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REGULAR ARTICLE

A Co-relative study on DDR Diamond and Si-based IMPATTs in Terahertz Regime

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The possibility of a type-IIb diamond as the foundation for double-drift region (DDR) impact avalanche transit time (IMPATT) devices that operate at THz frequencies has been investigated. In this study, the large-signal (L-S) simulation model is employed. The top cut-off frequency for DDR type-IIb diamond IM-PATTs is 1.5 THz, while for Silicon (Si) IMPATTs, it is 0.5 THz. According to the Large signal simulation da-ta, the diamond IMPATT (DIMPATT) device exhibits a peak RF power of 891mW with an 11.02% conversion efficiency at 0.3 THz, taking voltage modulation of 50%. Whereas for Si IMPATTs the RF output power 173 mW with a 3% conversion efficiency is obtained for the same percentage of voltage modulation. A co-relative study has been presented for DDR IMPATT based on Si and type-IIb diamond, which shows the superiority of DIMPATT, in terms of power and DC to RF conversion efficiency at the THz domain.

Keywords: Diamond, IMPATT, Large Signal, Silicon, Terahertz.

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1. INTRODUCTION

The capacity of impact avalanche transit time (IMPATT) devices to generate sufficient RF power at microwave, mm-wave, and THz frequency bands has been widely demonstrated in [1, 2]. Research based on the Terahertz (THz) frequency domain (0.1 – 10 THz) is currently a hot topic of interest because lower frequency bands are already too congested. Several potential applications focus on the THz domain due to wider bandwidth reliability [3-7]. Despite the high likelihood of applications for the THz frequency spectrum, there are no such developments in the THz sources to address the need. So, a potential source is required to avail the benefits of higher bandwidth reliability in THz. To address the need for a THz source, the authors have designed and performed a large signal analysis of the DDR IMPATT based on diamond.

The capacity of Single Drift (SDR) and Double Drift region (DDR) Silicon diodes to generate high power with good efficiency at mill-metric wave frequencies has attracted significant attention due to the extremely rapid growth of silicon technology [7-9]. The diamond-based IMPATTs have recently demonstrated the capacity to produce RF power at terahertz and mm-wave levels [10, 11]. Diamond was first identified as carbon in 1796, and it was only synthesized in 1954. Chemical vapor deposition (CVD) is the most used process for making diamonds. Eversole used the first CVD process in 1962 [12]. Later, Railkar et al. [13] thoroughly investigated the CVD diamond technique. In terms of this work, a co-relative study between Si and Diamond (type-IIb) is being conducted at several THz frequency bands to determine the effectiveness of Diamond IMPATT as a suitable solid-state source at the mentioned terahertz frequency bands.

2. DESIGN AND SIMULATION METHODOLOGY

We have taken a one-dimensional DDR model shown in Fig. 1 for simulation purposes.

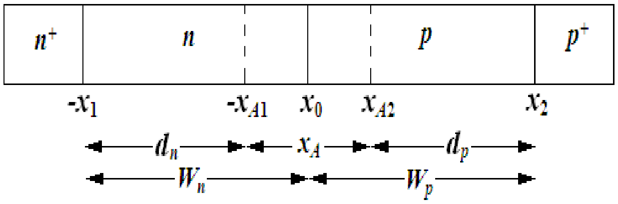

Fig. 1 – DDR IMPATT structure

The DDR IMPATTs based on different semiconducting materials operating in several THz frequency bands have a space charge layer w ($w = w_n + w_p$), where 'n' and 'p' are for electrons and holes, 'w_n' & 'w_p' indicates the width, N_D and N_A are doping concentrations [14]. The design parameters are

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listed in Tables 1 and 2 for IMPATT based on Si and diamond respectively.

