Future Prospects of Diamond in High Power MMW Application

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ABSTRACT

Use of Diamond for electronic applications was started for development of photoconductive detectors. However limitations in size and control of properties naturally limited the use of Diamond to a few specialty applications. With the development of Diamond synthesis from vapour phase has come a more serious interest in developing diamond based electronic devices. Diamond (band gap energy = 5.6 eV at 300K) supports peak internal electric field about 6 times higher than those of Si and GaAs, resulting in higher breakdown voltage, which is extremely important for devices handling high power. Another consequence of higher electric field and higher doping density is the width reduction in the drift region. Thus, not only high power but also the high frequency (MM/sub-MMW) operation capability is expected from this wide band gap semiconductor based devices. Hence Diamond based devices are expected to operate at higher voltage at the same operating frequency. Diamond is less noisy and is chemically very stable at high temperature. The expected excellent performances of diamond devices can be assessed by considering Keyes' FOM (considering the speed of transistors and their thermal limitations) and Johnson's FOM (considering the HF and high power capability of devices). Assuming Keyes' and Johnson's FOM for Si as unity, the Keyes' FOM and Johnson's FOM for GaAs are 0.45 and 7.1 respectively; those for Type II-diamond are 2.5 and 800 respectively. This clearly indicates that the HF and high temperature performance of Diamond devices would be much superior as compared to conventional Si and GaAs. The extensive simulation results reveal that MITATT diode based on Diamond gives better performance in terms of efficiency and output power. The design results and the proposed experimental methodologies presented in this paper will be helpful to realize Diamond MITATT oscillators for Terahertz communication.

Keywords

Diamond, MITATT diode, Terahertz frequency

1. INTRODUCTION

MITATT diodes are considered as strong resources that can produce high frequency RF power at microwaves, millimeter waves and sub-millimeter waves , so that coverage of a large band of frequency is possible. Since terahertz science is progressing rapidly all over the world [1], there is strong interest in the exploitation of terahertz-frequency range in almost every stream of scientific applications. In this context, Mitatt diodes can play a very important role as the most powerful solid-state source in varieties of civilian and space-communication systems as well as in high-power radars, missile-seekers etc. Up till now appreciable performance in generating power and efficiency has been reported on Impatt diodes and oscillators, which can perform well in the frequency range of 30 to 300 GHz or even more. The Terahertz (THz) frequency range (0.1 — 10 THz) is an intermediate between microwaves and infrared , based on which electronics can find an interface with optics. As a consequence of this in frequency spectrum, a surfeit of metrological applications with high impact on industries exist [2]. The THz territory is fulfilled with outstanding possibilities in remote sensing, imaging, spectroscopy, and communication. Moreover to detect hidden physical weapons, explosives from suspicious objects etc. applications in this frequency range have an immense effect. Various secure fields as well as military applications prefer this THz operation. Now-a-days, with available power sources, researchers are patenting potential THz wavelength applications in many fields [3]. MITATT(Mixed Tunneling and Avalanche Transit Time) is basically a mode of operation on transit time device , e.g. IMPATT diode , which is obtained at very high frequencies, where both tunneling and impact ionization mechanisms are present. As some limitations are there in the material parameters of Si, Ge, GaAs semiconductors, therefore on THz frequency operation of transit time devices in Mitatt mode based on these conventional semiconductors are restricted. The research trend is now to find new materials for MITATT diodes such that they overcome these limitations and produce high power at higher frequency. However, wide bandgap semiconductor such as Diamond, occupies many fold advantages compared to traditional Si, Ge, GaAs , such as possibility of operation with a higher output power resulting from increased critical field, higher bandgap energy, higher saturation velocity and much better thermal conductivity [4]. This wide band gap semiconductor with some excellent material properties is recently being studied as base material for high frequency semiconductor devices. Diamond based MITATT diodes operating at Terahertz frequencies has not been viewed so far — only few reports based on simulation are available in the literature to the best of authors' knowledge[5], [6], [7], [8]. Diamond acquires suitable material parameters with respect to conventional semiconductors. The critical electric field (Ec),being many times higher , doping level in the depletion layer of the device can be grown up to reduce considerably the width of the active region. Therefore the device layers become skinny, which enables Diamond based MITATT diodes a potential candidate for THz power generation. Diamond is less noisy and is chemically very stable at high temperatures. Moreover, due to higher electric field and higher doping density the width reduction in the drift region occurs. Therefore , not only high power but also the high frequency (THz) operation capability is desired from this wide band gap based devices [9], [10]. The expected exemplary performances of wide band gap devices can be evaluated by considering Keyes' FOM (based on the speed of transistors and their thermal limitations) and Johnson's FOM (based on the HF and high power capability of devices). Assuming Keyes’ and Johnson’s FOM for Si as unity, the Keyes’ FOM and Johnson’s FOM for GaAs are 0.45 and 7.1 respectively; those for Type II-diamond are 2.5 and 800 respectively. This clearly indicates that the HF and high temperature performance of Diamond devices would be much superior compared to other semiconductors [11]. In the submillimeter/THz region, high power MITATT oscillators are extremely useful solid state sources. To satisfy the quest of increasing demand for high power THz sources, the authors have designed a symmetrically doped flat profile p+pnn+ Diamond DDR MITATT at THz region. The DC and small signal properties have been investigated to explore the potentiality of the device as probable solid state source at THz frequency after which a self-consistent large-signal model of Double-Drift MITATT diode with general doping profile is derived. This paper will act as a guide to device engineers to realize low Noise electrically controlled Type II Diamond based MMW power source for medical imaging.

