High-Performance InP Gunn Devices for Fundamental-Mode Operation in D-Band (110–170 GHz)

Heribert Eisele and George I. Haddad

***Abstract*—InP Gunn devices with an n^+nn^+ structure and a graded doping profile in the active region were designed, fabricated, and tested for fundamental-mode operation at D-band frequencies. Improved heat dissipation significantly increased the available RF output power and power levels of more than 90 mW up to frequencies around 135 GHz, more than 130 mW at 131.7 GHz, and more than 60 mW at 151 GHz in fundamental-mode operation. These are the highest RF power levels reported to date from any Gunn devices. These InP Gunn devices with dc-to-RF conversion efficiencies up to 2.5% around 132 GHz also exhibit excellent noise performance and the typical phase noise up to the highest RF power levels is well below −100 dBc/Hz, measured at a frequency off-carrier of 500 kHz.**

I. Introduction

THERE has been an increasing demand for high-power low-noise oscillators beyond 100 GHz for applications in high-resolution radars and as drivers for multipliers in radio astronomy receivers and for spectroscopical studies of the atmosphere. A self-consistent Monte-Carlo program was developed recently to study the performance of InP Gunn devices at D-band (110–170 GHz) frequencies [1]. These studies investigated the design of device structures with graded doping profiles for enhanced performance in fundamental mode and also revealed some thermal limitations at upper D-band frequencies. This Letter reports on the results of efforts to significantly improve the heat dissipation in InP Gunn devices and to generate RF power levels of more than 100 mW at D-band frequencies.

GaAs transit-time diodes are routinely mounted on diamond heat sinks to lower the operating junction temperature and to at least double the available RF output power. Therefore, a well-established selective etching technology [2] was adopted for the InP/InGaAs system. Devices were fabricated from MOCVD-grown epitaxial material and tested in a top-hat full-height WR-6 waveguide cavity. Preliminary results with power levels of more than 50 mW around 130 GHz from the first D-band devices on diamond heat sinks [3] clearly showed that the improved heat dissipation significantly increased the available RF output power. Experimental results from millimeter-wave GaAs Gunn devices on integral heat sinks [4] indicate that the device performance benefits from positioning the anode close to the heat sink. Therefore, the processing steps were modified to investigate whether the position of the anode with respect to the heat sink affects the performance of devices made from the same MOCVD-grown epitaxial material as reported in [1] and [3].

Manuscript received May 15, 1995. This work was supported in part by the Center of Space Terahertz Technology under contract NAGW 1334.

The authors are with the Department of Electrical Engineering & Computer Science, Solid-State Electronics Laboratory, The University of Michigan, Ann Arbor, MI 48109-2122 USA.

IEEE Log Number 9414647.

II. Technology

The fabrication steps for devices with the anode close to the heat sink are as follows: First, the standard Ni/Ge/Au/Ti/Au metal layers [1] for the top ohmic contact are deposited onto the heavily doped n^+ layer and selectively electroplated [1] with gold up to a thickness of several microns. The sample is then glued down on a carrier [5] for substrate removal in diluted hydrochloric acid. Subsequently, the $In_{0.53}Ga_{0.47}As$ etch-stop layer is removed, and, for good heat transfer from the active region to the heat sink, the heavily doped n^+ buffer layer is also thinned down to 0.2–0.3 μm. For the bottom ohmic contact, the same Ni/Ge/Au/Ti/Au metal layers [1] are deposited on the entire sample, and gold is selectively electroplated to form a supporting grating [4]. Then, the sample is removed from the carrier and flipped over to be glued down again on the carrier. From this step on, processing follows the same procedure as reported in [3] and includes removing the thin metal layers between the plated top contacts, mesa etching, removing from the carrier, and standard contact annealing on a hotplate. Devices with nominal diameters between 40–55 μm and appropriate dc characteristics are selected and thermocompression-bonded onto a metallized diamond heat sink. For RF testing, an open package with four quartz standoffs provides sufficiently low parasitics and is the preferred method.

