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A Novel GaN-based Monolithic SAW/HEMT Oscillator on Silicon

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***Abstract* — This work presents the first fully integrated surface acoustic wave (SAW) oscillator based on AlGaN/GaN structures grown on Si substrates. In addition to the material advantages such as wide-bandgap, and chemical and thermal stability, the use of crystalline III-nitride semiconductors enables a seamless integration of an acoustic device with its peripheral control circuits. The 252-MHz oscillator prototype was implemented by monolithically integrating a two-port SAW delay line with electronics using AlGaN/GaN high electron mobility transistors (HEMTs). Measurements show that the SAW device exhibits a high quality factor (*Q*) of up to 1000 and an excellent power handling capability. The oscillator is suitable for sensing applications in harsh environments and can potentially be extended to high power RF systems.**

***Index Terms* — AlGaN/GaN, HEMT, monolithic integration, oscillator, sensor, surface acoustic wave.**

I. INTRODUCTION

Surface acoustic wave (SAW) technology has been used extensively in commercial applications such as telecommunications, automotive and environmental sensing for several decades. Monolithic integration of SAW devices with on-chip electronics yields a compact system-on-chip (SoC) solution, which has advantages in both detection and communication applications. The advantages include improved performance, increased yield, reduced form factor and lower overall cost. The first demonstration of a monolithic integrated SAW oscillator on a GaAs substrate can be traced back to 1999 [1]. Recently developed III-nitride materials, with better piezoelectric property for SAW devices, and chemical and thermal stability are better suited for this application.

III-nitride semiconductors, which offer high SAW propagation velocity (~4800 m/s) and relatively low temperature coefficient of frequency (TCF) (−60 ppm/℃), are beneficial for SAW devices [2]. Their inherent chemical inertness and thermal stability also make them good candidates for sensing applications in harsh environments [3]. In addition, high-quality single crystalline AlGaN/GaN heterostructures on silicon substrate have been successfully grown to fabricate high-performance high electron mobility transistors (HEMTs). These properties pave the way for the development of nitride-based monolithic SAW/HEMT integrated circuits on a single low-cost silicon substrate.

In this study, we demonstrated an on-chip nitride-based monolithically integrated SAW/HEMT oscillator for the first time. It consists of a two-port SAW delay line and a five-stage amplifier in a feedback loop. The excellent power handling capability with compromised phase noise performance of the oscillator is discussed in detail. Demonstration of this highly integrated device suggests the potential future deployment of integrated miniature sensor systems in harsh environments, such as high temperature or erosive conditions. The superior power handling capability can also be applied to high power RF applications.

This paper is focused on the development of a fully integrated SAW/HEMT oscillator and is organized as follows: in Section II, integration consideration, circuit design and device fabrication process are explained; in Section III, experimental results are discussed; and Section IV is the conclusion.

II. CIRCUITS DESIGN AND FABRICATION

A. Process Integration Consideration

Piezoelectric materials that couple strain and electric field provide a convenient medium to launch SAW using interdigitated transducers (IDTs). To launch an acoustic wave, a RF electrical signal is applied on the IDT to create elastic deformation in a piezoelectric material, epitaxial GaN in this case. Since AlGaN/GaN heterojunction is the starting material for the oscillator, the presence of two-dimensional electron gas (2DEG) in the channel screens the applied electric field and prohibits the acoustoelectric transductions in the IDTs. The top AlGaN barrier layer was locally dry-etched away and the SAW devices were fabricated on the exposed GaN surface, while the active HEMTs were fabricated on the mesa where the AlGaN barrier layer remains [4].

B. SAW Delay Line Oscillator Design

A SAW oscillator consists of an amplifier configured in a feedback loop with a SAW delay line. The amplifier must provide sufficient gain at a desired oscillation frequency to compensate the insertion loss of the SAW device.

In this work, a five-stage HEMT amplifier was designed with a gain of over 40 dB and each stage was an

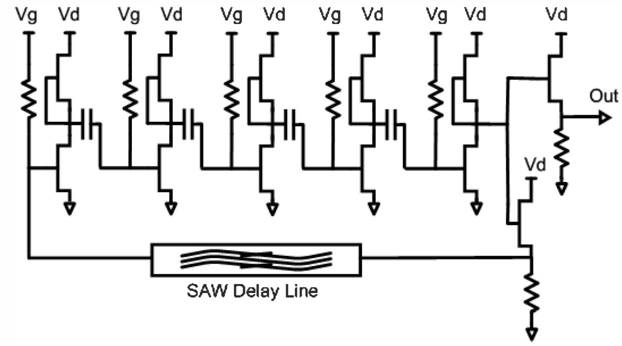

Fig. 1. Schematic of a SAW delay line oscillator circuit.

