GaN-based Gunn Diode for High Frequency Signal Generation

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Abstract— **The dynamic characteristics of *GaN--based Gunn diode* are reported at *D*-band and the device properties are compared at the same operating conditions and frequency of operations with GaAs-based Gunn diode. The results indicate that GaN-based Gunn diode generates at least 100 times more power than corresponding GaAs-based Gunn diode at same operating conditions.**

Index Terms- Domain formation, Gunn diode, High Frequency, Simulation

I. INTRODUCTION

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 [1-2]. High power *GaN*-based transistors and even high-frequency devices such as *GaN*-based *IMPATTs* with excellent electrical characteristics have been reported recently [3, 4]. Important properties of major importance for electronic applications of this material include a large value of wide band gap (*3.4eV*), high electrical breakdown filed (E_v*~2MV/cm*), high saturation velocity of electrons (v_{sn}*~2x10*^{7}*cm/sec*) and high thermal conductivity (nearly two times more than *GaAs*). The fundamental properties of *GaN* indicate that it also exhibits transferred electron effect. Increased electrical strength, a higher threshold filed, 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-Vs*. The increased value of E_{th} (threshold value) was caused by a large separation between the high and low mobility valleys in *GaN* (*ΔE~2.1eV*) compared to *0.3eV* in *GaAs*. Studies showed that the energy relaxation time in *GaN* is far shorter than that of *GaAs*. Transit times are far smaller due to high electron velocity. Based on all these fundamental properties of *GaN* semiconductors, it is expected that *Gunn* diode using this material would manifest much higher output capability in the *mm-wave*/*tera-hertz* range than traditional *GaAs*, *InP*-based *Gunn* diodes explored so far.

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To the best of our knowledge, the feasibility of using *GaN* in *Gunn* diode has not yet been explored properly theoretically except the preliminary work shown by pavlidis *et al* [5]. However many research groups is trying to fabricate GaN-based Gunn diode. The theoretical study of Pavlidis et al is preliminary and a detail study such as effect of notch, reverse injection, heterostructre etc has not been studies which improves the Gunn performance in GaAs-based devices [6, 7, 8]. Hence a detailed and systematic study is necessary at the present stage to see the potentiality of *GaN* and its compounds to use as *Gunn* diode at *mm-wave* and *tera-hertz* frequency range. A theoretical study including all these aspects will be very much helpful to research community before the material is dedicated to grow and fabricate the device. The aim of this presentation is to develop a model and study some of the parameters to see the potentiality of GaN-based Gunn diode. Model developed and its validity is discussed in next section.

II. MODEL DEVELOPED

A one-dimensional model is considered to study the domain dynamics in the device because the domain propagation occurs between the parallel contacts, and because the length of the uniformly doped active n-layer is typically much smaller than the device diameter.

A finite difference numerical method is developed to solve the carrier continuity equation, Poisson's equation, and space charge equation with a realistic velocity-field characteristic in the device. It forms a set of practical differential equations with two independent variables, time and distance. The field dependent diffusion is taken into consideration. The velocity field characteristics and all other material parameters used here are same as that of the material parameters used in [3, 4] for *GaN*-based *IMPATTs*.

The analysis is performed by dividing the sample into small cell of finite width in space. The charge and field quantities are regarded as constant in each of these cells and are evaluated at regular intervals. The cells in time and space are made small enough to get an exact solution. Taking initial value of *n* (concentration), *E* (electric field) from the one end (cathode contact), *E* and *n* is updated in each cell and the end value of *E* is then dictated by the

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boundary conditions. The boundary conditions can be either voltage or current boundary conditions. Voltage boundary conditions are used in this model, which requires the integral of the electric field across the device to be equal to the applied voltage (V_{dc}). Also, the boundary conditions are that the device contacts are ohmic and the total current density must be continuous throughout the device. Applying zero electric field boundary conditions at the outer metal contact edges of the n^+ region (anode and cathode end) frees the E fields to become time dependent at the edges of the active region. Finally, the terminal voltage is derived from the electric field profile. The limits on the dimensions of space width (Δx) and time width (Δt) were derived from simple physical considerations. For example, the electron density should not change too much between neighboring spaces cells *i.e.* Δx must be less than the dielectric relaxation length. In summary, the device simulation consists of:

