Monolithic VCO and Mixer for Q-band Transceiver Using InP-Based HBT Process

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ABSTRACT

Monolithic VCOs and mixers have been developed for Q-band FMCW transceiver applications using an InP-based HBT process. Tuning range, output power, and phase noise have been characterized for the HBT VCOs, while conversion loss and noise figure were measured for the Schottky diode mixers. The VCO shows 10-dB better phase noise performance over a similar design based on a GaAs HBT process. Measured at very low IF, the InP-based Schottky diode mixer demonstrates more than 1 dB noise figure improvement over the same design based on GaAs Schottky process. The InP mixer also requires a very low LO power at only 1 dBm for a 8-dB conversion loss.

INTRODUCTION

Heterojunction Bipolar Transistor (HBT) technology provides a foundation for high performance frequency conversion functions. It is well known that due to their vertical device structure, HBTs have superior low frequency noise characteristics compared to FET-type devices. Consequently, HBTs can realize state-of-the-art low phase noise VCOs at microwave/millimeterwave frequencies. Monolithic oscillators based on both GaAs and InP HBTs have been demonstrated [1]-[2]. In addition, the HBT technology allows the monolithic integration of high performance Schottky diodes with cut-off frequencies exceeding 1 THz [3]. These Schottky diodes are vertical devices which have minimum series resistance and surface recombination noise. Vertical Schottky diode mixers have been integrated with High Electron Mobility Transistor (HEMT) devices in a LNA/mixer monolithic chip at W-band [4] using two different types of material grown on the same wafer. In an HBT process, the vertical Schottky diodes can be integrated without additional material growth. Mixers using Schottky diodes in a standard GaAs HBT process have been demonstrated at X- and K-bands [3], [5].

There are advantages in using InP HBTs over their GaAs counterparts. The higher mobility and higher saturation velocity in InP HBTs with InGaAs base and collector layers result in lower transit time and parasitic resistances, and hence higher f_t and f_{max} can be realized. The InP HBT also offers low 1/f and burst noises due to the lower surface recombination velocity and the absence of deep level DX centers in the emitter, as compared to the GaAs-based HBT. In addition, the Schottky diodes using InP HBT process have a lower threshold voltage (less than 0.2 V, compared with 0.7 V for GaAs-based diodes), which can reduce the LO power requirement for the mixers.

This paper presents the design and the performance of a monolithic VCO/mixer chip used in a Q-band FMCW transceiver using an InP-based HBT technology. The transceiver block diagram is

This work is supported by MIMIC Phase 2 Program (Contract No. DAAL01-91-C-0156) from ARPA and Army Research Laboratory.

95CH3577-7/95/0000-0101$01.00 © 1995 IEEE

shown in Fig. 1. There are two MMIC chips in this transceiver: a VCO/mixer chip using HBT technology and a double/amplifier chip using HEMT technology. The VCO/mixer chip consists of a K-band (19.5 GHz) HBT VCO together with a buffer amplifier and a Q-band (39 GHz) Schottky diode singly balanced mixer. The signal generated by the VCO is multiplied by the doubler in the other chip and serves as both transmitter signal and LO drive for the receiving mixer.

DEVICE CHARACTERISTICS AND CIRCUIT DESIGN

For comparison, we present the fabrication and resutls of both the GaAs and the InP VCO/mixer chips. The GaAs HBT process is the baseline TRW HBT production line process with 2 µm emitter width. The main features of the HBTs are the 30% Al mole fraction in the AlGaAs emitter, and the self-aligned base ohmic metal. A 2x10µm^2 four-emitter HBT device used in the VCO has a typical unit current gain frequency (f_t) of 22 GHz and maximum oscillation frequency (f_{max}) of 40 GHz. The Schottky diode is realized by using the collector layer of the HBT which results in an ideality factor near 1.0 and a 1 THz cutoff frequency [4]. The detailed GaAs HBT device process and characteristics were documented in previous works [6]-[8].

