HIGH-FREQUENCY INP GUNN OSCILLATORS: SIMULATION AND EXPERIMENT

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Abstract

A self consistent ensemble Monte Carlo model for the simulation of InP Gunn devices has been developed and was presented in an earlier report [1]. The choice of the InP material parameters has been found to be critical to the validity of the model. Appropriate parameters were estimated by comparing the model predictions and experimental results. However, only experimental data around 83 GHz were available at that time.

Recently, very promising experimental results were obtained from 1 μm InP Gunn structures. Two doping profiles were chosen: a uniform doping of 2.5×10^{16} cm^{-3} and a graded doping increasing linearly from 7.5×10^{15} cm^{-3} at the cathode to 2.0×10^{16} cm^{-3} at the anode. Diodes having the flat doped structure gave 33 mW of RF power at 108.3 GHz while diodes with the graded structure yielded 20 mW at 120 GHz, 10 mW at 136 GHz and 8 mW at 155 GHz. Low measured Q values indicated that these results correspond to a fundamental mode of operation. Details of the experimental results will be presented in a separate paper. With this additional experimental data, a better estimation of InP material parameters is possible. A comparison of the resulting Monte Carlo model predictions and the experimental results is carried out. The potential of InP Gunn devices for power generation in the D-band (110 GHz - 170 GHz) is then discussed.

[1] R. Kamoua, H. Eisele, J.R. East, G. I. Haddad, G. Munns, and M. Sherwin, "Modeling, Design, Fabrication, and Testing of InP Gunn Devices in the D-band ", *Third International Symposium on Space Terahertz Technology* March 24-26, 1992, Ann Arbor, MI.

1 Introduction

InP is recognized to have superior characteristics compared to GaAs for power generation in the millimeter wave region [1, 2]. Fundamental mode operation up to 110 GHz has been achieved with InP Gunn devices whereas GaAs Gunn devices are believed to operate in second harmonic mode at around 94 GHz [3]. This paper reports on the development of InP Gunn devices in the D-band (110 GHz - 170 GHz).

A physical model based on the Monte Carlo technique is developed to simulate, design, and predict the performance of Gunn structures for high frequency operation. A characteristic of the Monte Carlo method, as applied to the simulation of semiconductor devices, is the requirement of accurate values for a large number of material parameters. This is not an easy task, especially for the less technologically developed compounds such as InP. The typical material parameters given in the literature have been found to be inadequate in predicting our experimental data. Based on comparisons between the model and experimental results from a well characterized InP Gunn diode, more accurate material parameters were estimated.

2 Simulation Model

The self-consistent Ensemble Monte Carlo model is used to estimate the performance of InP Gunn devices at millimeter wave frequencies. This model is an extension of the one-particle Monte Carlo technique [4]. The simulation algorithm monitors the evolution in real space and momentum space of an ensemble of electrons. The simulation time is partitioned into time steps ($\Delta t = 5 \times 10^{-15}$ sec), and each time step is terminated by a call to a Poisson equation solver in order to update the electric field. In each time step, every electron is submitted to successive free flights terminated by a scattering process which is selected using a random number generator. When all electrons are simulated for one time step, the carrier density is calculated and the electric field is updated.

To predict the performance of a particular Gunn structure a sinusoidal RF voltage is applied across the device and the current response is simulated over many RF periods (about 10). A Fourier analysis of the resulting particle current density gives the current's fundamental component which is subsequently used to determine the device admittance per unit area. To estimate the RF output power, the Gunn device is assumed to be connected to a resonant circuit represented by a load resistance and a resonating inductance. A series resistance is included in the equivalent circuit to take into account effects of contact resistances, any substrate resistances, and skin effect losses.

3 Estimation of InP Material Parameters

In this section, the material parameters needed for the Monte Carlo model are estimated. The accuracy of the model is strongly dependent on the accuracy of the material parameters used. Unfortunately, a wide range of values is given in the literature. In particular, some of the material parameters that are important to the Gunn effect have the following range of values ([5, 6, 7, 8, 9]):

$\Gamma - L$ valley separation (eV)	0.4	$\longleftrightarrow$	0.832,
L valley effective mass ratio ($\frac{m}{m_0}$)	0.26	$\longleftrightarrow$	0.4,
$\Gamma - L$ coupling constant ($\times\ 10^9$ eV/cm)	0.1	$\longleftrightarrow$	2.5,
$\Gamma - X$ coupling constant ($\times\ 10^9$ eV/cm)	0.43	$\longleftrightarrow$	1.0.

