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ANALYTICAL MODEL FOR FREQUENCY RESPONSE OF A GUNN DIODE IN TRANSIT TIME MODEAND APPLICATION FOR GALLIUM NITRIDE BASED DIODES

By

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Abstract:

Gunn oscillation can occur via the transferred electron effect or the negative differential mass effect. We have mathematically formulated the frequency response of a Gunn diode operating in the transit time mode independent of the mechanism responsible for Gunn oscillation in bulk semiconductors. Domain growth dynamics with space and time, variation of domain velocity, and frequency response have been simulated for Gallium Nitride (GaN) by using our mathematical equations. Our simulation shows that gallium nitride based Gunn diodes at an active length of 5 micrometer can produce frequency around 40 GHz for DC biasing 150 V.

Keywords:

Domain growth dynamics, domain velocity, frequency response, GaN-Gunn diode

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1. Introduction:

Gunn diodes, based on conventional materials like Gallium Arsenide (GaAs) and Indium Phosphite (InP) have been employed for microwave and millimeter-wave generation [1]. In recent times, III-Nitrides, especially Gallium nitride (GaN) is exhibiting impressive performance in modulation doped field effect transistors [2], optoelectronics [3], and terahertz technology [4]. Monte Carlo studies have shown that all III-Nitride wurtzite phase binaries and ternaries exhibit negative differential resistivity (NDR) in their velocity-field characteristics [3, 6]. The conduction-band structure of GaN presents an ambiguous situation with respect to high field transport. The NDR can arise from either the transferred-electron effect or as a consequence of the negative effective mass beyond the inflection point depending on the energy of the upper valley [7]. Experimentally, the first stable NDR is reported in 2007 by Yilmazoglu et al. on vertical GaN-based Gunn device [8, 9]. The inherent material properties, like, high saturation drift velocity of electrons, lower dielectric constants, higher critical fields for binary III-Nitrides are very promising for high frequency and high power devices, as well as for Gunn oscillation. GaN is expected to exhibit significantly better power and frequency performance than conventional Gallium Arsenide (GaAs)-based diodes [1]. Monte Carlo simulations have demonstrated an NDR relaxation frequency of 740 GHz in GaN while in GaAs, it is only 109 GHz [4].

In this paper, a novel analytical expression with one fitting parameters for frequency response of a Gunn diode operating in the transit time mode has been presented.

2. Model developed:

The necessary expressions for the domain electric field and boundary conditions have been developed by us [10].

2.1. Frequency response:

When the diode is biased, i. e., $V \neq \mathbf{0}$ V, there establishes two types of electric fields: $\boldsymbol{E}_{dom}$ and $\boldsymbol{E}_r$. Now from the equal-area rule [11] it is clear that

$$\boldsymbol{E}_r = \boldsymbol{E}_r(\boldsymbol{E}_{dom}) \qquad (1)$$

and previously [10], we got

$$E_{dom} = E_{dom}(x, t) \tag{2}$$

So E_{dom} can be thought as a function of both space and time. But this is indeed not the situation when we want to calculate the current density due to the domain field. Because E_{dom} is entirely a localized field while E_r is a globalized field, as far as the diode dimension is concerned. E_r is uniformly distributed over the diode length expect the domain vicinity [11]. Taking this aspect in account, we have the current density due to only E_r can be given by

$$J_r(t) = q n_0 v_r(E_r) \tag{3}$$

The domain will contribute in the external circuit when it touches the anode terminal, i.e., at $t = t_{tr}$, t_{tr} be the transit time, mathematically we can express the fact as

The current density J_{dom} can be calculated from the continuity equation. But n is not a continuous function in $[t_{tr}, t_{tr} + \Delta t]$, where $\Delta t \to 0$, hence the derivative of the right-hand side of the current continuity equation does not exists. To solve the problem n can be considered as a multiple of the Heaviside "step-function" θ :

$$n(L, t_{tr}) = m\theta(-(t - t_{tr})) \tag{5}$$

where m is a multiplier, represents the magnitude of $n(\xi, \xi)$.

where is the Dirac-delta function, we have

$$\frac{\partial J_{dom}}{\partial x}\bigg|_{x=L} = mq\,\frac{d\theta\left(-(t-t_{tr})\right)}{dt}\bigg|_{t=t_{tr}}$$

Finally, the total current density $J_{total}(t)$ is computed as

$$J_{total}(t) = J_r(t) + J_{dom}(L, t_{tr}) \tag{7}$$

2.2 Transit-time:

The transit-time is defined as the time required reaching the domain at the end terminal of the device. But the domain does not travel along the device length in a uniform velocity, rather $v_{dom} = v_{dom}(E_{dom}(x,t))$, hence we define

$$\mathbf{t_{tr}} \equiv \sum_{\iota=1}^{N} t_\iota = \sum_{\iota=1}^{N} \frac{x_\iota}{v_{dom}(E_{dom}(x_\iota, t_\iota))} = \sum_{\iota=1}^{\xi-1} \frac{x_\iota}{v_{dom}(E_{dom}(x_\iota, t_\iota))} + \frac{\sum_{\iota=\xi}^{N} x_\iota}{\mathbf{v_{sat}}} \tag{8}$$

where v_{dom} is the domain velocity and the point has been defined by

$v_{dom}(E_{dom}(\xi, \xi)) \equiv v_{sat}$.

3. Matreial properties and fitting parameters used:

Experimental reports on high-field transport in III-Nitride binaries are very limited at present. There exist discrepancies in material parameters reported experimentally [5, 8, 9] and extracted by Monte Carlo simulations [6, 3]. However, all the parameters used in this paper to evaluate the velocity-field characteristics have been listed in Table 1 for AlN, GaN, and InN.

