Studies on the Characteristics of GaN-based Gunn Diode for THz Signal Generation

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***Abstract* — A new technique has been developed to explore the potentiality of the newly emerging GaN material for use as Gunn diode and to study the device characteristics of the device. The results obtained for GaN diode are compared with those for GaAs-based Gunn diode. It is observed that GaN-based Gunn diode can generate two orders of magnitude more power than GaAs-based Gunn diode at similar operating conditions. The reported improvement in the mm-wave/THz-wave performance are supported by the high value of GaN Pf^2Z figure of merit, which is 50-100 times higher than that for GaAs, indicating a strong potential of GaN for mm-wave signal generation. A detail study and suggestions are provided to the fabricators to fabricate GaN-based Gunn diode of different structures (like general profile, notch, forward and backward injection of the charge carriers, heterostructure etc). A novel method has also described to obtain the first hand data on thermal analysis. An output power of 1400kW/cm^2 from the GaN Gunn diode as compared to the same of 4.9kW/cm^2 from GaAs diode is note worthy.**

***Index Terms* — Gunn diode, GaN, Power, Oscillator, active device.**

I. INTRODUCTION

Many applications in the millimeter and submillimeter wave regions of the electromagnetic spectrum require compact solid-state local oscillators that provide low noise and adequate power levels. IMPATT (IMPact Avalanche Transit Time) and Gunn diodes are two such Solid State Devices which are widely used as generators [1-4]. IMPATT is known for high noise [2] and hence the only choice left to use as low noise compact solid state local oscillator is Gunn diode. Oscillators based on *GaAs* and *InP Gunn* devices have been widely used to serve this purpose at frequency upto *140GHz* [3-6]. These devices have proved to be reliable with excellent amplitude and phase noise characteristics. For high frequency operation, the principal limiting factor is the semiconductor material itself as the *Gunn* effects is directly related to the band structure and the material properties of the semiconductor. *Gunn* devices based on *GaAs* are limited to *W*-band (*70-110 GHz*) whereas *InP* devices have been shown to generate considerable power level upto *140 GHz* [6, 7]. However, wide band gap semiconductors like *GaN* and compounds based on it have recently been established as technologically important materials for both electronic and optoelectronic devices to obtain high power [8-9] at high frequency. High power *GaN*-based transistors and *IMPATTs* with excellent electrical characteristics have been reported recently [1, 2, 10, 11]. Even preliminary fabricated GaN-based Gunn diode has shown the oscillation characteristics and is seen in literature recently [12, 13].

As a first order, the oscillation frequency of a *Gunn* device is proportional to the space charge layer transit velocity, which can be approximated by the saturated velocity. It is clear that *GaN* has a saturated velocity, which is higher than the corresponding velocity in *InP* by a factor of two, has the potential of operating at a much higher frequency than *InP* (or *GaAs) Gunn* devices. Other properties which make *GaN* attractive include higher thermal conductivity and a much higher breakdown electric field [8-9]. Currently the feasibility study of using *GaN* in *Gunn* diode has been limited to some preliminary theoretical works [14, 15] and some preliminary experimental works [12, 13]. The recent reports in this regard is not only encouraging but is notable [12-15]. However, the issues, which play key roles in the realization of Gunn diode and its high power generation capability, like presence of notch near the cathode, reverse injection, heterostructure near cathode etc. need to be discussed rigorously before the material is dedicated for the fabrication of Gunn diode. Hence a detailed and systematic study has become essential at the present stage to recognize the potentials of *GaN* and its compounds for use as *Gunn* diode at *mm-wave* and *tera-hertz* frequency range.

With this in mind, the authors have reported here a detailed theoretical study on *GaN*-based *Gunn* devices and have compared the results obtained from *GaAs*-based *Gunn* diodes operating under similar conditions. Device operation is studied over a wide range of frequencies. A new technique of solution has been developed to study the dynamic properties of such devices. The developed program is a generalized one and can be used at any operating conditions and for any type of *Gunn* device structures (such as flat profile, notch profile and heterostructure). The results show that *GaN* Gunn diodes can offer twice/thrice the frequency capability of the *GaAs* Gunn diodes (*90GHz* versus *40GHz*), while their output power density can go as high as 2×10^6 W/cm^2 compared to

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~10^3 W/cm^2 for the *GaAs* devices. The reported improvements in the mm-wave performance are supported by the high value of the *GaN* pf^2z figure-of-merit, which is 50-100 times higher than that for *GaAs*, indicating a strong potential of *GaN* for the microwave signal generation. The developed simulation method has been verified with the available experimental and theoretical report of GaAs-based Gunn diode. The device is computed for different structures (such as flat profile, heterostructure, notch, forward and reverse bias injection, graded injection etc) with different lengths, concentrations, anode and cathode size and the obtained results will be presented in the conference. The dependence of the oscillation frequency and output power on the diode design and operating conditions will also be reported. The outline of the simulation scheme and material parameters used in this study are presented in the next section. The results obtained from this study are presented in Section III. Finally a conclusion is drawn in Section IV.

