Theoretical and Experimental Comparison of Optimized Doping Profiles for High-Performance InP Gunn Devices at 220–500 GHz

Ridha Kamoua[1] and Heribert Eisele[2]

[1]Department of Electrical Engineering, SUNY at Stony Brook, Stony Brook, NY 11794-2350
[2]School of Electronic & Electrical Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom

Abstract — **Different types of doping profiles are investigated theoretically and experimentally for their potential of improving the performance of InP Gunn devices at *J*-band (220–325 GHz) frequencies and above. As initial experimental results, devices with an optimized graded doping profile generated output power levels approximately twice the previous state-of-the-art values at 280–300 GHz. Simulations identified a flat doping profile with a notch at the cathode as even more promising. For example, an RF output power of 50 mW at 240 GHz is predicted for this profile compared to 42 mW at 240 GHz from an optimized graded doping profile.**

I. Introduction

Compact, reliable, efficient, and low-noise sources of coherent radiation are key components for emerging systems application at submillimeter-wave frequencies, such as imaging, chemical, or biological sensing, and ultra wide-bandwidth communications [1]. GaAs and InP transferred-electron or Gunn devices have been employed in low-noise oscillators up to millimeter-wave frequencies since their inception more than three decades ago. However, basic material properties were thought to impose fundamental frequency limits on GaAs and InP Gunn devices of approximately 100 GHz and 200 GHz, respectively. Fig. 1 shows previous experimental results from InP Gunn devices under continuous-wave (CW) operation above 80 GHz and these results appear to confirm those early predictions.

However, recent experimental work as summarized in [2] indicated that suitable device structures and much improved heat dissipation extend the operation of Gunn devices, in particular, of InP Gunn devices, to much higher frequencies. These studies were based on devices that were designed for optimum operation in the fundamental mode [2], [3], but they also showed that radio-frequency (RF) power extraction at the second-harmonic frequency is a very efficient method of reaching submillimeter-wave frequencies [3], [4]. Exemplary results are the RF output power (and corresponding dc-to-RF conversion efficiencies) of 34 mW (0.74%) at 193 GHz [4] and 1.1 mW at 315 GHz [2]. These studies also indicated that the oscillator circuit imposes different impedance limits on devices operating in a second-harmonic mode and that, therefore, areas smaller than those of devices operating in the fundamental mode must be chosen.

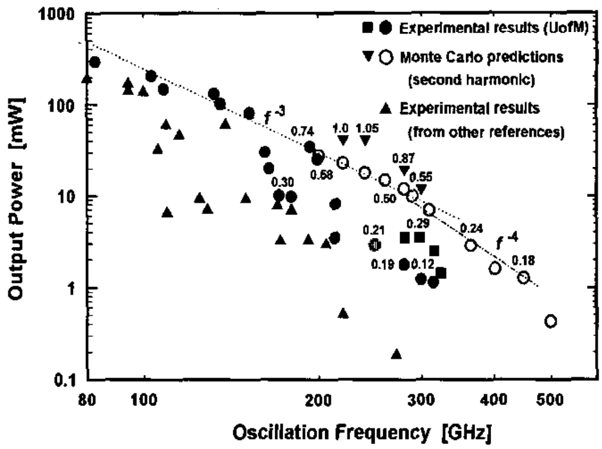

Fig. 1. Comparison of predicted (O, ▼) and measured (●, ■) CW RF power levels from InP Gunn devices with an $n^+n^-n^+$ structure and a doping gradient in the active region for the 100–400 GHz frequency range. O, ●: doping profile designed for operation in the fundamental mode; ■, ▼: doping profile designed for second-harmonic power extraction.

Smaller devices tend to dissipate heat better into the heat sink, and, therefore, a wider range of doping levels is available to optimize the performance in a second-harmonic mode without exceeding safe operating temperatures. Different doping profiles result in different ways of how domains form in the active region of a Gunn device. These ways, in turn, critically affect the harmonic content in the terminal current and voltage waveforms.