active-load common-source amplifier, as shown in Fig. 1. All HEMTs in the circuit operates in depletion-mode (D-mode). Active load is formed by connecting the gate and source of a D-mode transistor together, so that the transistor is biased at on-state all the time. Totally 12 HEMTs are used in this design, including two source-follower buffers. The gate length of all the HEMTs is 1.5 µm and the source-to-gate distance and drain-to-gate distance are both 1 µm. Passive elements including metal-insulator-metal (MIM) capacitors and mesa resistors are fabricated on the same chip. On-chip bypass capacitors are also included for the gate (V_g) and drain (V_d) supplies, which are not shown in the schematic.

The operation frequency of a SAW delay line oscillator is determined by the acoustic velocity, the wavelength and the path length between the two IDTs. In this study, the IDT finger width and the spacing between two adjacent IDT fingers are both 4 µm, resulting in an operation frequency of approximately 250 MHz. Both the input and output IDTs have 50 pairs of fingers. The electrode separation of the two IDTs is 480 µm, 30 times longer than wavelength, and the IDT aperture is 300 µm.

C. Circuit Fabrication

The AlGaN/GaN epitaxial heterostructures used in this work were grown on silicon (111) substrates by metal-organic chemical vapor deposition (MOCVD). The structure consists of a high temperature AlN seed layer, a SiN_x mask layer, a 1 µm thick GaN buffer layer and an AlGaN barrier layer. A thin interlayer was inserted in the GaN buffer to counter-balance the tensile strain produced by the mismatch of thermal expansion coefficients between the substrate and the epi-layers, and to prevent cracks on the surface. The fabrication process was modified from a conventional AlGaN/GaN HEMT process flow, as illustrated in Fig. 2. Firstly, the top AlGaN barrier layer was selectively etched by Cl_2-based inductively coupled plasma (ICP) etching for not only isolating active devices but also removing the 2DEG within the heterojunction channel for acoustoelectric transduction in the IDTs, as shown in Fig. 2(a). Secondly, the source/drain ohmic contacts of HEMTs were formed by e-beam evaporation of Ti/Al/Ni/Au and liftoff process, followed by rapid thermal annealing (RTA) at 850 ℃ for 30 seconds, as shown in Fig. 2(b). Thirdly, the Schottky metal for forming the IDTs of the SAW device, gate electrodes of HEMTs and the bottom metal plates of MIM capacitors were patterned by e-beam evaporation of Ni/Au and liftoff process, as shown in Fig. 2(c). Then, a 2000 Å silicon nitride layer was deposited by plasma enhanced chemical vapor deposition (PECVD), serving as both interlevel dielectric and MIM capacitor dielectric. Finally, reactive ion etching was used for via opening, and the whole processing was completed with the formation of the interconnections, as shown in Fig. 2(d). A microphotograph of a fabricated circuit is given in Fig. 3 and the one-stage active-load amplifier is shown in detail. The oscillator circuit size is approximately 2×1.2 mm^2.

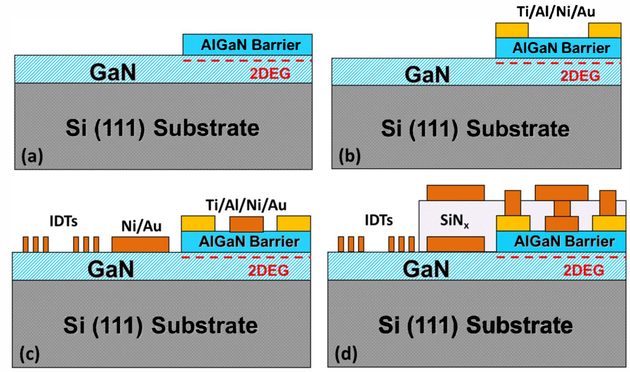

Fig. 2. Schematics showing the process flow of a monolithic integration of SAW delay line oscillator: (a) Mesa etch; (b) Ohmic contacts; (c) Schottky contacts for IDTs, gates and bottom metal plates of capacitors; (d) SiN_x deposition, Via opening and interconnection formation.

III. Experimental Results and Discussions

A. SAW Delay Line Characterization

The S-parameters between 100 and 600 MHz of the SAW device were measured on-wafer using a network analyzer. The magnitude of S_{21} of the SAW delay line is shown in Fig. 4. A sharp peak was clearly observed at 252.3 MHz, which indicates the propagation of the Rayleigh waves. The measured insertion loss at the operation frequency is 28.2 dB and the quality factor (Q) is approximately 1000. Low insertion loss and high-Q are both desirable for frequency-selective components in high performance oscillator systems. Another peak with lower Q at around 500 MHz is believed to be another mode of acoustic waves propagating through the multilayers structure.