There is more than an order of magnitude uncertainty in the Γ to L intervally coupling constant. The appropriate material parameters are determined by comparing measurements at high frequencies with results predicted by the model. The structure considered for comparison is shown in figure 1. It has a 1.7 μm long active 1×10^{16} cm^{-3}, a 0.1 μm cathode region doped at 3×10^{17} cm^{-3}, and a 0.2 μm anode region doped at 3×10^{17} cm^{-3}.

An InP wafer with this structure has been processed. Diodes with various sizes have been mounted on copper heat sinks. Tapered leads were thermocompression bonded to

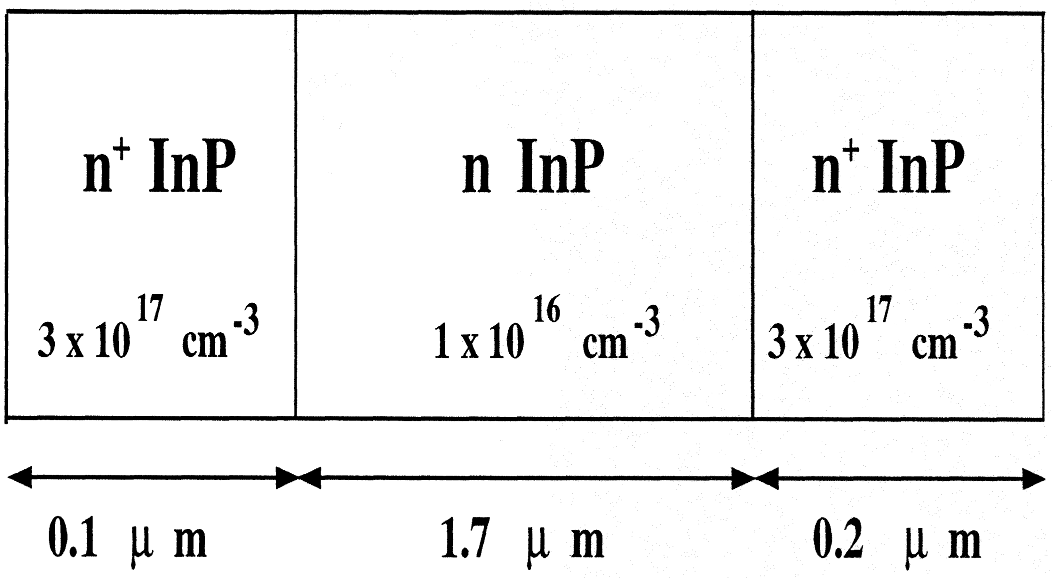

Figure 1: Gunn structure used in the model to determine more accurate InP material parameters.

the diode and to four metallized quartz standoffs. For some diodes, a metallized quartz ring was used instead of the standoffs.

A 50 μm diode was tested in a W-band resonant cavity with the following results: 40.0 mW output power at an oscillation frequency of 80.0 GHz and an efficiency of 1.6 %. The bias voltage was 5.0 V and the dc current was 500 mA. The structure shown in figure 1 is simulated using the Monte Carlo model. The dc bias voltage is set to 5.0 V and the temperature to 450 K. A starting set of material parameters is assumed and is taken from various sources in the literature. These parameters are listed in the second column of table 1 and constitute the the initial parameter set. No oscillations were obtained with these values for frequencies ranging from 75 GHz to 120 GHz. It appears that the $\Gamma - L$ intervalley energy separation of 0.8 eV is too large.

A systematic procedure for changing the values of the different parameters is adopted. In particular the values used for the intervalley energy separation and the effective mass in each valley are targeted. It is expected that the occurrence of oscillations will be enhanced if the electron effective mass in the satellite valleys is increased, the intervalley

parameter		typical value	this paper
Energy Separation (eV)	Γ-L	0.832	0.45
	Γ-X	1.5	0.775
Effective Mass ($\frac{m}{m_0}$)	Γ	0.082	0.082
	L	0.26	0.5
	X	0.325	0.5
Nonparabolicity factor (1/eV)	Γ	0.83	0.83
	L	0.23	[illegible].23
	X	0.38	0.38
Intervalley Coupling Constant (10^9 eV/cm)	Γ-L	0.506	1.0
	Γ-X	0.498	1.0
	L-X	0.468	0.468
	L-L	0.575	0.575
	X-X	0.28	0.28
Acoustic Deformation Potential (eV)	Γ	7	5
	L	7	5
	X	7	5
LO Phonon Energy (eV)	Γ	0.043	0.043
	L	0.0423	0.0423
	X	0.0416	0.0416
Static Dielectric Constant		12.61	12.61
Optical Dielectric Constant		9.61	9.61

