Short Papers

GaAs TUNNETT Diodes on Diamond Heat Sinks for 100 GHz and Above

H. Eisele and G. I. Haddad

Abstract—**Single-drift GaAs TUNNETT diodes were mounted on diamond heat sinks for improved thermal resistance and evaluated around 100 GHz in a radial line full height waveguide cavity. The diodes were fabricated from MBE-grown material originally designed for diodes that operate in CW mode around 100 GHz on integral heat sinks. An RF output power of more than 70 mW with a corresponding dc to RF conversion efficiency of 4.9% was obtained at 105.4 GHz. This is the first successful demonstration of GaAs TUNNETT diodes mounted on diamond heat sinks. To the authors' knowledge, these dc to RF conversion efficiencies and RF power levels are the highest reported to date from TUNNETT diodes and exceed those of any single discrete device made of group III-V materials (GaAs, InP, etc.) at this frequency. Free-running TUNNETT diode oscillators exhibit clean spectra with an excellent phase noise of less than −94 dBc/Hz, measured at a frequency off-carrier of 500 kHz and an RF output power of 40 mW.**

I. Introduction

TUNNEl injection Transit-Time (TUNNETT) diodes were originally proposed in 1958 as a high-frequency device [1]. Despite some encouraging results at millimeter- and submillimeter-wave frequencies from GaAs TUNNETT diodes under pulsed conditions in 1979 [2], GaAs transit-time diodes for CW operation with low multiplication factors were first realized in 1990 [3] and significant improvements in RF power performance for application in local oscillators were demonstrated recently [4], both from material grown by molecular beam epitaxy (MBE). The diodes in [4] were designed for operation around 100 GHz and exhibit one remarkable characteristic: neither RF output power nor dc to RF conversion efficiency saturate up to the maximum applied bias in more than 95% of the tested diodes [4], [5]. This leads to the conclusion that the performance of these diodes on integral heat sinks is limited by a maximum operating junction temperature of 250°C, chosen to ensure good reliability and long lifetime. Therefore, mounting the same devices on a better heat sink is expected to enhance the RF power performance considerably.

II. Technology

A selective etching technology has been established for fabrication of state-of-the-art GaAs W-band and D-band IMPATT diodes on diamond heat sinks [6, 7]. Therefore, basically the same technology was employed to fabricate TUNNETT diodes for diamond heat sinks from the same MBE-grown material as reported in Reference 4. A detailed description of the various steps in this technology was given in [6]. As a consequence, only the main steps and major modifications of this technology will be mentioned here. First, the top p^+ layer is metallized with Ti/Pt/Au. This metallization is selectively electroplated with 10 μm to 15 μm of gold not only to form a grating as the mechanical support for the last processing steps, but additionally to provide a more than 100-μm wide integral heat sink for a large percentage of the diodes on the sample. This way, diodes for both types of heat sinks are obtained in one batch from the same sample. The diodes with integral heat sinks are mounted and packaged with quartz standoffs and tapered ribbons as described in [4]. These diodes are used to assess the quality of the batch more easily and economically. To ensure compatibility with the cleanroom environment, no lapping is performed. Instead, the substrate is thinned in a standard etch of sulfuric acid and hydrogen peroxide. The $Al_{0.55}Ga_{0.45}As$ etch-stop layer is removed in hydrofluoric acid and the n^+ layer is metallized with Ni/Ge/Au/Ti/Au [4]. The ohmic contacts are annealed in a nitrogen atmosphere on a hot plate at 425°C. Devices with nominal diameters between 20 μm and 30 μm are thermocompression bonded onto a metallized diamond heat sink. An open package with four quartz standoffs and tapered ribbons was found to be the best choice to minimize parasitic elements of the package and to approach an optimum impedance transformation, although reproducible results require diligent manual work.

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III. Results

All diodes were tested in a full height WR-10 waveguide cavity with a resonant cap on top of the diode and a tunable back short at one flange of the cavity. Both GaAs IMPATT diodes on diamond heat sinks and GaAs TUNNETT diodes on integral heat sinks exhibited state-of-the-art performance in this type of cavity at W-band frequencies [5], [7], and a scaled version of this cavity for a WR-6 waveguide was also used successfully for state-of-the-art GaAs IMPATT diodes and InP Gunn devices at D-band frequencies [8], [9].

