Chapter-6

Studies on GaN based Gunn Diode
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6.1 Introduction

Wide bandgap 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 and is a suitable material of choice is seen from last chapter for IMPATT diodes. Major important properties for electronic applications of this material include a large value of wide band gap (3.4 eV), high electrical breakdown field ($E_v \sim 2 \text{ MV/cm}$), high saturation velocity of electrons ($v_{sn} \sim 2 \times 10^7 \text{ cm/sec}$) and high thermal conductivity (nearly two times that of GaAs) [18]. The fundamental properties of GaN indicate that it also exhibits transferred electron effect. Increased electrical strength, a higher threshold field, and the possibility of faster operation due to a larger electron velocity and reduced energy-relaxation time are expected to be the key features of GaN against traditional III-V semiconductors [18]. The increased value of $E_{th}$ (threshold field) is caused by a large separation between the high and low mobility valleys in GaN ($\Delta E \sim 2.1 \text{ eV}$) compared to 0.3eV in GaAs. Studies have shown that the energy relaxation time in GaN is far shorter than that in GaAs. Intuitively, from these fundamental properties of GaN, it is expected that Gunn diode using this material would manifest much higher output capability in the mm-wave and tera-hertz range than the traditional GaAs and InP-based Gunn diodes explored so far. A recent report on Gunn diode by Yilmazoglu et al is not only encouraging but also notable [20]. 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.

Keeping all these in mind, the author has reported here a detailed theoretical study on GaN-based Gunn devices in this chapter. The necessary mathematical formulation, validity of the model developed for Gunn diode, material parameters data etc are presented in chapter 3 of the thesis. A computer software has been developed to study the dynamic properties of such devices using the method described in chapter 3 of thesis. 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). Gunn diode with different structures are generated and simulated to find out the potential of each structure. The results have been compared with those obtained from GaAs and its compound based Gunn diode operating under similar conditions. 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 $2 \times 10^6$ W/cm$^2$ compared to $\sim 10^3$ W/cm$^2$ for the GaAs devices. The reported improvements in the mm-wave performance are supported by the high value of the GaN pfz 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 detail results of such study are presented in the next section. Gunn diode will have the heating problem. Hence a simple thermal model has also developed to assess the thermal limit of a power generating device and is presented in this chapter.
6.2 Results and Discussion

We have widely varied the structural and operating parameters of the GaN Gunn diode and computed the output power density in each case. The results of our investigation are recorded in figures 6.1, 6.2, and 6.3. Figure 6.1 is a depiction of the effect of cathode/anode doping on the power density of the Gunn diode for a fixed background doping density and bias. This figure in addition, shows the existence of a power output peak at a given frequency and this frequency for obvious reason need to be chosen as the operating frequency of the Gunn diode oscillator. It is interesting to observe from figure 6.1 that the power density peak gradually steepness with increase in cathode/anode doping. However, this can not be increased indefinitely and an optimum value of the same need to be chosen for a good power output.

Figure 6.2 shows the effect of change in active region length on the output power density. It is observed that a decrease in length of active region records an increase in output power density. However, the length can not be decreased to an arbitrarily lower value because the relation, $n \times L > 4E_F \delta / q$ has to be maintained. Further, for a given choice of frequency of operation the length variation need to be restricted to a limited range. Keeping these in view, an optimum value for $L$ has been selected.
Some Studies on the High-Frequency Properties of IMPATT and Gunn Diodes

Gunn diode for W-band operation

1. L=3\mu m
2. L=4\mu m
3. L=5\mu m

Fig 6.1: Frequency versus Power Density for different values of anode and cathode concentration

Fig 6.2: Frequency versus Power Density for optimization active device length. The structure is \( N_d = 1 \times 10^{17}/\text{cm}^3 \), \( l_a = 0.3\mu m \), \( l_c = 0.2\mu m \)
The applied bias has a definite effect on the output power density. This has been presented in figure 6.3. It is interesting to observe that there is an optimum value of bias for which the power density is maximum; an increase or decrease in bias from this value reduces the power output. The optimized value of bias is chosen from such graph. Other structural parameters like cathode/anode region length and active region doping density also affect the output power. These parameters have also been varied (graphs not shown for the sake of brevity) and the optimized values in each case have been chosen. All such optimized parameters for two structures are shown in Table 6.1.

