PERFORMANCE OF GAAS TUNNETT DIODES AS LOCAL OSCILLATOR SOURCES

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Abstract

Improved heat dissipation in TUNNETT diodes on diamond heat sinks has lead to RF power levels of up to 95 mW and dc to RF conversion efficiencies of up to 5.9 % between 104 GHz and 111 GHz. These values for power and efficiency exceed those of Gunn devices in this frequency range and together with the clean spectra and demonstrated phase-locking capabilities make GaAs TUNNETT diodes suitable for local oscillator applications. TUNNETT diodes in second-harmonic mode yielded an RF output power of up to 0.6 mW between 210 GHz and 220 GHz. Diodes on diamond heat sinks show clear signs of saturation in the dc to RF conversion efficiency, which can be attributed to about 60 % higher bias current densities than originally assumed in the structure design. Extensive numerical simulations using a computer program with an energy-momentum model show good agreement between predictions and experimental results and can provide realistic estimates for the RF performance at higher submillimeter-wave frequencies.

1. Introduction

Tunnel injection transit-time (TUNNETT) diodes for power generation at high frequencies were first proposed in 1958 [1], but the lack of refined growth techniques required for the high doping levels and steep transitions in the doping profile impeded significant power levels in CW operation of TUNNETT diodes until a few years ago. Commercially available systems for epitaxial growth, such as molecular beam epitaxy (MBE) or metallorganic chemical vapor deposition (MOCVD), now routinely provide the necessary material quality. Better understanding of the device characteristics have lead from the first experimental results [2,3] to RF power levels of up to 95 mW at 104.2 GHz, which clearly demonstrate the potential of GaAs TUNNETT diodes as powerful oscillators at submillimeter-wave frequencies. This paper reviews the fabrication processes and their impact on the device performance and compares the experimental results with the predictions of detailed device simulations.

2. Fabrication technologies and their impact on the RF performance

W-band GaAs TUNNETT diodes were first designed for operation on integral heat sinks at oscillation frequencies around 100 GHz. A versatile selective etching technology [4,5] was employed to fabricate diodes on integral heat sinks. These diodes yielded an RF output power of up to 40 mW around 103 GHz and dc to RF conversion efficiencies over 4 %. Since neither RF output power nor dc to RF conversion efficiency saturated up to the maximum applied bias, diodes on integral heat sinks were considered to be thermally limited and RF power levels were expected to increase significantly on better heat sinks. Therefore, a selective etching technology that has been successfully used to fabricate GaAs W- and D-band impact ionization avalanche transit-time (IMPATT) diodes on diamond heat sinks was adopted [5,6]. This well-established fabrication process was slightly modified [7] to obtain diodes on integral heat sinks as well as diodes for mounting on diamond heat sinks in one batch. All GaAs TUNNETT diodes were packaged in the same open structure with quartz standoffs and tapered leads and tested in several identical full-height waveguide cavities with resonant caps for frequency and impedance tuning.

RF output power levels up to 95 mW and corresponding dc to RF conversion efficiencies up to 5.9 % were achieved with diodes on diamond heat sinks, whereas diodes on integral heat sinks of the same batch showed performance similar to previously tested diodes. Figure 1 summarizes the best results of all tested diodes on diamond heat sinks and compares them with the best results of about 70 % of the tested diodes on integral heat sinks. RF power levels are more than doubled through the improved heat dissipation whereas dc to RF conversion efficiencies typically increase by a factor of 1.5. All diodes on diamond heat sinks exhibit clear signs of saturation in the efficiency and, therefore, must be considered electronically limited.

