Chapter

IMPATT Diodes Based on GaAs for Millimeter Wave Applications with Reference to Si

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Abstract

The small signal characteristics of DDR IMPATTs based on GaAs designed to operate at mm-wave window frequencies such as 94, 140, and 220 GHz are presented in this chapter. Both the DC and Small signal performance of the above-mentioned devices are investigated by using a small signal simulation technique developed by the authors. The efficiency, output power and power density of GaAs IMPATT is higher than that of Si IMPATT. Results show that the DDR IMPATTs based on GaAs are most suitable for generation of RF power with maximum conversion efficiency up to 220 GHz. The noise behavior of GaAs IMPATT yield less noise as compared to Si IMPATT.

Keywords: GaAs, IMPATT diode, ionization rates, efficiency, noise

1. Introduction

The revolution of electronic device in 20th century is mostly based on silicon and is regarded as the first generation semiconductor. Before the beginning of 21st century gallium arsenide (GaAs) and indium phosphide (InP) have evolved as second generation semiconductors constituting the base for the wireless and information revolution. However, at the begin of the 21st century, silicon carbide (SiC) and gallium nitride (GaN) are emerge as the wide bandgap semiconductors can work at high temperature and at high voltage and they may be regarded as third generation semiconductors used in the electronic and optoelectronic industries. Moreover the superior properties of wide bandgap semiconductors and the recent rush of research on wide bandgap semiconductor based electronic devices; one might speculate that wide bandgap semiconductors like diamond, AlN, etc. may be the future generation semiconductors. However, all the semiconductors have their vital performance in the field of information and communication.

The tremendous growth in information and communication technology has resulted in demand for millions of channels simultaneously. In order to avoid the interference between individual communications, the frequency of operation has been increased to a high value (i.e. the microwave and millimeter wave range). The advancement in solid state devices has contributed significantly towards the feasibility of modern microwave and mm-wave systems. Among several solid state devices capable of producing millimeter wave, IMPATT (IMPact Avalanche Transit Time) diode is considered as a leading source of solid-state power. The high power generating capability and high efficiency of IMPATT diode makes it attractive both at commercial and military sectors. The device has the dominant characteristics over other microwave and millimeter wave sources both with respect to the frequency coverage and output power. Later the report of first experiment of the microwave oscillation [1] the efficiency and output power has been increased with frequency. And some of the records making output from IMPATT diode are 42 W of pulsed power at 96 GHz [2], 520 mW at 217 GHz [3] and a continuous wave (CW) power 980 mW near 100 GHz and 50 mW at 220 GHz [4] have been reported. Again IMPATT diode being fabricated from any semiconductor, it has made itself an attractive device for both theoretical as well as experimental study.

IMPATT diodes are well recognized two terminal solid-state devices to deliver sufficiently high power at both microwave and mm-wave frequency bands [5]. Silicon is the most popular base material for IMPATT diodes from the point of view of its advanced process technology [6–10]. However, GaAs is a vibrant base semiconductor for IMPATT diodes at the both microwave and mm-wave frequencies. Since early seventies, several researchers have fabricated IMPATT diodes based on GaAs and obtained higher DC to RF conversion efficiency and better avalanche noise performance of those as compared to their conventional Si counterparts [11–16].

This chapter looks at the benefits of GaAs in power electronics applications, reviews the current state of the art, and shows how it can be a strong and feasible candidate for IMPATT. It is also well known that at a given frequency the microwave and millimeter wave power output of an IMPATT diode is proportional to the square of the product of semiconductor critical field and carrier saturation velocity. Again heat generation and dissipation in IMPATT diodes can severely limit the performance of IMPATT diodes. GaAs is, therefore, an ideal semiconductor for IMPATT diodes over Si, because it offers higher (i) critical electric field, (ii) carrier saturation velocity and (iii) thermal conductivity. These properties can lead to high-performance IMPATT diodes for microwave and millimeter wave applications. Some theoretical work using drift–diffusion methods for IMPATT device simulation confirmed that GaAs devices operated in the pulsed mode can offer very high power in the short-wavelength part of the millimeter range. So in this chapter, we have explored the device properties of GaAs IMPATT diode using a small signal model for mm-wave applications around the design operating frequencies of 94, 140, 220 and 300 GHz. The power performance and noise behavior of the diode is determined and compared with the Si base double drift region (DDR) IMPATT diode.