(i) up date the electric field at the future time step by solving Poisson's equation and satisfying the condition $V^{t+\Delta t} = -\int_0^L E dx,$ where,

$V^{t+\Delta t}$ = terminal voltage at t+Δt and L = device length.

(ii) Compute the electron mobility from the velocity-field characteristics and the diffusion coefficient from the Einstein's relation at every node,

(iii) solve the current continuity equation for the carrier concentration at the future time step,

(iv) if simulation time is not reached, repeat all above again from step (i).

The presence of Gunn domains led to fluctuations of voltage and current, which gradually built-up into sustained large-signal oscillations. The regions of voltage *v(t)* and current *I(t)* waveforms corresponding to sustained oscillations were subjected to harmonic analysis and the resulting power spectrum was used to determine the frequency and power of the Gunn diode oscillators. The details described below.

The fluctuations terminal voltage calculated can be represented as:

$$V(t) = V_{dc} + V_{rf} Sin(wt) \qquad (1)$$

The current density across the device is expressed as

$$J_T = qnv + \varepsilon \frac{\partial E(x,t)}{\partial t} \qquad (2)$$

Since the total current density is independent of x, integrating equation (2) over the length of the device results in

$$\int_0^w J_T dx = \int_0^w qnv + \frac{\varepsilon}{W} \int_0^w \frac{\partial E(x,t)}{\partial t} \qquad (3)$$

The first term on the right hand side corresponds to the average particle current density J_p and the second term to the displacement current density. For the purpose of determining the device performance it is only necessary to consider the first term and then add the device cold capacitance to the equivalent circuit. The resulting particle current density is Fourier analyzed to extract the dc and the fundamental components.

$$J_{DC} = \frac{1}{2\pi} \int_0^{2\pi} J_p(\omega t) d\omega t \qquad (4)$$

$$J_F = a_1 \cos(wt) + b_1 \sin(wt) \qquad (5)$$

where,

$$a1 = \frac{2}{T} \int_0^T J_p(t) \cos(wt) dt \qquad (6)$$

$$b1 = \frac{2}{T} \int_0^T J_p(t) \sin(wt) dt \qquad (7)$$

The device admittance per unit area is given as

$$Y_D = -G_D + jB_D \qquad (8)$$

where,

$$G_D = \frac{b1}{V_{rf}} \qquad (9)$$

and

$$B_D = \frac{a_1}{V_{rf}} + \frac{\omega\varepsilon}{W} \qquad (10)$$

The generated rf power is given by

$$P_{rf} = \frac{1}{2} V_{rf}^2 A G_{D,} \qquad (11)$$

Where, A is the device area. From here the dc conversion efficiency can be calculated as P_{rf}/P_{dc} where $P_{dc}=V_{dc} x I_{dc}$ and I_{dc} can be calculated from equation 4. Thus the power obtained and *DC* to *RF* conversion efficiency for any type of Gunn diode can also be computed from our simulation program. The results obtained form this computation is presented in the next section. The validity of the model, choosing the material parameters etc are discussed elsewhere.

