Power Generation with Fundamental and Second-Harmonic Mode InP Gunn Oscillators - Performance Above 200 GHz and Upper Frequency Limits

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Abstract

This paper investigates the performance of InP Gunn devices at high millimeter- and submillimeter-wave frequencies through computer simulations. The objective is to estimate the highest frequency at which InP Gunn devices can realistically be used as oscillators. The simulation tool uses the ensemble Monte Carlo method to model the Gunn device while the harmonic balance technique is employed to describe the device-circuit interaction. Thermal effects are taken into account by coupling a heat flow equation to the Monte Carlo algorithm. Results based on this model showed good agreement with available experimental data both for fundamental and second harmonic InP Gunn oscillators. This agreement establishes an acceptable confidence level on the applicability and accuracy at high frequencies. Therefore, the model is used to predict the device performance when the length of the active region in the device is scaled down to less than 1 μm. Results indicate that oscillations up to at least 500 GHz are possible in a second-harmonic mode. These simulations take into consideration realistic load and series resistances as well as safe operating temperatures.

1 Introduction

Oscillators based on InP Gunn devices were demonstrated experimentally up to 315 GHz when operated in the second harmonic mode [1]. RF Power levels of 3.5 mW at 213 GHz and 1.1 mW at 315 GHz were obtained. Efficient fundamental-mode operation of InP Gunn devices was originally thought to be limited to frequencies well below 140 GHz [2]. These results clearly indicate that InP Gunn devices could generate power at much higher frequencies than previously thought. Such sources of RF power reduce the number of multiplier stages required to reach higher terahertz frequencies. The main objectives of this paper are (1) estimates of the power levels that could be obtained from optimized structures with graded doping profiles between 200 GHz and 300 GHz, and (2) the prospects of RF power generation with InP Gunn devices at even higher frequencies.

Results reported in this paper are based on a computer model which incorporates the physical phenomena relevant to the trasferred-electron (or Gunn) effect. The model employs an ensemble Monte Carlo technique coupled to Poisson's equation. It can analyze Gunn device structures with arbitrary doping profiles in the active region and various heterostructure injectors at the cathode [3]. At frequencies above 100 GHz, the Monte Carlo method is more appropriate than other techniques that solve for the different moments in the Boltzmann transport equation. In particular, the Monte Carlo method considers the various scattering mechanisms individually rather than through some average relaxation time parameters. This is important in the case of a Gunn device where the operation is based on the intervalley transfer of electrons. Thermal effects are accounted for by coupling a heat flow equation to the basic Monte Carlo method. This allows the device temperature and the various scattering rates to evolve with time until a stable solution is reached. The harmonic balance technique describes the interaction of the device with the circuit and in conjunction with the Monte Carlo method determines a solution that satisfies the oscillation condition. Simulation results obtained with this model were compared with experimental data. Very good agreement was achieved for InP Gunn devices operating in the fundamental and second harmonic modes [3].

2 Simulation Results above 200 GHz

The good agreement between predictions and experimental data establishes the validity of the Monte Carlo/harmonic balance model for describing Gunn oscillator operation. Therefore, performance estimates at frequencies above 200 GHz are presumed to be quite accurate as well. The typical Gunn device structure considered in the simulations has a moderately n-doped active region sandwiched between two n^+ layers forming the cathode and anode terminals. The doping in the active region plays a major role in determining the performance of the device. Two types of doping profiles in the active region were considered: uniform and linearly graded. Various Gunn device structures were simulated with the simulation tool as decribed in the previous section. To identify a structure that yields the optimum performance at a given frequency, the following device parameters were varied: doping at the cath-

$N_{cathode}$ (cm^{-3})	N_{anode} (cm^{-3})	P_{RF} (mW)	η (%)	T (K)
1.0	1.0	11.2	0.43	400
1.5	1.5	21.0	0.65	424
1.8	1.8	26.5	0.47	440
2.0	2.0	15.8	0.4	450
0.75	1.5	15.5	0.6	400
0.9	2.25	24.5	0.8	420
1.2	2.25	25.0	0.6	415
1.5	2.2	29.0	0.5	428

Table 1: Simulation results for different 1.0-μm-long InP Gunn device structures on diamond heat sinks at 240 GHz and a bias voltage of 4.5 V.

ode side of the active region ($N_{cathode}$), doping at the anode side of the active region (N_{anode}), bias voltage (V_{DC}), and device diameter (D). Table 1 summarizes the results for 1-μm-long InP Gunn device structures with different doping profiles at 240 GHz and a bias voltage of 4.5 V.