2. Material parameter and design consideration of Si, GaAs IMPATT diodes

The material parameters take the vital role for the design of the diodes as well as the IMPATT operation. We have used the values of material parameters of the semiconductors under consideration i.e. the carrier ionization rate, saturation drift velocity of electron (v_{sn}), and hole (v_{sp}), mobility (μ), permittivity (ε_s) etc. obtained from the research reports [17–26]. The material parameters used for the computer simulation IMPATT diodes based on the semiconductors concerned are summarized in **Table 1**. Besides theses parameters for IMPATT it is required to consider about the diode area, junction temperature and the operating current density at the desired design frequency. In this case we have taken the uniform diode area and junction temperature, but the current density is taken as per the operating frequency.

Parameters	Si	GaAs
Energy band gap, E_g (eV)	1.12	1.42
Critical Electric Field, E_c ($\times 10^6$ V/m)	—	0.65
*A_n ($\times 10^8$ m^{-1})	0.62	5.6
*B_n ($\times 10^8$ V m^{-1})	1.31	2.41
* A_p ($\times 10^8$ m^{-1})	2.0	1.5
*B_p ($\times 10^8$ Vm^{-1})	2.17	1.57
*m	1	1
Saturation drift velocity of electron, v_{sn} ($\times$ 10^4 m/s)	10.5	10.0
Saturation drift velocity of holes, v_{sp} ($\times 10^4$ m/s)	8.1	10.0
Electron mobility, μ_n ($m^2V^{-1}S^{-1}$)	0.058	0.85
Hole mobility μ_p ($m^2V^{-1}S^{-1}$)	0.04	0.019
Permittivity, ε (10^{-11} F/m)	10.0	11.4

*$\alpha_n = A_n \exp[-(B_n/E)]^m$, $\alpha_p = A_p \exp[-(B_p/E)]^m$.

Table 1.
Material parameters of Si and GaAs semiconductors.

To design an IMPATT diode one needs to consider its efficiency, frequency of operation, low cost, low loss thermal and electrical constants, output power and it is also important to achieve the breakdown condition for IMPATT operation. Energy band gap, ionization rate, dielectric constant, thermal conductivity, saturation drift velocity of electron and hole and break down field are the key factors to acquire the simulation results of efficiency, breakdown voltage and the output power of IMPATT. Taking into account the suitability of all these material properties, we have used the design criteria as $W = 0.5\, v_{sn,sp}/f_d$; where W, $v_{sn,sp}$ and f_d are the total depletion layer width, saturation velocity of electrons and design operating frequency respectively and chosen the double drift region (DDR) optimized structure to explore the potential of GaAs IMPATT diode. The schematic diagram of the DDR structure is shown in **Figure 1**. This structure depends on the saturation velocity and design operating frequency.

The diodes have the doping distribution of the form n^+npp^+ and are designed to operate at a frequency of 94, 140 and 220 GHz. Each n and p-region has width as well as the total width for the active region which has been mentioned in the **Table 2**. The width of the n^+ and p^+ are negligible and are hence used for ohmic contacts. The doping concentration for each n and p region of all structures have been mentioned in **Table 2**, while the doping concentration for each n^+ and p^+ region are taken as 1.0×10^{26} m^{-3}. The optimized operating current density, junction temperature and diode area are taken for window frequency of 94 GHz, 140 GHz and 220 GHz and listed in **Table 2**. Again the junction temperature and diode area are taken as 300 K and 1.0×10^{-10} m^2 respectively.

