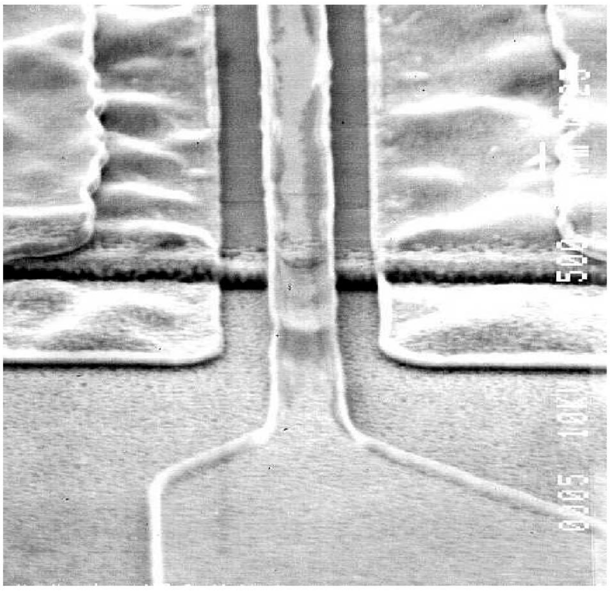

Fig.1: SEM photograph of *1μm*-gate AlGaN/GaN HEMT

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DC characteristics of integrated microwave devices with $1\mu m$-long $2\times50\mu m$-wide gates AlGaN/GaN HEMTs were measured and typical transfer characteristics are shown in Fig.2. The microwave devices demonstrated channel current capability of *~600mA/mm* and a threshold voltage V_{TH} of *–7V*. The extrinsic transconductance g_m^{ext} peaked at *130mS/mm* for gate-source voltage V_{GS} of *–3.5V* and drain-source voltage of *10V*. The drain-source breakdown voltage exceeded *25V*.

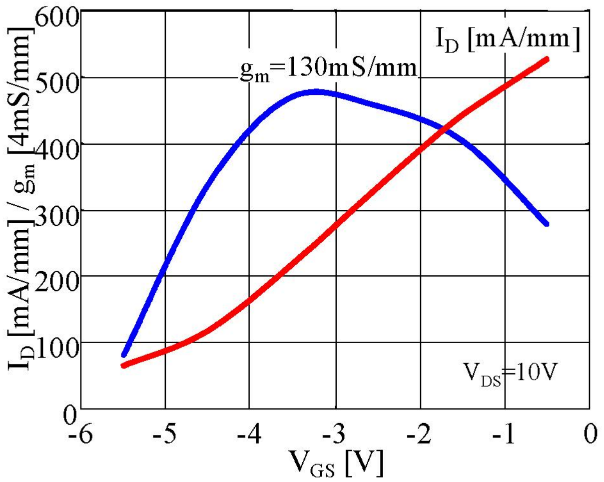
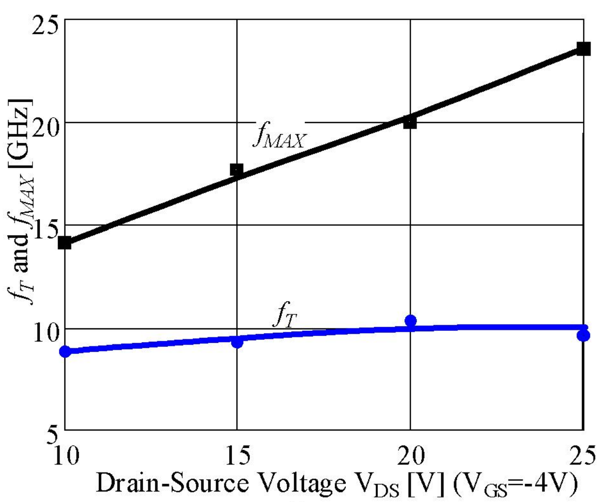
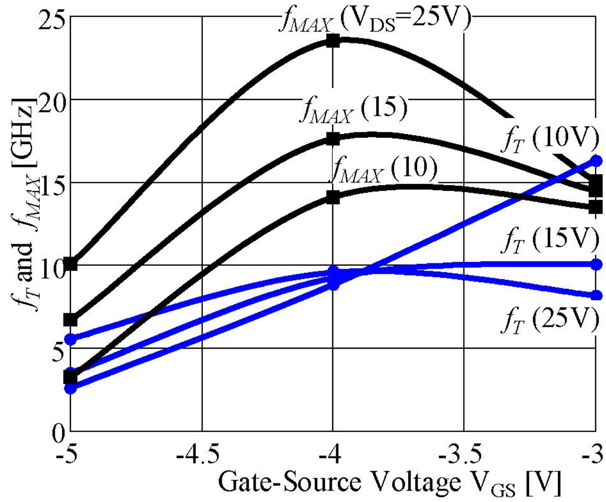