The InP-based HBT process is a 1µm self-aligned InAlAs/InGaAs HBT process on 2"-diameter InP substrates. The HBT device structures are grown by solid source Molecular Beam Epitaxy with Be and Si used as p- and n-type dopants, respectively. The lightly doped 5x10^{15} cm^{-3} InGaAs collector with the thickness of 7000 Å allows a high breakdown voltage BV_{ceo} of 11 V. The base is 1000 Å thick and doped to 3x10^{19} cm^{-3}. The emitter-base junction consists of a compositionally graded InAlGaAs layer which gives consistent dc beta and low V_{be} turn-on voltage. The typical beta across the wafer is in the 20 to 25 range at collector current density J_c = 20kA/cm^2. The 1x10µm^2 four-emitter HBT device used in the VCO typically has an f_t of 60 GHz and an f_{max} of 180 GHz as extrapolated from the unilateral power gain. This InP HBT MMIC process has been used to demonstrate several MMIC amplifiers and VCOs up to 40 GHz [2].

Fig. 2 shows the photographs of both of the VCO/mixer chips using GaAs and InP based HBT processes. They both have the same chip size of 4.0x1.5 mm^2. For the GaAs HBT chip, the 19.5 GHz VCO uses a common-collector bias-tuned VCO topology and 2x10 µm^2 four-emitter HBT device. The desired tuning bandwidth is 1 GHz. A two-stage self-biased feedback buffer amplifier is cascaded with the VCO to desensitize the loading effect of the output port and provide higher output power. The complete VCO is designed on a single +5V bias voltage operation. The same circuit topology is used for the InP HBT chip except that the output amplifier is only a single-stage design due to the higher gain of the InP HBT. Also, the device size is altered to a 1x10 µm^2 four-emitter device.

The Q-band mixer is a singly balanced diode mixer. It uses a pair of 7x7 µm^2 Schottky diode in series. A 90° Lange coupler together with a 90° 50-Ω microstrip delay line is used as the balun. A shunt high impedance line is placed in both RF and LO input high pass filter design to provide the diode dc return. A radial stub is used for RF ground between the diodes. The IF signal is led out from the center of diode pair through a simple low pass filter. The identical design is employed in both the chips fabricated with either GaAs or InP based HBT process.

MEASUREMENT RESULTS

For the InP-based HBT VCO plus buffer amplifier, we obtained 800-MHz tuning range centered at 19.6 GHz with an output power of 9 dBm under a 4.5-V bias voltage. Fig. 3. shows the phase noise measurement data over offset frequencies from 100 kHz to 3 MHz. A phase noise of -110 dBc/Hz at 1 MHz offset is achieved. This is a 10-dB improvement in phase noise over the GaAs-based HBT design which shows -100 dBc/Hz at 1 MHz offset. The GaAs chip shows 11dBm of output power for a 1 GHz tuning range centered at 19.5 GHz.

For the diode mixer using the InP HBT process, we have observed that the conversion loss stays at 8 dB for an IF range of 10 MHz to 510 MHz and an LO power range of 1 to 13 dBm at 39 GHz. On the other hand, the diode mixer using the GaAs HBT process has a measured conversion loss of 7 dB with an LO drive of 10 dBm, and the conversion loss starts to increase significantly for the LO power below 7 dBm. This indicates that the low threshold voltage of the Schottky diodes on InP substrate indeed saves the LO power of the mixer. The measured double side band (DSB) noise figure of the mixers is plotted in Fig. 4 for an IF range from 1 to 500 MHz with LO frequency of 39 GHz. It shows that the diode mixer using the InP HBT process has a better noise figure than that using the GaAs HBT process by more than 1 dB for IF below 10 MHz. In particular at 1 MHz IF, the mixer using InP based diode has a noise figure of 11.5 dB. It is noted that this noise figure at 1 MHz in these vertical diode mixers presented in this paper are much better than those using planar HEMT gate diode mixers which exhibits more than 20-dB noise figure at 1 MHz IF [9].

SUMMARY

We have presented the performance of monolithic K-band VCOs and Q-band mixers using two different HBT technologies. The measurement results shows that the VCO using InP HBTs has a 10-dB better phase noise over that using conventional $Al_{.30}Ga_{.70}As$ HBT devices. The Schottky diode mixer using the InP HBT process is advantageous over that using the GaAs HBT process requiring lower LO power and offering a better noise figure at low IF frequency. These results demonstrate that the InP based HBT MMICs can indeed benefit the system performance at millimeter-wave frequencies.