II. Simulation Method And Material Parameters

A computer technique for the simulation of carrier transport in semiconductor devices has been employed to obtain the results presented in this paper. This tool is capable of analyzing *Gunn* structures with any doping profile in the active region with various injectors at the cathode terminal. The input to the program consists of device doping profile, material composition of the various regions, DC bias conditions, and device size. For a given frequency, the program starts with a small RF voltage and performs the simulation for a number of periods. The current response is then computed as a function of time and the output RF power, conversion efficiency, and DC current are then obtained from Fourier analysis of the current response. Simulation results obtained from this complete model have been shown to yield good agreement with the experimental results in the mm-wave region [16] for *GaAs*-based *Gunn* diode and hence can be used for *GaN* case also. We report results based on this model for *GaN*-based *Gunn* devices with emphasis on operation at high-frequency in the next section. The details of computation technique will be described in the full paper.

Since material parameters play a major role in the outcome of the simulation, appropriate parameter values for *GaN* [17] were selected based on an extensive search of data reported in [1, 2]. The v-E characteristics of *GaN* used for this study were based on Monte Carlo simulation of Albrecht *et al* [17]. The threshold field for the intervalley transfer E_{th} is much larger in *GaN* (*150 KV/cm*) than in *GaAs* (*3.5 KV/cm*). The separation between the high and low mobility valleys (ΔE) in *GaN*, the effective mass (m^*) etc are taken from different experimental reports. The energy-relaxation time (τ_{ER}) was calculated as ($\tau_{ER}=(2m^*\Delta E/qE_{th})^{0.5}$) and the intervalley transfer relaxation time τ_{ET} was evaluated from the results of Monte Carlo studies of ballistic transport. Based on this, the NDR relaxation frequency of *GaN* was found to be *740 GHz* compared to *110 GHZ* of *GaAs*. All the material parameters used for *GaAs* and *AlGaAs* are taken from experimental reports and are presented in our earlier work on IMPATTs. The material parameters for GaN have also been used earlier by our Group for GaN-based IMPATTs [1, 2] and have shown to obtain good acceptable results for IMPATT devices.

The Gunn device for the present study was designed using the standard criterion given elsewhere. The schematic diagram is shown in Fig. 1. The results obtained from our simulation method are presented in the next section.

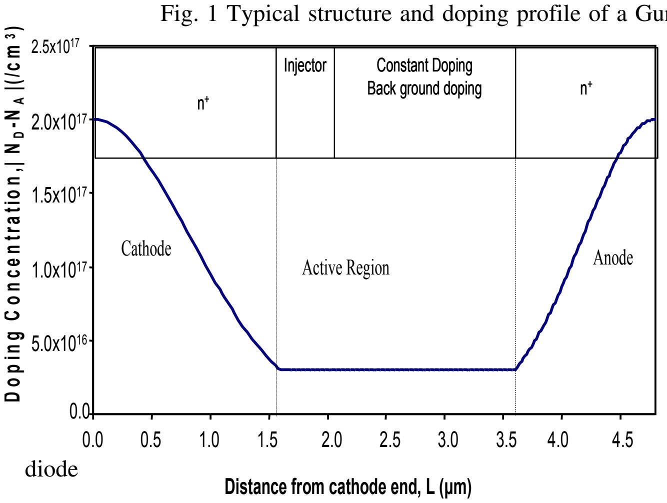

Fig. 1 Typical structure and doping profile of a Gunn diode

III. Results And Discussion

The results obtained from the above described simulation scheme are presented here. The device properties for *GaN* Gunn diodes have been computed for W-band and THz frequency ranges for different device structures and are compared with those of *GaAs* and its heterostructure *GaAs/AlGaAs*. The power obtained from the computation are shown in Figs. 2 and 3 respectively for THz and W-band GHz frequency ranges.