This paper describes two different approaches to enhance the performance of InP Gunn devices at submillimeter-wave frequencies. The first approach relies on a linearly graded doping profile in the active region, whereas the second approach considers a structure with a doping notch at the interface between the cathode and the active region.

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II. Overview Of The Design tool

The theoretical results reported in this paper are based on a computer model that incorporates the physical processes relevant to the transferred-electron (or Gunn) effect. The model employs a self-consistent ensemble Monte Carlo technique for the simulation of carrier transport in the device and any suitable doping profile in the active region may be chosen [4]. At frequencies above 100 GHz, the Monte Carlo method is much more appropriate than other techniques that solve the moments of the Boltzmann transport equation. In particular, the Monte Carlo method considers the various scattering mechanisms individually rather than through averaged relaxation time parameters. This is important in the case of a Gunn device since its operation is based on the inter-valley transfer of electrons.

Thermal effects are accounted for by coupling the Boltzmann transport equation with a heat flow equation. This allows the device temperature and the various scattering rates to be continuously updated until a stable solution is reached. Interaction between the Gunn device and the resonant circuit is accounted for by harmonic balance technique. Results obtained with this model agree very well with experimental data from devices operating in the fundamental mode and in a second harmonic mode [5].

III. Performance Potential of InP Gunn Devices at Submillimeter Wave Frequencies

A. Devices with Graded Doping Profiles

Theoretical considerations and experimental results have established that Gunn devices with linearly graded doping profiles yield superior performance compared to devices with a uniform doping. This improvement is attributed to the enhanced electric field near the cathode and the corresponding faster transfer of electrons to higher energy valleys. Initially, a structure that was optimized for operation in the fundamental-mode at *D*-band frequencies (110–170 GHz) was considered. This same structure was evaluated for second-harmonic power extraction with measured power levels of more than 1 mW up to 315 GHz [2]. The circuit presented to the Gunn device second-harmonic frequency differs from the one at the fundamental frequency. Therefore, new profiles were investigated for optimum performance at the second-harmonic frequency.

Fig. 2 shows initial RF power levels as measured from such a structure. They indicate an improvement in the state of the art approximately by a factor of two at 280–300 GHz and, in addition, the dc-to-RF conversion efficiencies compare quite favorably with Schottky-diode multiplier chains [6]. Furthermore, the measured results of Figs. 1 and 2 at 300 GHz and above represent the most powerful fundamental solid-state RF sources operated in any RF circuit at room temperature.

Based on the promising results [2], simulations were also performed to determine the potential for Gunn operation at even higher frequencies. By systematically varying the length of the device and the doping profile, oscillations up to 500 GHz were predicted 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 [5].

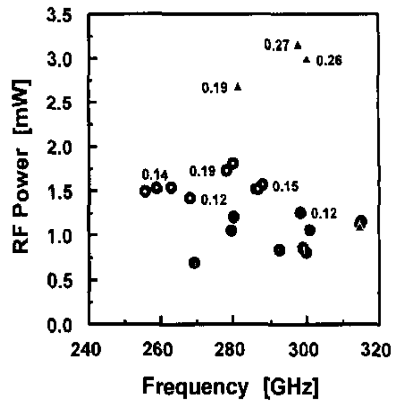

Fig. 2. Measured RF performance of InP Gunn devices on diamond heat sinks operating in a second-harmonic mode in the 240–320 GHz frequency range. O, ◐ denote results from devices optimized for fundamental mode operation and ▲ denote initial results from devices optimized for operation in a second-harmonic mode.

B. Devices with Notch Doping Profile

A notch structure is considered for further improvement in RF performance at high frequencies. A doping notch is positioned between the cathode and a uniformly or flat doped active region. The notch, consisting of a thin undoped epitaxial layer, reshapes the electric field near the cathode. The excess negative charge in the notch results in two effects that enhance Gunn operation. The first effect is an increase in the field right at the cathode, which, in turn, reduces the so-called 'dead zone.' The second effect is a decrease in the peak electric field compared to the graded structure and a flatter field profile throughout the active region.