In Fig. 1, the RF output power, the dc to RF conversion efficiency, and the oscillation frequency are plotted as a function of the dc bias. The back short of the cavity was adjusted for maximum output power at each bias point. No E-H tuner or other tuning elements in the cavity were used at this point. Two mode jumps occur depending on the bias current and the tuning of the back short. The first jump in frequency from 102.81–103.80 GHz was measured between 75 and 80 mA. The output power increases monotonically up to the maximum applied bias current if the back short is only slightly retuned at each bias point. For the maximum applied bias current, an output power of 50 mW with a corresponding efficiency of 3.6% was obtained at 104.90 GHz. If the position of the back short is changed by more than a quarter wavelength, another frequency jump occurs from about 104.25–104.84 GHz around a bias current of about 130 mA. As can also be seen from Fig. 1, the RF output power increases again monotonically with increasing bias current, but is significantly higher than for the previous position of the back short, and reaches more than 70 mW at the maximum applied bias. Similarly, the back short was only slightly retuned at each bias point. The corresponding dc to RF conversion efficiency clearly saturates and slightly drops down to 4.9% at the maximum applied bias. Another diode yielded an RF output power of more than 60 mW at a still higher oscillation frequency of 111.2 GHz with a corresponding dc to RF conversion efficiency of 5.3%. These RF power levels and dc to RF conversion efficiencies exceed those values of any single discrete device made of group III-V materials (GaAs, InP, etc.) in the same frequency range and those of GaAs and InP Gunn devices in particular [10]–[12]. The highest oscillation frequency of another TUNNETT diode was

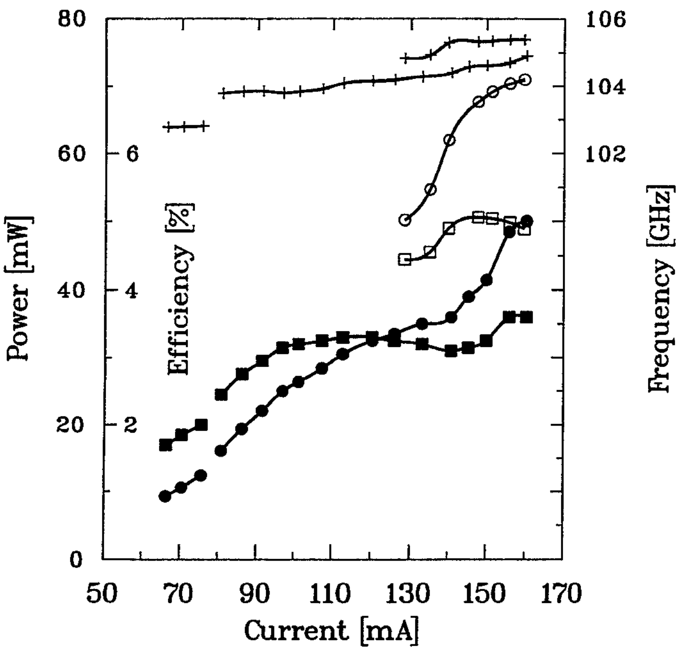
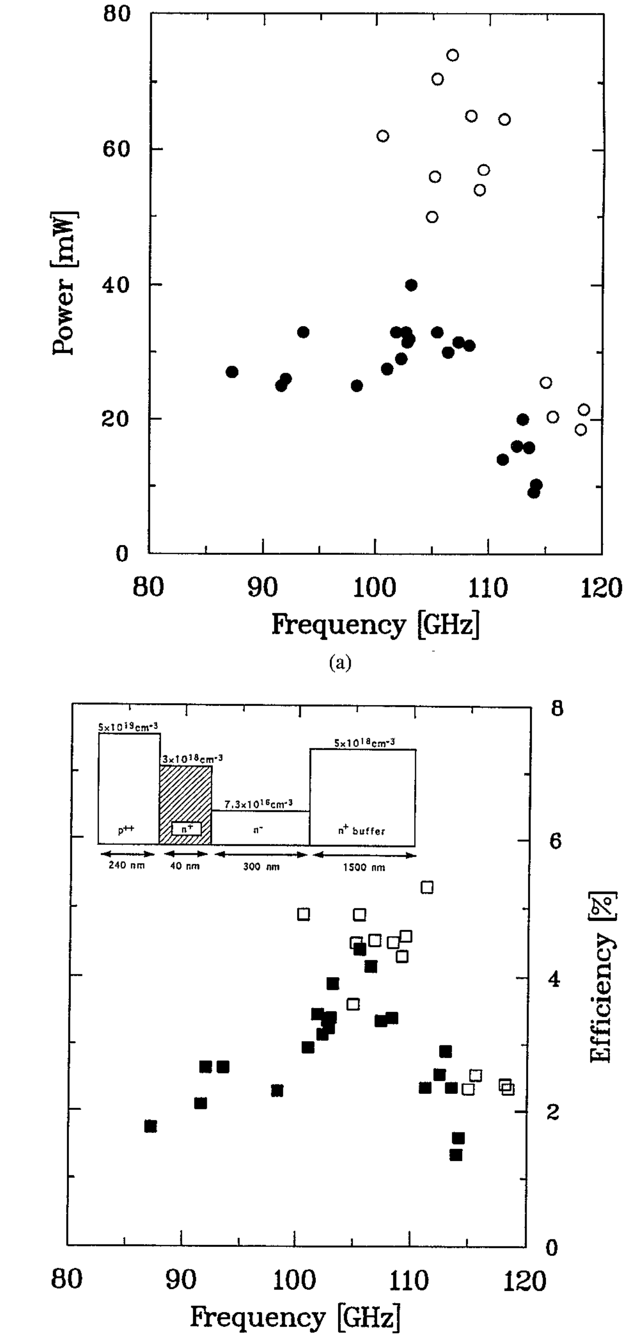


