16.8 1GHz GaN-MMIC Monolithically Integrated MEMS-Based Oscillators

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Low phase noise oscillators are essential building blocks in the front end of all communication systems. With the continuous demand for higher data rates and reduced size, weight, and power consumption, significant research in the past decade has been geared toward integrating high-Q GHz frequency MEMS resonators with standard circuit technologies [1],[2]. This paper presents monolithic integration of GaN MEMS resonators in GaN MMIC technology, which has become mainstream in RF LNA and PA design. Groups at MIT, Michigan and IEMN have previously demonstrated GaN MEMS resonators co-fabricated with HEMTs. This work is the demonstration of a single-chip closed-loop oscillator circuit implementing both passive and active devices in this growing technology platform.

The oscillators presented in this work are realized in a Au-free GaN HEMT process, using a GaN-on-Si heterostructure manufactured by Raytheon, comprised of molecular beam epitaxy (MBE) Al-GaN(25nm)/GaN(1.7µm) on (111)-Si using a thin AlN nucleation layer [3]. Au is usually used in GaN MMIC technology to provide ohmic contact for the 2D electron gas (2DEG), but presents a major barrier to GaN MMIC integration in CMOS foundries and also a major source of acoustic losses in GaN MEMS. Au-free technology on a silicon substrate was chosen due to its capacity for heterogeneous integration with CMOS and lower cost relative to SiC or sapphire [4].

Figure 16.8.1 illustrates the process of fabricating Lamb mode GaN resonators side-by-side with HEMTs. Only two processing steps were added to the standard HEMT flow: (1) a deep etch through the GaN layer to define the resonator, and (2) a silicon etch to release the resonators creating a freely suspended structure. An 11th harmonic Lamb mode is excited in the resonator using an inter-digitated transducer (IDT) formed from the HEMT gate metal (100nm Ni). In the resonator area, the AlGaN layer is etched prior to depositing these electrodes to eliminate the 2DEG and enable efficient piezoelectric transduction over the entire thickness of the GaN layer. A PECVD Si_3N_4 layer (150 nm) is deposited to passivate the surface and protect the 2DEG channel of the HEMTs [3]. This process was performed in MIT's Microsystems Technology Laboratories (MTL), with HEMT channel length of 1µm.

A scanning electron micrograph of the fabricated resonator is shown in Fig. 16.8.2 along with the modified Butterworth-Van-Dyke (BVD) equivalent circuit model used for oscillator design. Equivalent circuit parameters were fitted to 2-port RF measurements of the resonators (Y_{21} shown in Fig. 16.8.2). This helps capture any systematic asymmetry in the electrodes or resonator. Fabricated resonators exhibit a resonance frequency of 1.019GHz, quality factor of 4250 and motional resistance R_m of 390Ω, with feed-through capacitance of 47.5fF. The transduction efficiency k_{eff}^2 is 0.24%.

For the purpose of oscillator design, a representative HEMT model was needed. The MIT virtual source (MVS) GaN-RF model [5] was modified to incorporate mobility-limited carrier transport to enable modeling of long channel HEMTs in the process under consideration (L=1µm). The MVS model parameters were extracted from measured HEMTs with varying dimensions.

Pierce and Colpitts oscillator topologies were selected as the core can be designed using a single transistor, hence increasing yield and reducing footprint and power consumption. Schematics for oscillators presented in this work are shown in Fig. 16.8.3. The design includes resistors routed in the 2DEG (400 Ω/□) and metal-insulator-metal (MIM) capacitors defined across the 150nm SiN passivation. Since the HEMTs require a negative V_{gs} to operate, a source resistance R_S is necessary for the Pierce oscillator for unipolar supply operation. The gate is biased to ground through the resistance R_g. In both topologies, the core current is controlled by the HEMT dimensions and the resistance R_S. Both circuits work by having the core circuit provide an equivalent impedance Z_C to the resonators (Fig. 16.8.3) with a negative real component. Such negative resistance cancels out the resonator motional resistance R_m as the energy lost in the resonator is compensated by the active core, hence enabling sustained oscillation at the resonance frequency. The impedance Z_C also contains an imaginary component, which induces frequency pulling, shifting oscillation frequency from the natural frequency of the resonator.

