An X-Band Carbon-Doped InGaP/GaAs Heterojunction Bipolar Transistor MMIC Oscillator

Young-Gi Kim, Chang-Woo Kim, Seong-Il Kim, Byoung-Gue Min,
Jong-Min Lee, and Kyung Ho Lee

This paper addresses a fully-integrated low phase noise X-band oscillator fabricated using a carbon-doped InGaP heterojunction bipolar transistor (HBT) GaAs process with a cutoff frequency of 53.2 GHz and maximum oscillation frequency of 70 GHz. The oscillator circuit consists of a negative resistance generating circuit with a base inductor, a resonating emitter circuit with a micro-strip line, and a buffering resistive collector circuit with a tuning diode. The oscillator exhibits 4.33 dBm output power and achieves –127.8 dBc/Hz phase noise at 100 kHz away from a 10.39 GHz oscillating frequency, which benchmarks the lowest reported phase noise achieved for a monolithic X-band oscillator. The oscillator draws a 36 mA current from a 6.19 V supply with 47.1 MHz of frequency tuning range using a 4 V change. It occupies a 0.8 mm × 0.8 mm die area.

Keywords: MMIC, oscillator, X-band, HBT.

I. Introduction

With the development of microwave device technology, the demands for low-phase and high-power oscillators operating at these frequencies have increased because the oscillator is an essential component for microwave communication systems. GaAs metal-semiconductor field effect transistor (FET) oscillators suffer from a high phase noise level which comes from 1/f noise generated mainly due to the existence of trap centers in the FETs [1]. On the other hand, oscillators fabricated with Si bipolar transistors exhibit low phase noise; however, they are available only at low frequencies.

Since the superior 1/f noise characteristics of Si bipolar transistors are due to their vertical structure with small numbers of surface recombination traps, oscillators with GaAs-based hetero-junction bipolar transistors (HBTs) can offer both low phase noise and a high frequency performance. GaAs's high electron mobility and high dielectric constant make it a good material for monolithic microwave integrated circuits (MMICs). Several leading GaAs HBT oscillator developments have already demonstrated a superior phase noise performance compared to metal semiconductor field effect transistor (MESFET) oscillators and a comparable performance to silicon bipolar-based oscillators at C- and Ku-band frequencies [2], [3]. Recent literature has shown that HBT oscillators offer additional performance advantages in terms of dc-rf conversion efficiency in L-band frequencies [4].

The InGaP/GaAs heterojunction in the emitter region of the HBT will improve carrier injection efficiency. It offers lower 1/f base band noise mainly due to fewer trap-related DX (deep level) centers with respect to AlGaAs/GaAs [5]-[7]. The InGaP/GaAs HBT has shown lower 1/f base-band noise than

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the high electron mobility transistor. The excellent noise characteristics of an InGaP/GaAs HBT make it an attractive choice technology for a lower phase noise monolithic oscillator [8]. Carbon is known to be an excellent p-type dopant in the InP/GaAs HBT due to its low diffusivity in GaAs and high current gain stability under both a high current bias and high temperature [9].

The possibility of very low phase noise in an InGaP/GaAs HBT oscillator has been demonstrated in a C-band hybrid dielectric resonator oscillator, which also has demonstrated the importance of the circuit topology and tuning circuit for a low phase noise oscillator [10]. Several low-noise MMIC oscillators have been reported by previous distinguished research groups. As for Si-based oscillators, a 13 GHz SiGe HBT voltage-controlled oscillator (VCO) and a 10 GHz CMOS VCO were reported to have a phase noise of –113.7 dBc/Hz at 10 MHz [11] and –101 dBc/Hz at 400 kHz [11], offset from the carrier. A 11.48 GHz MESFET VCO, an 8.3 GHz AlGaAs/GaAs HBT VCO, and an 18 GHz InAlAs/InGaAs HBT VCO have been demonstrated for compound semiconductor-based oscillators with a respective single-side band (SSB) phase noise of –91 dBc/Hz [3], –112 dBc/Hz [2] and –72 dBc/Hz [13] at a 100 kHz offset. An 18.6 GHz InP HBT VCO and a 13.54 GHz InGaP/GaAs HBT VCO have also been published with a phase noise of –90 dBc/Hz [14] and –113.8 dBc/Hz [15], respectively, at a 1 MHz offset.