These results indicate that Gunn devices with graded doping profiles yield higher power and efficiency compared to uniformly doped devices. More importantly, a graded doping profile results in a lower operating temperature. This is an important consideration as excessive heating represents a major problem and limiting factor in Gunn devices at these frequencies.

3 Upper Frequency Limits

The fundamental oscillation frequency of a Gunn device is determined mainly by the thickness of the active region. Therefore, submicron devices need to be considered if RF power generation at frequencies above 300 GHz is to be investigated. The results presented in this section correspond to InP Gunn devices with graded doping profiles and power extraction at the second-harmonic frequency. Table 2 summarizes the best results obtained as the active region thickness L is reduced.

The first submicron device considered has a 0.8 μm active region and a linearly graded doping increasing from 0.9×10^{16} cm^{-3} at the cathode to 3.0×10^{16} cm^{-3} at the anode. Oscillations were obtained at 360 GHz and 400 GHz with output power levels of 2.9 mW and 1.5 mW, respectively. At 0.7 μm, the optimum oscillation frequency is about 450 GHz with a corresponding power level of 1.3 mW. A further reduction

L (μm)	f (GHz)	$N_{cathode}$ (cm^{-3})	N_{anode} (cm^{-3})	D (μm)	V_{DC} (V)	P_{RF} (mW)	η (%)	T (K)
0.8	360	0.9×10^{16}	3.0×10^{16}	26	4.25	2.9	0.24	397
0.8	400	0.9×10^{16}	3.0×10^{16}	24	3.8	1.5	0.16	381
0.7	450	0.9×10^{16}	4.7×10^{16}	20	3.3	1.3	0.18	380
0.6	500	0.9×10^{16}	5.0×10^{16}	15	2.9	0.4	0.11	367

Table 2: Simulation results for submicron InP Gunn devices.

of the active region yields optimum performance at 500 GHz with an output power level close to 0.5 mW. These RF power levels are still sufficient to drive a diode mixer at these frequencies in heterodyne receiver applications. The operating temperatures are below 400 K for all investigated devices. The operating temperature is only 367 K for the 0.6 μm device. This clearly indicates that power generation at frequencies above 300 GHz is not necessarily limited by heat dissipation but rather by the ability to match the device to the external circuit. As the frequencies become higher, the negative resistance provided by the Gunn device decreases which renders matching to the load and overcoming any circuit losses more challenging. As illustrated in Table 2, matching to load resitance of 1 Ω requires the device diameter to be decreased from 26 μm at 360 GHz to 15 μm at 500 GHz.

A simple estimation of the fundamental mode oscillation frequency based on the thickness of the active region and the saturation velocity indicates that a 0.6 μm InP Gunn device should have a fundamental frequency close to 166 GHz. However, the Monte Carlo simulations described earlier provide a much higher frequency of 250 GHz. The simple estimation would even result in a lower frequency if the effect of temperature on the saturation velocity is taken into account. The higher oscillation frequency is attributed to two electron velocity overshoot effects. Figure 1 shows the time evolution of the average electron velocity along the device at eight intervals in one RF period while Figure 2 shows the corresponding electric field profiles. Velocity overshoot is observed in two different parts of the device. As “cold” electrons enter the active region from the n^+ cathode contact, they experience a large increase in the electric field over a short distance. This results in much higher velocities (close to 4.0×10^7 cms^{-1}) compared to the saturation velocity over a region that extends about 0.25 μm into the active region. In addition to velocity overshoot near the cathode, higher velocities are also observed when the space charge layer is collected at the anode and the electric field rises rapidly in time. This is illustrated by the velocity