III. Experimental Results

Most of the devices were evaluated in a standard full-height WR-6 waveguide cavity with a tunable noncontacting back short at one flange [2]. Resonant caps with typical diameters between 0.5–1.2 mm allowed coarse frequency tuning of the device under test, and no other tuning elements, e.g., an E-H tuner, were found necessary. Each device was tested at between two and seven different frequency points, and Fig. 1 summarizes the best results from a series of measurements in the frequency range from 125–159 GHz. RF power levels of over 130 mW at 131.65 GHz, the highest reported to date

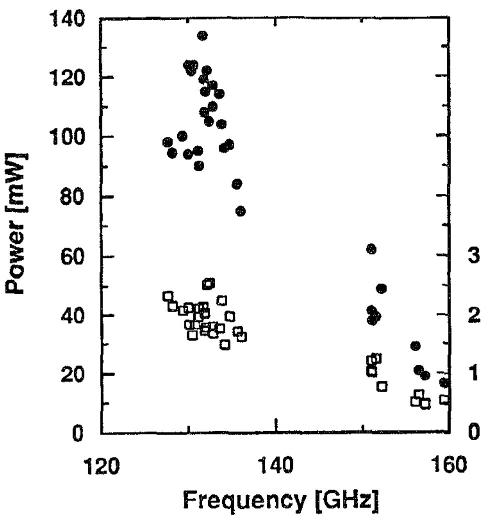

Fig. 1. Output power (•) and efficiency (□) versus oscillation frequency in D-band for different InP Gunn devices with the anode close to the heat sink.

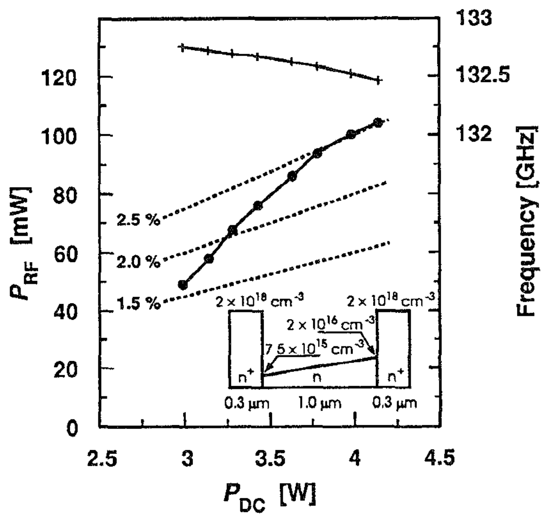

Fig. 2. Bias-dependent RF characteristics of a D-band InP Gunn device (•: output power, +. oscillation frequency, - - -: lines of constant efficiency).

from any Gunn device, confirm the long-predicted capabilities [6], [7] of InP Gunn devices and can compete with those of Si D-band IMPATT diodes on diamond heat sinks [8], [9]. DC-to-RF conversion efficiencies of up to 2.5% are also comparable to values reported recently from InP Gunn devices in second-harmonic mode around 140 GHz [10]. The thermal analysis for devices on diamond heat sinks in [7] predicts heat-flow resistances from 47 K/W down to 31 K/W for the aforementioned range of diameters, and active-layer temperatures are estimated to be below 200°C for the maximum dc input power applied at the devices of Fig. 1. Three devices were also tested in a WR-10 waveguide version of the above-mentioned cavity. Although these Gunn devices are not optimized for operation at W-band (75–110 GHz) frequencies, one device yielded the state-of-the-art RF output power of 185 mW at 102 GHz.

