AlGaN/GaN high electron mobility transistor oscillator for high temperature and high frequency

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Introduction: Electronics capable of good performance under harsh environments is an ever increasingly necessity for multibillion corporations [1]. Dealing with high-temperature scenarios is a challenge ever since the substitution of vacuum tubes for solid-state electronics. Affecting a wide scope of fields and employed both, in commercial and military markets, they range from well logging for oil and gas exploration in energy industries to automotive and aerospace applications. The aiming of components capable of performing at high frequencies in sensing and monitoring systems at high temperatures is to eliminate the currently employed expensive and bulky cooling systems.

On the one hand, radio frequency (RF) communication, and particularly the development to this end of microwave blocks, such as oscillators, would reduce the system weight and complexity, consequently, saving costs. On the other hand, high-temperature electronics (HTE) gets within reach due to the evolution of semiconductor technologies. Conventional silicon semiconductor operation is physically limited due to thermal effects; therefore, this has become the leading motivation for switching to wide bandgap materials [2], which allows high-temperature operation before the thermally activated carrier current causes latch up [3]. Included in this category are silicon carbide (SiC) and gallium nitride (GaN), with bandgaps wider than those of silicon and gallium arsenide (GaAs). Previous works on SiC have shown the application of such material in a 1 GHz oscillator working up to 270 °C [4]. However, despite the good behaviour of GaN transistors at high temperature and the excellent performance of this semiconductor based on its high peak and saturation velocities, high electron mobility and low intrinsic carrier concentration [5], applications of this technology to high temperature and high frequency cannot be found in open literature.

This work presents the design of a 2.1 GHz oscillator based on a AlGaN/GaN high electron mobility transistor (HEMT) grown by metalorganic vapour phase epitaxy (MOVPE) on sapphire, suitable for high-temperature operation. The device is designed, implemented and characterised up to 230 °C, which is the maximum operating temperature of the available equipment. The experimental measurements show a promising performance of a 0 dBm output power and a −74 dBc/Hz phase noise at an offset of 1 MHz from the oscillation. To the best knowledge of the authors, this is the first time such a topology is chosen for a HEMT: (a) I–V curve dependence with temperature for constant Vgs; (b) I–V curve third quadrant high electron mobility transistor (HEMT) performance at room temperature.

A high-temperature 2.1 GHz oscillator based on a AlGaN/GaN high electron mobility transistor (HEMT) is successfully designed, implemented, and characterised for the first time. The system is explicitly designed such that the final circuit consists of a single transistor bonded to a printed circuit board (PCB), and no further passive components besides the transmission lines to attach the connectors are used. Extensive characterisation of the high electron mobility transistor has been carried out up to 300 °C in order to extract large- and small-signal models. Since the system does not rely on passive tolerances and a specific model of the used transistor has been extracted, a sustainable oscillation of the design at high temperature is assured. The capabilities of the designed circuit are verified by measurements up to 230 °C, showing a promising performance with around 0 dBm output power and a phase noise of −74 dBc/Hz at 1 MHz offset at the highest characterised temperature.

Transistor modelling: This work is based on the performance of an in-house fabricated AlGaN/GaN HEMT on sapphire. The layout of the transistor, presented in Fig. 1, has a two-finger 0.7 μm gate and is suitied for GSG measurements, hence, both DC and two port S-parameter measurements were carried out on wafer. In addition, the source terminal presents two pads not connected via air bridge, thus, it is intrinsically grounded in the measurements through the RF probes. Continuous wave DC measurements clearly show the self-heating effect in the measured results plotted in Fig. 2(a). The transistor has been characterised at room temperature for bias voltages ranging from −12 to 0 V for Vgs, from 6 to 0 V for Vds and in the ranges from 0 to 12 V and −1 to 1 V, respectively, up to 300 °C, as shown in Fig. 2. The technology can be suitable for higher, up to ceramic values, temperatures. Therefore, measurements up to 800 °C are ongoing. The former results show the performance of the transistor and have been used in order to extract its model.

The employed advanced spice model for HEMT (ASM-HEMT) is a physics-based model specific for GaN transistors [6]. It covers the
reversed bias $V_{ds}$ values, that is, the third quadrant from the $I$–$V$ characteristic transistor curve, unlike other physics-based models as the MIT virtual source GaNFET or empirical based as the Angelov (Chalmers) model. Moreover, its temperature dependence model has been verified up to 500°C. The fitting curves have been simulated in Keysight advanced design systems. Fig. 2(a) shows a good agreement between the measurements and the extracted model at room temperature. The hereby obtained temperature-dependent model is crucial for the success of the design.