II. Device Structure and Performance

A cross-sectional view of the HBT used in the oscillator circuit is shown in Fig. 1. The epitaxial layers were grown on (100)-oriented semi-insulating GaAs substrates using metalorganic chemical-vapor deposition. The n- and p-type dopants were Si and C, respectively. The epitaxial layer mainly consisted of a 500 Å thick n-InGaP ($n = 5 \times 10^{17}$ cm^{-3}) emitter layer, an 800 Å thick p-GaAs ($p = 4 \times 10^{19}$ cm^{-3}) uniform base layer, a 5000 Å thick n-GaAs ($n = 2 \times 10^{16}$ cm^{-3}) collector layer, and a 5000 Å thick n-GaAs ($n = 4 \times 10^{18}$ cm^{-3}) sub-collector layer.

The 2 µm × 20 µm emitter configuration shown in Fig. 2 was employed as a unit cell. We measured the dc and rf characteristics of the one-finger HBT devices with an emitter area of 2 µm × 20 µm using an HP semiconductor parameter analyzer, an HP 8510B network analyzer, and a Cascade probe station.

The devices showed an offset voltage of 0.11 V and a common-emitter current gain of 85. The breakdown voltage with open emitter (BV_{CBO}) was 18.8 V. The cut-off frequency, f_T, and the maximum oscillation frequency, f_{max}, were 53 and 70 GHz, respectively, at a V_{CE} of 2 V and J_c of 75×10^4 A/cm^2.

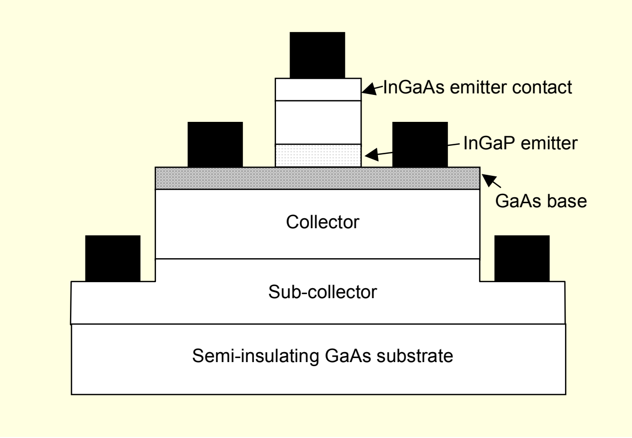

Fig. 1. Cross-section of an InGaP/GaAs HBT.

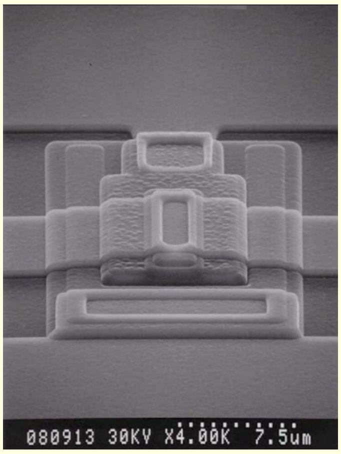

Fig. 2. SEM photograph of a fabricated InGaP/GaAs HBT.

III. Oscillator Circuit Design

Negative resistance, which is essential for a stable oscillation, is obtained by inductive feedback L_n at the base of the circuit as shown in Fig. 3. Then, the L_n is directly ac grounded by C_{d2}. Resistances R_{b1} and R_{b2} are self-bias resistances with stable dc emitter feedback resistance R_{fb}. The ac voltage drop across the R_{fb} is bypassed by C_{bp}. The coupling capacitor, choke inductor, and decoupling capacitor are C_c, L_c, and C_{d3} , respectively.