Based on the above structure, it is found that the current density variations with respect to time are periodic in nature which agrees with experimental result of Pavlidis et al at 94 GHz. For the *GaAs/AlGaAs* type *Gunn* diodes the frequency of operation is in the range of *10-80 GHz*, whereas for the *GaN* based *Gunn* diodes it is in the range *400-1500 GHz* for the same structural parameters. The peak values of the current density for *GaAs* were about *80 KA/cm^2* and for *GaN* it is *28000 KA/cm^2*. The above signal is Fourier analyzed to determine the power generated by the device. The power generated at different dc voltages with the frequency is shown in figure 2 for a 0.2um length flat profile device assuming a 50um diameter to show that such type of Gunn devices can operate at THz frequency ranges. It shows that with increase in dc voltage the power generated increases and is maximum for a particular frequency (in this case around *1.1THz*). For the *GaAs* based *Gunn* diodes the peak power obtained ranges from *2-4 mW* and for *GaAs/AlGaAs* hetero-structure it is around *20-70 mW*. However, in case of *GaN* based *Gunn* diode the power produced comes out in the range of *1 to 30 W*.

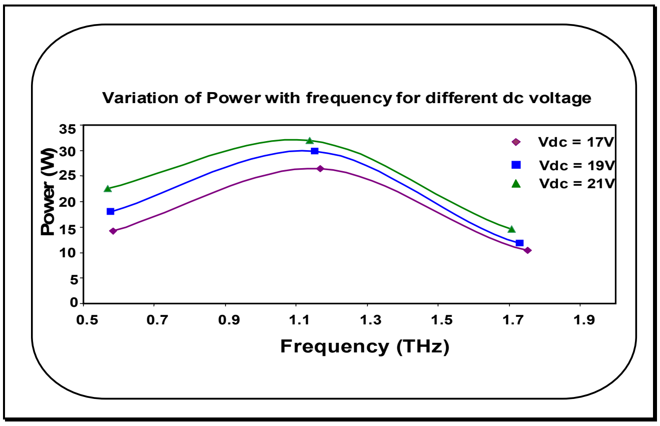

Fig 2 Graph showing the variation of power with frequency for different values of dc voltage for GaN-based Gunn diode.

The high power at high frequency is due to high saturation velocity of the electrons in *GaN*. With the increase in applied voltage the power increases up to some limit. It is seen that depending on the length of the device, the resonant frequency varies. With increase in the length of the device the transit time is increased as a result the frequency of operation decreases. Depending on the resonant frequency for the device the power will peak at a suitable frequency. However, the power generation increases with the increase in the active region length. Such curves for different length of the active device for W-band frequency region is shown in Fig. 3.

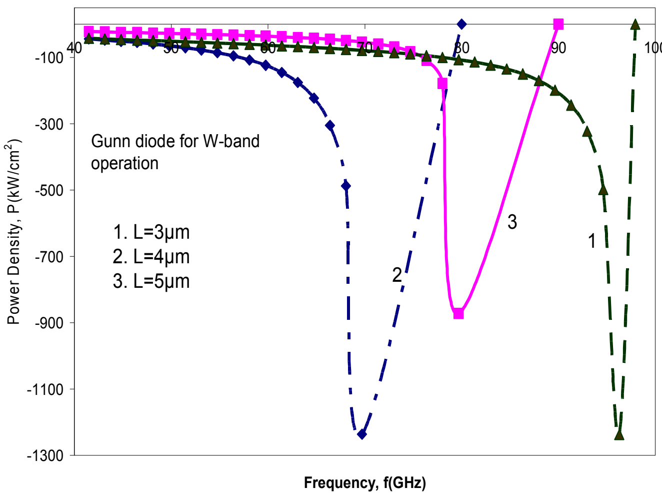

Fig.3 Frequency versus Power Density for optimization active device length. The structure is Active doping concentration $=N_d = 1x10^{17}/cm^3$, Length of the anode= l_a=0.3μm, length of the cathode l_c = 0.2μm

The powers have also been computed for different values of active region doping concentrations as a function of frequency. As the charge bunch moves across the active region it grows in size. The rate at which it grows depends on the available electrons and hence the active region doping concentration. So with the increase in the active region doping concentration the power obtained will increase.

The device can operate at different harmonics also. Figure 4 shows the conductance versus frequency curves for the same structure as of Fig. 2. It is seen from Fig. 4 that the device at second and third harmonics generates better negative conductance values compare to the fundamental mode of GaAs-based device at the same operating conditions. Further, Fig. 4 shows the oscillation conditions of GaN based diode can be easily pushed to THz frequency range.