A typical bias-dependent characteristic of a free-running oscillator is shown in Fig. 2. The position of the back short was adjusted for maximum RF output power of more than 100 mW at maximum dc input power and kept fixed throughout this measurement. Single-mode operation is achieved between about 3–4.2 W of dc input power and, in this bias range, the oscillation frequency decreases monotonically by about 250 MHz. This makes the oscillator ideally suited for phase locking. The insert of Fig. 2 also shows the nominal doping profile of the n^+nn^+ epitaxial layer sequence. By moving the position of the back short, a typical instantaneous tuning range of several GHz around the optimum oscillation frequency of between 125–159 GHz was achieved with most of the tested devices. No mode jumps occurred in such a tuning range and more than 50% of the maximum RF power was available. In Fig. 3, the mechanical tuning characteristic is shown for the Gunn device of Fig. 2. No mode jumps occur between 131–135.5 GHz and an RF output power of more than 80 mW is available over a tuning bandwidth of 2.8 GHz.

A still wider instantaneous tuning bandwidth was observed in a commercially available test fixture for Si CW D-band IMPATT diodes, which is a reduced height waveguide cavity

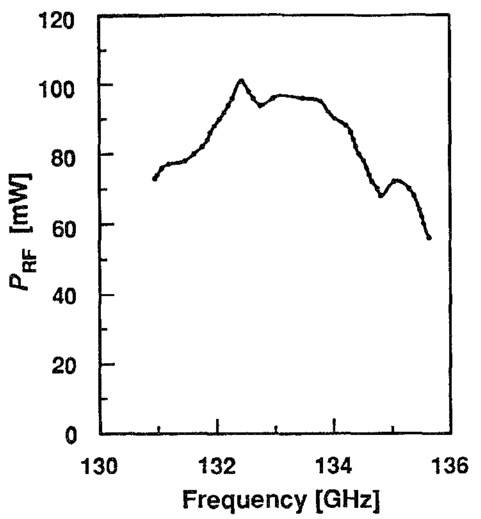

Fig. 3. Mechanical tuning characteristic for the D-band InP Gunn device of Fig. 2 at maximum applied bias.

with a coaxial post (Hughes 47138H-1600) and requires a different style of diamond heat sink. Back short tuning changed the oscillation frequency linearly from about 113.3–125.9 GHz with RF power levels between 20–44 mW. Another device yielded around 50 mW at oscillation frequencies between 120–122 GHz. No attempt was made at this point to optimize post diameter, length, and shim thickness for higher output power and/or oscillation frequency. More than 10% tuning bandwidth in a cavity with a coaxial post, wide tuning bandwidth and low Q values in a resonant-cap configuration as well as bias voltages of around half of those in a second-harmonic mode [10] are strong indications of operation in a fundamental mode. Second-harmonic power extraction up to 290 GHz with devices from the same epitaxial material was already shown in [3].

These InP Gunn devices in free-running oscillators exhibit clean spectra up to the highest power levels and oscillation frequencies. As an example for a Gunn device with 120 mW at 132.13 GHz, the measured phase noise of -105 dBc/Hz as taken from the spectrum analyzer at 500 kHz off the carrier corresponds to a large-signal noise measure M of 25 dB. This phase noise is less than 1 dB above the (uncorrelated) noise floor of the employed spectrum analyzer with a harmonic mixer. Therefore, the corrected phase noise and noise measure are estimated to be below -108 dBc/Hz and 22 dB, respectively. Typical (uncorrected) phase noise measured in six tested devices at a frequency off-carrier of 500 kHz remains well below -100 dBc/Hz up to the highest power levels, and loaded Q values from 50–200 were determined using a self-injection locking technique [11] with a directional coupler (nominal coupling value 20 plus 0.5 dB waveguide attenuation) and a tunable back short. Corresponding (uncorrected) noise measures typically remain below 25 dB even for RF power levels from 70–120 mW around 132 GHz. As a second example, a Gunn device with 58 mW at 151 GHz had a phase noise of -100 dBc/Hz as taken from the spectrum analyzer at 500 kHz off the carrier and a corresponding large-signal noise measure of 23 dB. For the same reasons as stated above, the corrected phase noise and noise measure are estimated to be below -103 dBc/Hz and 20 dB, respectively.