![Graph showing frequency versus power density](image)

**Table 6.1 Optimized design parameters for GaN-based Gunn diode to operate at 94GHz**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Length of the anode, $L_a$ (μm)</th>
<th>Length of the cathode, $L_c$ (μm)</th>
<th>Length of the active region ($L_{active}$) (μm)</th>
<th>Background doping concentration ($n$) (1/cm$^3$)</th>
<th>Active region doping (n) (1/cm$^3$)</th>
<th>Biasing DC value (V)</th>
<th>Doping of anode and cathode region (1/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Str1</td>
<td>1.2</td>
<td>0.8</td>
<td>5</td>
<td>$10^{13}$</td>
<td>$10^{16}$</td>
<td>90</td>
<td>$10^{19}$</td>
</tr>
<tr>
<td>Str2</td>
<td>0.3</td>
<td>0.2</td>
<td>3</td>
<td>$10^{13}$</td>
<td>$10^{17}$</td>
<td>90</td>
<td>$10^{19}$</td>
</tr>
</tbody>
</table>
The response time of a domain to electric field alternations is important in estimating the maximum signal processing rate of logic devices. The current waveform resulting from bulk non-uniformity of limited extent and hence the electric field distribution depicting the physical behavior of the devices at different time of the flow of electrons is shown in figure 6.4. GaN offers higher peak and saturation velocities than GaAs, which leads to increased transit-time frequency. The threshold and breakdown fields are also large in GaN, which allow operation at a higher bias, leading to an increased output power. The increased electrical strength of GaN also results in reduced NDR relaxation time, suggesting higher frequency of operation. When the bias was increased, the oscillation frequency of both the GaN and GaAs oscillators decreased steadily in agreement with the experimental trends observed for GaAs Gunn diodes.

![W-band GaN-based Gunn diode](image)

**GaAs Gunn diodes.**

<table>
<thead>
<tr>
<th>Electric Field, E(x,t)(kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

Transit Mode:
- \( n = 5 \times 10^{16} \text{cm}^{-3} \)
- Active Length \( L = 5 \mu \text{m} \)
- \( nxL = 2.5 \times 10^{13} \text{cm}^{-2} \)
- \( V_{dc} = 80 \text{V} \)

**Fig 6.4:** Gunn electric field formation from cathode end to anode end at different time interval
The possibility of increased doping in GaN Gunn diodes also leads to a reduction of the differential dielectric relaxation time and as a result, an enhanced growth rate of the Gunn domains. The presence of Gunn domains led to fluctuations of voltage and current, which gradually built-up into sustained large-signal oscillations. This is shown in figure 6.5 for GaN structure. It is seen that the charge nucleation begins at around 1.0µm distance from the metal contact (cathode end). Once the charge bunch is formed it slowly travels along the device and begins to grow in size. The charge bunch is then collected at the anode contact. It is seen that current strength of GaN-based Gunn diode is a thousand times higher and hence power delivered/generated is also expected to be higher by the same order of magnitude. To show the strength of GaN-based Gunn diode, the RF power generated by GaAs and GaN-based devices are also compared. The power obtained from GaAs-based Gunn diode (shown in figure 6.2) is 98mW (4.9kW/cm²) where as that from GaN based Gunn diode is found to be 27.49W (1400kW/cm²) for a device of 50 micron diameter (on the basis of figure 6.3). This shows a 280 times increase in power generated from GaN-based Gunn diode compared to the same from the corresponding device based on GaAs.
As noted above from figure 6.5, Gunn domain starts generating after a distance of around 1.5 micron from cathode end and hence negative power could not be generated from this region of the cathode end. The presence of this dead zone in the diode impacts negatively on the efficiency of the oscillator, because the length of the active region in which the domain can grow, decreases. Smaller domains translate into smaller output power. Thus optimizing Gun diodes involve decreasing the dead zone. To improve the power performance and to reduce the dead zone, different techniques are used in GaAs-based structures. We have used the same technique here to explore the possibility of generating higher power output from GaN-based Gunn diodes.

The performance of standard Gunn diode may be improved by injecting electrons from the cathode end with an energy equal to the inter valley energy difference, $E_{F-L}$, in two ways. Firstly, the dead space – the distance over which the electrons must drift before acquiring sufficient energy to scatter into the $L$ valleys is reduced to approximately the mean free path for inter valley scattering. Consequently,
electrons may be heated more efficiently, improving device performance. Secondly, the first inter valley scattering event for electrons entering the drift region is reduced by varying the position at which the characteristic of the Gunn effects are formed. This is usually taken care by heterostructure, graded barrier, and notch structure. Hence the structures like notch, injection of the charge carrier, and heterostructure are considered here to explore the possibility of improving GaN-based Gunn device performance.