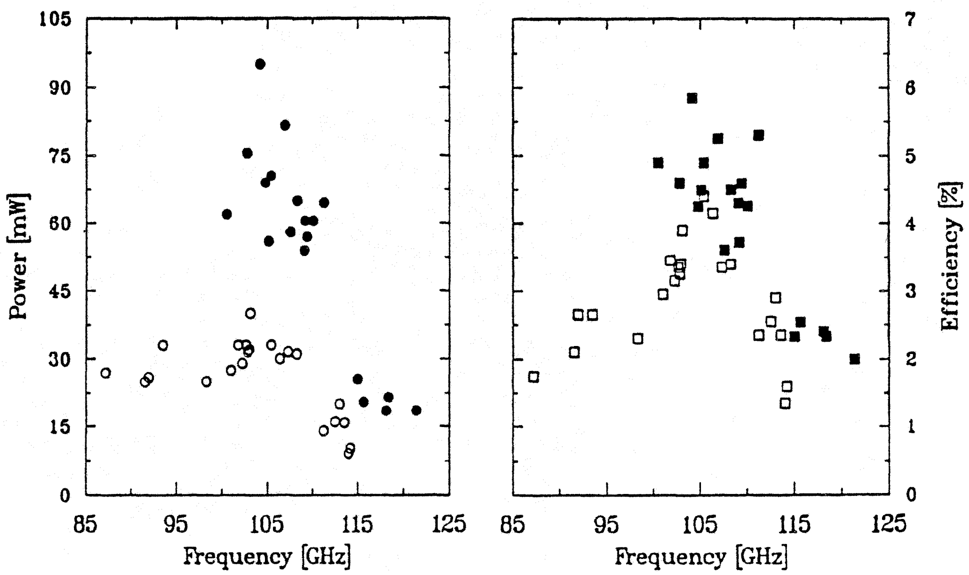

Fig. 1: RF output power (●, ○) and dc to RF conversion efficiency (■, □) vs. oscillation frequency for GaAs TUNNETT diodes on integral (closed symbols) and diamond (open symbols) heat sinks.

A detailed thermal analysis that also included the experimental results of W- and V-band IMPATT diodes predicts thermal resistances between 80 KW^{-1} and 100 KW^{-1} for nominal diameters between 20 μm and

25 μm. Since the dc input power for diodes on diamond heat sinks typically ranges from 1.4 W to 1.7 W for a maximum RF output power above 50 mW, the operating junction temperature can be safely assumed to be well below 200 °C for a cavity at room temperature.

Different diodes on diamond heat sinks were more similar in RF performance than their counterparts on integral heat sinks, but several pairs of diodes on both types of heat sinks were sufficiently matched to attempt power combining in a dual-cavity configuration [8]. Combining efficiencies were typically around 80 % and more than 140 mW were measured with the best pair on diamond heat sinks at an oscillation frequency of 103.9 GHz. In this case the overall dc to RF efficiency was 4.3 % and the combining efficiency exceeded 85 %.

GaAs TUNNETT diodes can be phase locked as shown by the spectrum in Figure 2 for a configuration with a narrow loop bandwidth (< 25 kHz) [9]. The spectrum was measured at the intermediate frequency of the phase-locked loop to bypass the upconverted phase noise of the spectrum analyzer.

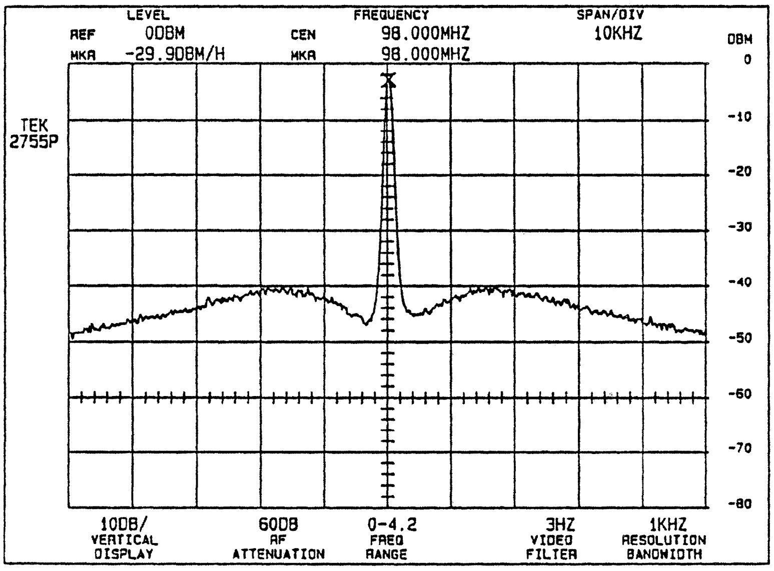

Fig. 2: Spectrum of a phase-locked GaAs TUNNETT diode oscillator at 107.758 GHz, power level 40 mW, center frequency 98.000 MHz, vertical scale 10 dB/div, horizontal scale 10 kHz/div, BW 1 kHz, VideoBW 3 Hz.

