RF PERFORMANCE CHARACTERISTICS OF INP MILLIMETER-WAVE N^+-N^--N^+ GUNN DEVICES

H. Eisele, G. O. Munns[1], and G. I. Haddad

Solid-State Electronics Laboratory
Department of Electrical Engineering & Computer Science
The University of Michigan, Ann Arbor, Michigan 48109-2122

Abstract

A selective etching technology for the fabrication of InP Gunn devices on diamond heat sinks was established recently. Using MOCVD-grown material, state-of-the-art RF power levels of more than 130 mW at 131.7 GHz and more than 60 mW at 151 GHz were obtained in the fundamental mode. No deterioration was observed in one of these devices monitored for more than 6500 hours. Power combining of two devices resulted in an RF output power of 130 mW at 136 GHz with a combining efficiency of more than 85 %. After evaluating CBE-grown material with devices on integral heat sinks, different doping profiles for devices operating at D-band frequencies were designed and grown in a CBE system. Preliminary results with RF power levels of more than 100 mW around 130 GHz indicate that CBE can provide the high-quality material required for InP Gunn devices and that RF power levels above 150 GHz can be increased significantly with optimized device structures. No differences in the excellent noise performance of devices fabricated from either MOCVD- or CBE-grown material were found.

Summary

There has been an increasing demand for high-performance low-noise sources at frequencies above 100 GHz. Vapor-phase epitaxy (VPE) [1,2] and metalorganic chemical vapor deposition (MOCVD) [3] have so far been the only epitaxial growth processes that provide the high-quality semiconductor material for millimeter-wave InP Gunn devices. We used MOCVD-grown epitaxial material to establish a versatile selective etching technology for InP Gunn devices on diamond heat sinks [4]. This technology allowed the fabrication and direct comparison of devices from the same epitaxial material with a graded doping profile, but with either polarity, *i.e.*, cathode or anode near the heat sink [4]. Recently, we obtained state-of-the-art RF power levels of more than 130 mW at 131.7 GHz and more than 60 mW at 151 GHz in the fundamental mode and in a configuration with the anode near the heat sink. Low heat-flow resistances on diamond heat sinks significantly reduce the operating active-layer temperature and are expected to improve reliability and lifetime of $n^+n^-n^+$ InP Gunn devices. Therefore, one of the devices from the work presented in Reference 4 has been monitored under continuous operation at an ambient temperature between 20 ˚C and 24 ˚C in a still ongoing experiment since mid-April 1996. Recorded variations in bias current and RF output power were less than – 1 % and – 3 %, respectively, over more than 6500 hours. The recorded RF power levels for the time period of the first 240 days are plotted in Figure 1 as one data point per day. The oscillation frequency has not been monitored continuously, but was measured a few times over the time period of Figure 1. Changes in the oscillation frequency were found to be less than – 5 MHz.

In a first attempt at power combining, an in-line configuration with two full-height WR-6 waveguide cavities as shown in Figure 2 was employed. This dual-cavity configuration was quite successful with InP Gunn devices [5] and W-band (75-110 GHz) GaAs tunnel injection transit-time (TUNNETT) diodes [6]. The device with the wide tuning range [4] was chosen for device A, and another device with the similar RF output power of more than 100 mW at 131.19 GHz, as device B. The oscillation fre-

[1] Present address: Applied Epi
1290 Hammond Road
Saint Paul, Minnesota 55110

0-7803-4603-6/97/$5.00 (c) IEEE

quency of the combined devices was 134.19 GHz with little variation as the position of the back short was changed. At this frequency, device B generates less than half the power of device A in a single-cavity oscillator, which explains the combined RF output power of 100 mW and the combining efficiency of 65 % at 134.19 GHz. Therefore, the device in cavity B was replaced with a new device that yielded more than 100 mW at 135.50 GHz and 90 mW at 135.96 GHz. Figure 3 illustrates the tuning characteristics of the individual single-cavity oscillators.

