GaAs HBT Operating as Integrated V- to W-Band Gunn Oscillator

Matthias Rudolph, Ralf Doerner, and Peter Heymann

Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH), D-12489 Berlin, Germany

Abstract — **Experimental results on GaAs HBT oscillators are presented exploiting the Gunn effect in the collector region. The HBTs are operated beyond f_{max} as MMIC-compatible two-port transferred-electron devices (TEDs) oscillating at millimeterwave frequencies. The oscillation frequency of a single device can be tuned in the range of 40–80 GHz, mainly depending on collector voltage. Maximum output power is 0.3 mW at 62 GHz. Phase noise can be considerably improved by subharmonic injection achieving values of -90 dBc/Hz @ 100 kHz.**

I. Introduction

Commercial radar and communications systems demand for MMIC oscillators in the millimeterwave region. An example are collision-avoidance radar systems at 77 GHz. In all cases, affordable and small components are required. For the oscillator, this leads to a fully monolithic integration of HEMT or HBT-based circuits. This paper shows an alternative, cost–effective approach to generate millimeterwave oscillations in GaAs-based HBT technology. The basic idea is to generate Gunn oscillations in the HBT's collector region.

Negative resistance effects or oscillations due to the negative slope of the v-E characteristic in GaAs have been exploited for more than 25 years. The well-known Gunn diodes are used extensively. Inserted in a high-Q resonator they form powerful millimeter wave sources, but there is no possibility of monolithic integration. Another drawback is that they naturally are one-port devices.

One MMIC approach is to employ planar MESFET-like structures [1], utilizing the Gunn effect in the gate-drain region. GaAs HBTs are possible devices for that purpose as well. In the literature, it has been stated that Gunn oscillations are possible in the HBT collector region. However, it is usually not observed, since in conventional HBTs base push-out (KIRK effect) will occur and prevent the formation of domains. Therefore, it was suggested to insert a narrow, highly doped collector layer at the base-collector interface in order to delay the base push-out [2]. Based on this theoretical work, an HBT TED structure with a graded collector layer demonstrated oscillations at 77 GHz. A 2.8 GHz locking range and an output power of -9 dBm is reported [3].

The approach taken here, on the other hand, employs a HBT structure with a wide, uniformly doped collector. It is advantageous, that the Gunn effect takes place in the collector space-charge region of these devices. Thus, the oscillation frequency is controlled by the bias point instead of the metallurgical collector width and may be tuned in a wide range.

II. The New Approach

In conventional HBTs, the effective length of the collector rapidly is reduced with growing current due to the base push-out effect, which thereby suppresses any formation of Gunn domains. The basic idea of the device presented here is to increase collector thickness and doping so that Gunn oscillations at high current become possible. The HBT then acts as a two-port transferred-electron device (TED) with a negative output resistance in the millimeterwave frequency range. Frequency of oscillation can be controlled in a wide range by the bias point. Depending on current density, the devices either act as conventional HBTs in the microwave range (low current) or in the millimeterwave range as TED (high current) generating oscillations. Although the devices do not have gain in the millimeterwave range, the oscillations can be controlled by subharmonic injection below 20 GHz. Thereby, monolithically integrated millimeterwave oscillators with good phase-noise properties can be realized by combining a microwave HBT oscillator circuit with a subsequent two-port injection-locked TED oscillator acting as an up-converter to millimeterwaves, on the same chip. This allows one to extend the frequency range of an HBT technology with relaxed geometry significantly.

In this work, measurement results of HBT TEDs are presented. The frequency range of operation as well as output power and the properties of sub-harmonic injection are discussed, demonstrating the capabilities of the new devices.

III. Device Structure

The HBTs considered here have uniformly doped, but very thick collector regions [4]. A cross sectional view is shown in Fig. 1. In contrast to conventional HBTs, collector is 2.8 μm thick (instead of typical 1 μm otherwise) with ($n = 2\times10^{16}$ cm^{-3}) Si doping. The single-finger devices have an emitter size of 3×30 μm^2 in coplanar layout.

0-7803-7239-5/02/$10.00 © 2002 IEEE

2002 IEEE MTT-S Digest

They are operated in common-emitter configuration. All epi-layers were grown by MOCVD. The devices were fabricated using the 4"-GaInP/GaAs-HBT process line of the Ferdinand-Braun-Institut, Berlin.