Table 1: InP material parameters: typical values and values used in this paper.

energy separation is reduced, and the scattering rates to the satellite valleys are increased. The combined effect of these changes is to increase the transfer to the satellite valleys for the same bias voltage and reduce the average electron velocity at high electric fields. As a consequence a larger negative differential mobility is obtained which is more favorable for nucleating space charge layers. Upon making the above changes a set of parameters, listed in the last column of table 1, was obtained which will be shown to yield good agreement with the experimental results.

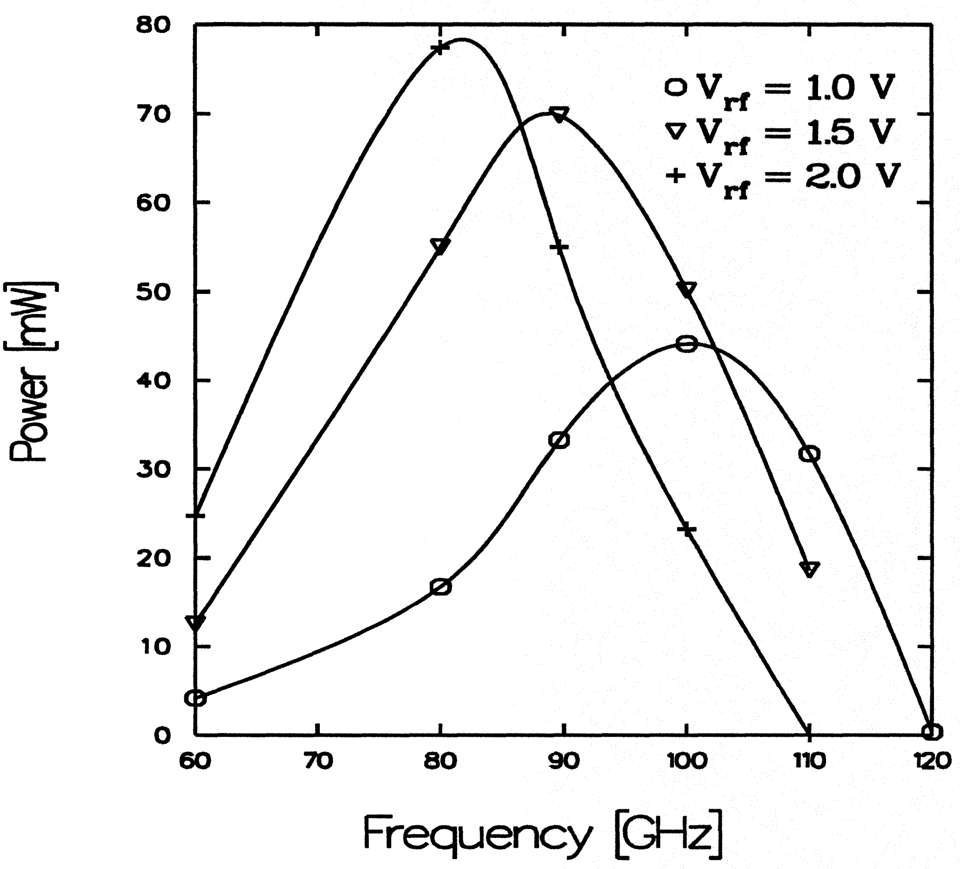

Figure 2: Predicted output power as a function of frequency from the W-band structure for three RF voltages (1.0 V, 1.5 V, and 2.0 V). The dc voltage is 4.0 V and the operating temperature is 450 K.