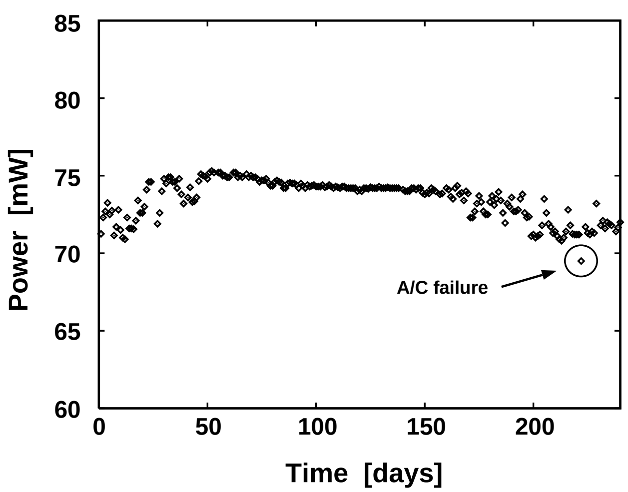

Figure 1: Long-term stability of the RF output power.

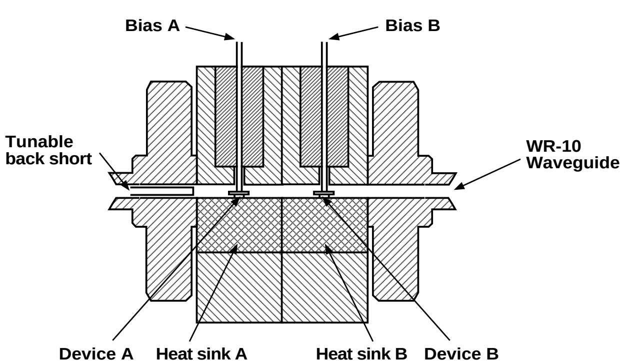

Figure 2: Schematic of the dual-cavity waveguide circuit for Gunn device power combining.

In the dual-cavity combiner circuit, a maximum RF output power of 130 mW at 135.98 GHz was measured, which corresponds to a combining efficiency of more than 85 % and an overall dc-to-RF conversion efficiency of 1.25 %. Similar combining efficiencies were reported previously from this type of in-line configuration using GaAs TUNNETT diodes in full-height WR-10 waveguide cavities [6].

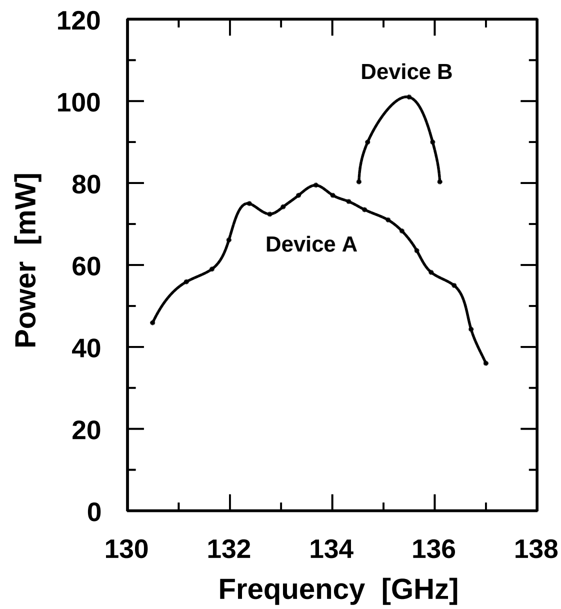

Figure 3: Tuning characteristics for devices A and B in individual single-cavity oscillators at maximum dc input power for device B and 80 % of the maximum dc input power for device A, respectively.

With a phase noise of less than - 106.5 dBc/Hz as taken from the spectrum analyzer at a frequency off the carrier of 500 kHz, this oscillator with two power-combined devices demonstrated as clean a spectrum as was already seen in free-running oscillators with single devices [4]. Figure 4 summarizes the best results from single-cavity oscillators in the frequency range from 125-165 GHz, and the result from power combining in the dual-cavity oscillator is included for comparison.