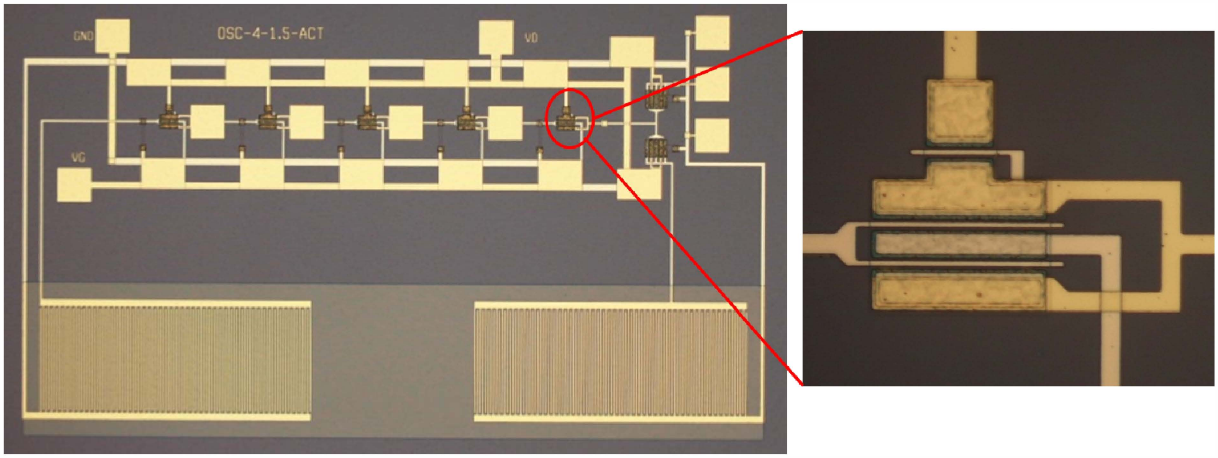

Fig. 3. Microphotograph of a fabricated SAW delay line oscillator.

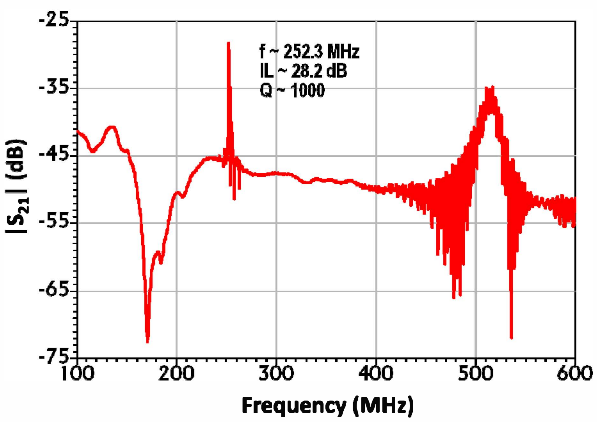

Fig. 4. Measured S_{21} of the fabricated SAW delay line.

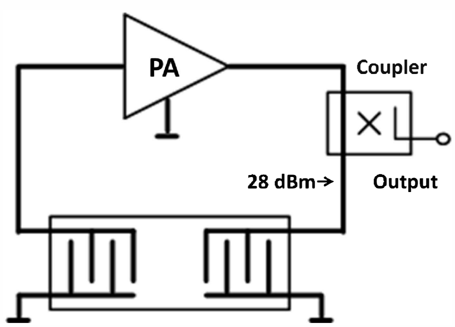

Fig. 5. Schematic of power handling test setup.

The power handling capability of the SAW device was also assessed by configuring a discrete sustaining power amplifier along with the SAW device into an oscillator loop and measuring its incident power level [5], as shown in Fig. 5. The SAW device was kept running at an input power level of 28 dBm (630 mW). No measurable performance degradation was observed after the power handling test, indicating that the SAW device is able to tolerate even greater input power levels. The excellent

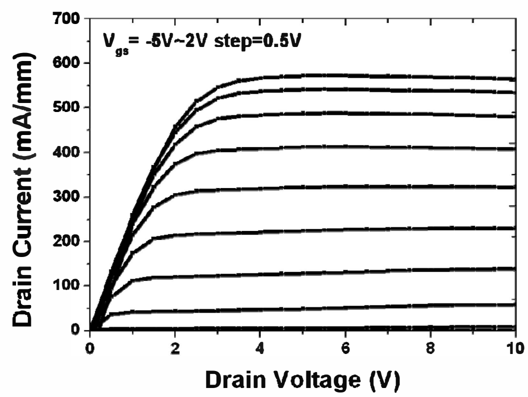

Fig. 6. DC IV characteristics of a HEMT.