In order to compare the theoretical predictions with the experimental results, the diameter of the device is set to 50 μm which corresponds to the size of the tested diode. As a result, the load resistance of the resonant circuit is adjusted until the oscillation condition is satisfied. This procedure is repeated at various frequencies and RF voltages. Figure 2 shows the predicted output power as a function of frequency for three RF voltages (1.0 V, 1.5 V, and 2.0 V). At a given RF voltage, the power curve exhibits a peak as a function of frequency. This peak occurs at 100 GHz for an RF voltage of 1 V and has a value of 43 mW. As the RF voltage amplitude is increased, the peak value increases and shifts to lower frequencies: 90 GHz for an RF voltage of 1.5 V and 80 GHz for an

RF voltage of 2.0 V. A peak is obtained because the power is directly proportional to the RF voltage amplitude and the device equivalent negative conductance. The conductance decreases as the RF voltage is increased, therefore the product of the conductance and the RF voltage amplitude exhibits a maximum. The simulation predicts oscillations in a wide-band of frequencies from 60 GHz to 110 GHz. This is in agreement with the known behavior of Gunn devices as well as our experimental results. The model predicts up to 80 mW at 80 GHz with an RF voltage of 2.0 V.

It is now possible to compare the experimental with the theoretical results. Referring to figure 2 reveals that the predicted output power at 80 GHz varies from 15 mW to near 80 mW as the RF voltage is increased from 1.0 V to 2.0 V. Therefore there exists an intermediate RF voltage that yields an output power of 40 mW which is the experimentally obtained value. It is important to realize that higher power levels could be predicted by increasing the dc voltage and changing the RF voltage. However such operation point might correspond to an excessive temperature rise or require unrealistic load impedance level. In the actual operation of the Gunn device, the resonant cavity determines the oscillation frequency according to the impedance it provides to the diode terminals.

4 1.0 μm InP Gunn Structures

In order to achieve higher fundamental frequencies, it is necessary to decrease the device length and increase the doping level in the active region. In this section, two 1 μm structures with different doping profiles are considered.

4.1 Flat Doping Profile

A 1.0 μm InP structure has been designed with a flat doping profile. The wafer was grown by CBE (Chemical Beam Epitaxy). The doping in the active region was estimated to be 2.5×10^{16} cm^{-3} from C-V measurements. This doping is slightly higher than what is typically used for 1 μm structures. The wafer was processed and 35 μm diodes were packaged and tested in a resonant cap waveguide cavity. Oscillations were obtained at 108.3 GHz with 33 mW CW output power and 1.87 % efficiency. The diode was biased at 4.1 V and has a dc current of 430 mA.

A structure similar to the experimental device has been simulated. The bias voltage was set to 4.1 V and the operating temperature to 480 K. The actual device operating temperature is estimated to be close to 500 K since most of the devices failed as the bias voltage is increased beyond 5 to 5.5 V. The performance was evaluated as a function of frequency and for different RF voltages (1.0 V, 1.5 V, 2.0 V, and 2.5 V). Figure 3 shows the RF output power versus frequency. More than 60 mW output power is predicted near 120 GHz. For an RF voltage of 2.5 V, the power peaks near 108 GHz and the oscillation bandwidth becomes smaller compared with lower RF voltages. The predicted power at 108.3 GHz in this case is approximately 50 mW. This value is in good agreement with the experimental results when taking into account cavity losses.

4.2 Graded Doping Profile

This section examines ways of enhancing the performance of InP Gunn devices in the D-band. One method consists of specifying a nonuniform doping profile in the active region and in particular, a linearly graded profile. In this case, the doping should increase from the cathode region toward the anode region, otherwise the performance is likely to be worsened [10]. The advantages of a linearly doping profile include reducing the peak electric field, lowering the current density, and improving the efficiency and output power. The peak electric field in a Gunn structure occurs near the anode region. With a linear doping profile, the peak is reduced because electrons diffuse from the high doped region near the anode to the low doped region at the cathode. The reduction in the field has two desired effects: first, a higher cathode field results in a larger fraction of the electrons transferring to the upper valleys over shorter distance, second a lower anode