Fig.2: Typical transfer characteristics of AlGaN/GaN HEMTs

On-wafer small-signal S-parameters of integrated microwave devices were measured up to *25.5GHz* and used to extract current-gain (f_T) and maximum-power-gain (f_{MAX}) cutoff frequencies. The dependence of f_T and f_{MAX} on the applied bias is shown in Fig.3a and Fig.3b. f_{MAX} increased from 14 to 24 GHz as the drain-source bias was varied from *10* to *25V* due to the increase of the output resistance RDS and the slight increase of transconductance g_m and, thus, f_T.



(a)



(b)

Fig.3: Drain-source and gate-source bias dependence of f_T and f_{MAX} in AlGaN/GaN HEMTs

Peak f_{MAX} of *24GHz* occurs for V_{DS}*=25V* and V_{GS}*=-4V* while peak f_T was at V_{DS} of *10V* and V_{GS} of *–3V*. The recorded high-frequency characteristics represent state-of-the-art f_T and f_{MAX} figures of merit obtained for GaN-based HEMTs fabricated by optical contact lithography.

III. DESIGN AND FABRICATION OF AlGaN/GaN HEMT MMIC ATTENUATORS

As a first demonstration of the feasibility of using AlGaN/GaN HEMTs in microwave monolithic integrated circuits we have realized monolithic attenuators for signal-control applications. Attenuator MMICs in a π-configuration were studied. Such circuits consisted of one HEMT connected in series and two HEMTs connected in shunt in a coplanar transmission line configuration as shown in Fig.4.

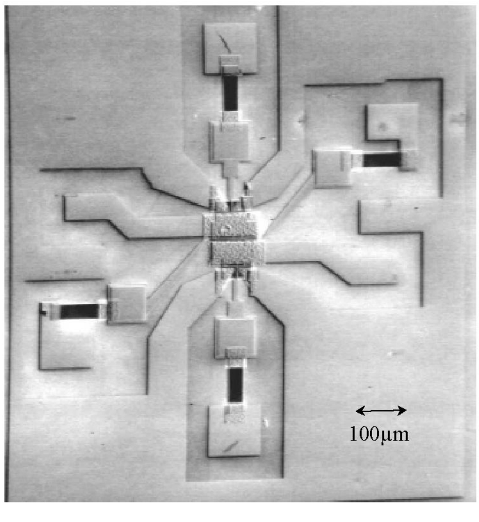


Fig.4: SEM photograph of GaN-based π–attenuator MMIC

All three devices had $1\mu m$-long and $100\mu m$-wide gates and the MMIC occupied *~1sq.mm.* Independent biasing networks with *RF*-choking resistors are also integrated on chip so that the bias voltage controlling the impedance of the HEMTs can be applied directly to the bias pads without disturbing the high-frequency characteristics of the MMICs. The biasing resistors (750Ω each) were fabricated using AlGaN/GaN active layers, which had sheet resistivity of $300\Omega/sq$.

The fabrication of monolithic integrated circuits was completed by deposition of *Ti/Au* layers forming interconnects, coplanar-waveguide transmission lines, ground planes, and microwave test pads.

IV. SMALL-SIGNAL CHARACTERISTICS OF AlGaN/GaN HEMT π–ATTENUATOR MMICs

In the "minimum attenuation" state of the π–attenuator MMIC, the channel of the series HEMT is open ($V_{G1}=0$), while the channels of the shunt HEMTs are fully depleted ($V_{G2,3}$=$-15V$). In the "maximum attenuation" state, the channel of the series HEMT is depleted (V_{G1}=$-15V$), while the impedance of the shunt HEMTs is kept low ($V_{G2,3}$=$0V$) to provide additional attenuation.

Measured insertion loss and matching for the "minimum attenuation" and the "maximum attenuation" states are shown in Fig.5. The minimum loss was *4dB*, and remained less than *5dB* up to *18GHz*. The investigated circuit demonstrated "maximum attenuation" of more than *35dB* up to *22.5GHz*.