Though the applications of IMPATT diode are mostly realized on the basis of double drift region structures, we have considered the symmetrical double drift region (DDR) IMPATT diode structures with doping distribution of the form n^+npp^+ as shown in **Table 2** for the DC, small signal and noise analysis. 1-D schematic diagram of the proposed DDR IMPATT diode structures are shown in **Figure 1**. The n^+ and p^+ regions of the diode are heavily doped with each having a doping concentration of 1.0×10^{26} m^{-3}. Each n- and p-regions has a moderate doping concentration for different materials based on the optimized current

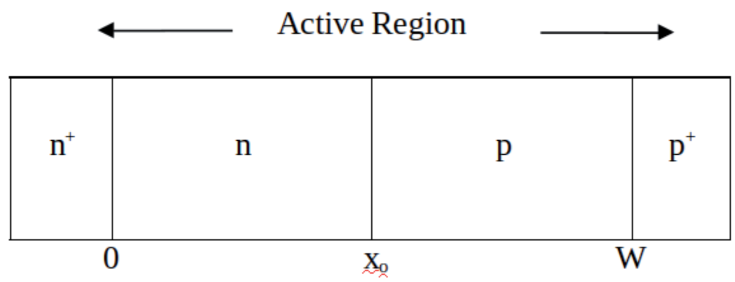

Figure 1.
A 1-D schematic diagram of the proposed DDR IMPATT diode.

Design frequency (GHz)	Materials	Width of active region (nm)		Doping concentrations ($\times 10^{23}$ m^{-3})		Current density (J) ($\times 10^{8}$ Am^{-2})
		n-region (W_n)	p-region (W_p)	n-region N_D	p-region N_A	
94	Si	555	430	0.80	0.85	3.2
	GaAs	530	530	0.65	0.65	2.0
140	Si	360	285	1.40	1.45	6.8
	GaAs	355	355	1.1	1.1	5.0
220	Si	245	185	2.70	2.75	15.0
	GaAs	225	225	2.00	2.00	7.3

Table 2.
Design parameters of Si and GaAs DDR IMPATT.

density as given in **Table 2**. The total active regions width is taken along with different space points of 1 nm each on both p-region and n-region. The values of doping concentrations and diode active region width are taken for optimum conversion efficiency and operation at atmospheric window frequencies of 94 GHz, 140 GHz and 220 GHz. The net doping concentration at any space point is hence determined by using the exponential and error function profiles.

3. Millimeter-wave properties of Si and GaAs DDR IMPATT diodes

The various properties of IMPATT diodes based on the fundamental semiconductor materials like Si and GaAs have been found by the simulation method. The properties like DC characteristics, small signal characteristics and noise behaviors have been computed in DDR structures based on Si and GaAs. The details of the results are discussed in the following sections.

3.1 DC characteristics

The computer simulation method [27] has been applied to a DDR structures IMPATT diode based on Si and GaAs and yields the results of different characteristics. The essential DC characteristics such as peak electric field (E_{max}), breakdown voltage (V_B), avalanche zone voltage (V_A), efficiency (η), avalanche zone width (X_A) and ratio of avalanche zone width to total depletion layer width (X_A/W) of the designed DDR IMPATTs are obtained from DC simulation.. The analysis of comparative description of the prospects of GaAs for IMPATT diode with reference to Si IMPATT diodes at different operating frequencies such as 94 GHz, 140 GHz

Design frequency f_d (GHz)	Material	Peak electric field E_{max} ($\times 10^7$ Vm^{-1})	Breakdown voltage V_B (volt)	Drift voltage V_D (volt)	X_A/W (%)	Efficiency η (%)
94	Si	4.90	23.35	8.72	38.80	11.89
	GaAs	4.81	29.48	12.28	41.42	13.26
140	Si	5.46	17.91	6.31	44.5	11.22
	GaAs	5.19	22.25	8.39	47.8	12.00
220	Si	6.27	13.18	4.29	45.48	10.36
	GaAs	5.83	14.91	5.44	48.22	11.62

Table 3.
DC properties of Si and GaAs DDR diodes at 94 GHz, 140 GHz and 220 GHz with design parameter of ***Table 2****.*

and 220 GHz are presented in **Table 3**. At different frequencies all the considered IMPATT diodes show different kinds of behavior.