Fig. 1. Output power (o •) efficiency (■ □,) and oscillation frequency (+) of a TUNNETT diode on a diamond heat sink as a function of dc bias.

118.2 GHz with over 20 mW RF output power. Even though these results are still thought preliminary, they already demonstrate that power levels of diodes on diamond heat sinks can approximately be doubled compared to those of diodes on integral heat sinks whereas their efficiencies are up to one and a half times higher than those of diodes on integral heat sinks. This is depicted in Fig. 2 which summarizes the experimental results of the 12 best devices on integral heat sinks and the six devices on diamond heat sinks.

Although the thermal resistance of the GaAs TUNNETT diodes on the diamond heat sinks has not yet been measured, the operating junction temperature can be estimated to be below 200°C by assuming thermal resistances similar to those of GaAs IMPATT diodes with the same nominal diameters and the same fabrication and packaging technology [6], [8]. Lower operating junction temperatures cause higher saturated drift velocities [13], [14]. Therefore, the peak in output power is shifted toward higher frequencies and the maximum observed oscillation frequency increases. Both trends can be seen in Fig. 2 for the diodes on diamond heat sinks and they corroborate the above estimation. Diodes on integral heat sinks from the same batches were also tested in the same waveguide cavity. As an example, RF power levels of 13 mW at 113.2 GHz and 31 mW at 108.25 GHz were obtained. The corresponding dc to RF conversion efficiencies were 2.1% and 3.4%, respectively. Also, as can be seen from Fig. 2, these power levels and efficiencies are comparable to the values reported before and indicate that the increase in RF output power for diodes on diamond heat sinks can be attributed mainly to improved heat dissipation in these diodes, but not to lower contact and series resistances nor to lower losses in the impedance transformation.

In contrast to the diodes on integral heat sinks, all tested diodes on diamond heat sinks clearly show signs of saturation in the dc to RF conversion efficiency near the maximum applied bias, although the RF output power still increases monotonically. This can be attributed mainly to a doping concentration in the drift region of 7.3×10^{16} cm^{-3} (see nominal device structure in the inset of Fig. 2), which was calculated for a current density of 25 $kAcm^{-2}$ [4], but is too low for current densities of more than 40 $kAcm^{-2}$ as at the maximum applied bias of the diode in Fig. 1.



(b)

Fig. 2. Output power (o •) efficiency (■ □) versus oscillation frequency in W-band for different TUNNETT diodes on integral heat sinks (closed symbols) and diamond heat sinks (open symbols). Inset: Nominal doping profile.

The spectra of free-running oscillators with TUNNETT diodes have been found to be clean up to the highest power levels. An example is given in Fig. 3 for a diode with an RF output power of 40 mW at 107.7 GHz. As can be seen in Fig. 3 for a resolution bandwidth of 100 kHz, an excellent phase noise of −94 dBc/Hz was measured at a frequency off-carrier of 500 kHz. At 1 MHz offset, the phase noise drops below −100 dBc/Hz. This phase noise is less than 3 dB above the noise floor of −103 dBm/Hz for the harmonic mixer and spectrum analyzer and, therefore, the actual phase noise at 1 MHz off the carrier is closer to −103 dBc/Hz. With a lower resolution bandwidth of 10 kHz, a phase noise of −77 dBc/Hz and −84 dBc/Hz

