5-GHz VCO with a wide tuning range using an InP-based RTD/HBT technology

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Abstract — **This paper presents a fully integrated 5 GHz voltage-controlled oscillator (VCO) with a wide frequency tuning range based on an InP-based RTD/HBT technology. In order to increase the frequency tuning range of the VCO, the base-to-collector p-n junction of HBT is exploited as a varactor of an LC resonator. The VCO generates a maximum output power of -19.5 dBm which is operated at a bias current of 9.5 mA and a supply voltage of 0.8 V with a corresponding DC power consumption of about 7.6 mW. The fabricated RTD/HBT VCO shows a wide frequency tuning range of 710 MHz. In addition, a low phase noise of -115 dBc/Hz at 1 MHz offset was obtained.**

I. INTRODUCTION

Recently, many novel devices using quantum transport phenomena in a nano scale dimension have been introduced, such as a resonant tunneling diode (RTD), a single electron transistor (SET), a resonant interband tunneling diode (RITD), and a heterojunction interband tunnel diode (HITD). These devices have attracted a great deal of interests for high-frequency/low-power applications due to their properties of intrinsic negative differential resistance (NDR) characteristic and high cutoff frequencies [1]. Among these devices, the RTD shows the unique NDR characteristic at a room temperature, hence it is considered as a very promising device in nano–electronics for low-power microwave applications. In previous works, several microwave circuits using the NDR characteristic of tunneling diodes have been widely investigated for low power microwave applications, such as a 5.8 GHz HBT/RTD oscillator [2] and 6 GHz HEMT/HITD voltage controlled oscillators (VCOs) [3]. The important requirements in VCOs for microwave applications are a sufficient frequency tuning range and a low phase noise with low-power consumption. However, the previously reported MMIC VCOs based on the NDR characteristic have shown relatively a low frequency tuning range and a high phase noise.

In this work, a monolithically-integrated RTD/HBT VCO with a wide frequency tuning range and a low phase noise was successfully implemented by using an InP-based RTD/HBT technology. The fabricated VCO is designed to have a wide frequency tuning range by using the base-collector p-n junction of HBT as a varactor in the integrated LC resonator. In addition, a low phase noise performance of the VCO is expected by using the InP HBT-based technology, which is known to have low phase noise characteristics.

II. OSCILLATOR DESIGN

Fig. 1 shows the circuit schematic of the RTD/HBT VCO. It consists of a series-connected RTD/HBT block and an LC parallel resonator. The design concept of the VCO is based on the one-port negative resistance oscillator topology. In order to initiate the oscillation, the reflection coefficient (Γ_R) of the RTD/HBT block and the reflection coefficient (Γ_{LC}) of the LC resonator must satisfy the following condition:

$$\left|\Gamma_R \cdot \Gamma_{LC}\right| \geq 1.$$

When the supply voltage (V_{CC}) and base voltage (V_B) are chosen such that the RTD is biased at the negative differential resistance region, the RTD/HBT block generates the magnitude of reflection coefficient greater than 1 which compensates for the loss in the LC resonator. In fact, an RTD only can play the same role as the RTD/HBT block, but it usually gives rise to the problem of bias instability [3]. Hence, a 3-terminal device, such as the HBT, is used for biasing the current of VCO. This simple RTD/HBT VCO topology has several advantages. First, the sub-1 V operation of oscillator is possible. Hence, the RTD/HBT VCO consumes much less power than the conventional VCOs [4]. The supply voltage (V_{CC}) is determined by the following equation:

$$V_{CC} = V_{RTD} + V_{CE}$$

where V_{RTD} is the voltage of the RTD at the NDR region, V_{CE} is the collector-emitter voltage of HBT and the voltage drop across the LC resonator is negligible. V_{RTD} at NDR region is 0.5 V and V_{CE} is set to be 0.35 V. Therefore, at a low bias voltage of 0.85 V, the circuit is operated as a VCO. An additional advantage expected from the RTD/HBT technology is that, due to the low noise active/passive devices based on an InP technology [5], good phase noise characteristics of the RTD/HBT VCO are expected compared to the conventional VCOs [4]. The HBT shows a relatively low flicker noise, and passive devices on InP substrate show a high quality factor. These lead to the phase noise of the VCO to be reduced. The measurement results will be discussed in the section IV. Finally, the frequency tuning range of the VCO can be increased by the varactor which has not been realized in the previous works of RTD based oscillators. In the InP based RTD/HBT technology, the varactor can