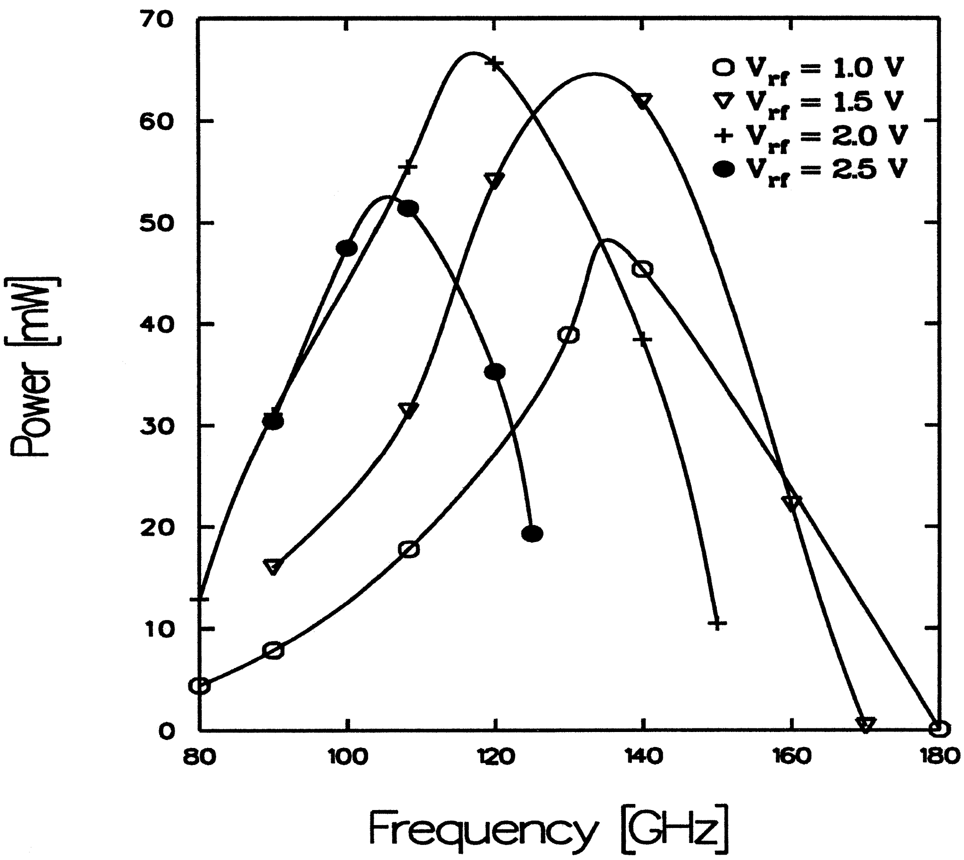

Figure 3: Predicted output power as a function of frequency for a 1 μm Gunn structure with flat doping profile. The dc voltage is 4.1 V and the operating temperature is 480 K.

field allows the application of a larger dc bias without reaching breakdown. These effects improve the the efficiency and the output power. A graded doping profile also results in a lower current density than would be obtained from a uniformly doped structure with similar doping level. This behavior is a consequence of the higher fraction of electrons in the upper valleys which reduces the average velocity.

A wafer with a graded doping profile was designed and grown by MOCVD. The structure has a 1 μm active region with a doping linearly increasing from 7.5×10^{15} cm^{-3} at the cathode side of the active region to 2.0×10^{16} cm^{-3} at the anode side. Samples were processed with integrated heat sinks consisting of plated gold and silver layers. 45

μm diodes were mounted on copper heat sinks and tested in a D-band waveguide cavity. Oscillations were obtained with 20 mW at 120 GHz, 10 mW at 136 GHz and 8 mW at 155 GHz. These devices are believed to operate in the fundamental mode since the measured Q values were between 30 and 100 around 120 GHz using a self-injection locking method. Low Q values are not a characteristic of a harmonic mode operation [11, 12]. These results represent the best performance from Gunn Devices reported at these frequencies.