The breakdown voltage for GaAs IMPATT diode shows the high value over Si IMPATT. This high value of break down voltage produces high RF power output as compared to Si IMPATT. Again, GaAs IMPATT provides more efficiency than Si IMPATT and the efficiency values are given in **Table 3**. The percentage of the ratio of avalanche zone width to total drift layer width (X_A/W) for all the diodes structure under consideration increases with higher operating frequencies. Higher value of X_A/W describes wider avalanche zone which leads to higher avalanche voltage (V_A) and lower drift zone voltage (V_D). In case of GaAs-based DDRs X_A/W is 42.36% at 94 GHz but it rises to 48.22% at 220 GHz which causes the decrease of efficiency (η) at 220 GHz. But in Si DDRs at 94 GHz, X_A/W is 42.7%, whereas it is 45.48% at 220 GHz and this leads to fall in efficiency (η) at higher mm-wave frequencies.

3.2 Small signal characteristics

The DC output simulation parameters have been used as the input for simulation of small signal analysis. The significant high-frequency or small signal parameters obtained from this analysis are optimum frequency (f_p), peak negative conductance ($-G_o$), negative resistance (Z_R), RF power output (P_{RF}) and output power density (P_D). These parameters are obtained from the high-frequency simulation of GaAs and Si DDR IMPATTs at several biased current density and represented in **Table 4**.

Design frequency (GHz)	Materials	Negative conductance ($-G_o$) $\times 10^7$ Sm^{-2}	Negative resistance ($-Z_R$) $\times 10^{-9}$ Ωm^2	Power density (P_D) $\times 10^9$ Wm^{-2}
94	Si	2.55	17.3	1.74
	GaAs	1.91	8.49	2.07
140	Si	6.11	9.42	2.45
	GaAs	4.89	4.70	3.07
220	Si	15.6	3.96	3.40
	GaAs	10.4	1.59	3.92

Table 4.
Small signal characteristics of Si and GaAs DDR IMPATT diodes at design frequency of 94, 140 and 220 GHz.

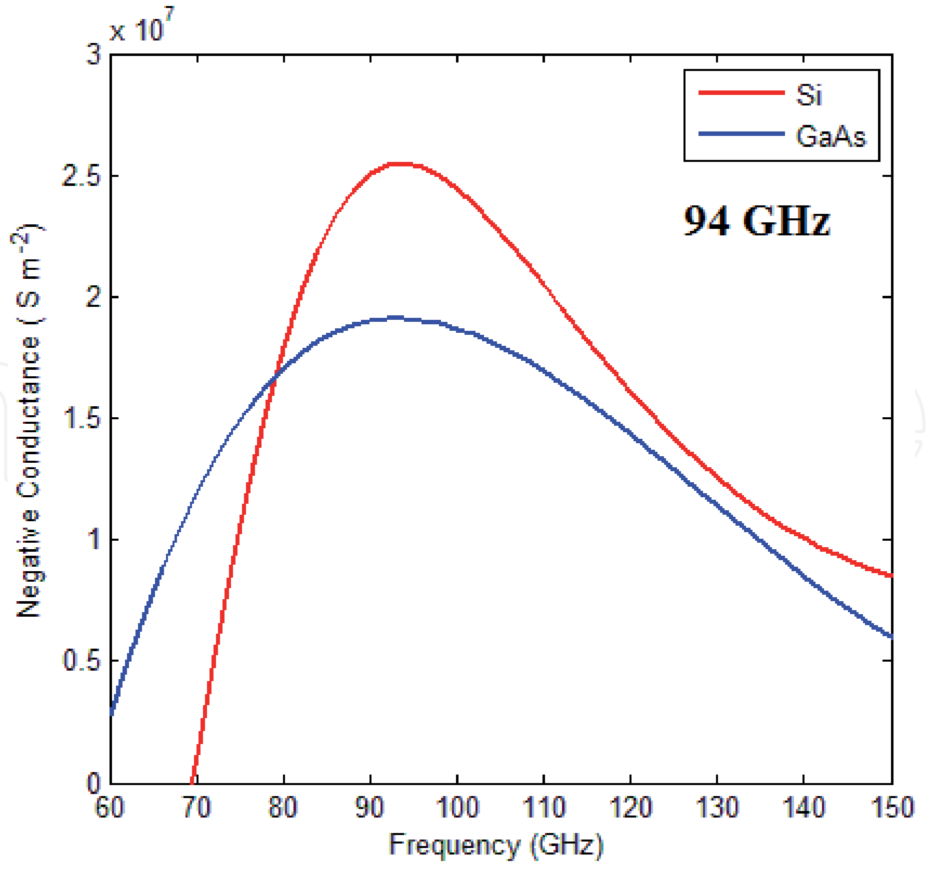

Figure 2.
Variation of negative conductance with frequency for DDR IMPATT operating at 94 GHz.