If the magnitude of the negative resistance is a linearly decreasing function of the amplitude of the current, the initial real impedance R_L and imaginary impedance X_L for maximum oscillator power are chosen such that initial real impedance R_{IN} is negative, with initial real load impedance R_L and imaginary load impedance X_L given by (1) and (2) [16], [17].

$$R_L = \frac{|R_{IN}|}{3} \tag{1}$$

$$X_L = -X_{IN} \tag{2}$$

The steady state oscillation condition is established by

$$\Gamma_{IN}\mathrm{T}_L = 1\,. \tag{3}$$

However, in practice the real impedance value should be as close to zero as possible to reduce the phase noise and to increase the efficiency of the oscillator circuit. Therefore, the load impedance must be almost reactive by increasing the resonator Q [4].

The change of the real value of the impedance is much larger than that of the imaginary one as signal power increases in most active circuits. As a consequence, it is so hard to get the linear maximum oscillation condition of (1) and (2) at the same time in the circuit design that the second condition is preferred. The design value of input impedance X_{IN} at 10.4 GHz is –8.9–j9.7 ohm. The loading resonating circuit impedance value of X_L is tuned to 3.6+j9.7 ohm.

The micro-strip line in the GaAs MMIC process is made of a very high conductive metal and semi-insulating substrate, and is therefore a high Q in an X-band frequency and precisely modeled up to a mm-wave frequency. It also provides more tuning flexibility than lumped inductors. A metal-insulator-metal (MIM) capacitor has a high Q. The phase noise performance is very sensitive to the Q of the resonating circuit components. Therefore, they are connected for the load resonating circuit as shown in Fig. 4. The phase noise is not greatly affected by the Q of the base feedback inductor L_n or choke inductor L_c of which Q is 6.94.

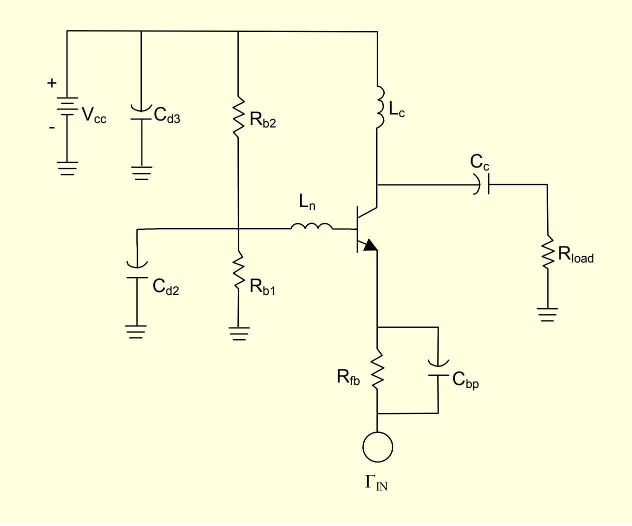

Fig. 3. Negative resistance generating circuit with inductive base feedback.

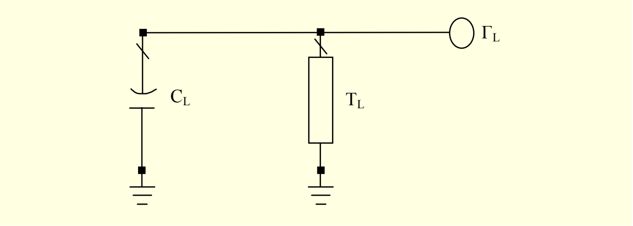

Fig. 4. Load resonating circuit.