The improved heat dissipation on diamond heat sinks also increased the available RF output power in second-harmonic mode and up to 0.6 mW was measured at 209.5 GHz. A similar setup for these measurements was reported recently [10], and it should be noted again that the available RF power levels of diodes on both types of heat sinks might be significantly higher. Figure 3 shows the measured spectrum of a free-running TUNNETT diode oscillator in second-harmonic mode with an RF output power of 0.57 mW. This demonstrates that clean spectra can be achieved in second-harmonic mode although the noise floor of the harmonic mixer and spectrum analyzer inhibit accurate phase noise measurements. Oscillations up to 235 GHz in second-harmonic mode are the highest reported to date for CW operation of any GaAs transit-time device.

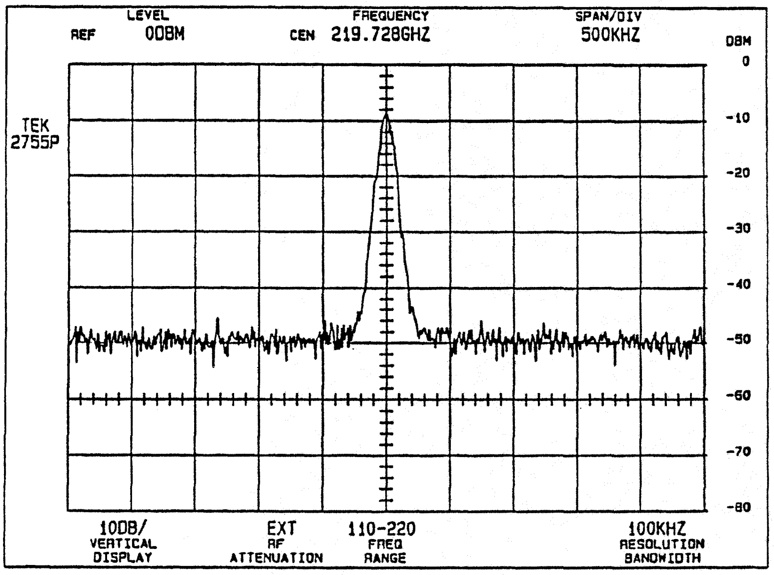

Fig. 3: Spectrum of a GaAs TUNNETT diode free-running oscillator, power level 0.57 mW, center frequency 219.728 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, BW 100 kHz.

3. Predicted performance vs. experimental results

Numerical simulation programs that are based on the drift-diffusion and energy-momentum transport models and include interband tunneling have been developed to predict the performance of two-terminal transit-time devices. A detailed description of the models can be found in Reference 11 and an accompanying paper [12] describes its application to InP transit-time devices. The material parameters such as band gap lowering or drift velocities, diffusion coefficients, ionization and tunneling rates of electrons and holes, need to be chosen carefully to ensure realistic estimates from the simulations. Diffusion coefficients and drift velocities were taken from Monte-Carlo simulations and "curve fitted" to published or unpublished results of measurements [13] or simulations. The high-field ionization rates were assumed to be equal and derived from breakdown voltages of various GaAs IMPATT diodes [6,13]. Previous simulations of GaAs W- and D-band IMPATT diodes predicted bias voltages typically within ± 5 % of the measured values at the maximum RF output power and provided good agreement between predicted and measured RF performance as well if contact resistances were taken into account [14]. Tunneling rates were based on a simple theoretical model [15] and adjusted accordingly to match the bias voltages of diodes on integral heat sinks as well as on diamond heat sinks typically within 10 %. In addition to an accurate prediction of the bias voltages, the chosen tunneling rates ensure that about the same portion of the total bias current is generated through tunneling as can be extrapolated from the measured current-voltage characteristics under operating conditions [7].