In order to account for fabrication variations, two versions of the Pierce oscillator were implemented for different motional resistance, Pierce A was designed for 600Ω while Pierce B was over-designed for 2kΩ. The Colpitts oscillator uses a resonator identical to that in Fig. 16.8.2, and is optimized to support 1kΩ motional resistance resonators. The Colpitts oscillator benefits from lower supply voltage due to the lack of R_D and a single resonator terminal connected to the core. It also provides zero DC bias for the resonator. A 50Ω buffer was implemented to efficiently drive the measurement instruments without loading the oscillators. An optical micrograph of the Pierce oscillator circuit is shown in Fig. 16.8.7.

Oscillators were tested under vacuum (~10^{-5} Bar) in a Cascade probe station. Two Keithley 2400 SMUs were used to power the oscillator core and buffer. An Agilent PXA N9030A spectrum analyzer was used to measure the oscillators' output spectrum (Fig. 16.8.4) and phase noise (Fig. 16.8.5). The phase noise shows a characteristic -30dB/dec slope corresponding to flicker (1/f) noise. The measured characteristics of the three oscillators in this work are tabulated in Fig. 16.8.6. The smallest rectangles enclosing both resonator and core are 268 x 214 µm^2, 268 x 205 µm^2 and 300 x 185 µm^2, for Pierce A, B and Colpitts oscillators, respectively. The output frequency is ~1.02GHz for all devices. Pierce A consumes 1.06mW, whereas Pierce B consumes 4.7mW as it was over-designed to support 2kΩ resonator motional resistance. The figure of merit (FOM) at 100kHz is -205.9dBc/Hz, -202.4dBc/Hz, and -205.5dBc/Hz for Pierce A, B, and Colpitts oscillators, respectively. The table in Fig. 16.8.6 compares state of the art GHz-frequency MEMS-based oscillators [1-2,6-7] to the devices in this work. The presented oscillators' area is comparable to [1], ~8x smaller than [2] and ~6x smaller than [7]. The presented oscillators advance the state of the art, being monolithically integrated GaN-MEMS oscillators in a technology increasingly used for front-end LNAs and PAs. They are >10x smaller than multi-chip FBAR oscillators [6], out-perform similar sized oscillators [1], and provide comparable performance to much larger monolithic oscillators [2] and to multi-chip AlN LBAR oscillators [7]. Moreover, the resonator frequency is defined lithographically, enabling multiple frequencies on a single chip. Depending on the application, this provides a major advantage over thickness mode resonators such as FBARs.

In conclusion, the implementation of monolithic GaN MMIC MEMS-based oscillators has been demonstrated. State-of-the-art Lamb-mode resonators were monolithically integrated side-by-side with HEMTs and passives in a Au-free GaN MMIC process. 1GHz Pierce and Colpitts oscillators were realized achieving FOM of -205.9dBc/Hz in an area of 0.057mm^2, with power consumption of 1.056mW. This design and technology platform enable monolithic oscillators with lithographically defined frequency, providing a compact, reliable, and low power solution for GaN RF communication system front-ends.

Acknowledgements:
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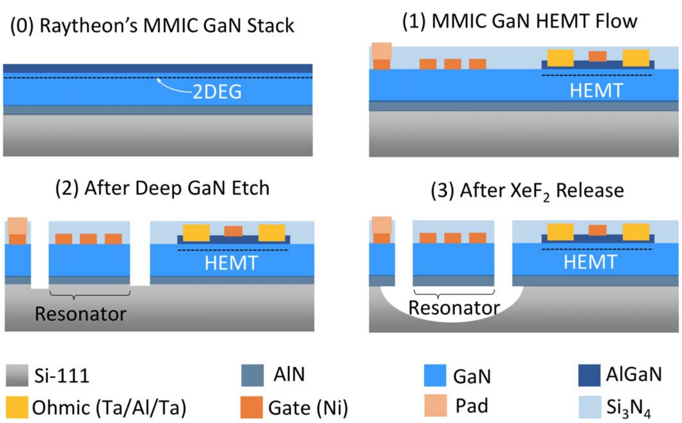


Figure 16.8.1: Au-free MMIC HEMT process modified for GaN resonators.