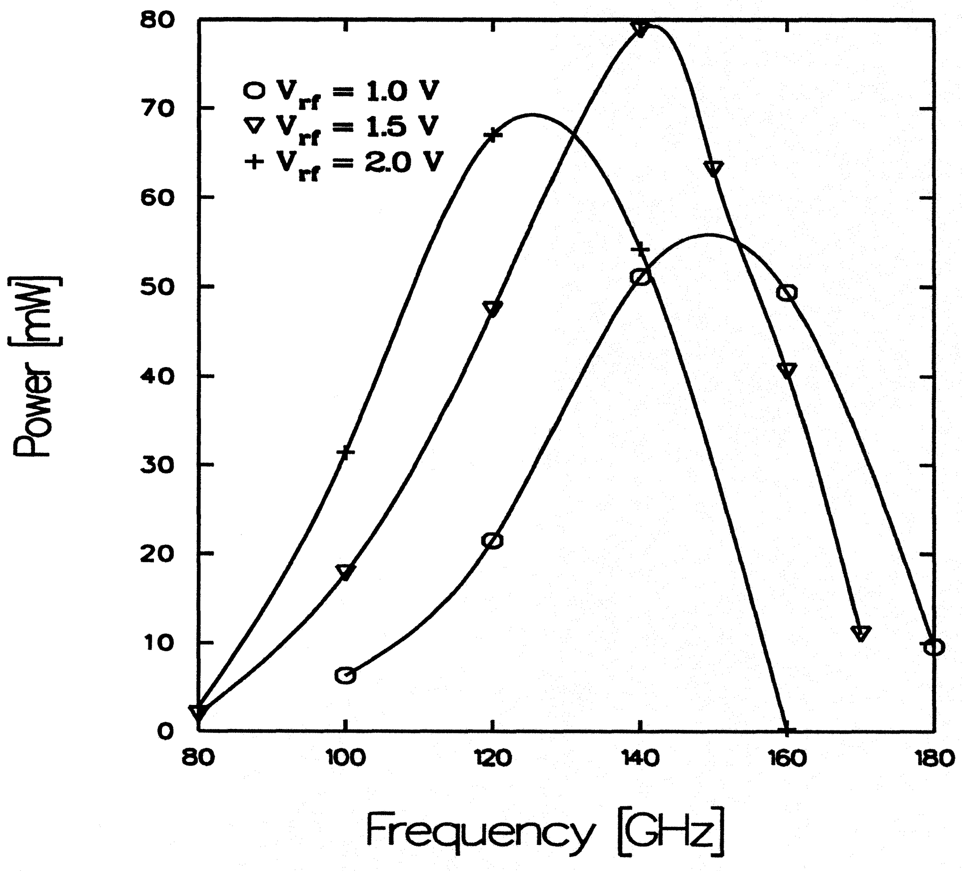

Figure 4: Predicted output power as a function of frequency for a 1 μm Gunn structure with graded doping profile. The dc voltage is 4.1 V and the operating temperature is 400 K.

Simulations were carried out on a similar structure using the Monte Carlo model. The dc bias voltage was set to 4.1 V, the operating temperature at 400 K, and the device diameter was fixed at 45 μm. Figure 4 shows the predicted output power as a function of frequency at various RF voltages. The oscillations occur at frequencies ranging from 80 GHz to 180 GHz, however at the two extremes the oscillation condition requires load resistances less than 1 Ω. The output power peaks near 140 GHz where 80 mW is predicted for an RF voltage of 1.5 V. The simulation predicts oscillations in a frequency range corresponding to what has been observed experimentally, but with higher output power levels. Although the experimental results are very promising, more work need to be done to further improve the performance of the graded structures in the D-band.

5 Conclusions

A method has been developed for estimating the material parameters used in the Monte Carlo model. By comparing simulation and experimental results at high frequencies, more accurate material parameters were obtained. It was found necessary to use low values for the intervalley energy separation and high values for the deformation potentials than normally used in the literature. A possible reason for these trends is the high operating temperature of the Gunn device.

Simulation results have shown that it is possible to operate fundamental mode InP Gunn devices in the D-band frequency region. The operation requires structures with near micron dimensions. Two such structures have been designed, modeled, fabricated, and tested. The first structure consisted of a 1 μm active region uniformly doped at 2.5 $\times$ 10^{16} cm^{-3}. The second structure had a linearly graded doping profile increasing from 7.5 $\times$ 10^{15} cm^{-3} at the cathode side to 2.0 $\times$ 10^{16} cm^{-3} at the anode side. Experimental results from these structures were very encouraging and represent the state of the art at these frequencies. Both structures operated over roughly the same frequency range, however the graded structure yielded better performance at the high frequency end. This observation confirms the claim that nonuniform doping profiles are superior to flat doping profiles in terms of performance and high frequency capabilities.

The theoretical simulations with the improved material parameters predict even higher power levels at these frequencies. It is the opinion of the authors that better experimental results could be achieved around 140 GHz. This requires optimizing the doping profile, reducing further the contact resistances, developing better heat sinks and packaging techniques, and employing current limiting contacts.

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