The aforementioned fabrication process leads to some undercut in the diodes and impedes an accurate measurement of the actual diode diameter unless the packaged diode is destroyed. Therefore, the current densities were estimated to be in range of 40 $kAcm^{-2}$ to 45 $kAcm^{-2}$. Figure 4 shows the predicted dc to RF conversion efficiencies as a function of the RF voltage for the lower and upper limit of the estimated current densities. The terminals of the diode are not accessible inside the package at millimeter-wave frequencies to measure the actual RF voltage between the p^+ and n^+ contacts of the diode or to verify the embedding impedance. Although the embedding impedance could be determined with acceptable accuracy using scale models and S-parameter measurements or could be calculated using appropriate models for the resonant cap structure or the versatile HFSS (high-frequency structure simulator by Hewlett Packard) software package, the strong back bias effect in TUNNETT diodes itself gives an accurate estimate of the actual RF voltage across the terminals. The predicted change of the bias voltage in percent is plotted in Figure 4 as a function of the RF voltage and compared with the measured change of a diode that yielded an RF output power of more than 80 mW at an oscillation frequency of 106.9 GHz. The predicted dc to RF conversion efficiencies between 5.43 % and 5.61 % for a typical RF voltage of 6.5 V are close to the measured value of 5.3 % for this particular diode and actually tend to saturate as

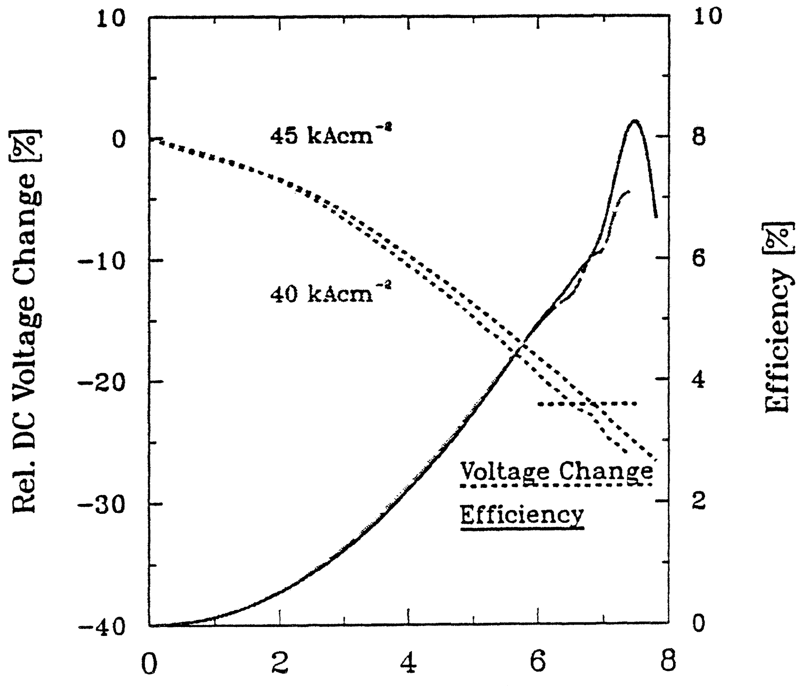

Fig. 4: Predicted dc to RF conversion efficiency and relative change of bias voltage as a function of RF voltage.

seen in all tested diodes on diamond heat sinks. The predicted RF power levels exceed the measured values of the three best diodes by no more than 2 dB and demonstrate the validity of the simulations. The simulations also reveal that the peak in the injected current occurs within 10 degrees of the maximum in the RF voltage and that the mode of operation is very close to the mode of in-phase carrier injection as proposed in Reference 1. The good agreement between experiment and numerical simulations shows that these simulation programs can be used as a powerful tool to find a more optimized device structure and to predict the performance at higher submillimeter-wave frequencies [11].

Acknowledgment

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