Table 1 – Design Parameters of Si at THz frequencies

Substrate	f_d (GHz)	W_n (nm)	W_p (nm)	N_D ($\times 10^{23}$ m^{-3})	N_A ($\times 10^{23}$ m^{-3})	N_{Sub} ($\times 10^{26}$ m^{-3})
Si	300	132.0	112.0	6.00	7.30	1.00
	500	72.0	70.0	15.0	16.2	1.00

Table 2 – Design Parameters of Diamond (type-IIb) at THz frequencies

Substrate	f_d (GHz)	W_n (nm)	W_p (nm)	N_D ($\times 10^{23}$ m^{-3})	N_A ($\times 10^{23}$ m^{-3})	N_{Sub} ($\times 10^{26}$ m^{-3})
Diamond	300	220.0	220.0	2.050	2.220	1.00
	500	120.0	120.0	3.750	4.100	1.00
	1000	52.0	52.0	9.500	10.00	1.00
	1500	30.0	30.0	36.00	37.00	1.00

Using the developed simulation method in MATLAB, DC, and high-frequency characteristics are obtained for DDR IMPATTs under consideration. The simulation flowchart for DC and high frequency is given below in Figs. 2 and 3. The author's previous work also reports the detailed approach and the transport equations related to the analyses [15].

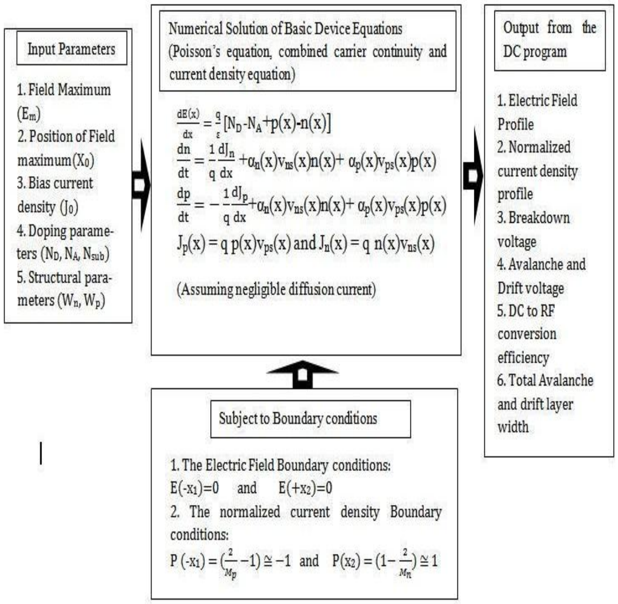


Fig. 2 – Flow chart for DC simulation.

3. RESULTS AND DISCUSSION

3.1 The Static and High-Frequency Properties

Important static and high-frequency properties like peak electric field (E_m), breakdown voltage, avalanche voltage drop, optimal frequency (f_p), peak negative conductance (G_p) and susceptance (B_p), Q factor at f_p ($Q_p = -B_p/G_p$), RF power output (P_{RF}), and efficiency of DC to RF conversion (η_L) are evaluated from simulation program. The variation of the said parameters with design frequencies are exhibited both in tabular and graphical format (Tables 3 and 4, Figs. 5 and 6). It is noticed from the tables that an upper cut-off frequency of 1.5 THz is obtained for diamond-based DDR IMPATTs where it is 0.5 THz for Si IMPATTs. It is observed that peak e-field increases with design frequency where breakdown voltage, avalanche drop, and avalanche layer width decrease with frequency. The higher value of breakdown voltage is obtained for diamond-based IMPATTs than Si IMPATTs because of having a wider bandgap of a diamond. The magnitude of peak negative conductance increases with design frequency for both IMPATTs whereas the magnitude of negative resistivity falls with frequency.