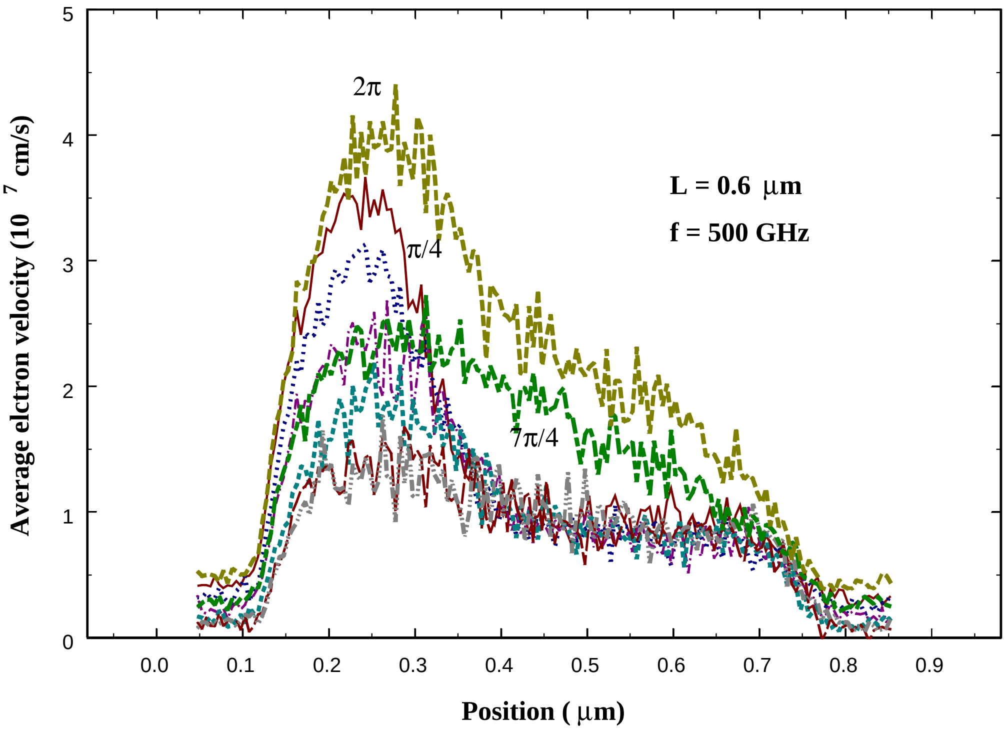

Figure 1: Time evolution of the average electron velocity for a submicron Gunn device structure with a length of the active region of 0.6 μm.

profile at phases $\frac{7\pi}{4}$ and 2π. In particular, at 2π the average velocity is higher than 2.0×10^7 cms^{-1} over most of the active region. These two overshoot effects contribute to a higher effective electron velocity in submicron devices and therefore a higher oscillation frequency.

Figure 3 summarizes the simulation results described in this paper and provides a comparison with the current state-of-the-art performance of InP Gunn devices [1]. The data represented by solid circles denote experimental results, which were obtained at the University of Michigan from devices with a graded doping profile. These results already represent the highest measured power levels at frequencies between 100 GHz and 320 GHz. Simulation results (open circles) indicate that significant improvement in the frequency range from 200 GHz to 320 GHz could be obtained with proper device and circuit design. In addition, the highest frequency of InP Gunn devices is estimated to reach at least 500 GHz. The predicted output power is proportional to f^{-3} at frequencies up to 320 GHz and f^{-4} up to at least 450 GHz. The f^{-4} dependence probably underestimates the performance that can be expectected from