ACKNOWLEDGMENT

The authors would like to thank K. Tan, S. Esparza, M. Biedenbender, D. Smith, and K. W. Chang for their help. Thanks also go to the other members of the RF Product Center of TRW for their technical support.

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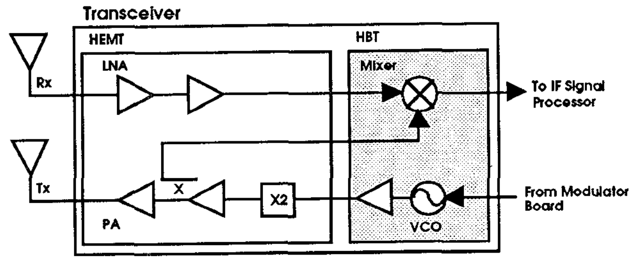
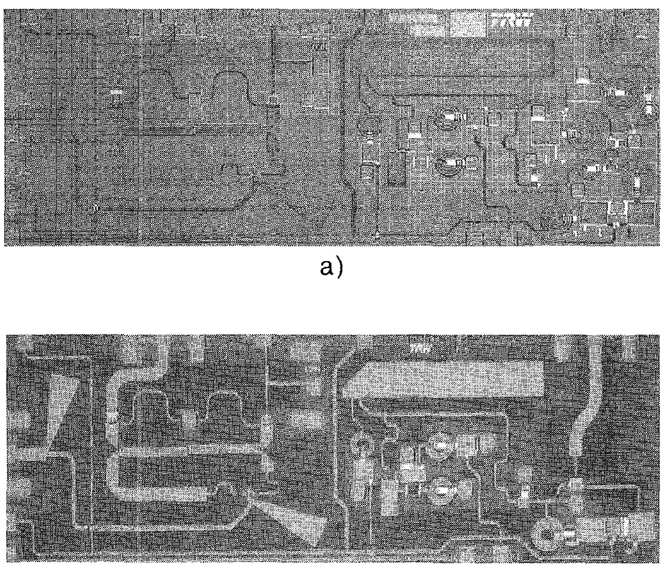


Fig. 1. The block diagram of the Q-band transceiver. The shaded area indicates the HBT VCO/mixer MMIC chip.



a)

b)

Fig. 2. The chip photograghs of the monolithic VCO/mixer using (a) GaAs- and (b) InP-based HBT processes.

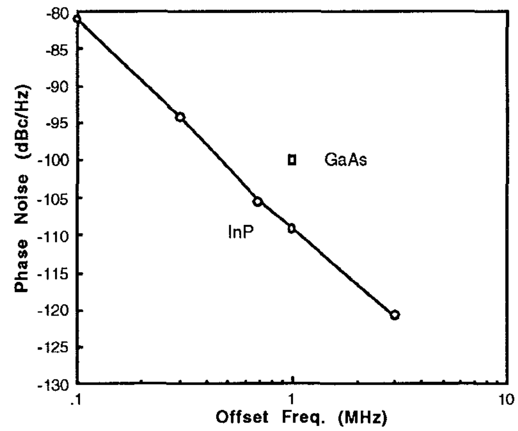


Fig. 3. The phase noise performance of the MMIC InP-based HBT VCO for offset frequency from 100 kHz to 3 MHz.

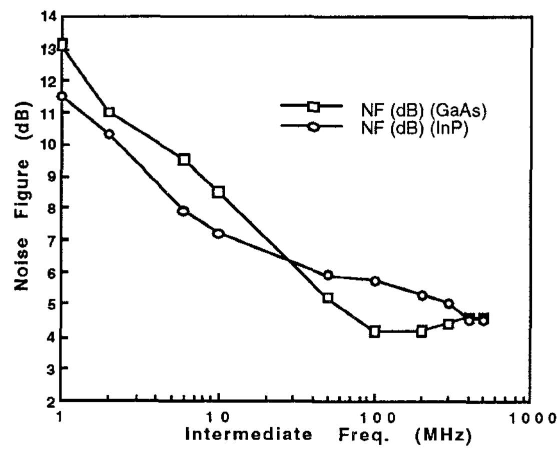


Fig. 4. The measured DSB noise figure of the Schottky diode mixers for an IF range from 1 to 500 MHz.