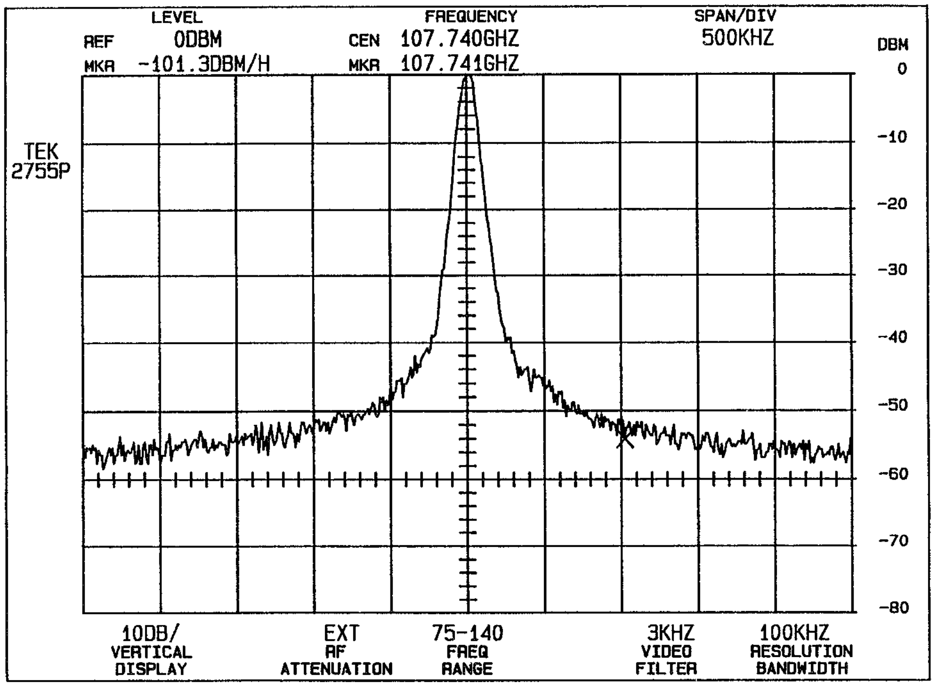


Fig. 3. Spectrum of a GaAs W-band TUNNETT diode free-running oscillator, power level 40 mW, center frequency 107.738 GHz, vertical scale 10 dB/div, horizontal scale 200 kHz/div, BW 10 kHz, VBW 3 kHz.

was measured at a frequency off-carrier of 100 kHz and 200 kHz, respectively. The loaded Q value of the cavity was determined to be 60 using a self-injection locking technique with a tunable short and a high directivity directional coupler (coupling value = 20 dB). The measured phase noise shows a corner frequency of about 100 kHz in the $1/f$ flicker noise, which is quite low and similar to the corner frequency of the $1/f$ flicker noise in GaAs W-band IMPATT diodes around 94 GHz [15].

The I/V characteristics of a TUNNETT diode in the oscillating mode and nonoscillating mode at two different temperatures of the cavity in Fig. 4 clearly exhibit a negative temperature coefficient of the bias voltage up to operating conditions and indicate that the carrier injection is predominantly through interband tunneling. The portion of the dc bias that is purely generated by tunneling can be roughly estimated from the same I/V curves in double-logarithmic scale. These curves exhibit a straight section for bias voltages between about 3 V and 5 V as depicted in Fig. 4. If a constant junction temperature of $T = 300$ K is assumed, the extrapolation of this linear section gives a current of more than 20 mA as induced by tunneling at the maximum applied bias voltage. The maximum applied bias raises the operating junction temperature in this diode closer to 470 K. Such a junction temperature more than doubles the current values at constant bias voltages, as can be seen for the straight section in Fig. 2 of Reference 4. This leads to the conclusion that, for the diode of Fig. 4, more than one third, i.e., 45 mA, is generated through tunneling at the maximum bias current of 130 mA and an estimated operating junction temperature of 470 K. This is in excellent agreement with the results of detailed device simulations [16], which show carrier injection mainly through tunneling and a back bias effect comparable to the one in Fig. 4. A multiplication factor of less than three, which can be derived from the aforementioned ratio, is significantly lower than the factor eight, which was reported for a similar structure at somewhat lower frequencies [17]. The strong back bias effect in the I/V-characteristics, together with the clean spectrum, suggest future applications of a TUNNETT diode in a self-mixing oscillator.