IV. Conclusion

InP Gunn devices for operation in a fundamental mode at D-band frequencies were successfully fabricated, mounted on diamond heat sinks, and tested at frequencies between 125–159 GHz. Devices with the anode close to the heat sink deliver more than twice the RF output power than the devices reported in [3]. This increase is only partly attributed to better heat dissipation from the anode region of the device because significantly higher threshold currents in some of the devices of Fig. 2 indicate larger device areas. Further investigations are aimed at finding a correlation between device area and RF output power as well as an optimum device area. With noise measures below 25 dB up to the highest RF power levels around 132 GHz and with a noise measure below 23 dB at 151 GHz, these D-band Gunn devices show better noise performance than present transit-time diodes with high avalanche multiplication factors (IMPATT and MITATT diodes in GaAs and Si, with more details in [3]), and, probably due to easier impedance matching, offer much higher RF power levels and dc-to-RF conversion efficiencies than present GaAs single-drift IMPATT and MITATT diodes [2], [3] at these D-band frequencies. They even approach the highest RF power levels reported from Si IMPATT diodes [8], [9], and the typical dc-to-RF conversion efficiencies are quite similar. Additionally, the estimated active-layer temperature of these Gunn devices are much lower than usual operating junction temperatures of 280°C or higher, which are reported for the Si IMPATT diodes with the best CW results.

Acknowledgment

The authors are indebted to J. Morgan for machining some of the waveguide and other mechanical parts with excellent skill.

References

[1] R. Kamoua, H. Eisele, and G. I. Haddad, "D-Band (110–170 GHz) InP Gunn devices," *Solid-State Electron.*, vol. 36, pp. 1547–1555, 1993.
[2] H. Eisele and G. I. Haddad, "GaAs single-drift flat-profile IMPATT diodes for CW operation in D band," *Electron. Lett.*, vol. 28, pp. 2176–2177, 1992.
[3] ——, "D-band InP Gunn devices with second-harmonic power extraction up to 290 GHz," *Electron. Lett.*, vol. 30, pp. 1950–1951, 1994.
[4] J. Ondria and R. L. Ross, "Improved performance of fundamental and second-harmonic MMW oscillators through active doping concentration contouring," in *1987 IEEE MTT-S Dig.*, 1987, pp. 977–980.
[5] H. Eisele, "Selective etching technology for 94 GHz GaAs IMPATT diodes on diamond heat sinks," *Solid-State Electron.*, vol. 32, pp. 253–257, 1989.
[6] M. R. Friscourt and P. A. Rolland, "Optimum design of n^+-n-n^+ InP devices in the millimeter-range frequency limitation RF performances," *IEEE Electron Dev. Lett.*, vol. EDL-4, pp. 135–137, 1983.
[7] I. G. Eddison, "Indium phosphide and gallium arsenide transferred-electron devices," *Infrared and Millimeter Waves, Millimeter Components and Techniques, Part III*, vol. 11. Orlando: Academic, 1984, pp. 1–59.
[8] D. H. Lee and R. S. Ying, "Ion-implanted complementary IMPATT diodes for D-band," *Proc. IEEE*, vol. 62, pp. 1295–1296, 1974.
[9] K. Chang, W. F. Thrower, and G. M. Hayashibara, "Millimeter-wave silicon IMPATT sources and combiners for the 110–260 GHz range," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 1278–1284, 1981.
[10] J. D. Crowley, C. Hang, R. E. Dalrymple, D. R. Tringali, F. B. Fank, L. Wandinger, and H. B. Wallace, "140 GHz indium phosphide Gunn diode," *Electron. Lett.*, vol. 30, pp. 499–500, 1994.
[11] K. Kurokawa, "Noise in synchronized oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 234–240, 1968.