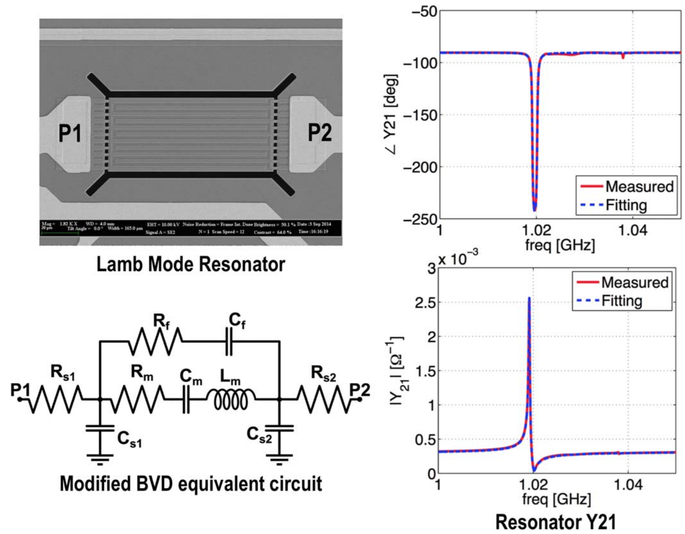


Figure 16.8.2: Lamb Mode GaN MEMS resonator.

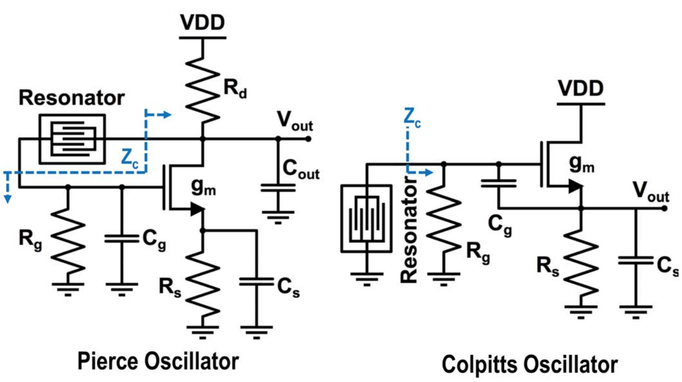
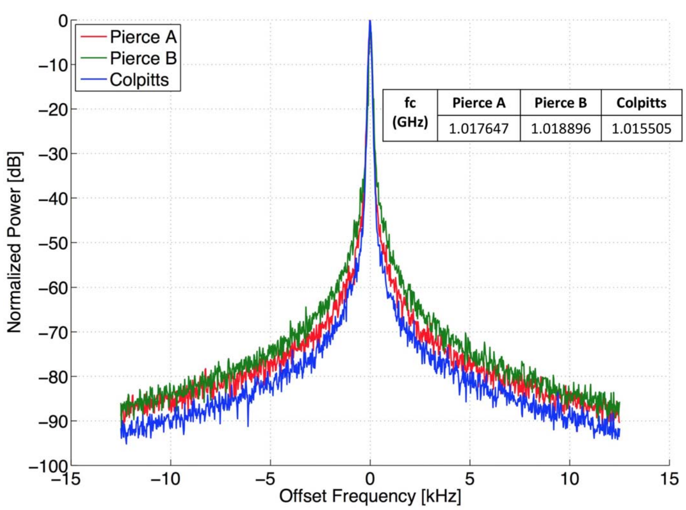
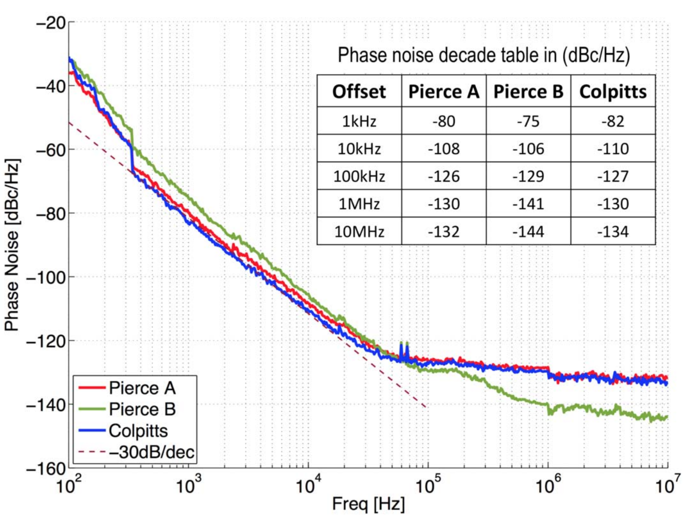


