Dynamic Range-enhanced Electronics and Materials (DREaM)

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Over the past two decades, DARPA has enhanced gallium nitride (GaN) technology to deliver high power RF signals at higher frequencies, bandwidths and efficiencies under the WBGS-RF, NEXT and MPC programs. While existing GaN transistors are being adopted into many commercial and military platforms, emerging smaller and more distributed platforms demand higher output power density at even higher operating frequencies, beyond today's technology. The growing complexity and signal bandwidth in a crowded and contested electromagnetic spectrum also demands high linearity amplification for robust operation. To meet these needs, the DARPA Dynamic Range-enhanced Electronics and Materials (DREaM) program is developing advanced high power and high dynamic range transistor technology by combining innovations in epitaxial materials, device structures, and/or fabrication processes.

Introduction

DARPA has long recognized gallium nitride (GaN) as the material of choice for a broad array of defense applications due to its combination of high breakdown voltage, high sheet charge density, and high electron saturation velocity. Through DARPA investment in GaN technology in the previous DARPA WBGS-RF, NEXT, and MPC programs, GaN has been established as a critical material platform for high power RF components and modules that operate at microwave frequencies with large bandwidth and efficiency [1]. Today, large numbers of commercial and military users have crowded the limited electromagnetic spectrum. This creates a complex operating environment for RF systems to support generation and amplification of signals of interest without being obscured by undesirable large in-band interferences. The congested electromagnetic spectrum demands a new class of device technology that delivers high output power as well as high linearity to support high dynamic range RF electronics in microwave and millimeter-wave regimes.

To overcome the propagation loss at high frequencies in a congested and contested spectrum, next generation RF systems are expected to transmit high power density to deliver sufficient signal strength and attain high linearity reception with low power consumption. As illustrated in Figure 1, the output power of today's amplifiers is reduced towards higher frequencies, and is fundamentally limited by transistor technologies. The reduction of amplified output power is especially significant at millimeter wave frequencies, where it is very challenging to apply circuit techniques, such as power combining. As a result, new power transistor technology to deliver high power density, linearity and efficiency is needed at millimeter-wave frequencies.

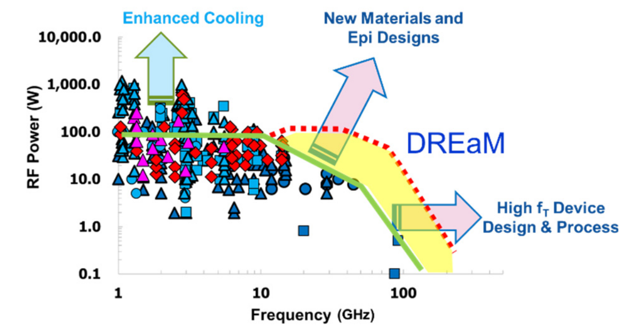

Figure 1. Plot showing output power vs frequencies for state of the art amplifiers.

A figure of merit (FOM) to measure transistor linearity can be defined as the output third order intercept point (OIP3) normalized to the DC power consumption (P_{DC}). The linearity

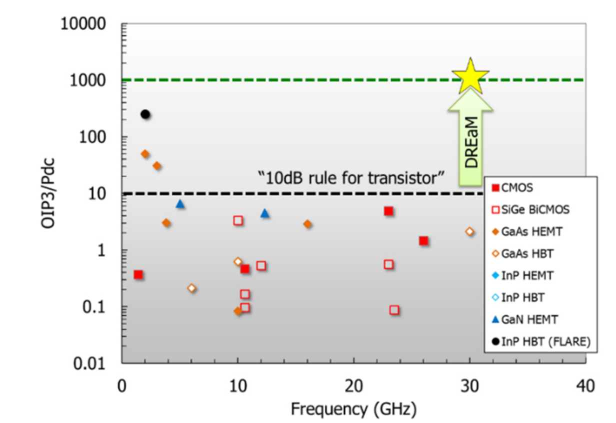

Figure 2. Plot showing OIP3/P_{DC} for various semiconductor devices from 0.5 to 40 GHz.