This is the first successful demonstration of power combining at D-band frequencies, and, to the authors' knowl-

0-7803-4603-6/97/$5.00 (c) IEEE

edge, the RF power levels are the highest reported from any Gunn devices.

Initial results from InP Gunn devices on integral heat sinks indicated that chemical-beam epitaxy (CBE) not only can provide the high-quality epitaxial material that is required for high-performance InP Gunn devices, but also could offer tighter doping control at doping levels below $5 \cdot 10^{16}$ cm^{-3} using elemental-source Si. Devices with a 1.7-mm-long active region at a doping level of $9 \cdot 10^{15}$ cm^{-3} yielded RF power levels (and corresponding dc-to-RF conversion efficiencies) between 38 mW (2.1 %) and 62 mW (1.9 %) in the fundamental mode around 80 GHz. In a second-harmonic mode, RF power levels of more than 13 mW at 151 GHz and more than 9 mW between 157 GHz and 159 GHz were obtained from similar devices, again on integral heat sinks.

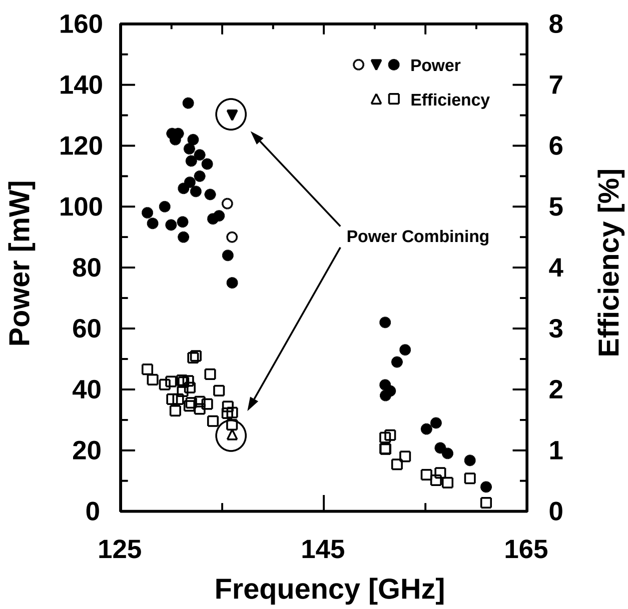

Figure 4: RF output power and dc-to-RF conversion efficiency versus oscillation frequency for D-band InP Gunn devices fabricated from MOCVD-grown material.

Subsequently, doping profiles with and without grading in the approximately 1-mm-long active regions were designed for devices that can operate in the fundamental mode at D-band (110-170 GHz) frequencies, and the material was grown by CBE. The above selective etching technology was employed to fabricate devices to be mounted on diamond heat sinks. The devices that were tested first had a 1.0-mm-long active region at a doping level of $2.5 \cdot 10^{16}$ cm^{-3} and, as a preliminary result, yielded RF power levels of up to 104 mW around 130 GHz with corresponding dc-to-RF conversion efficiencies around 1.5 %. Subsequently, devices were tested that had a nominally 0.9-mm-long active region with a grading in the doping profile from nominally $8.0 \cdot 10^{15}$ cm^{-3} to $2.3 \cdot 10^{16}$ cm^{-3}. As expected, the first devices already yielded higher dc-to-RF conversion efficiencies of around 2.0 % at oscillation frequencies around 130 GHz. These preliminary values are quite similar to those shown in Figure 4 for devices that were fabricated from MOCVD-grown material. Measured RF power levels of around 80 mW are slightly lower than those of Figure 4 around 130 GHz. This can be attributed to the fact that the optimum device area and the optimum impedance matching has not yet been found for the first devices from CBE-grown material with a graded doping profile in the active region. As shown in Figure 5 for an RF output power of 94 mW at 130.8 GHz, free-running oscillators with these devices from CBE-grown material exhibit very clean spectra with a phase noise of less than 103 dBc/Hz at a frequency off the carrier of 500 kHz. These excellent phase-noise levels are comparable to those reported in Reference 4 for devices from MOCVD-grown material. Measured RF power levels as well as current densities at the bias point agree well with the predictions from an Ensemble Monte-Carlo simulation program [7].