The introduction of notch near the cathode to improve microwave device performance of GaAs and InP-based Gunn diode has also been used widely. It is one of the ways of reducing dead zone, since it forces a high electric field at the notch. This stronger field will accelerate the electrons faster than would otherwise be the case. The electrons will therefore gain enough energy for transfer to the L-valley in a shorter time and distance. The authors have therefore analyzed here the dynamic properties of GaN-Gunn devices with notch. When a notch with 20% less doping is considered near the cathode and same voltage as earlier is applied to the diode, a dipole high-field domain nucleates and travels towards the anode and correspondingly the frequency of the signal generation at the output decreases. However, the power generated improves (as shown in Figure 6.6). As for comparison, the power output of 900kW/cm² (curve 3 of Figure 6.3) in case of GaN-based diode without notch gets enhanced to more than 1100kW/cm² (curve 2 of Figure 6.6) when a notch of 20% less doping is introduced to the structure. However, with further decrease in notch doping, the power output decreases. Similarly an increase of notch doping from 80% also reduces the power output as seen form Figure 6.6. Thus an optimum value of notch doping needs to be chosen.
It is also believed that Gunn diode with hot cathode contacts exhibit improved RF performance. Hence, we have determined here the exact influence of heterojunction cathode contacts on the operating mode. This kind of cathode contact is an injecting one. Over the last few years the injection of hot electrons into GaAs using Al$_x$Ga$_{1-x}$As has been demonstrated/exploited to enhance the microwave oscillations in a GaAs Gunn diode. Hence, we have also compared here the domain formation characteristics of heterojunction injection AlGaN/GaN Gunn diode with the conventional Gunn diode. Cathode contact is forward biased when the current flows from the material with the high energy bandgap to the material with the lower energy bandgap. The effect of AlGaN/GaN heterostructure on the field stability across a Gunn diode is simulated here for three different kinds of structure, (a) Flat/Constant AlGaN barrier, (b) forward injection graded AlGaN barrier and (c) reverse injection graded AlGaN barrier and some of the results are presented here (Figures 6.7 and 6.8).
First, a constant barrier heterostructure Gunn diode is considered and the Al mole fraction is varied from x=0 to x=0.6 in $Al_{1-x}Ga_xN$. We observe a good power output in the range of x=0.1 and 0.2. However, the properties degraded with increasing Al mole fraction. Also, the operating frequency decreases with increase in Al mole fraction. At x=0.4, the operating frequency decreases to 65GHz compared to 99GHz at x=0.1. This is depicted in Figure 6.7. Next a graded $AlGaN$ injector is considered. For this, the doping profile near the cathode must be carefully controlled so that the field from the ionized impurities in the depletion layer is formed properly when the $AlGaN$ injector is forward biased and does not suppress the formation of the charge instabilities. Keeping it in mind, Al mole fraction is varied from 0 to 0.5 within a distance from the cathode end to use as injector. The reverse barrier graded junction is also used for the same structure and the results obtained under these three conditions are presented in figure 6.8. It is seen that the oscillation frequency decreases for constant barrier and forward injection barrier condition. It becomes 65.5GHz and 74.5GHz respectively as against 94.5GHz in reverse barrier case. This trend is consistent with that observed in traditional $GaAs$ and $InP$-based Gunn diodes [103,182]. The results can be understood in the following way. It can be noted that compared with the conventional structure, the electric field has a stronger variation in the constant and forward barrier case. When injected into the active region, the electrons acquire an energy equivalent to the barrier. Therefore they need to travel a shorter distance to acquire energy necessary to transfer to the upper valley. This results in smaller dead zone region.
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Fig 6.7: Heterostructure GaN/AlxGa1-xN Gunn diode for different values of Al mole fraction

![Graph showing heterostructure GaN/AlxGa1-xN Gunn diode for different Al mole fractions:]

1. Constant Barrier
2. Forward barrier injection
3. Reverse barrier injection

Structure:
Active Length L=5μm
V_{dc}=80V
Active Doping Concentration = 1x10^{19}/cm³

Fig. 6.8: Heterostructure Constant barrier, forward barrier injection and reverse barrier injection in Gunn diode

![Graph showing power density vs frequency for different injection types:]

1. Constant Barrier
2. Forward barrier injection
3. Reverse barrier injection

Structure:
Active Length L=5μm
V_{dc}=80V
Active Doping Concentration = 1x10^{19}/cm³
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°C for room temperature operation. This heating problem is certainly detrimental to the life and efficiency of these devices. This problem has been analyzed in two parts in this paper. 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 in figure 6.9. 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.