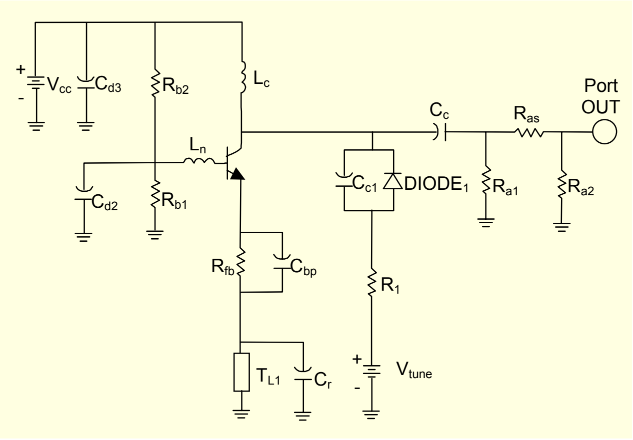

Fig. 5. X-band HBT oscillator circuit.

After establishing the basic oscillating circuit by connecting the negative resistance generating circuit and the resonating circuit, a Π type resistive attenuating circuit for buffering is added by R_{as}, R_{a1} and R_{a2} as shown in Fig. 5. A diode tuning circuit with DIODE_1, R_1 and C_{c1} is attached at the collector of the transistor rather than at the resonating circuit. Balanced oscillator circuit topology with the diode tuning at the collector [15] shows better phase noise performance than that at the emitter [18]. Similarly, using the collector tuning circuit topology in a single transistor oscillator, we can minimize the phase noise because the noise generating tuning circuit has reduced the effect on the resonating circuit. Output impedance also can be tuned for better matching. As a trade off, however, the tuning frequency range becomes narrow.

The base and collector do not have any hetero-junctions, so the collector-base junction has fewer defects than the emitter-base junction in an HBT structure. Since the defects in the PN junction are believed to be the main sources of phase noise in the oscillator circuit, the former will produce better phase noise performance than the latter. A low doped collector layer also can help the wide tuning range of the junction capacitance. Therefore, the collector-base reversed biased junction of the transistor is used for the diode. A layout-induced parasitic effect is considered using a micro-strip line inter-connection simulation.

IV. Circuit Fabrication and Performance

Based on the simulation result, a monolithic oscillator circuit was fabricated as shown in Fig. 6. An InGaP-GaAs HBT with an emitter area of 2 μm × 60 μm is used for the active device. The wafer is attached with a metal back after being lapped to 100 μm. The total chip area is 0.8 mm × 0.8 mm. The oscillator chip is wire-bonded to a test board for free running measurements with an HP8563E spectrum analyzer.

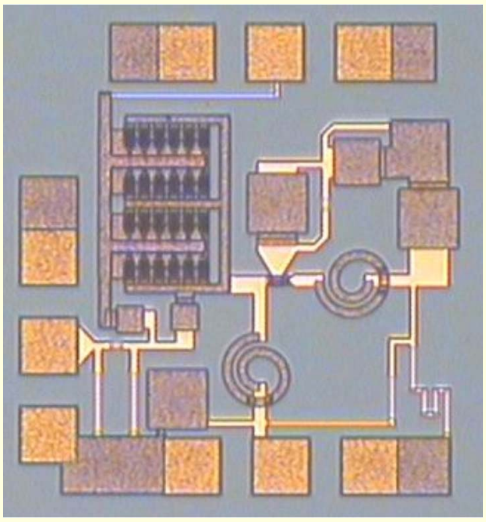

Fig. 6. Photomicrograph of the HBT oscillator.

The oscillator achieves a 4.33 dBm output power at a 10.39 GHz oscillating frequency with 2.67 dB of cable loss calibration as shown in Fig. 7.

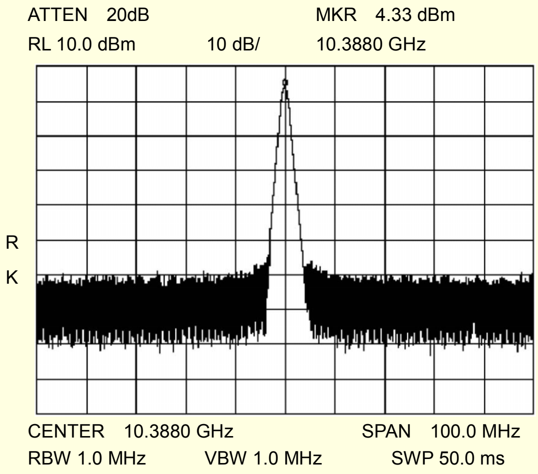

Fig. 7. Output spectrum of an HBT MMIC oscillator.