2. MODELLING AND SIMULATION

2.1 Dc Analysis

The main physical phenomena take place in the semiconductor bulk along the symmetry axis of the mesa structure of transit-time diodes(a basic IMPATT structure is considered). One dimensional equations of device are numerically solved in the present method. The fundamental device equations i.e., Poison’s equation, current density equation and continuity equation involving mobile space charge in the depletion layer are simultaneously solved under appropriate boundary conditions by using a double iterative field maximum computer method as described below:

The Poisson’s equation is given by

$$\frac{\delta E(x)}{\delta x} = \frac{[q(N_D - N_A) + \rho(x)]}{\varepsilon} (1)$$

where ‘ε’ is the di-electric constant of the semiconductor and N_D and N_A are the densities of the ionized donors and acceptors respectively. ρ(x) = q(p-n) is the net density of mobile charge carriers.

The continuity equations are

$$\frac{\delta n}{\delta t} = \frac{1}{q}\left(\frac{\delta Jn}{\delta x}\right) + g - Un (2)$$

$$\frac{\delta p}{\delta t} = \frac{1}{q}\left(\frac{\delta Jp}{\delta x}\right) + g - Up (3)$$

where ‘g’ is the generation rate due to impact ionization only, because tunneling generation is neglected and U_n , U_p are the recombination rates of electrons and holes respectively. Recombination effects are not included in the analysis since the transit time of carriers in the depletion layer of an Impatt diode is several orders of magnitude shorter than the recombination time. The generation rate due to impact ionization is given by

$$g = \left(\frac{1}{q}\right)\left[\alpha_n |J_n| + \beta_p |J_p|\right] (4)$$

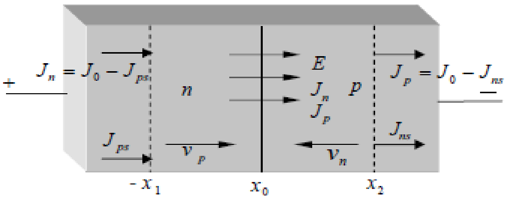

Fig.1 Depletion layer of a p-n junction diode reverse-biased to breakdown

2.2 BOUNDARY CONDITIONS

The electric field is very low at the edges of the depletion layer. So for all practical purposes the boundary conditions for the electric field is given by

$$E(-x_1) = 0 \wedge E(x_2) = 0 (11)$$

where $-x_1$ and x_2 define the edges of n and p layers respectively (Fig. 1). The boundary conditions for $J_{diff}(x)/ J_0$ at the depletion layer edges are given by,

$$\left(\frac{J_{diff}(x)}{J_0}\right)_{x=-x1} = \left\{1 - \frac{2}{M_n}\right\} (12)$$

$$\left(\frac{J_{diff}(x)}{J_0}\right)_{x=x2} = \left\{\frac{2}{M_p} - 1\right\} (13)$$

In the present method the computation starts from the location of field maximum in the depletion layer and the field maximum is assumed to be located very close to the junction at x= x_0 , where x = 0 is the location of the p-n junction.