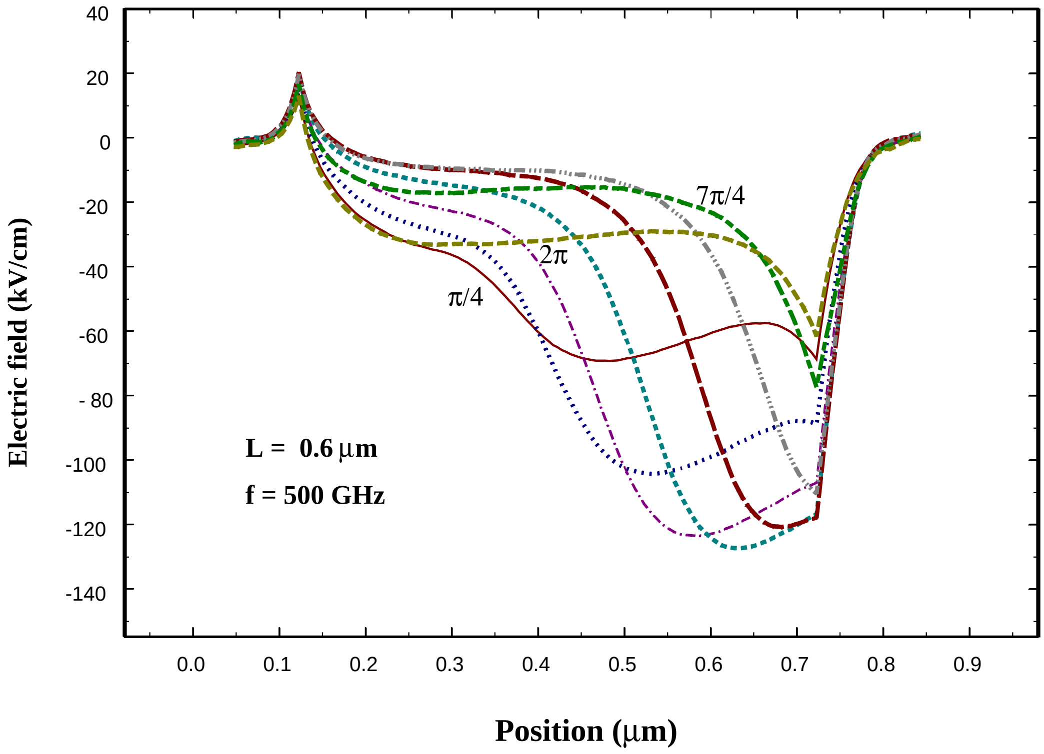

Figure 2: Time evolution of the electric field for a submicron Gunn device structure with a length of the active region of 0.6 μm.

InP Gunn devices in this frequency range as the results in this paper are preliminary. More optimized device structures will result in further improvement of the device performance.

4 Conclusion

Realistic simulations of InP Gunn devices for operation above 200 GHz were carried out to identify an optimum design at 240 GHz and to estimate the upper frequency limits of InP Gunn devices operated in the second harmonic mode. At 240 GHz, RF power levels close to 30 mW are predicted for devices with a 1.0-μm-long active region and a graded doping profile. Operating temperatures remain below 430 K. Decreasing the length of the active region results in oscillations up to 500 GHz, with RF output power levels of 2.9 mW at 360 GHz; 1.5 mW at 400 GHz; 1.3 mW at 450 GHz; and 0.4 mW at 500 GHz. Below 300 GHz, the power generation capabilities of InP Gunn devices are regarded as mainly thermally limited, whereas above 300 GHz, matching to the load becomes more restricting and challenging.

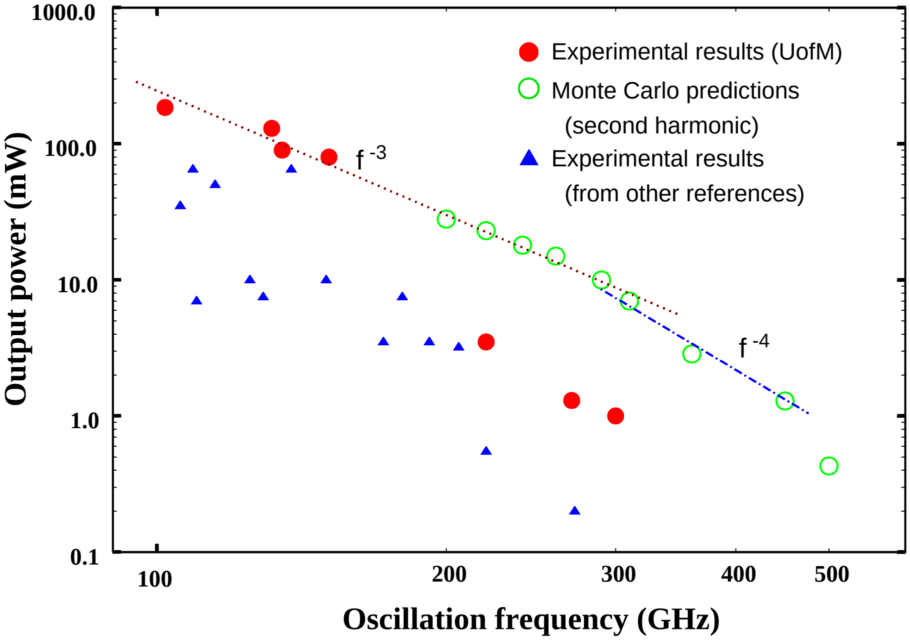

Figure 3: State-of-the-art RF output power from InP Gunn devices and predicted RF performance based on Monte Carlo simulations.

Acknowledgements

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