III. Results and Discussion

The results obtained from the above described simulation scheme are presented here. Figure 1 shows the doping profile of chosen Gunn diode. The concentration of anode and cathode first varies for different active region concentration and an optimized doping concentration and optimized width of anode and cathode are chosen. Figure 1 shows such a sample of doping profile. From the solution of above described method, it is seen that the current density variations with respect to time are periodic in nature. The variation of current density with respect to time and its periodic repetition are shown in figure 2 for different applied bias voltage for GaN-based Gunn diode. It is found from the figure that the diode is operating in between 100 to 120GHz with the variation of DC biasing. However, in GaAs-based Gunn diode, the frequency of operation under same conditions of operating is at 10-18GHz. The high operating frequency in case of GaN-based Gunn diode is mainly for high saturation carrier velocity. The peak values of the current density for *GaAs* were about *10 KA/cm²* and for *GaN* it is 130 *KA/cm²*. This shows the current strength of the device. The above signal is now Fourier analyzed to determine the power generated by the device. The power generated at different dc voltages with the frequency is shown first for GaAs-based Gunn diode in figure 3 to test the validity of the model. The results and power obtained in figure 3 matches with the results obtained by previous researchers and also is in close agreement with the experimental results. It shows that with increase in dc voltage the power generated increases. Further, power obtained is maximum for a particular frequency (in this case around 100GHz for a DC biasing of 4.0V). Hence, for a particular operating frequency, a fixed DC value is obtained. The power obtained in this case is found to be 100mW at 90GHz for a GaAs-based Gunn diode of 50µm radius. This shows that GaAs-based Gunn diode produce around 100mW at W band.

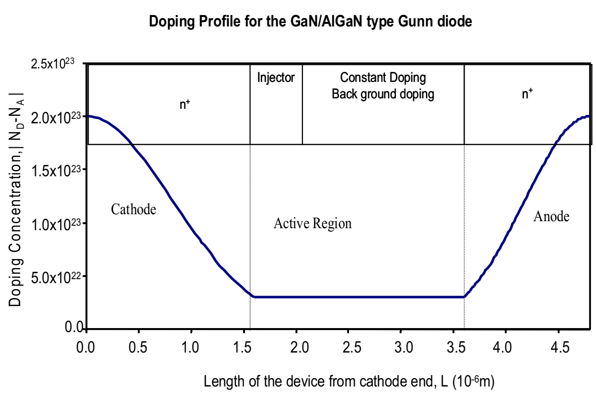

Fig 1: Structure and doping profile of a Gunn diode

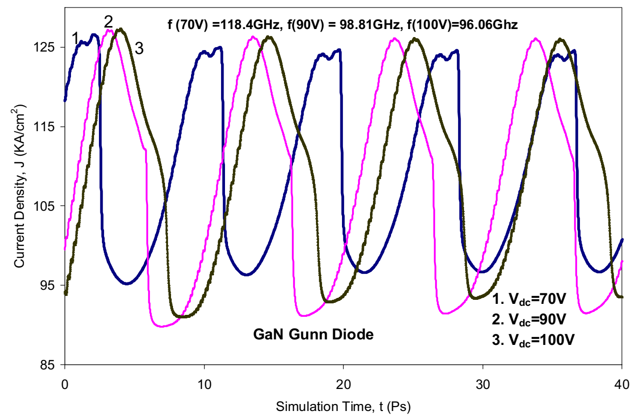

Fig 2: Simulation time versus current density showing oscillation in GaN Gunn diode

The power generated from *GaN* based *Gunn* diode for different DC biasing voltages are shown in figure 4. In this case the DC biasing voltage is varied from 70V to 100V to operate at W-band. The active length of the device chosen was 5µm.

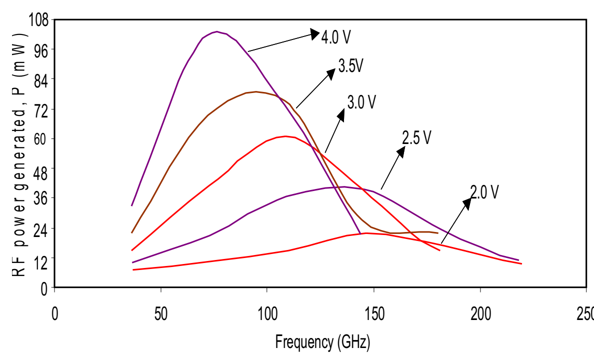

Fig 3: Frequency versus rf power obtained from different *GaAs*-based Gunn diode for verification purpose with experimental result.