Therefore, $\left|\frac{\delta E}{\delta x}\right|_{x=x_0} = 0$

Using the above condition the following relation is obtained from Poisson’s eqn. as,

$$|q(N_D - N_A)|_{x=x_0} = -|\rho(x)|_{x=x_0} (14)$$

The magnitude of $(J_{diff}(x)/ J_0)$ at $x=x_0$ is given by

$$\left(\frac{J_{diff}(x)}{J_0}\right)_{x=x_0} = \left\{\frac{v_{diff}(x_0)}{v_T(x_0)}\right\} + \left\{\frac{2|v_n(x_0)J_p(x_0) - v_p(x_0)J_n(x_0)|}{v_T J_0}\right\} (15)$$

where $v_{diff} = (v_p - v_n)$ and $v_T = (v_p + v_n)$.

The magnitude of peak electric field E_m and its location from the junction x0 are suitably chosen for a given doping profile and direct current density (J_0). The values of $|J_{diff}(x)/ J_0|_{x=x0}$ and ρ(x0) are obtained from respective equations. Double iterations over E_m and x0 are carried out to solve equations (1), (6), (8) and (10) simultaneously till the boundary conditions for E(x) and $J_{diff}(x)/ J_0$ are simultaneously satisfied at the depletion layer edges within a fixed accuracy limit. Once the solution for E_m and x0 are obtained , the computer simulation program provides the E(x) and $J_{diff}(x)/ J_0$ profiles in the depletion layer of the diode for a particular bias current density. Here we have used the **Diamond** as the material for this diode structure.

3. HIGH FREQUENCY FIELD MAXIMA LARGE SIGNAL SIMULATION

Based upon voltage-excitation method[12], where a sinusoidal voltage being simulated, leads to generation of a particular device current that is readily analyzed using conventional mathematical tools[12] and subsequently the device admittance ξ_d is found out. This admittance is a figure of merit which governs the large signal perspective attitude of the negative resistance diode and helps to evaluate the power and efficiency variations with increasing frequency as well as voltage modulations. Obviously the admittance has an intimate dependence on the operating frequency and fluctuating current index[12], so quite admissible in this regard that

$$\xi_d = \xi_d\ (f,m)$$

where f is the operating frequency and m is the modulation index given by $m=\frac{I_f}{I_{dc}}$, I_f being the rf current component

3.1 Results Obtained

The approximated material parameters of Diamond are enlisted in Table I. The structural parameters of symmetrically doped Diamond MITATT is furnished in Table II. Considering the optimized design parameters of DDR MITATT enlisted in Table III, it is observed that Diamond MITATT is a high current and high power device at the same operating frequency. As furnished in Table III, it is clear that based upon material and structural parameters (Table I & II), Diamond based MITATT can be operated upto 1THz frequency range, with the target of generating an output power of 16.6mW , where about 3.3% efficiency in its operation is achievable. The entire simulation was carried out at a voltage modulation of 50% (i.e., half of the breakdown voltage). The successive simulation outcome on this model provided the values of negative conductance (-G) as 55X10^6 S/m^2 at a voltage modulation of 5% , 54X10^6 S/m^2 at a voltage modulation of 20% and 53.8 X 10^6 S/m^2 at a voltage modulation of 30% and so on. This clearly indicates the large signal effect on degradation of negative conductance of Diamond MITATT as expected. Figure 3 shows the effect of increasing voltage modulation on negative conductance – susceptance plot, where the peak was obtained approximately at 1THz. Figure 4 and 5 show the effect of increasing frequency on device power and efficiency, where calculations were conducted at 50% voltage modulation. The peak power of 16.6mW and efficiency of about 3.3% were obtained near 1THz frequency, which start decreasing with rise in frequency as well as voltage modulation further. Here although we have shown only the effect of frequency on power and efficiency in this literature, but the results obtained at different stages of simulation are in close proximity of the desired output.

