THE POTENTIAL OF InP IMPATT DIODES AS HIGH-POWER MILLIMETER-WAVE SOURCES: FIRST EXPERIMENTAL RESULTS

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Abstract

Extensive simulations of GaAs and InP transit-time diodes clearly show the advantages of the InP material system. RF power levels of more than 1 W as well as dc-to-RF conversion efficiencies of more than 18 % around 100 GHz can be expected from optimized diodes. The fabrication process was adopted from the process for InP Gunn devices on integral heat sinks. Typical RF power levels were around 80 mW from about 60 GHz to 80 GHz with corresponding dc-to-RF conversion efficiencies ranging from 3 % to 4 %. The best device yielded more than 110 mW (more than 5 %) at 64.7 GHz, 82 mW (3.7 %) at 79 GHz and 55 mW (2.4 %) at 84.8 GHz. These preliminary experimental results are better than those of single-drift flat-profile GaAs IMPATT diodes on integral heat sinks and also indicate the strong potential for millimeter-wave InP IMPATT diodes.

Summary

InP impact ionization avalanche transit-time (IMPATT) diodes were long thought of as excellent candidates for high-power high-efficiency power sources at millimeter-wave frequencies [1-3], but only a few experimental results have been reported in the literature [4]. These results are from diodes in pulsed-mode operation, and diodes for CW operation have only been described in detail at microwave frequencies. Although these results were encouraging, experimental success was limited by the lack of adequate material growth techniques for p and n type layers and the lack of established fabrication and ohmic contact technologies.

Interband tunneling was incorporated in the equations of an energy-momentum model to simulate transit-time devices, and excellent agreement was found between predictions and simulations of GaAs IMPATT and tunnel injection transit-time (TUNNETT) diodes [5-7]. Material parameters mainly were either taken from published experimental results or derived from Monte-Carlo simulations of bulk material under uniform conditions and matched experimental results where possible. Compared to GaAs, InP shows more favorable material parameters such as higher thermal conductivity, higher carrier drift velocities, lower tunneling rates, lower ionization rates at lower electric field, and higher ionization rates at higher electric fields. Furthermore, ionization rates in InP do not show a pronounced tendency to saturate as seen in GaAs. These material parameters allow more confined avalanche regions and longer drift regions in millimeter-wave InP IMPATT diodes and, consequently, lead to higher impedance levels, RF power levels and conversion efficiencies in these diodes. Extensive device simulations clearly show the advantages of the InP material system. Figure 1 summarizes some of the predictions, and RF power levels of more than 1 W as well as dc-to-RF conversion efficiencies of more than 18 % around 100 GHz can be expected from optimized diodes.

To establish a fabrication process for InP IMPATT diodes, to optimize the technology for ohmic contacts on

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p type layers, and to verify some of the predictions, single-drift flat-profile structures were designed and grown in an in-house CBE system. This EPI Gen II system uses TMIn, TEG, 100 % AsH_3 and 100 % PH_3 for growing the InP and lattice-matched InGaAs layers. Conventional solid source Si and Be are evaporated from Knudson effusion cells for n and p type dopants, respectively. Arsine and phospine are co-injected from a common low-pressure cracker. The conditions for the growth of InGaAs and InP have been co-optimized [8]. Appropriate gas switching sequences have been established to minimize the intermixing of the Group V constituents at the InP/InGaAs heterojunction [9].