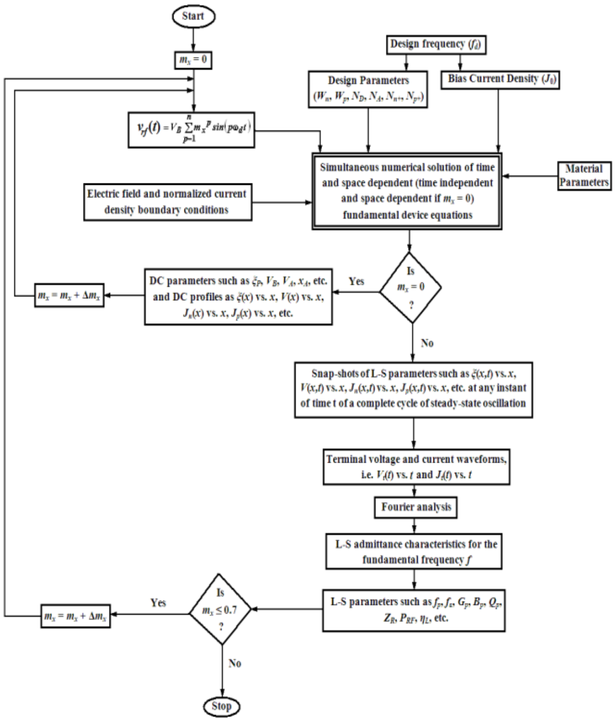
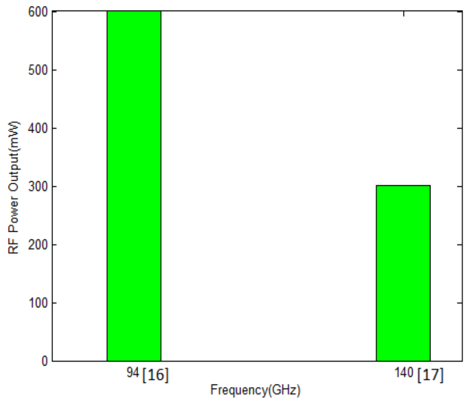


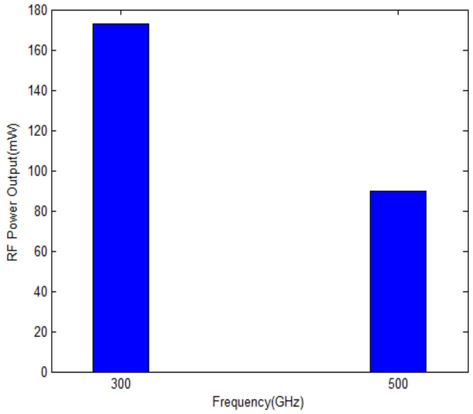
Fig. 3 – Flow chart for High-frequency simulation.

Thereby DC to RF power output (P_{RF}) decreases with operating frequency.

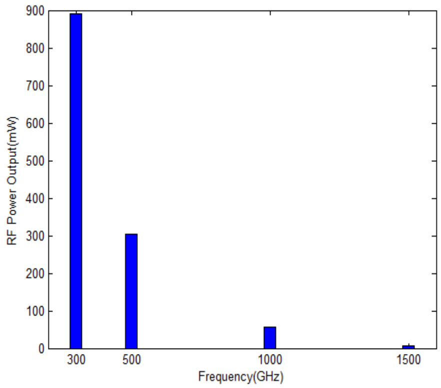
It is quite intriguing that diamond IMPATTs provide the highest RF output power (P_{RF}) with significantly higher conversion efficiency (η_L) than Si IMPATTs at 0.3 THz and 0.5 THz respectively, plotted in Fig. 4. Experimentally obtained power output from Si DDR IMPATTs at 94 GHz and 140 GHz are exhibited also below in the bar plot. It is quite evident that with increasing operating frequency power output decreases. Thereby it confirms our simulation results as well. But until now no experimental results are available regarding RF performance of DDR diamond IMPATTs. But the datasheet highlighted here can be considered for the design of Terahertz DDR diamond IMPATTs.



Experimental data of Si DDR IMPATTs



Simulated data of Si DDR IMPATTs



Simulated data of type-IIb Diamond IMPATTs

Fig. 4 – RF performance (simulated and experimental) of DDR Si and Diamond IMPATTs.