The diode negative conductance and negative resistance as a function of frequency for the different DDR IMPATT diodes of GaAs and Si are mentioned at different operating frequency. GaAs IMPPAT shows less negative conductance as compared to Si IMPATT. The diode negative conductance ($-G_o$) as a function of frequency for GaAs and Si DDR IMPATT is plotted in **Figures 2–4**. From the figures it is observed that, as the diodes are optimized with the current density, the peak of the negative conductance lies at the design operating frequencies 94 GHz, 140 GHz and 220 GHz and also it is noticed that the peak negative conductance of Si is remarkable higher. Subsequently in negative resistance case the behavior is directly reverse. The GaAs based IMPATT DDR diode gives less value of negative resistance ($-Z_R$) than that of Si DDR diodes.

The power density of GaAs bas IMPATT shows high value as compared to Si based IMPATT. The high value of power density indicates GaAs IMPATT diode is capable of high output power. Again it is noticed that the power density increases with increase in the operating frequency. This high power density of GaAs generates more noise in the device which is discussed in the subsequent section.

Over all, the variation of negative conductance with the different operating frequencies in **Figure 5** and it is also observed that the negative conductance of all the IMPATT diode based on Si and GaAs increases with the increase in operating frequency keeping area of the diode constant.

3.3 Noise properties

Since noise is an important aspect of IMPATT study, and hence, the noise characteristic of GaAs IMPATT diode has been analyzed and compared the results with Si based IMPATT diodes. In **Table 5**, the mean square noise voltage per band width of the three different diodes based on GaAs and Si at different

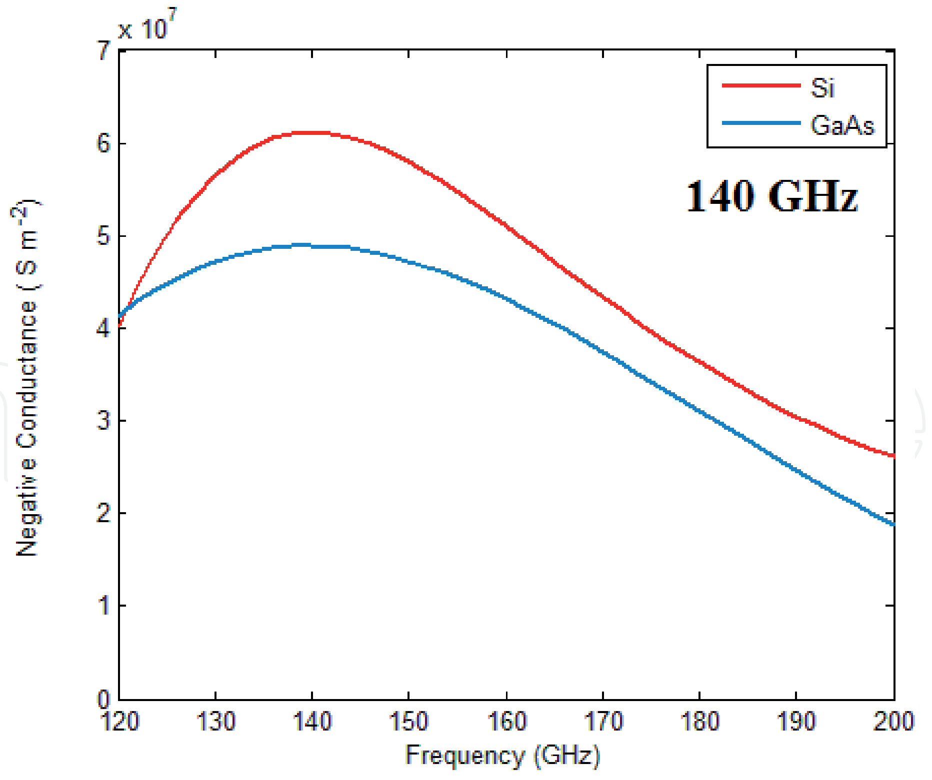

Figure 3.
Variation of negative conductance with frequency for DDR IMPATT operating at 140 GHz.