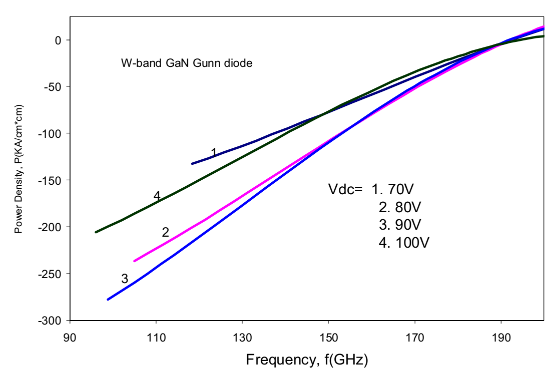

Fig 4: Frequency versus rf power obtained from different GaAs-based Gunn diode

With the increase in the applied voltage the power increases up to some limit like that of GaAs-based Gunn diode. The figure shows that the power produced comes in the range 300KW/cm^2. Thus assuming a device of 50µm radius, power generated is found to be around 25W which is 250 times more than that of GaAs-based Gunn diode at the same operating conditions with the same dimension. Thus GaN-based Gunn diode has more potential as a generator than corresponding GaAs-based Gunn diode at same operating conditions.

GaN can operate at very high frequency and can generate high power also. Devices for such cases are also studies by the authors and are presented in figure 5 for the benefit of the readers. The active length of the device is chosen to be 0.2µm and radius of 50µm is chosen for this case. The DC bias operating values varies from 17V to 19V and the power generated at different frequency is shown in figure 5. The frequency range in such cases is found to be 0.8THz to 1.8THz. The maximum power obtained is around 30W. This shows that GaN can produce substantial amount of power even at THz frequency range. The high power at high frequency is due to high saturation velocity of the charge carriers.

Though the GaN-based Gunn diode seems to have more potential, yet the other GaN-based structure such as heterostructure at different mole concentration, forward and reverse bias carrier injection, notch structures etc must be studied before the GaN material dedicated to the technologist to use it as a generator at high frequency of operation.

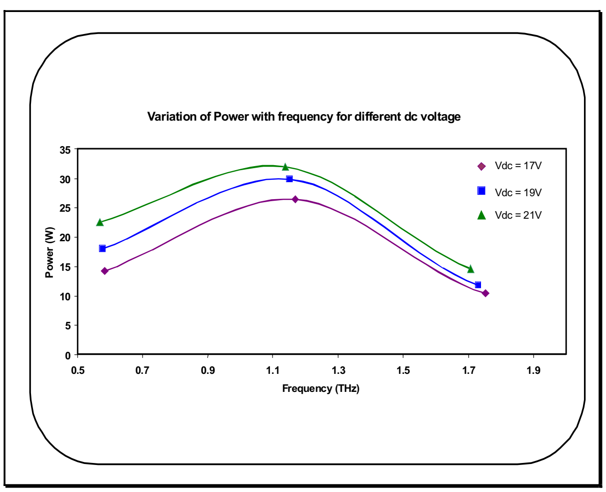

Fig 5 Graph showing the variation of power with frequency for different values of dc voltage for GaN-based Gunn diode at THz range frequency.

IV. Conclusion

In this report we have studied the feasibility of using *GaN* as a material of choice for different *Gunn* devices. It was found that due to the fundamental properties of the material, *GaN* NDR diodes offered twice/thrice the frequency capability of the *GaAs Gunn* diode, while their output power density was 300KW/cm^2 compared with $1KW/cm^2$ fort the *GaAs* devices. Though some more properties should be studied before it use as a generator, yet *GaN* is found to be better alternative material for fabrication of *Gunn* devices as compared to traditional *GaAs* and *InP*-based *Gunn* devices.

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