The oscillator shows 47.1 MHz of frequency tuning by 4 V change. The second harmonic suppression is 23.2 dBc as shown in Fig. 8.

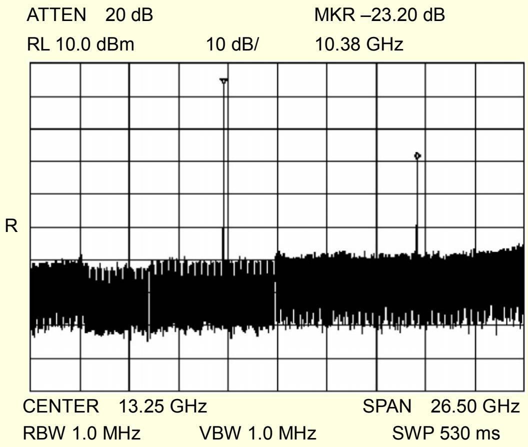

Fig. 8. Harmonic performance of an HBT MMIC oscillator.

The oscillator draws a 36 mA current from a 6.19 V supply. A 6.19 V lantern battery was used as a dc bias source for phase noise measurements to reduce the dc-FM noise contribution normally produced by a standard power supply [13]. The battery-powered measurement showed a 10.1 dB/Hz SSB phase noise improvement compared to that of a normal dc power supply. Figure 9 shows a -127.8 dBc/Hz SSB phase noise at a 100 kHz offset frequency when zero tuning diode voltage is applied. The phase noise result is comparable to other monolithic oscillators and is believed to be the first measured phase noise result for a monolithic X-band oscillator.

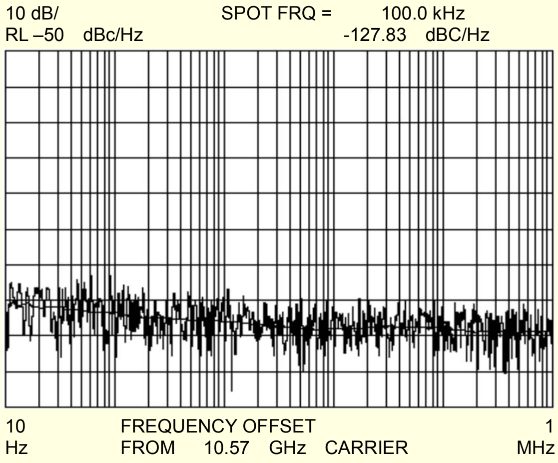

Fig. 9. Phase noise performance of an MMIC HBT oscillator.

V. Conclusion

A very low phase noise 10.39 GHz InGaP/GaAs HBT oscillator has been demonstrated. A diode tuning circuit is attached to a collector to reduce diode induced phase noise. The oscillator achieves a 4.33 dBm output power at a 10.39 GHz oscillating frequency. The oscillator shows 47.1 MHz of frequency tuning range by 4 V change. The SSB phase noise of -127.8 dBc/Hz at a 100 kHz offset frequency was measured, and it represents the first reported phase noise results on a monolithic X-band oscillator. A very low phase noise is achieved by combining excellent 1/f noise due to the reduced trap-related DX-centers in an InP/GaAs hetero-junction and collector tuning circuit topology, which is proposed in this paper.

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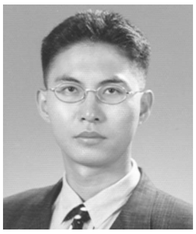

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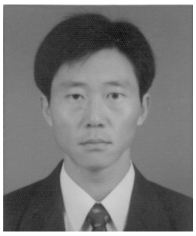

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