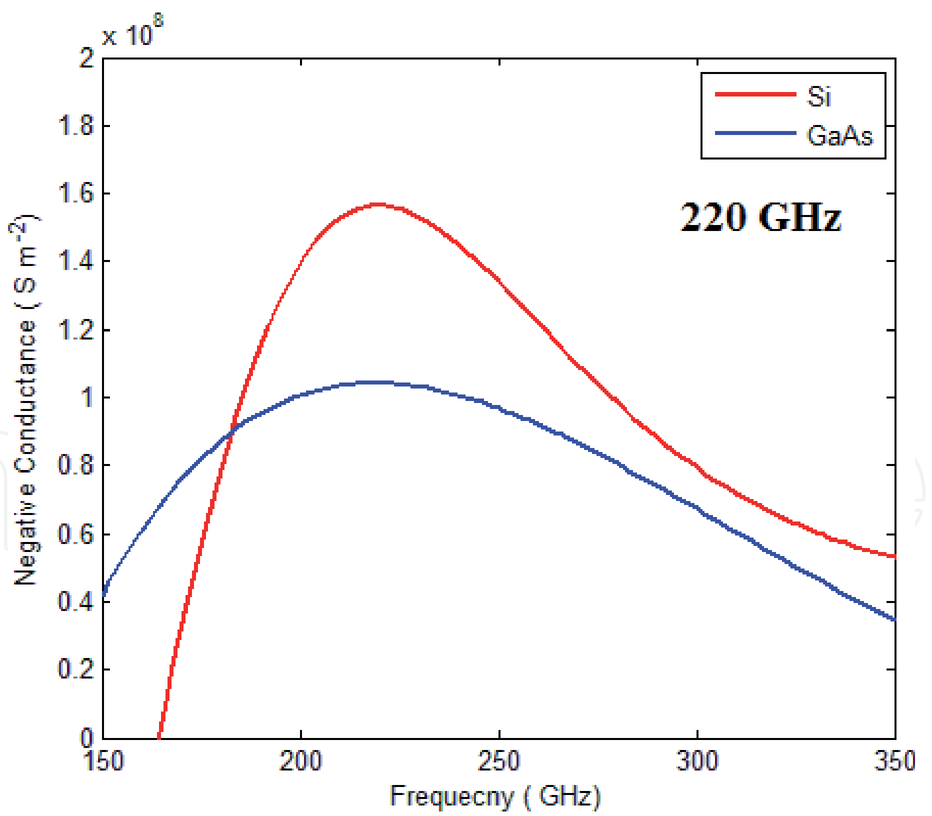

Figure 4.
Variation of negative conductance with frequency for DDR IMPATT operating at 220 GHz.

operating frequencies of 94 GHz, 140 GHz and 220 GHZ are represented. From **Table 5** it is seen that the peak values of mean square noise voltage per band width $(<v^2>/df)_{max}$ are found at the frequencies (f_p) of 75 GHz, 100 GHz and 160 GHz for Si for the operating frequency of 94 GHz, 140 GHz and 220 GHz,