Table 3 – DC and High-frequency characteristics of DDR Si IMPATTs

Parameters	f_d (GHz)	
	300	500
E_m (× 10^7V/m)	9.33700	12.3120
Breakdown voltage (V)	11.71	9.35
Avalanche Voltage drop (V)	9.25	7.84
X_a (μm)	0.136	0.089
f_p (GHz)	301.5	501.5
f_a (GHz)	141.3	196.7
G_p (× 10^7 Sm $^{-2}$)	– 5.7154	– 10.4471
B_p (× 10^7 Sm $^{-2}$)	40.5807	121.2923
Quality factor (– Q)	7.10	11.62
Z_R (× 10^{-10} Ωm $^{-2}$)	– 3.4031	– 0.7045
P_{RF} (mW)	173.12	89.61
η_L (%)	3.41	2.22

Table 4.1 – DC and High-frequency characteristics of IMAPTT based on diamond

Parameters	f_d (GHz)			
	300	500	1000	1500
E_m (× 10^7 V/m)	11.0065	11.6943	12.8940	14.6692
Breakdown voltage (V)	26.90	15.56	7.761	3.223
Avalanche Voltage drop (V)	12.57	7.941	4.283	2.094
X_a (μm)	0.132	0.078	0.038	0.016
f_p (GHz)	301.0	502.0	1002.0	1501.0
f_a (GHz)	192.1	283.9	469.0	704.4
G_p (× 10^7 Sm $^{-2}$)	– 5.5742	– 12.7406	– 37.7468	– 97.3996
B_p (× 10^7 Sm $^{-2}$)	16.0669	52.1542	252.0855	660.1105

Table 4.2 – DC and High-frequency characteristics of IMAPTT based on diamond

Parameters	f_d (GHz)			
	300	500	1000	1500
Quality factor (– Q)	2.88	4.09	6.68	6.78
Z_R (× 10^{-10} Ωm $^{-2}$)	– 19.2730	– 4.4202	– 0.5809	– 0.2188
P_{RF} (mW)	890.98	302.84	55.79	6.19
η_L (%)	11.02	9.91	9.39	8.17

4. CONCLUSION

Here, a thorough study of likelihood and potency in DDR IMPATT based on the type-IIb diamond at the THz level is conducted and compared to that of Si IMPATTs. The high cut-off frequency from the diamond IMPATT is 1.5 THz, compared to 0.5 THz for Si IMPATT. It was observed that the former one can generate significantly greater RF power output and conversion efficiency at the THz level.

This signifies the DDR Diamond IMPATTs as THz source. The design approach and results reported here are useful and extremely inspirational.

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Корелятивне дослідження IMPATT на основі алмазів DDR та кремнію в терагерцовому режимі

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Досліджено можливість використання алмазу типу IIb як основи для пристроїв з часом проходження ударної лавини (IMPATT) з подвійною дрейфовою областю (DDR), що працюють на терагерцових частотах. У цьому дослідженні використовується модель моделювання великого сигналу (L-S). Верхня гранична частота для алмазних IM-PATT DDR типу IIb становить 1,5 ТГц, тоді як для кремнієвих (Si) IMPATT вона становить 0,5 ТГц. Згідно з даними моделювання великого сигналу, алмазний IMPATT (DIMPATT) демонструє пікову радіочастотну потужність 891 мВт з ефективністю перетворення 11,02 % на частоті 0,3 ТГц при модуляції напруги 50 %. Тоді як для кремнієвих IMPATT вихідна радіочастотна потужність становить 173 мВт з ефективністю перетворення 3 % для того ж відсотка модуляції напруги. Було представлено корелятивне дослідження для DDR IMPATT на основі Si та алмазу типу IIb, яке показує перевагу DIMPATT з точки зору потужності та ефективності перетворення постійного струму в радіочастотний в терагерцовому діапазоні.

Ключові слова: Алмаз, IMPATT, Великий сигнал, Кремній, Терагерцевий діапазон.