***Table (1):** Fitting and material parameters used for the velocity-field characteristics of III-Nitrides [8].*

Parameters	**AlN**		**GaN**		**InN**	
	Γ-M	Γ-A	Γ-M	Γ-A	Γ-M	Γ-A
μ_o $(cm^2V^{-1}s^{-1})$	400	450	1000	1000	3150	3150
E_{cr} $(kVcm^{-1})$	420	400	215	200	90	90
υ_{sat} (10^7cms^{-1})	1.5	1.5	1.3	1.3	1.00	1.00
a	6.75	6.75	7.0	5.5	5.75	5.5
β_1	6.0	6.0	4.5	4.25	3.20	3.10
β_2	0.825	0.825	0.7	0.7	0.85	0.90
ε_s	8.5		9.8		15.3	

4. SIMULATION RESULT

We have chosen the active length of the device 5 micrometer. Our calculation exhibits transit time frequency about 40 GHz. From Fig. 1, it is evident that, the domain velocity decreases with the increasing domain field. The dynamic behavior of domain field increases with space and time until it reaches the saturation point, after which it has been assumed to be unchanged, as shown in Fig. 2. Initially the biasing voltage was chosen to set up a domain electric field of 300 kV/cm and the saturation has been assumed at 700kV/cm. The obtained current density is about 650 kA/cm^2. To the best of our knowledge, there is no experimental and theoretical report on GaN-based Gunn diodes at active length of 5μm , so it has not been possible for us to compare our predictions.

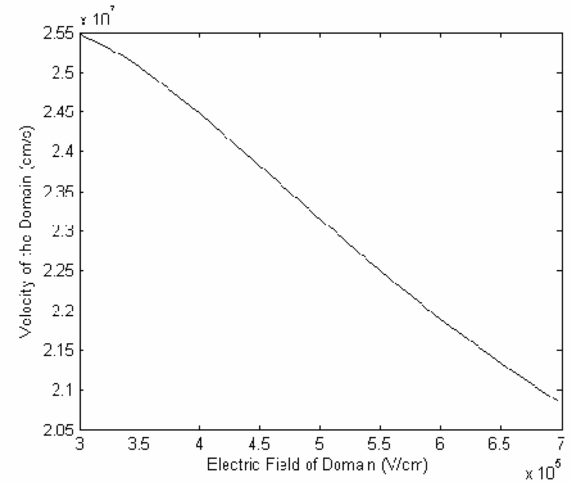

Figure 1. Variation of domain velocity with domain electric field.

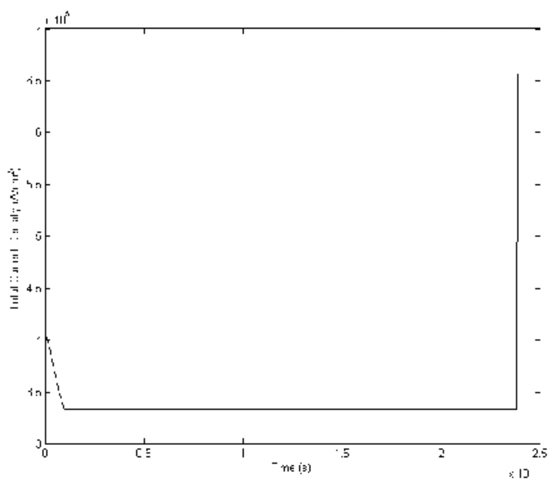

Figure 3. Frequency response of the diode.

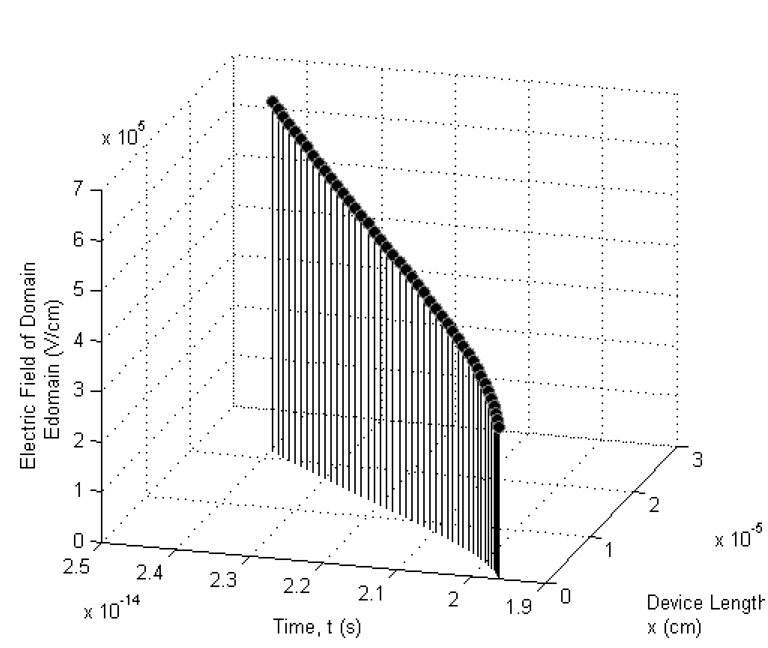

Figure 2. Three dimensional evolution of domain electric field

CONCLUSION

A novel analytical model for the domain response of a Gunn diode for the transit time mode has been presented. Different characteristics of Gunn diode, like the variation of domain velocity, domain electric field, and the current density have been simulated using the developed model which indicates the superior performance of GaN-based Gunn diode over the conventional GaAs-based Gunn diodes [1].

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