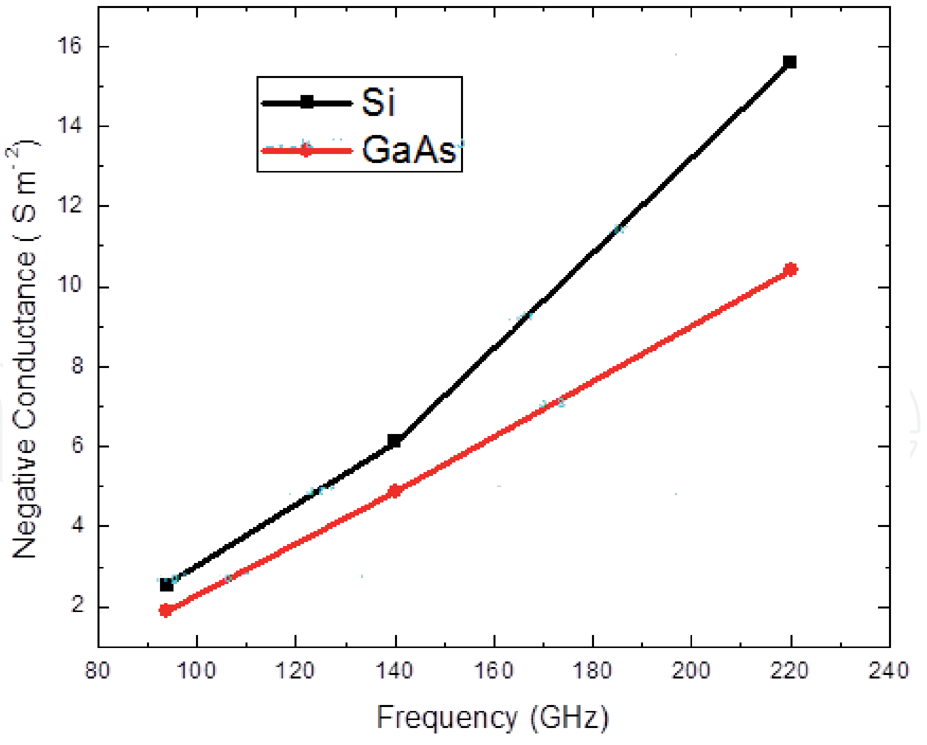

Figure 5.
Variation of negative conductance with operating frequency for DDR IMPATT diodes design to operate at 94, 140 and 220 GHz.

Material	Frequency at $(<v^2>/df)_{max}$ (GHz)	$(<v^2>/df)_{max}$ (V^2s)	f_d (GHz)	$(<v^2>/df)$ at f_d (V^2s)	NM at f_d (dB)
Si	75	1.59×10^{-14}	94	1.51×10^{-15}	27.23
	100	3.7×10^{-15}	140	6.51×10^{-16}	26.20
	160	8.95×10^{-16}	220	2.04×10^{-16}	24.94
GaAs	60	4.52×10^{-14}	94	5.54×10^{-16}	25.96
	110	9.75×10^{-15}	140	2.09×10^{-16}	24.28
	155	3.4×10^{-15}	220	5.98×10^{-17}	23.55

Table 5.
Noise properties of GaAs and Si DDR IMPATT diodes.

for GaAs IMPATT the frequencies of peak values of $<v^2>/df_{max}$ are 60 GHz, 110 GHz and 155 GHz. The corresponding values of mean square voltage per band width $(<v^2>/df)_{max}$ at the operating frequency of 94,140 and 220 GHz for all the diodes are given in **Table 5**. GaAs DDR IMPATT shows minimum mean square noise voltage per band width. The variation of mean square noise voltages per bandwidth (MSNVPBW) of the IMPATT diodes based on the semiconductors under consideration as a function of frequency are plotted in **Figures 6–8** for operating frequency of 94 GHz, 140 GHz and 220 GHz respectively.

Noise measure (NM), which is an indicator of noise to power ratio, is an important aspects for the study of noise behavior. The values of computed noise measure at the designed frequency are presented in **Table 5**. We have plotted noise measure as a function of frequency in **Figures 9–11** for both the IMPATT diodes based on GaAs and Si at different operating frequency of 94 GHz, 140 GHz and 220 GHz respectively. The comparative study of noise measure of Si and GaAs is