This is the first demonstration of high-performance InP Gunn devices fabricated from CBE-grown material. These results indicate that CBE is well suited for this purpose, and that considerably improved performance in the fundamental mode as well as a second-harmonic mode at frequencies above 150 GHz can be expected from InP Gunn devices on diamond heat sinks with optimized doping profiles.

0-7803-4603-6/97/$5.00 (c) IEEE

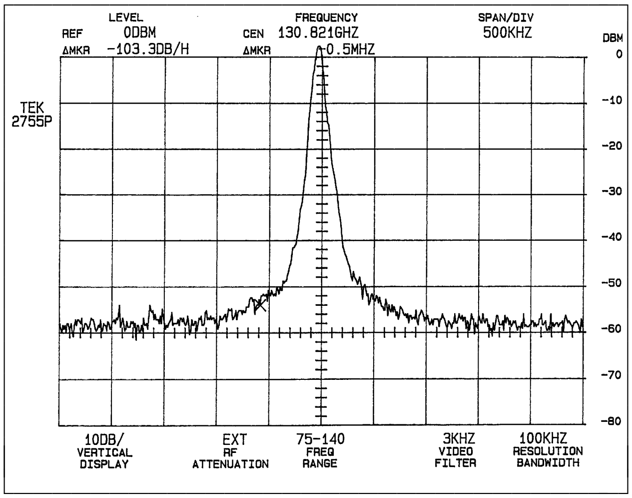

Figure 5: Spectrum of an InP Gunn device free-running oscillator, power level 94 mW, center frequency 130.821 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, BW 100 kHz, VBW 3 kHz.

References

[1] Crowley, J. D., Hang, C., Dalrymple, R. E., Hang, C., Tringali, D. R., Fank, F. B., Wandinger, L.: "InP Gunn Diodes Serve Millimeter-Wave Applications", *Microwaves & RF*, **33**(3), 1994, pp. 143-146.

[2] Eddison, I. G.: "Indium Phosphide and Gallium Arsenide Transferred-Electron Devices", *Infrared and Millimeter Waves*, Vol. 11, *Millimeter Components and Techniques, Part III*, Academic Press, Orlando, 1984, pp. 1-59.

[3] di Forte-Poisson, M. A., Brylinski, C., Proust, N., Pons, D., Secoué, M., Arsène Henry, P., Calligaro, M., Lacombe, J.: "LP-MOCVD InP Gunn Devices Developed for 94 GHz Millimeter Range Operation", *Proceedings of the First International Conference on Indium Phosphide and Related Materials for Advanced Electronic and Optical Devices*, Norman, Oklahoma, March 20-23, 1989, SPIE **1144**, 1989, pp. 551-560.

[4] Eisele, H., Haddad, G. I.: "High-Performance InP Gunn Devices for Fundamental-Mode Operation in D-Band (110-170 GHz)", *IEEE Microwave and Guided Wave Letters*, **MGWL-5**, 1995, pp. 385-387.

[5] Talwar, A. K.: "A Dual-Diode 73-GHz Gunn Oscillator", *IEEE Transactions on Microwave Theory and Techniques*, **MTT-27**, 1979, pp. 510-512.

[6] Eisele, H., Haddad, G. I.: "Enhanced Performance in GaAs TUNNETT Diode Oscillators Above 100 GHz through Diamond Heat Sinking and Power Combining", *IEEE Transactions on Microwave Theory and Techniques*, **MTT-42**, 1994, pp. 2498-2503.

[7] Kamoua, R., Eisele, H., Haddad, G. I.: "D-Band (110 GHz - 170 GHz) InP Gunn Devices", *Solid-State Electronics*, **36**, 1993, pp. 1547-1555.

0-7803-4603-6/97/$5.00 (c) IEEE