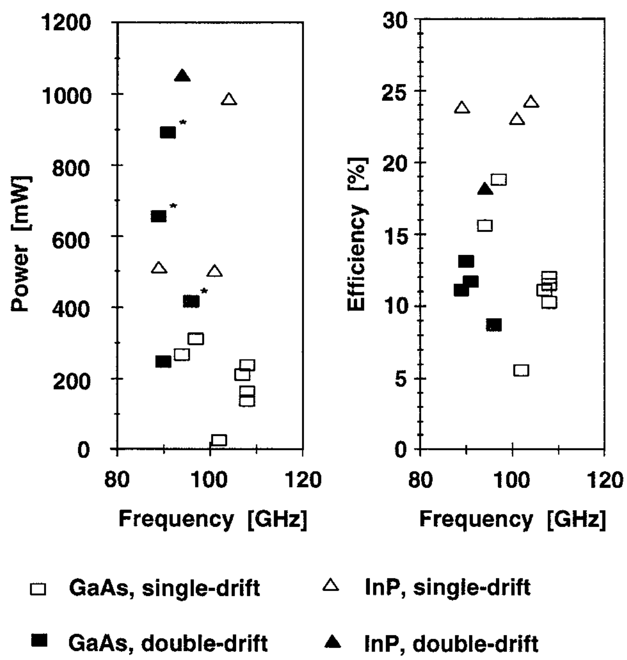

Figure 1: Predicted performance of InP and GaAs IMPATT diodes.

The fabrication process employs selective etching and, with some minor modifications, was adopted from the process for InP Gunn devices on integral heat sinks [10]. In this process, the ohmic contact for the n^+ top epitaxial layer on the side of the heat sink had to be replaced by a standard Ti/Pt/Au contact for the p^+ top layer on the side of the heat sink. The other annealed Ni/Ge/Au/Ti/Au contact [10] remained unchanged. Diodes on integral heat sinks with nominal diameters between 40 μm and 50 μm were mounted and packaged using four quartz standoffs and tapered leads. Several diodes were tested in standard full-height WR-15 and WR-10 waveguide versions (V-band, 50-75 GHz; W-band, 75-110 GHz) of a cavity with a resonant cap on top of the diode. Diodes from a wafer with a thin, highly p doped InP layer and a 0.45 μm long active region doped $1.5 \times 10^{17}\ cm^{-3}$ showed very promising results. Typical RF power levels were around 80 mW from about 60 GHz to 80 GHz with corresponding dc-to-RF conversion efficiencies ranging from 3 % to 4 %. Figure 2 shows RF output power and oscillation frequency of the best diode as a function of the dc input power. No saturation in the RF power can be observed up to the maximum applied input power of 2.2 W. This diode yielded more than 110 mW (more than 5 %) at 64.7 GHz, 82 mW (3.7 %) at 79 GHz and 55 mW (2.4 %) at 84.8 GHz, and the RF output power was thermally limited at each frequency. The highest oscillation frequency of another diode was 87 GHz.

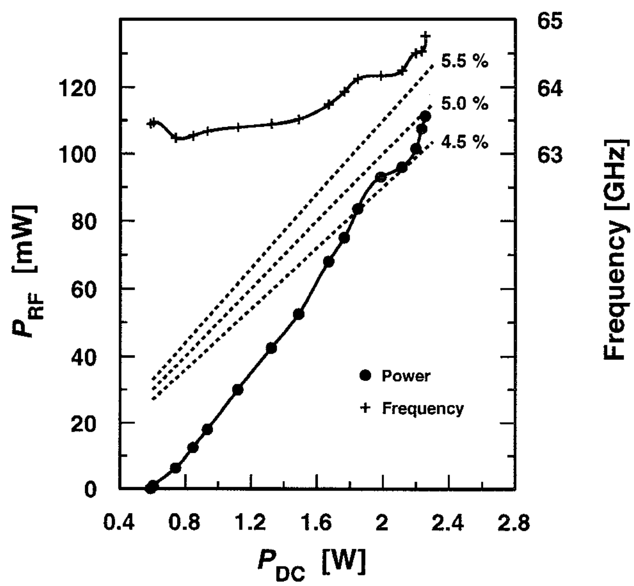

Figure 2: Measured performance of a millimeter-wave single-drift InP IMPATT diode.