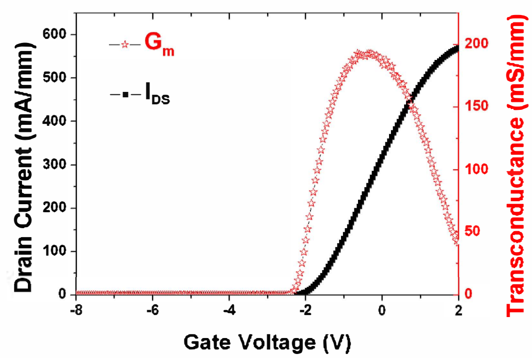

Fig. 7. Drain current and transconductance of a HEMT.

power handling capability highlights the potential of the nitride-base SAW oscillators for high power RF applications.

B. AlGaN/GaN HEMT DC Performance

The measured typical DC characteristics of a D-mode HEMT are shown in Fig. 6 and Fig. 7. The device shows a low DC output conductance and a peak transconductance

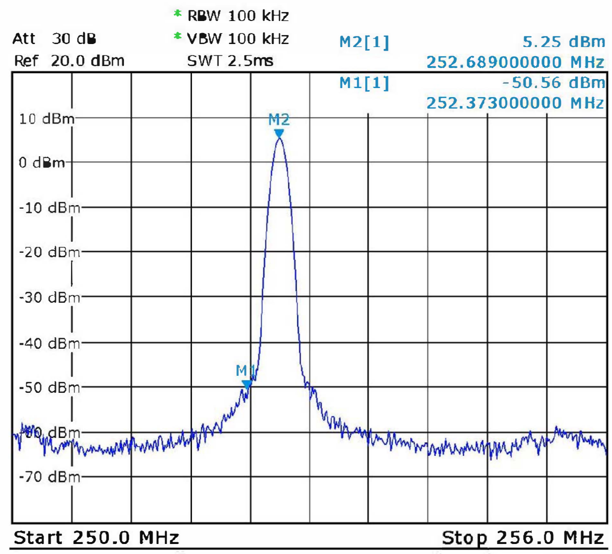

Fig. 8. Measured frequency spectrum of a SAW delay line oscillator operating at 252.7 MHz.

of 193 mS/mm with a threshold voltage of -2.1 V. Good uniformity of HEMT device performance over the whole wafer was achieved. The device gain satisfies the requirement of the oscillator design.

C. Measured Oscillator Performance

The integrated oscillator was tested on-wafer using a spectrum analyzer, with a V_d of approximately 10 V and a V_g of approximately −1.4 V. The oscillator operates at 252.7 MHz, which matches well with the SAW device characteristic, as shown in Fig. 8. The oscillator phase noise was estimated from the measured frequency spectrum. At 300-kHz offset frequency, the phase noise is approximately −105 dBc/Hz. The DC power consumption of this oscillator was 400 mW.

In this work, the impedances between the SAW device and the electronic circuits are not well matched, which results in high insertion loss. The oscillator DC power consumption and phase noise performances can be further improved if the SAW delay line were properly impedance-matched with the electronic circuits. Increasing the *Q* of the SAW device by using grooved IDTs is an alternative method to lower the phase noise [6]. Nevertheless, our results demonstrated, for the first time, the viability of SAW/HEMT integrated oscillator on a GaN-on-Si platform.

AlGaN/GaN HEMTs are inherently suitable for high-frequency and high-temperature operation. In this design, the oscillation frequency can be proportionally increased by down scaling the IDT features of the SAW device. Higher frequency leads to a wider bandwidth and higher speed communication applications, and a greater sensitivity in detection application. In addition, this nitride-based oscillator is developed on low-cost, easy-to-process silicon as opposed to SiC or sapphire substrates. Selective removal of the substrate allows the oscillator operation in Lamb-wave mode [7]. In Lamb-wave mode, the acoustic waves propagate in a relatively thin plate, resulting in stronger electromechanical coupling and higher sensitivity [8].

IV. CONCLUSION

For the first time, monolithic integration of a SAW/HEMT oscillator has been realized experimentally using AlGaN/GaN epi-structures directly grown on Si substrates. It is suitable for sensor systems in harsh environments and is promising for high power RF application as well.

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