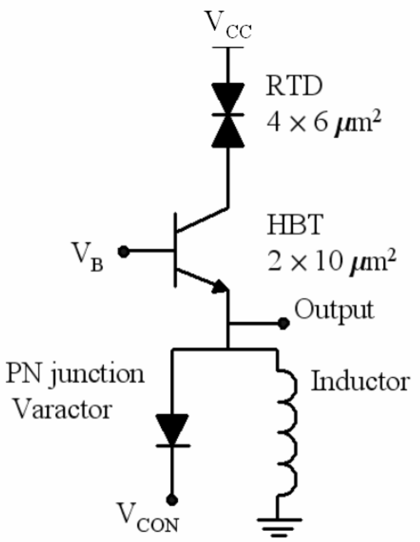


Fig. 1. Circuit schematic of the RTD/HBT MMIC VCO.

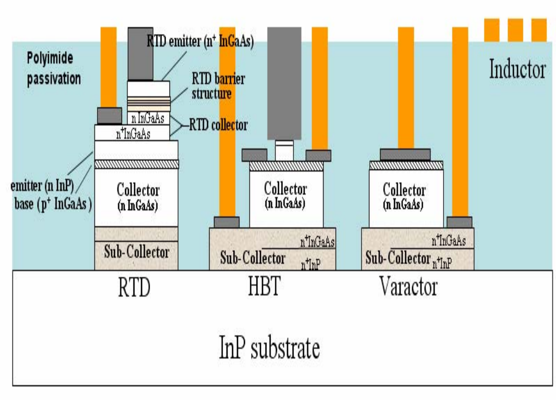
be easily integrated by using the base-collector p-n junction of HBT. The varactor in an RTD/HBT technology can show a sufficient capacitance ratio of 1.5 for frequency tuning of the VCO.

III. FABRICATION

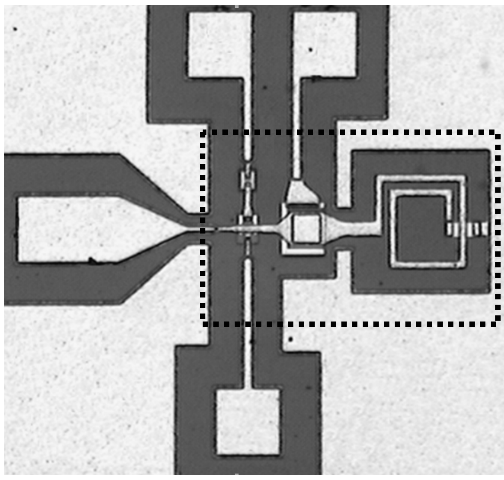
Fig. 2 shows a schematic cross-sectional view of the monolithically integrated RTD, HBT, varactor and inductor. First, InP/InGaAs single HBT layers were grown, then InP-based pseudormorphic AlAs/InGaAs/ InAs/InGaAs/AlAs RTD layers were grown by MBE. The RTD/HBT MMIC VCO was fabricated by using the optical lithography and wet etching technique. The RTD mesa was first defined, and then the HBT process was performed. The p-n junction varactor was simultaneously fabricated through the same sequence of the base-collector junction of the HBT. Further details on the HBT process are described elsewhere [6]. The spiral inductor was formed by using an interconnecting metal, of which thickness is 2 µm. The fabricated RTDs used in this study exhibit a peak-to-valley current ratio (PVCR) of 13 with a peak voltage (V_P) of 0.32 V and a peak current density (J_P) of 100 kA/cm^2 at a room temperature. The HBT shows a current gain of 50 with a turn-on voltage of 0.75 V. The maximum f_T and f_{max} of the fabricated HBT are 117 GHz and 150 GHz, respectively. The size of varactor is 50×50 μm^2 and the capacitance value varies from 1.3 pF ~ 0.9 pF under the control bias of 0 ~ 0.6 V with a quality factor of 39 at 5 GHz. The inductor in the resonator has the inductance of 0.5 nH with a quality factor of 14.7 at 5 GHz. A microphotograph of the fabricated RTD/HBT VCO is shown in Fig. 2(b). The area of the VCO core circuit excluding pads is about 500×260 μm^2.