Although these InP diodes lack a heavily p doped lattice-matched InGaAs cap layer for improved ohmic contacts and show at least twice the series resistance [11] of GaAs single-drift diodes with comparable areas and operating frequencies, their RF output power levels are higher at the same input power levels. The diodes in References 12 and 13, however, are mounted on diamond heat sinks, which allow much higher dc input power levels, and, therefore, yield higher RF output power at maximum dc bias. Half the current densities of GaAs IMPATT diodes at the onset of oscillations indicate higher impedance levels in InP IMPATT diodes and agree with more confined avalanche regions as seen in the above described simulations. Since RF power levels do not show saturation and are considered thermally limited, much higher power levels can be expected from these diodes when mounted on diamond heat sinks. To the authors' knowledge, this is the first demonstration of CW operation of millimeter-wave InP IMPATT diodes, and the oscillation frequencies are the highest reported to date from these diodes.

Subsequent re-runs of the simulation programs were based on the actual doping profile of the InP single-drift flat-profile IMPATT diode and were performed at the maximum bias current for the above mentioned measured RF power levels. The error between measured and predicted bias voltage is less than 3 %. At an operating frequency of 65 GHz, an RF output power of 190 mW and a corresponding dc-to-RF conversion efficiency of 7.5 % are predicted, if a typical load resistance of 0.6 Ω and a total specific contact resistance of $4 \times 10^{-6}\ \Omega cm^2$ for p and n type contacts together are assumed. The predicted RF power remains above 140 mW at a conversion efficiency of more than 5.4 % if delivered into the higher load resistance of 1 Ω. At the maximum bias for the diode on an integral heat sink, RF power generation is predicted up to a maximum oscillation frequency of approximately 90 GHz, which matches closely the above experimental findings. If the same diode structure is assumed to be mounted on a diamond heat sink and operated at a bias current density of $25\ kAcm^{-2}$, much higher power levels and operating frequencies are predicted. As an example, RF power levels of more than 1.5 W with corresponding dc-to-RF conversion efficiencies of more than 11 % are predicted at a frequency of 65 GHz assuming the same total specific contact resistance of $4 \times 10^{-6}\ \Omega cm^2$ and a load resistance of 1 Ω. In this case, thermal limitations for large diameters even on a diamond heat sink account for the size of the diodes and available RF output power. For good performance at higher frequencies however, the contact resistance needs to be improved. If the total specific contact resistance is reduced to $2 \times 10^{-6}\ \Omega cm^2$, RF power levels of more than 700 mW and corresponding dc-to-RF conversion efficiencies of more than 10 % are predicted for 80 GHz. Figure 3 summarizes the predictions for this InP IMPATT diode structure on a diamond heat sink at operating frequencies between 65 GHz and 85 GHz and the reduced contact resistance.

Preliminary experimental results and predictions based on this experimental diode structure indicate the strong potential for millimeter-wave InP IMPATT diodes.

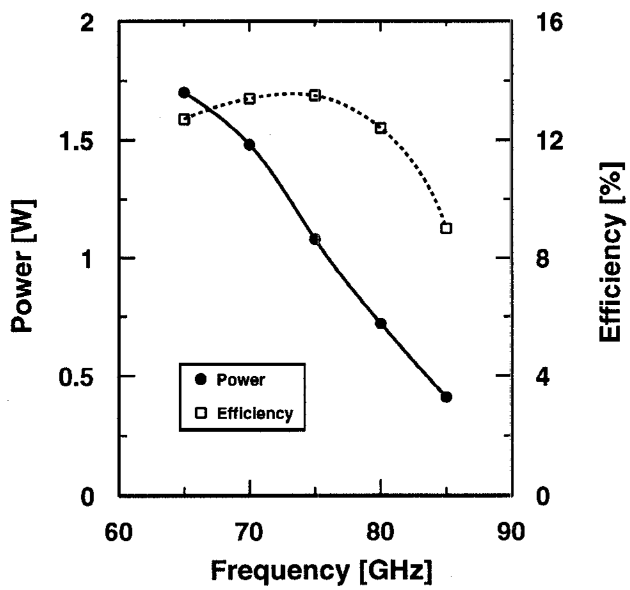

Figure 2: Predicted performance for a millimeter-wave single-drift InP IMPATT diode on a diamond heat sink.

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