Figs. 3 and 4 illustrate the evolution of the electric field profile in the graded and notch structures under the same bias conditions. The notch structure has a higher electric field near the cathode and a lower peak electric field of 110 kV/cm compared to more than 130 kV/cm in the graded structure. A reduction of the 'dead zone' improves the performance particularly at very high frequencies, where this notch structure is expected to outperform the graded structure. In addition, a lower peak electric field will result in more reliable operation and initial experimental results from devices with the notch structure are also quite promising.

Fig. 5 shows a comparison of the predicted output power from the notch and graded structures as described in Figs. 3 and 4, respectively. The notch structure results in more output power up to 260 GHz with more than 50 mW at 240 GHz compared to 42 mW for the graded device, also at 240 GHz.

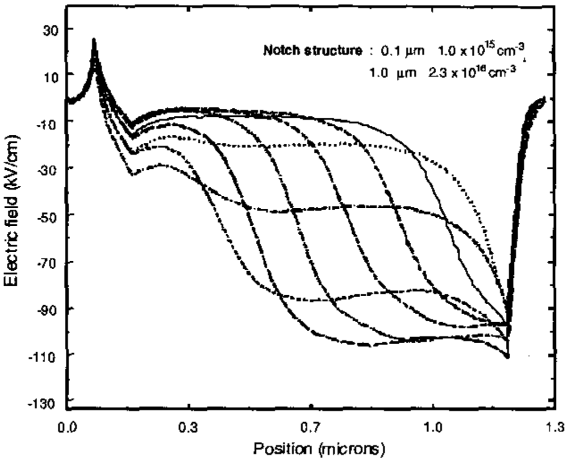

Fig. 3. Electric field profile across a notch Gunn device structure with an applied dc bias voltage of 5 V. The different curves correspond to different instants in one RF period.

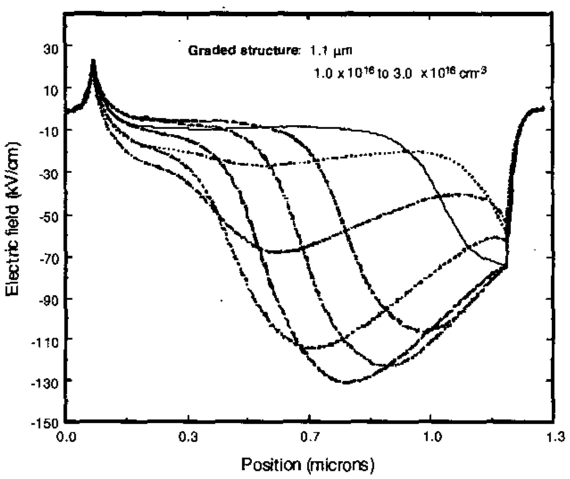

Fig. 4. Electric field profile in a graded Gunn device structure at a dc bias voltage of 5 V. The different curves correspond to different instants in one RF period.

Table 1 compares the predicted RF output power levels and dc-to-RF conversion efficiencies for graded and notch structures at three frequencies: 240 GHz, 360 GHz, and 500 GHz. These simulations assumed that all devices were mounted on diamond heat sinks and the maximum operating temperatures were kept below 420 K to ensure reliable long-term operation of fabricated devices. These results show that the improvements from notch structures are even more pronounced at higher frequencies. Specifically, notch structures resulted in an increase in RF output power by 17%, 55%, and 81% at 240 GHz, 360 GHz, and 500 GHz, respectively, compared to the optimized graded structures.