IV. MEASUREMENT RESULTS

The DC I-V characteristics of the series-connected RTD/HBT block are shown in Fig. 3. As shown in this figure, the unique NDR characteristic of the fabricated



(a)



(b)

Fig. 2. (a) Schematic cross-sectional view of the monolithically integrated RTD/HBT IC and (b) microphotograph of the fabricated RTD/HBT VCO.

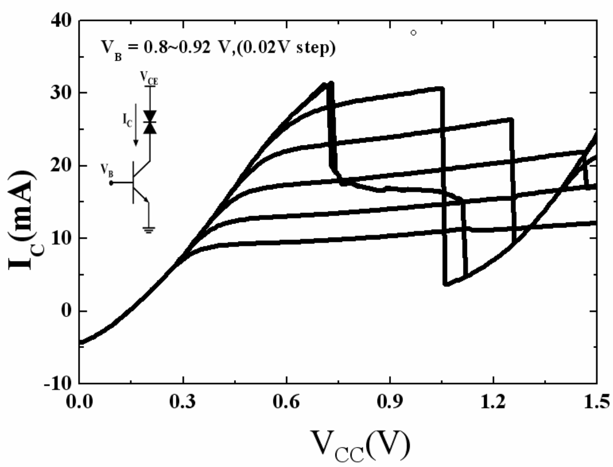


Fig. 3. DC I-V characteristics of the RTD/HBT block.

RTD/HBT block was obtained. In the NDR region, RTD/HBT block generates a negative resistance for oscillation. The oscillation frequency, output power, and phase noise characteristics of the RTD/HBT MMIC VCO have been measured on wafer, using an HP8764E spectrum analyzer. Fig. 4 shows the output spectrum of the fabricated VCO at an oscillation frequency of 5.4 GHz with a control bias of 0.45 V. The output power of –20.33 dBm was obtained at a bias current of 9.5 mA and a supply voltage of 0.8 V, with a corresponding dc power consumption of about 7.6 mW. The small output power is due to the non-optimized design for power generation and narrow NDR voltage span of the RTD. It will be improved by optimizing the layer structure of RTD and by including a matching network for a 50 Ω load. Fig. 5 shows the dependence of the oscillation frequency and output power on the control bias of the varactor from 0 to 0.6V. The frequency tuning range of 710 MHz was achieved from 4.77 GHz to 5.48 GHz. This value is the largest frequency tuning range to our knowledge for RTD-based MMIC VCOs operating in this frequency range, which is realized by using the base-collector junction capacitance of the HBT. The maximum output power was –19.5 dBm and the output power variation with respect to V_{CON} was less than 4 dB in the frequency tuning range.

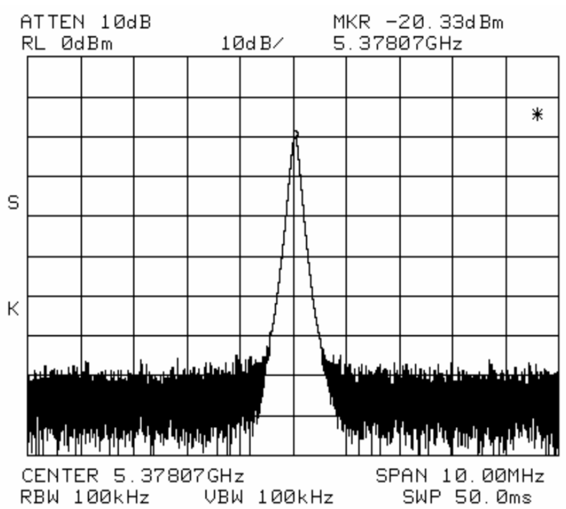


Fig. 4. Output spectrum of the RTD/HBT MMIC VCO at a bias current of 9.5 mA and a supply voltage of 0.8 V