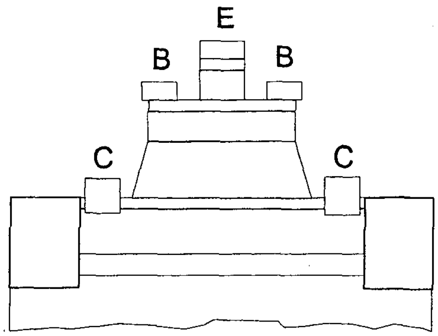

Fig. 1. Cross sectional view of the HBT (not to scale). Thickness and doping of the layers are: Emitter 40nm, 5×10^{17} cm^{-3} Si; Base 100 nm, 4×10^{19} cm^{-3} C; Collector 2.8 µm, 2×10^{16} cm^{-3} Si.

IV. SMALL-SIGNAL BEHAVIOR

Investigations of the linear behaviour of such devices [5] have shown negative output resistances at millimeterwave frequencies. This effect depends on the bias and occurs at collector voltages $V_c = 2...4$ V and at currents in the base push-out range, i.e., $I_c = 35...100$ mA for a single-finger device.

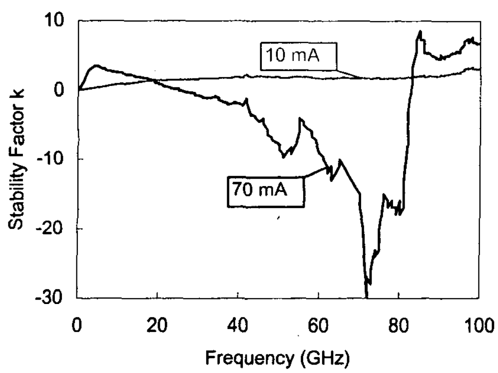

Fig. 2. HBT stability factor k for the two operation modes: 10 mA: conventional HBT operation; 70 mA: TED mode operation.

At smaller currents, the device operates as a common HBT with $f_t = 35$ GHz and $f_{max} = 85$ GHz. The peculiarity of the transistor with its inherent collector Gunn instability can be seen from k factor. Fig. 2 presents this data for two collector currents. In the conventional operation mode (10 mA), one finds a $k(f)$ dependence as expected with a transit to $k > 1$ at 13 GHz. At high currents (70 mA), however, beyond the onset of base push-out, a strong decrease of k is observed indicating the tendency to oscillate. The negative sign is caused by $|S_{22}|$ exceeding unity in this frequency range. Thus, from S parameter measurements the Gunn instability is to be expected between 40 and 80 GHz. Since the HBT is operated under base push-out conditions for TED operation, the effective width of the collector region depends strongly on bias point. Therefore, it is possible to vary the frequency of oscillation in a wide range. This is in contrast to the approach of [2], [3], where the metallurgical collector width mainly determines the oscillation frequency. It should be pointed out that the devices presented here exhibit maximum output power around 60 GHz, and are not yet optimized for higher frequencies or output powers.

V. OSCILLATOR MEASUREMENTS

Measurements were performed on-wafer with external harmonic mixers of a spectrum analyzer. The mixers were directly connected to the waveguide output of V- and W-band probes, respectively. The locking is realized in transmission type, i.e., the signal is applied to the transistor input (base-emitter) via a bias-tee. It is provided by a synthesizer with a phase noise of -100 dBc/Hz @ 100 kHz. Frequency and power of the free-running oscillations as a function of bias are shown in Figs. 3 and 4. The frequency is mainly controlled by the collector voltage, with a tuning sensitivity of –5 GHz/V. The curves in Fig. 3 indicate that there are several modes with different amplitude.

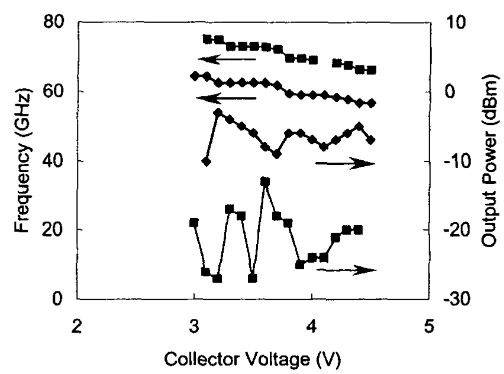

Fig. 3. Free-running oscillation of a single-finger (3×30 μm^2) device as a function of collector voltage (maximum power of -3 dBm at $f \approx 62$ GHz, $I_c = 40$ mA).

On the other hand, the frequency of the free-running oscillation depends only weakly on collector current, as depicted in Fig. 4. However, output power varies significantly, with an optimum at higher currents.