FOM of current power devices are shown in Figure 2 for a variety of materials and transistor topologies. Figure 2 shows the challenge in attaining OIP3/P_{DC} ratios beyond 10 dB in the microwave and millimeter-wave regime across today's semiconductor power devices. New fundamental technology development in linear and efficient power devices is needed to move past existing linearity FOMs.

Over the last decade, GaN technology has evolved to increased higher power densities without fundamentally changing the required power consumption for better linear and high dynamic range performance. Prior technology development has focused on device scaling, materials improvement, and fabrication development, yet still using the same horizontal device topology as the first field effect transistor. Continued performance growth for both higher power densities and higher linearity performance will require a new class of revolutionary transistor technology that will move beyond conventional topologies in practice today.

DARPA DREaM Program

The Dynamic Range-enhanced Electronics and Materials (DREaM) program was launched in 2018 to pursue foundational development of high power, high linearity device technologies by exploring non-traditional materials, new device topologies, and innovative transistor design and fabrication processes. The program aims to demonstrate transistors with 4X higher output power density or 100X better linearity compared to the state of the art. The DREaM program is structured to separately develop transistors with high power density and high linearity in parallel. High power density transistors are targeting an output power density of 20 W/mm with PAE of 50% at 30 GHz, while high linearity transistors developed in the program will have a minimum OIP3/P_{DC} of 30 dB at 30 GHz. The full program metrics are listed in Table 1.

Table 1. DREaM program metrics described by Phase

	Metric	Today	Phase I	Phase II	Phase III
	Center Frequency (GHz)	30			
TA1 High Power Track	Test Condition	Power Amplifier Focus (a)			
	Min CW Power Density (b) (W/mm or equivalent)	~4	10	15	20
	Min CW Power (Watt) (b)(c)	1~2	1	2	4
	Min OIP3/P_{DC} (dB) up to 10 dB backoff from peak PAE	<10	10	10	10
	Min PAE (%) (b)	35	40	45	50
TA2 High Linearity Track	Test Condition	Low Noise Amplifier Focus (a)			
	Max NF (dB)	3	2	2	2
	Min Gain (dB)	15	15	15	15
	Min Linear P_{out} (dBm)	0	0	0	0
	Min OIP3/P_{DC} (dB) up to 0 dBm Pout	<10	20	25	30

(a) All TA1 and TA2 device metrics will be measured in matched environment at 30 GHz. Additional on-wafer small-signal s-parameter measurements are required to demonstrate DREaM devices are capable of supporting 5% bandwidth operation around 30 GHz.
(b) Pout (W/mm and in W) and PAE must be achieved simultaneously. CW measurement required for Phase I only.
(c) Fixed baseplate temperature (≥25 °C), with either air cooling or no external cooling.

DREaM High Power Density Thrust

Achievement of high power density 30 GHz transistors will require a simultaneous increase in breakdown voltage and current density while maintaining high transistor cutoff frequencies and dc conversion efficiency. A typical approach to reaching high frequencies relies on reduction of transit time, the time required to transit the channel, through shrinking of the gate length. However, this scaled gate length leads to a high electric field in the device, which reduces the breakdown voltage and limit the operating voltage. To attain DREaM program goals, the power devices will need to operate under both high voltage and large current. The transistor designs demand combined high sheet charge densities, high saturation velocities, and high breakdown voltage in combination. High breakdown voltages have been demonstrated in GaN power amplifiers, but parasitics of the field plate and other fringe components in the transistors significantly impair their performance to produce high power at microwave and millimeter-wave frequencies.