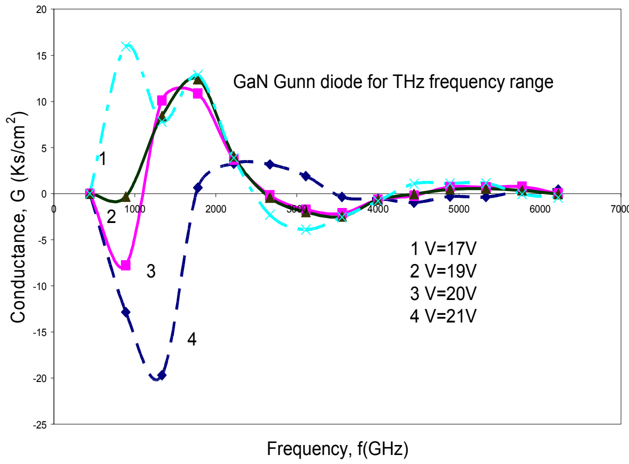

Fig. 4 Conductance versus frequency curves for the structure of figure 1.

The introduction of notch, injection barrier and heterostructure Gunn diode are designed and computed whose results will be presented in the conference.

Further, practical *GaAs Gunn* devices operate at about 3% DC-to-microwave conversion efficiency. This means, the device has to dissipate a large amount of energy in the form of heat. Even with efficient heat sink, the operating temperatures of practical devices range from about *50* to 200^0C for room temperature operation. This heating problem is certainly detrimental to the life and efficiency of these devices. This problem has been analysed in two parts and first is presented here. In the first part we have undertaken a realistic simulation by incorporating material parameters at the actual operating temperatures. For this the temperature has been varied from 300 K to 800 K and the power density has been computed at different temperatures. Curves obtained from such study are shown Fig. 5. It depicts that frequency of operation remains the same in all these cases unlike that of GaAs-based Gunn diodes. Though the power generated decreases with increase in temperature, the dynamic properties remain the same for temperature up to 400 K. This indicates that GaN-based Gunn diodes can be operated at higher temperature compared to the GaAs based Gunn diodes without a substantial effect on the output power and frequency.

We have developed a simple thermal model also to assess the thermal limit of a power generating device to study the heating problem on Gunn diode. This model can also be used for other two terminal devices like IMPATTs. A comparative account of the electro-thermal performance of *GaN* and *GaAs* helps to determine the maximum power that can be handled by a device for a given temperature requirement. It is seen that *GaAs* device reaches 640 K at a power density of 5×10^9 W/cm^3 where as *GaN* device can go up to a power density of 1.4×10^{10} W/cm^3 at the same temperature. This can be explained from the thermal conductivity of the materials. This shows that GaN based Gunn diode is a potential semiconductor device to operate at THz frequency range.

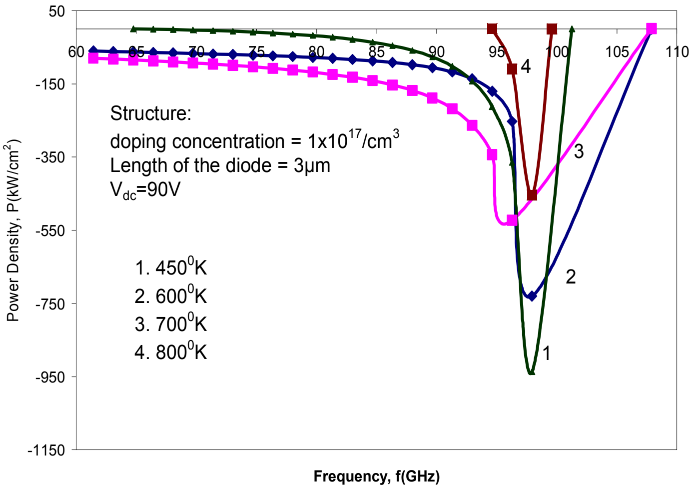

Fig.5 Effect of temperature on GaN-based Gunn diode

IV. Conclusion

Simulation studies based on the newly emerging wide bandgap material, *GaN*-based Gunn diode are presented. Several structural variations of the diode are considered to explore possibility of improving the performance. A 280 times higher power output for *GaN*-based Gunn diode compared to the *GaAs* based Gunn diode is noteworthy. Further, the *GaN*-based Gunn diode is observed to be less prone to degradation resulting from rise in temperature unlike the case of *GaAs* based Gunn diode. A basic thumb-rule has also been proposed for thermal analysis. It can be concluded that *GaN*-based Gunn diode is expected to be a better alternative, not only from electrical but also from thermal consideration, as compared to the same device based on *GaAs*.

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