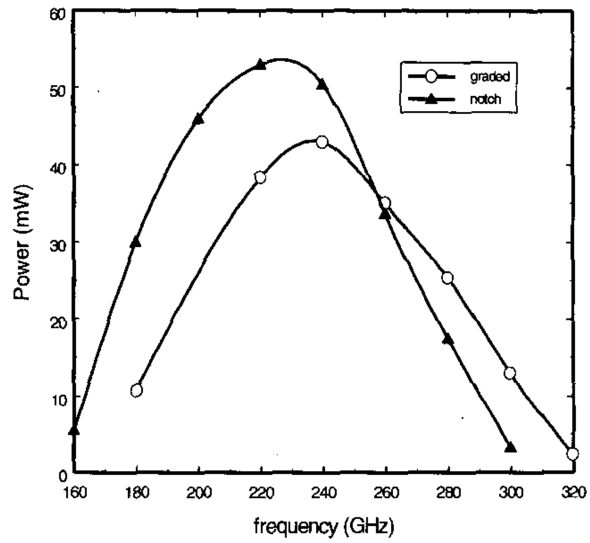

Fig. 5. Comparison of predicted RF Power from the notch structure of Fig 3 and the graded structure of Fig. 4.

For an explanation of these improvements, the effects of the so-called "dead zone" in a Gunn device need to be considered. This "dead zone" occurs right at the cathode where most electrons are in the lowest conduction-band valley. Therefore, this region is inactive and only contributes to the losses in the device, but not to the negative differential resistance.

Devices with a doping notch more effectively reduce the "dead zone" compared to devices with a graded doping profile. In both devices, the electric field initially is small right at the cathode; however the doping notch causes the field to rise more rapidly over a shorter distance, which, corresponds to a smaller "dead zone". At higher operating frequencies, the 'dead zone' occupies a larger fraction of the total active region in the device, and, therefore, any reduction of the 'dead zone' more effectively improves the RF performance the higher the operating frequency.

III. Conclusion

Two types of InP Gunn device structures, a notch structure and a graded one, are being investigated theoretically and experimentally for their potential as fundamental solid- state sources in the frequency range 220–500 GHz. By optimizing the doping profile in the active region, both structures were shown to generate significant RF power levels in this frequency range. In particular, the notch structure has a performance advantage that increases with frequency.

Initial experimental results from both structures are very promising. Oscillations up to at least 325 GHz as well as RF power levels (and corresponding dc-to-RF conversion efficiencies) of more than 3 mW (0.29%) at 300 GHz and more than 2 mW at 315 GHz from devices with the graded structure clearly demonstrate the expected improvements from doping profile optimization. They also show the strong potential of second-harmonic InP Gunn devices as compact, powerful, and reliable solid-state sources at submillimeter-wave frequencies.

Acknowledgement

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Device Structure	L [μm]	$N_{cathode}$ [cm^{-3}]	N_{anode} [cm^{-3}]	V_{dc} [V]	f_o [GHz]	P_{RF} [mW]	η [%]
Graded	1.1	1.0×10^{16}	3.0×10^{16}	5.0	240	43	1.11
	0.75	0.9×10^{16}	3.5×10^{16}	3.8	360	5.0	0.37
	0.6	0.9×10^{16}	1.1×10^{17}	2.9	500	2.6	0.25
Notch	1.0	2.3×10^{16}	2.3×10^{16}	5.0	240	50.5	1.17
	0.7	2.7×10^{16}	2.7×10^{16}	3.6	360	7.68	0.57
	0.4	8.0×10^{16}	8.0×10^{16}	2.9	500	4.7	0.38

Table 1. Comparison of the RF simulation results for InP Gunn devices with graded and notch structures. All notch structures have a 0.1-μm long undoped layer between the heavily *n*-doped cathode contact layer and the active region. L, $N_{cathode}$, N_{anode}, V_{dc}, f_o, P_{RF}, and η denote length of the active region, doping near the cathode, doping near the anode, applied dc voltage, operating frequency, RF output power, and dc-to-RF conversion efficiency, respectively.