Major thrusts to attain millimeter-wave high power density are in the exploration of emerging wide bandgap materials, CMOS-inspired GaN FinFET device topology, and innovative epitaxial engineering. As the breakdown voltage is directly determined by the bandgap of semiconductor material, devices fabricated in wider bandgap materials could provide higher operating voltage while maintaining high sheet charge density. Emerging wide bandgap materials under development include the use of scandium aluminum nitride (ScAlN) [2-3], perovskite materials [4], and AlGaN channel structures [5]. ScAlN is a transition metal nitride with spontaneous polarization that is 6X higher than GaN, theoretically providing a path to much higher charge density transistors [2-3]. High aluminum content in AlGaN channels also offers higher bandgap and operating bias than traditional GaN channels, but are challenged by its low channel mobility for high current operation. The DREaM program is investigating the tradeoffs between higher aluminum content materials and high performance devices [5]. Perovskite materials have demonstrated high polarization and high sheet charge densities, but have not yet been demonstrated within an RF transistor device. The transport characteristics of perovskites, including $BaSnO_3$ and $SrTiO_3$ are being explored, along with heterostructure designs implementing these materials within a 30 GHz transistor [4]. Ultra-wide bandgap diamond material is also under development within heterostructure bipolar transistors (HBT) to provide high breakdown and high current density. As part of the diamond HBT technology development, hetero-epitaxy bonding of AlGaAs/GaAs with diamond is being investigated for higher power density bipolar devices.

New device designs and topologies, such as use of multiple paralleled quantum-well channels, with stacks of GaN-channels and AlGaN-barriers, to increase the charge density and maximum current, are also being combined with unique gate geometries for high power transistor development. A 2DEG density of 5.2×10^{13} cm^{-2} with a high electron mobility of >1600 $cm^2/V\cdot s$ was demonstrated using a 16-channel AlGaN/GaN epitaxial structure. This technology is being combined with a new transistor topology with parallel cylindrical gates buried into the epitaxial layers to laterally control the 2DEG channels [6-7]. Another approach is adoption of the Super-Lattice Castellated Field Effect Transistor (SLCFET) structure demonstrated for RF switching [8], which has a super-lattice epitaxial channel combined with a three-dimensional gate over the fin-like etched superlattice structure, for high voltage and high current millimeter-wave power operations.

The third high power thrust area is engineering the epitaxial material stack. Traditional GaN transistors are prepared in the Ga-polar orientation, where the top barrier (typically AlGaN) is closer to the surface than the channel due to the direction of the polarization fields. In N-polar GaN with the opposite polarization field orientation, the barrier is grown below the channel, which provides a natural back barrier and better electron confinement and efficient modulation of charges in the channel. This structure has demonstrated transistor devices with 7.94 W/mm with a PAE of 26.9 % at 94 GHz, and is now being engineered to meet the 20 W/mm program goals at 30 GHz [9].

DREaM High Linearity Thrust

In the high linearity thrust of DREaM, the program goal is development of transistor technologies with an OIP3/P_{DC} ratio more than 1,000x at an operating frequency of 30 GHz. This linearity FOM must be demonstrated in conjunction with targeted noise figure, power gain, and output power. This technology thrust is a critical portion of the DREaM program, as higher linearity transistors will be required to enable high dynamic range RF systems that allow for efficient amplification of weak RF signals with low DC power consumption. Traditional GaN transistors suffer from poor linearity under large signal operation because of a rapid reduction in extrinsic transconductance (g_m) with increasing current density after the peak g_m value is reached [10-11].

Approaches to engineering of a flat g_m curve for highly linear signal amplification include modification of the channel epitaxial design, non-planar gate design, combination of parallel channels with different threshold voltage (V_{TH}), or composite channels for linear pinch-off. Graded AlGaN/GaN channels are being applied within a traditional transistor structure to allow engineering of the carrier charge distribution and compensate for g_m roll-off [10]. Development of a dual-threshold N-polar GaN transistor that incorporates traditional NMOS linearization, which effectively biases two parallel transistors with one gate bias as a single transistor, is underway. Nanowire channel HEMT structure are also being optimized to support 30 GHz frequencies with higher output power densities [10]. Exploration of theoretical frameworks that provide a more thorough understanding of nonlinearity are being developed in parallel to compliment experimental device design and characterization.

Conclusions

After a year of aggressive technology development, the DREaM program has begun paving the path for state of the art higher power density and higher linearity millimeter wave transistors. Teams are scaling gate lengths, developing new epitaxial structures and investigating unique transistor topologies. Multichannel AlGaN/GaN epitaxial stacks have already demonstrated record-high sheet charge density while maintaining high mobility, which is crucial to implement next generation devices. After successful DREaM transistor development, circuits leveraging these transistors will be developed, along with associated passive components for high frequencies and high power, to enable high power linear amplifiers for future RF systems.

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