Figure 16.8.3: Pierce oscillator (Left), Colpitts oscillator (right).



fc (GHz)	Pierce A	Pierce B	Colpitts
	1.017647	1.018896	1.015505

Figure 16.8.4: Measured output spectrum (normalized power vs. freq offset).



Phase noise decade table in (dBc/Hz)

Offset	Pierce A	Pierce B	Colpitts
1kHz	-80	-75	-82
10kHz	-108	-106	-110
100kHz	-126	-129	-127
1MHz	-130	-141	-130
10MHz	-132	-144	-134

Figure 16.8.5: Measured phase noise with 20 sample average.

	This Work			CICC	ISSCC	ISSCC	ISSCC
	Pierce A	Pierce B	Colpitts	2013[6]	2010[7]	2007[1]	2006[2]
Frequency (GHz)	1.017	1.018	1.015	1.16	1.006	2.145	5.46
Core Voltage (V)	11	13	7	1	1.5	2.5	2.7
Core Current (mA)	0.096	0.362	0.21	4.2*	7.13*	4.8	1.7
Core Power (mW)	1.056	4.706	1.47	4.2	10.7	12	4.59
Supply Pushing (ppm/V)	2.7	1.96	1.92	-	-	65	-
Phase Noise @ 100 kHz	-126	-129	-127	-144	-140*	-124	-117.7
Phase Noise @ 1MHz	-129	-140	-130	-173	-150	-145*	-
FOM @ 100kHz	205.9	202.4	205.5	219*	209.8*	199.8	205.8
FOM @ 1MHz	188.9	193.4	188.5	228.3	199.5*	200.8*	-
area (mm²)	0.057	0.055	0.056	0.6*	0.33	0.043	0.45
Process	1μm GaN MMIC (in-house process)			0.13μm CMOS	0.18μm CMOS	0.25μm BiCOMS	0.35μm BiCMOS
Resonator	Lamb-mode GaN			AlN CMR	AlN LBAR	SMR	FBAR
Multiple Freq. On Chip	YES			YES	YES	NO	NO
Monolithic	YES			NO	NO	NO	YES

$$FOM = \left(\frac{f_\circ}{\Delta f}\right)^2 \frac{1}{\mathcal{L}(\Delta f) \times P_{DC}}$$

*Results are calculated or found from a curve: not provided directly in the referenced work.

Figure 16.8.6: Comparison with GHz-frequencies MEMS-based oscillators.

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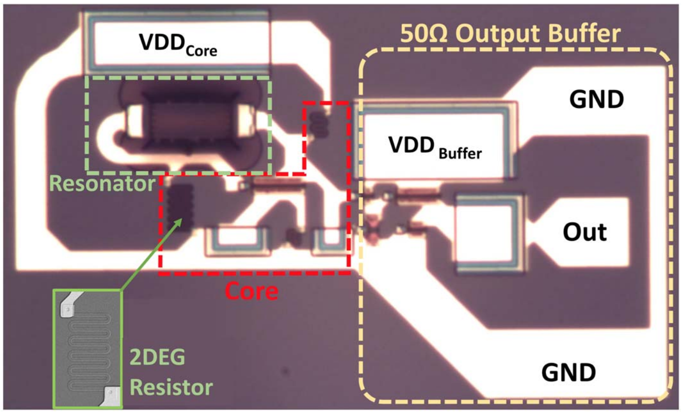

Figure 16.8.7: Circuit micrograph of 1GHz monolithic Pierce oscillator with GaN Lamb-mode MEMS resonator.

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