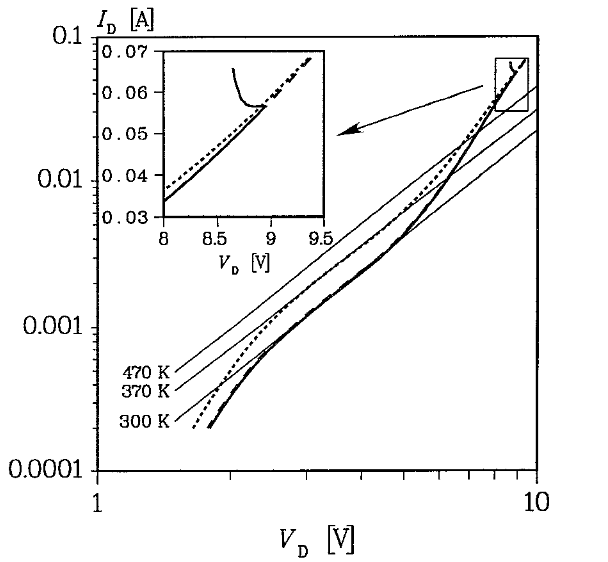


Fig. 4. Current-voltage characteristics of a TUNNETT diode at the onset of RF oscillations. ________: oscillating mode at 300 K. - - - -: nonoscillating mode at 305 K. ...... : nonoscillating mode at 475 K.

IV. Conclusion

Operation of GaAs TUNNETT diodes on diamond heat sinks was demonstrated for the first time. RF power levels over 70 mW and dc to RF conversion efficiencies up to 5.3%, measured between 104 GHz and 111 GHz, exceed those values of InP and GaAs Gunn devices in the same frequency range. GaAs TUNNETT diode free running oscillators exhibit clean spectra with an excellent phase noise of −94 dBc/Hz at a frequency off-carrier of 500 kHz and an RF output power of 40 mW. The device structure was originally designed for best operation at a current density of 25 kAcm^{-2} on an integral heat sink. However, diodes on diamond heat sinks reach current densities above

40 $kAcm^{-2}$, which leads to saturation in the dc to RF conversion efficiency. Therefore, still better performance can be expected from diodes specifically designed for operation on a diamond heat sink.

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Modelling Drain and Gate Dependence of HEMT 1–50 GHz, Small-Signal *S*-Parameters, and D.C. Drain Current

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***Abstract*— We present refinements to a previously validated HEMT model that improves the model's accuracy as a function of drain bias for simulating d.c. drain current and 1–50 GHz, small-signal *S*-parameters. By comparing simulation data with experimental data for a 0.4-μm-gate pseudomorphic HEMT, we have been able to establish the accuracy of the refined model, which predicts the device's d.c. current and *S*-parameters as a function of the applied drain and gate biases to within an accuracy of ~5%. The core of the model and, in particular, its bias dependence, are directly dependent on the HEMT wafer structure and the physical gate length.**

I. INTRODUCTION

In an earlier paper [1], we presented a semi-physical HEMT model based on a 1-D Poisson/Fermi-Dirac solver and a variable boundary electron transport model that produced a good fit to measured *S*-parameter data as a function of the gate bias for frequencies between 1 and 25 GHz. We later established [2] that the model in [1] was also useful for simulating d.c. drain current and 1–50 GHz *S*-parameters as a function of the gate bias. However, as will be shown here, this model does not predict the *S*-parameter (especially S_{22}) drain-bias dependency simultaneously.

In this paper, we present three refinements to the existing model which result in a significant improvement in the model's accuracy as a function of drain bias (especially S_{22}). We demonstrate the capacity of the refined model to simulate the d.c. drain current and the 1–50 GHz, small-signal *S*-parameters as a function of both the drain bias from near zero to well into the saturated region, and the gate bias from near pinch-off to well into forward bias. *S*-parameter and d.c. drain-current predictions are compared with experimental data measured on a 0.4 × 250 μm pseudomorphic HEMT similar to that described in [2] at seven drain biases ($V_{ds} = 0.1, 0.5, 1.0, 1.5, 2.0, 2.5$ and 3.0 V) and nine gate biases ($V_{gs} = -1.0, -0.8, -0.6, -0.4, -0.2, 0.0, +0.2, +0.4$ and $+0.6$ V), a total of 63 different biases. The device pinch-off is approximately -1.1 V.

The model represents a HEMT by an equivalent circuit constructed from lumped elements as shown in Fig. 1 in [1]. In the model, we used the composition of the HEMT wafer (including layer thicknesses, compositional fractions and doping density profile), and the gate length and width, as described in Section II and [1], to determine the gate- and drain-bias dependence of the transconductance (g_m), output conductance (g_{ds}), gate capacitance (C_{gs}) and gate-drain capacitance (C_{gd}). *S*-parameter and d.c. drain current dependence on both gate and drain bias are solely due to the bias dependence of these four elements.

II. MODEL REFINEMENTS

We have made three refinements to the existing model to improve the fit to measured data as a function of drain bias while maintaining a good gate-bias fit. This added three new parameters to the

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