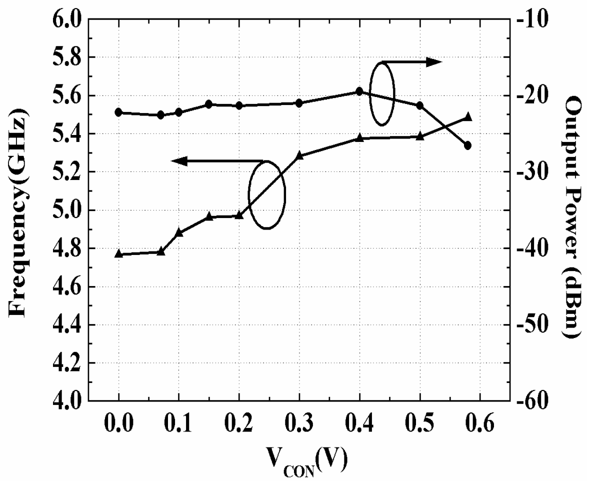


Fig. 5. The oscillation frequency and output power of the RTD/HBT MMIC VCO versus varactor control bias (V_{CON}).

As shown in Fig. 6, the measured phase noise of the VCO was obtained to be –115 dBc/Hz at 1 MHz offset at the operating frequency of 5.34 GHz. The detailed measurement results are summarized and compared in Table I with previously reported results of NDR-based VCOs [3]. Especially, the phase noise performance of the fabricated VCO is excellent compared to other NDR-based VCOs in the frequency range, but the DC power consumption is larger due to the larger bias current, which can be optimized. In order to compare the performance of VCOs, the figure of merit [7] is usually defined as

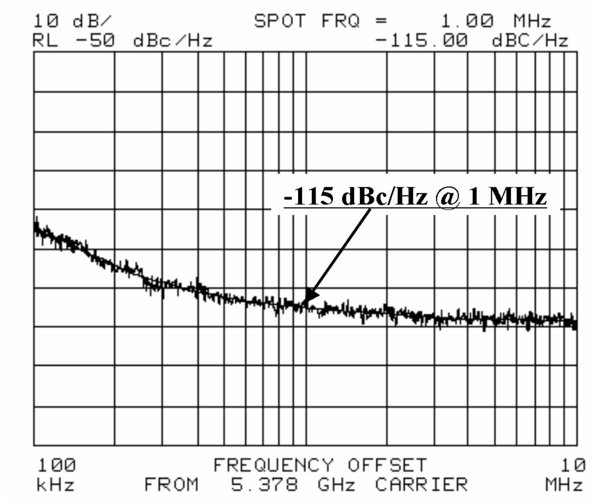


Fig. 6. Phase noise versus the offset frequency.

TABLE I

MEASURED RESULTS COMPARED WITH OTHER NDR-BASED VCOS.

Parameters	**This work**	HEMT/HITD VCO [3]
Supply Voltage	0.8 V	0.5 V
Bias Current	9.5 mA	1.8 mA
DC Power consumption	7.6 mW	0.85 mW
Center Frequency	5.125 GHz	6.15 GHz
Tuning Frequency	710 MHz	150 MHz
Max. Output Power	-19.5 dBm	-16 dBm
Phase noise	-115 dBc/Hz @ 1 MHz	-105 dBc/Hz @ 5 MHz
F.O.M (dBc/Hz)	-180 dBc/Hz	-167 dBc/Hz

$$FOM = L\{\Delta f\} - 20\log\left(\frac{f_o}{\Delta f}\right) + 10\log\left(\frac{P_{DC}}{1mW}\right),$$

where $L\{\Delta f\}$ is the measured phase noise at the frequency offset (Δf), f_o is the carrier frequency and P_{DC} is the measured DC power consumption. The figure of merit of the MMIC VCO reported in this work is -180 dBc/Hz, which is better than that of the previously reported InP-based HEMT/HITD VCO. Through further design optimization, the improved performances of the RTD/HBT MMIC VCOs are expected.

V. CONCLUSION

A monolithically integrated 5 GHz VCO using an InP-based RTD/HBT MMIC technology has been fabricated and characterized. In order to enhance the frequency tuning range of the VCO, the base-to-collector p-n junction of the HBT has been used as a varactor of the LC resonator. The VCO demonstrated the maximum output power of –19.5 dBm at the bias current of 9.5 mA and the supply voltage of 0.8 V, with a corresponding dc power consumption of 7.5 mW. The phase noise performance of –115 dBc/Hz at 1 MHz offset at the operating frequency of 5.34 GHz has been achieved from the RTD/HBT MMIC VCO with a wide frequency tuning range of 710 MHz.

VI. ACKNOWLEDGEMENT

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