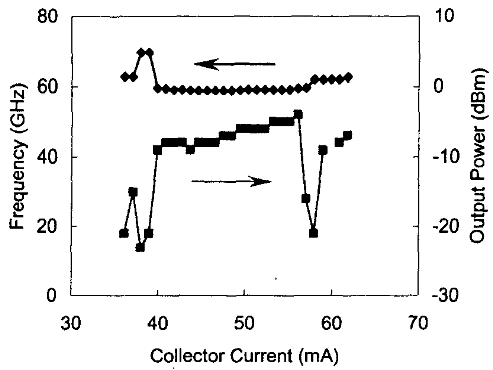

Fig. 4. Free-running oscillation of a single-finger ($3\times30\mu m^2$) device as a function of collector current. Bias: $V_c = 4$ V.

For the single-finger device, we observe a maximum output power of –3 dBm for the free running oscillation and –10 dBm for the locked condition. As mentioned above, the device has not been optimized for maximum P_{out} and 77 GHz operation.

Since the device itself shows spontaneous oscillations in a broad frequency range of 40–80 GHz, we will now investigate the possibility to stabilize and tune the oscillation frequency by subharmonic injection.

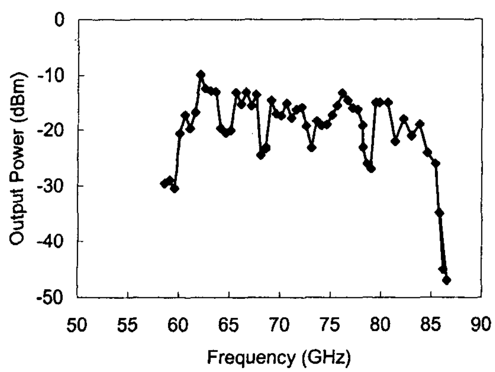

Fig. 5. Tuning range of the output frequency when injection-locking the 4th subharmonic (input: 14.5–21.8 GHz, $P = 7$ dBm).

As shown in Fig. 5, the output signal follows the frequency of the 4th subharmonic from 60 to 85 GHz. This extremely wide tuning range (20%) exceeds by far the locking range of conventional subharmonically locked millimeterwave oscillators. Moreover, the locking effect can be observed for a wide range of injection frequencies. Synchronisation is effective even down to the 15th subharmonic (5.07 GHz), as illustrated by Fig. 6.

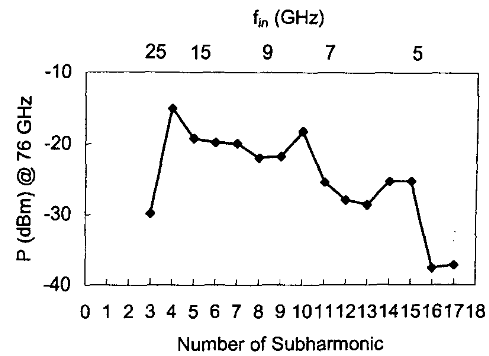

Fig. 6. Amplitude of the locked signal at $f = 76$ GHz for increasing subharmonic number (decreasing f_{in}); $V_c = 2.75$ V, $I_c = 70$ mA; $P_{in} = 7$ dBm.

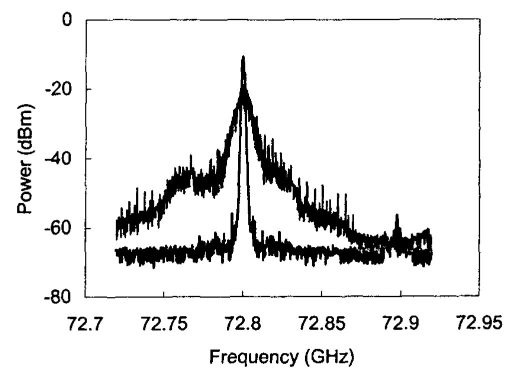

Fig. 7. Spectrum of free-running and injection-locked oscillation; bias: $V_c = 2.75$ V, $I_c = 36$ mA; injection with 7th subharmonic (10.4 GHz), $P = 7$ dBm; spectrum analyzer with external harmonic mixer (RBW = 1 MHz, VBW = 30 kHz).

Signal injection leads to substantial reduction of the phase noise as is well known from subharmonic locking theory [6]. The effect is clearly demonstrated in Fig. 7. The noisy spectrum of the free running oscillation is transformed into a high-quality signal. Thus the excellent spectral purity of microwave sources below 20 GHz can be preserved in the upconversion into the millimeterwave frequency range. We observed a phase noise of

-50 dBc/Hz @ 1 MHz for the free running state. Due to strong noise, specifying phase noise at the standard offset of 100 kHz is not useful here. A quantitative measurement of the locked signal is plotted in Fig. 8. One observes a drastic reduction down to -90 dBc/Hz @ 100 kHz.