Fig 6.9: Effect of temperature on GaN-based Gunn diode
In the second part of the study relating to heating problem on Gunn diode, we have developed a simple thermal model to assess the thermal limit of a power generating device. A schematic of the 1-D model is shown in figure 6.10 where \( L \) is the length and \( A \) the area of cross section assumed uniform through the device. Let \( p \) be the power dissipated per unit volume in the device. Consider a volume element \( dV = A \, dx \) at a distance \( x \) from one end of the device. The net rate of flow of heat into the volume element is given by \( KA \frac{d^2 \theta}{dx^2} \) where \( K \) is the thermal conductivity of the device and \( \frac{d\theta}{dx} \) is the temperature gradient at \( x \). The rate of heat generated in \( dV \) due to power dissipation is \( pA \, dx \). For steady state, the rate of increase of heat in \( dV \) must be equal to the rate of heat radiated by the volume element. This gives the heat flow equation as

\[
\frac{d^2 \theta}{dx^2} = \frac{E(\theta)C}{KA} \frac{p(x)}{K}
\]  

(6.1)

where \( E(\theta) \) is the rate of loss of heat per unit surface area per unit time by radiation and \( C \) is the circumference of the volume element. Consideration of detailed forms of \( E(\theta) \) under different conditions is beyond the scope of this paper.

![Fig 6.10: 1-D schematic of a Gunn diode for thermal analysis](image-url)
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For simplicity and limiting the discussion to a thumb-rule calculation we neglect radiation and set \( E(\theta) = 0 \). The power dissipated per unit volume \( p \), will in general be a function of \( x \) and will be given by

\[
p(x) = (1 - \eta)E_{dc}(x)J_{dc}(x)
\]

(6.2)

where \( \eta \) is the efficiency and \( E_{dc}(x) \) and \( J_{dc}(x) \) are the DC values of electric field and current density respectively. The \( x \) dependence of \( E_{dc} \) and \( J_{dc} \) can be obtained from the particular device analysis. However, for a simple estimation of thermal limit we have assumed them constants leading to a constant \( p \) throughout the device. Our heat flow equation thus reduces to

\[
\frac{d^2 \theta}{dx^2} = -\frac{p}{K}
\]

(6.3)

The solution of this equation can be written in the form

\[
\theta = -\frac{px^2}{2K} + C_1x + C_2
\]

(6.4)

where \( C_1 \) and \( C_2 \) are the two constants of integration. We assume that the two ends of the device are at temperature \( \theta_0 \). Imposing the boundary conditions at \( x=0 \) and \( x=L \) the solution comes out to be

\[
\theta = -\frac{px^2}{2K} + \frac{pLx}{2K} + \theta_0
\]

(6.5)

This equation gives the temperature distribution along the device. It can be found that the maximum temperature \( \theta_m \), will be recorded in the middle of the device at \( x=L/2 \) and will be given by

\[
\theta_m = \frac{pL^2}{8K} + \theta_0
\]

(6.6)
It may be noted that length $L$, of the device is restricted by the choice of frequency and doping level in a Gunn device. Even if it were allowed to vary it will not help in reducing $\theta_m$ because any attempt to reduce $L$ would in fact increase $\theta_m$ due to increase in $\theta_0$. Therefore the $p/K$ ratio is crucial in determining the maximum temperature of the device. $GaN$ with higher $K$ will certainly permit device operation at higher power compared to $GaAs$. A comparative account of the electro-thermal performance of $GaN$ and $GaAs$ based on equation (17) is shown in figure 6.11. This figure helps to determine the maximum power that can be handled by a device for a given temperature requirement. It may be noted from this figure that $GaAs$ device reaches 640K at a power density of $5 \times 10^9 \text{W/cm}^3$ where as $GaN$ device can go up to a power density of $1.4 \times 10^{10} \text{W/cm}^3$ at the same temperature.

![Graph showing power capability of GaN and GaAs Gunn devices from thermal conductivity consideration](image)
6.3 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.