Table 1. Material Parameters for Diamond

Sl. No.	Parameters	Values
1	Band gap energy (eV)	5.6
2	$A_n(10^8$ /m)	193.5
3	$b_n(10^8$ V/m)	7.749
4	$A_p(10^8$ /m)	193.5
5	$b_p(10^8$ V/m)	7.749
6	$Ah_n(10^8$ /m)	0.50
7	$bh_n(10^8$ V/m)	0.99
8	$Ah_p(10^8$ /m)	0.56
9	$bh_p(10^8$ V/m)	1.32
10	v_{sn} (10^5 m/s)	1.0
11	v_{sp} (10^5 m/s)	0.76
12	μ_n (m^2/Vs)	0.05
13	μ_p (m^2/Vs)	0.018
14	Permittivity ($10^{-9}Fm^{-1}$)	0.088

A_n,A_p, b_n,b_p are Ionization coefficients of electrons and holes respectively at low E-field

Ah_n,Ah_p, bh_n,bh_p are Ionization coefficients of electrons and holes respectively at high E-field

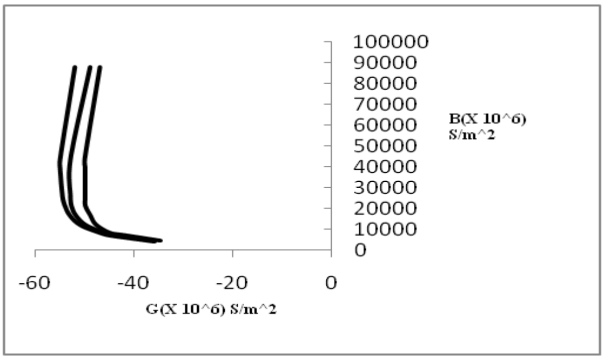

Fig.3 Conductance-Susceptance plot of Diamond MITATT at Terahertz frequency

Table 2. Structural parameters of Diamond

Sl. No.	Parameters	Values
1	Width of n-epilayer(nm)	5
2	Width of p-epilayer(nm)	5
3	Doping concentration of n region(m^{-3})	1.8 X 10^{23}
4	Doping concentration of p region(m^{-3})	2 X 10^{23}
5	Current density(A/m^2)	0.1 X 10^9

Sl. No.	Parameters	Values
6	Substrate doping(m^{-3})	1 X 10^{26}
7	Area of the diode (m^2)	1X10^{-9}

Table 3. DC and FMLS analysis of Diamond MITATT

Sl. No.	Parameters	Values
1	Peak Electric field (V/m)	2.424 X 10^8
2	Breakdown voltage (V)	51
3	Peak frequency (THz)	1.0
4	Peak conductance (S/m^2)	-51.3 X 10^6
5	Output power	16.6mW
6	Efficiency	3.3%

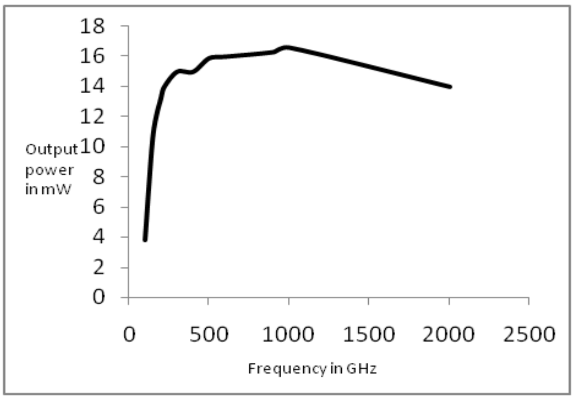

Fig.4 Variation of power with frequency

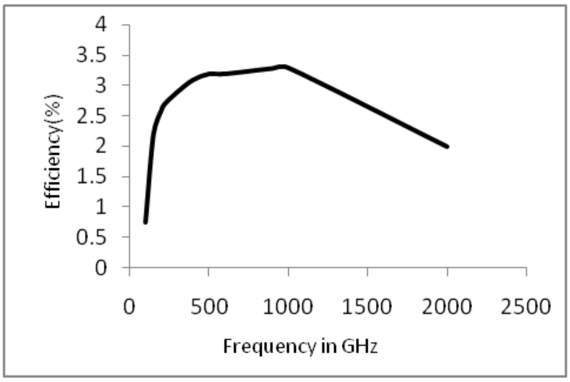

Fig.5 Variation of Efficiency with frequency

4. CONCLUSION

The simulation of DC and high frequency properties of Diamond based MITATT yields that in future rigorous analysis depending on experimentally verified parameters can lead to much better output in both power and efficiency , so that it can be made suitable as a powerful Terahertz oscillator.

5. ACKNOWLEDGEMENT

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