Based on measured small-signal S-parameters, values of equivalent-circuit elements for $1\mu m\times100\mu m$ AlGaN/GaN HEMTs were extracted. The resistance of the open channel (R_{CH}) was 35Ω, while the resistance of the fully depleted channel (R_{DS}) was 600Ω.

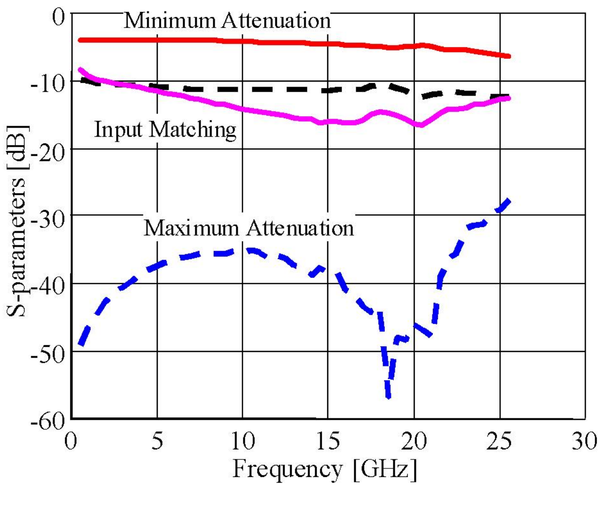


Fig.5: Measured microwave performance of AlGaN/GaN HEMT π–attenuator MMIC

The input matching was better than *10dB* for all tested frequencies and attenuation states. Such excellent matching characteristics were made possible by proper selection of the size of transistors and design of the MMICs based on the good scalability of GaN-based HEMTs as previously reported by the authors [7]. Using $100\mu m$-wide AlGaN/GaN HEMTs resulted in small variation of input impedance Z_{IN} for all attenuation states (between *33* and 71Ω). The choice of small periphery transistors also allowed to minimize displacement current effects, which, if pronounced, may lead to severe degradation of isolation.

A high dynamic range of signal attenuation (*>30dB*) over broad bandwidth (*18GHz*) was possible with the GaN-based MMICs due to the good high-frequency characteristics of the realized AlGaN/GaN HEMTs. The measured MMICs show characteristics equivalent to those reported for high-performance InP-based HEMT MMICs [3], but offer improved power-handling capability due to the increased electrical strength of GaN-based semiconductor materials.

V. LARGE-SIGNAL CHARACTERISTICS OF AlGaN/GaN MMIC ATTENUATORS

An on-wafer load-pull system was used to evaluate the large-signal characteristics of the fabricated AlGaN/GaN HEMT MMIC attenuators. For this purpose, the attenuation level was measured as a function of input power for different bias control voltages. On-wafer power saturation characteristics of the AlGaN/GaN HEMT π-attenuator measured at *8GHz* are shown in Fig.5. The MMIC operation was possible under *1.6W* of *CW* of input power corresponding to a power density in excess of *15W/mm* per single transistor. This presents a *15-20dB* improvement in power handling capability over high-performance InP-based MMICs reported in [3].

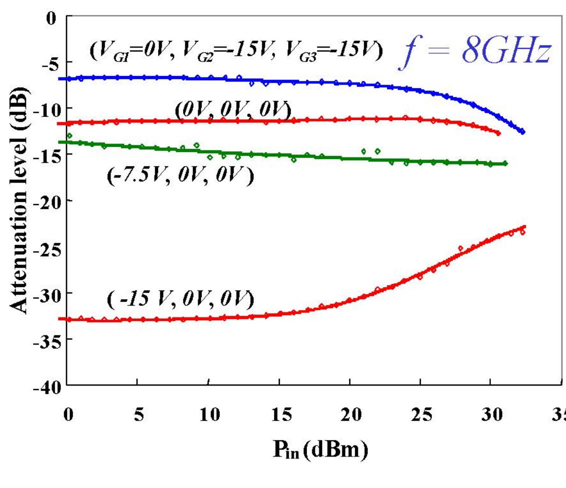


Fig.6: Power characteristics of GaN-based π–attenuator

VI. CONCLUSIONS

GaN-based HEMT MMIC attenuators are reported for the first time. The AlGaN/GaN HEMTs demonstrated f_T*=17GHz* and f_{MAX}*=24GHz,* which represent record-high values for *1μm*-gate devices fabricated by optical contact lithography. Monolithic attenuators realized using these devices as control elements demonstrated broadband (*up to 18GHz*) and high dynamic range (*>30dB*) operation comparable to InP- and GaAs-based MMICs but provided significantly higher power handling (*15W/mm*).

VII. REFERENCES

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