Oscillator topology: Although the ASM-HEMT covering this biasing region was initially intended for switching applications, it can also be applied for the proposed reverse channel oscillator topology. The principle of operation for this configuration was proven in [7] for a high-power oscillator based on a single GaAs MESFET. Such a topology relies on a common-source configuration with reverse $V_{ds}$ bias. This means that the drain becomes electrically the source. When a three-terminal device such as a transistor is structured with a certain specific reactance feedback configuration it becomes a two-port, and it is considered by a connected load as a negative resistance, as shown in Fig. 3(a). Then, the device is brought to oscillation when (1) and (2) are fulfilled [8]:

$$\text{Re}(Z_L) + R_C = 0 \quad (1)$$
$$\text{Im}(Z_L) + X_C = 0 \quad (2)$$

where $R_C + jX_C$ is the impedance of the negative resistance generator connected to the load, and $R_C = -R$. The oscillating frequency is determined by the tank connected to the free second port.

As the employed transistor consists of two separated source pads not connected on-chip, the implementation of the reverse-channel topology simplifies further circuitry elements by grounding both sides. For a particular studied set of bias conditions, the now equivalent negative resistance configuration is a common drain with a series inductance to ground, as studied in [9] and shown in Fig. 3(b). By means of a 50-Ω load connected to drain and source, the oscillation conditions are fulfilled and additional passives can be avoided. The resonance tank is the proper parasitic gate-to-source capacitance of the transistor together with the inductances from the bonding wires at these ports. The schematic of the system is plotted in Fig. 3(c).

This configuration leads to an oscillator circuit with no additional passive components needed, besides the feeding bias tees. In consequence to this simplicity, a testing board on a ROGERS 350B ($\varepsilon = 3.59$) 756 μm substrate has been fabricated without further concern regarding the passives performance over temperature. Four transmission lines are added and the bias tees are externally connected to the SubMiniature version A (SMA) connectors. The PCB with the transistor is presented in Fig. 4.

Experiment set-up: The PCB has four SMA connectors, two for the two source terminations and the rest for drain and gate. Source lines are grounded by short terminations, see Fig. 4. The diced transistor is attached on a copper pad connected to the ground through via holes, and the centre distance between the pad to the microstrip line is approximately 2.5 mm. Thus, the inductance of the bonding wires can be approximated to 3 nH. The external bias tees are connected to the gate and the drain connectors, and at the same time, the Agilent N6705B DC source is connected to the bias tees. The RF path for the gate is left open. For the drain a coaxial cable is used to connect it to the Rohde & Schwarz Vector Signal Analyser, which acts as a 50-Ω load.

In order to perform temperature measurements the PCB was placed on a hot chuck, whose maximum set temperature is 280°C. However, due to the connector’s volume the heat transmission is impeded, as the energy flow from the chuck to the PCB requires the touching of the former and the latter. Therefore, a metallic prism of approximately 10 mm height is added between the hot plate and the bottom copper layer of the PCB. The temperature is monitored per the chuck’s set-up, an infrared thermometer and an infrared camera pointing at the PCB’s substrate, which is the assumed temperature working conditions for the oscillator.

The measurement set-up is given in Fig. 5, where the spectral measurements at room temperature show signals up to the seventh harmonic. A 3 dBm output power is observed at the fundamental oscillation frequency, and a difference of more than 10 dB to the second and third harmonics is measured. The measurements are presented for the biasing conditions of $-7$ V and $-6.5$ V at the gate and drain, respectively. These biasing values are chosen as they ensure oscillation condition over the whole temperature range. It is worth mentioning that when the $-6.5$ V are applied to both terminals, no significant difference to the behaviour at $-7$ V at the gate is observed, which shows an additional advantage of the oscillator topology, where the polarity and bias voltages of both ports can coincide as well as vary over a wide range. Other bias points were as well tested. Under $-5$ V gate and drain bias, the oscillation condition is satisfied at around 170°C. This can be improved by inserting a mechanical external impedance tuner between the output port of the oscillator and the load, that is, properly loaded the oscillation can be maintained up to approximately 220°C.

High-temperature measurement results: The measurements are taken by slowly increasing the temperature of the chuck. Each step is maintained in time an average of $15$–$20$ min, until the temperature of the PCB, which is placed on top of the metallic spacer, stabilises and does not change. In order to assure that the temperature is uniform across the entire PCB, the board is covered by a silicone piece and this is sustained by a weight on
kilohertz only. Therefore, it can be concluded that the oscillation frequency and output power are very little dependent on temperature over the large range from room temperature up to 230°C. At 230°C the output power barely decreases compared to the power at 200°C. The phase noise observed at this temperature is −74 dBc/Hz at 1 MHz offset.

The limiting factor of the measurements is the saturation of the heat transfer that makes it impossible to increase the temperature of the chip with the employed chuck and set up more than the already studied 230°C. Further measurements with a thinner material gap between PCB and chuck can be employed to measure higher operation temperatures with the available equipment.

**Conclusion:** HTE is a necessary and promising field of study, especially when the semiconductor technology is allowing further improvement in high-frequency and high-temperature circuits. The here detailed work presents a novel application for the oscillator reverse channel topology that now takes advantage of the possibilities of GaN transistors. The designed circuit exploits the own device parasitics in order to achieve a low-complexity and thus rugged design, which has been successfully validated.

This work, for the first time, reports the design, implementation and characterisation of a 2.1 GHz oscillator capable of operating up to at least 230°C based on GaN technology.

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