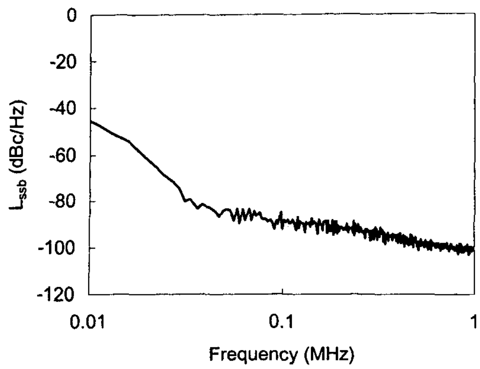

Fig. 8. SSB phase noise of a 80 GHz, P_{out} = -15 dBm signal locked by f_{in} = 20 GHz, P_{in} = 7 dBm, Bias: V_c = 2.75 V, I_c =37 mA.

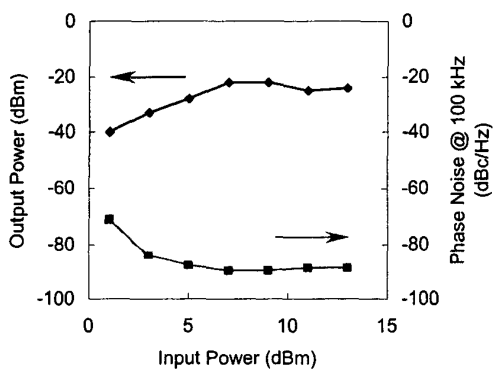

Fig. 9. P_{out} @ 60 GHz and phase noise reduction with increasing P_{in} @ 15 GHz. Bias: V_c = 4 V, I_c = 42 mA.

Fig. 9 shows the phase-noise reduction with increasing injection power. Beyond a certain level, the noise remains constant around -90 dBc/Hz, which is about 10 dB above the injected signal. This is in agreement with the results in [7] and much less than what can be expected from frequency multipliers (20 log(N)).

VI. Conclusions

It is shown that GaAs-based HBT with thick collector exhibit spontaneous oscillations in V- and W-band. This is caused by the Gunn effect occurring in the collector region under high-injection condition. Oscillation frequency can be controlled in a broad range depending on the bias point. The so-far non-optimized HBT structure with 3x30 μm^2 emitter area exhibits free-running oscillations in the range 40...80 GHz with a maximum output power of -3 dBm around 60 GHz. The oscillation can be exceptionally stabilized by transmission-type subharmonic injection locking and reaches a phase-noise level of -90 dBc/Hz at 100 kHz offset. In this case, output power is about -10 dBm in a broad frequency range. A tuning range of 20 GHz is achieved. Thus, the Gunn-effect HBT proves to be a promising candidate for millimeterwave generation in HBT technology with relaxed geometry.

Acknowledgments

The authors would like to thank the material and process technology departments of the FBH, particularly Dr. P. Kurpas, for providing the HBTs, S. Schulz for performing measurements, and Dr. W. Heinrich for helpful discussions and continuous encouragement.

References

[1] A. L. Springer, Ch. G. Diskus, K. Lübke, H. W. Thiem, "A 60-GHz MMIC-compatible TED-oscillator", *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 114–116, Apr. 1995.

[2] V. A. Posse, B. Jalali, "Novel transient phenomena in heterojunction bipolar transistors", *Solid State Electron.*, vol. 41, pp. 527–530, Apr. 1997.

[3] J. K. Twynam, M. Yagura, N. Takahashi, E. Suematsu, H. Sato, "Demonstration of a 77-GHz heterojunction bipolar transferred electron device", *IEEE Electron Dev. Lett.*, vol. 21, pp. 2–4, Jan. 2000.

[4] P. Kurpas, F. Brunner, W. Doser, A. Maaßdorf, R. Doerner, M. Rudolph, H. Blanck, W. Heinrich, J. Würfl, "Development and characterization of GaInP/GaAs HBTs for high voltage operation", in *Int. Conf. GaAs MANufacturing TECHnology*, Las Vegas, USA, 21.-24. Mai 2001.

[5] M. Rudolph, R. Doerner, P. Heymann, "On the Gunn effect in GaAs HBTs", in *IEEE MTT-S Int. Microwave Symp. Dig.*, 2001, pp. 683–686.

[6] S. Kudszus, W. H. Haydl, M. Neumann, A. Bangert, A. Hülsmann, "Subharmonically injection locked 94 GHz MMIC HEMT oscillator using coplanar technology", in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1998.

[7] X. Zhang, X. Zhou, A. S. Daryoush, "A theoretical and experimental study of the noise behaviour of subharmonically injection locked local oscillators", *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 895–902, May 1992.