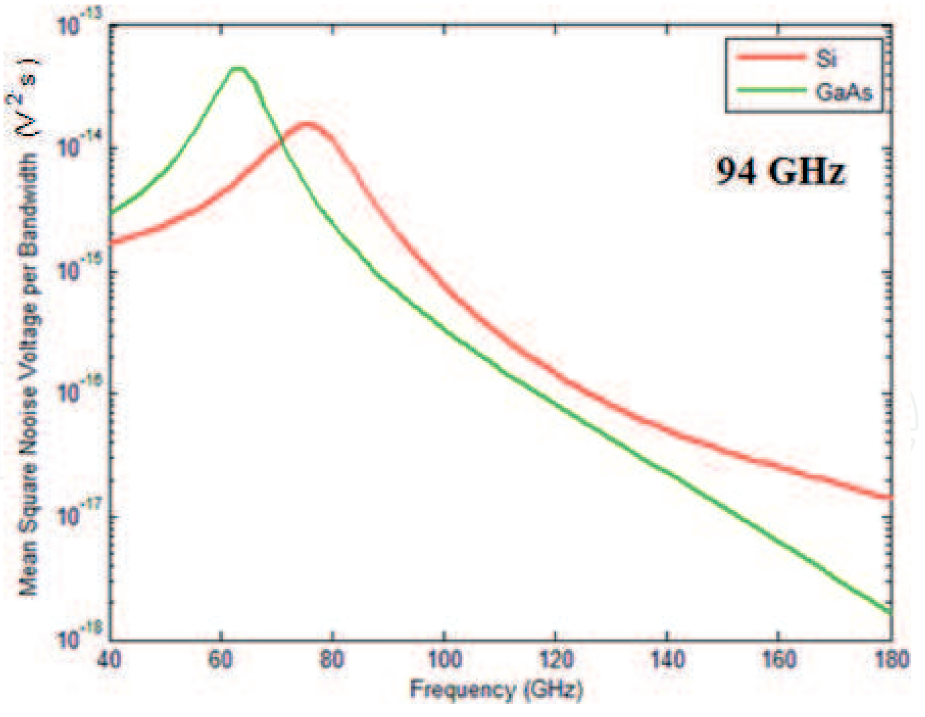

Figure 6.
Variation of mean square voltage per bandwidth with frequency for DDR IMPATT diodes operating at 94 GHz.

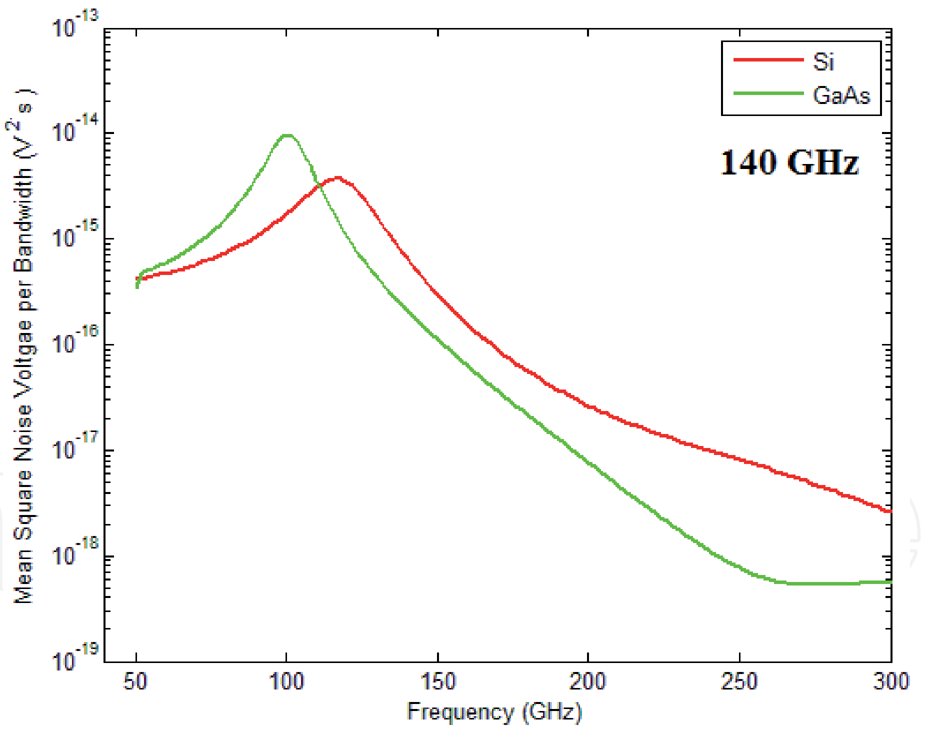

Figure 7.
Variation of mean square voltage per bandwidth with frequency for DDR IMPATT diodes operating at 140 GHz.

given in **Table 5**. GaAs IMPATT produces less noise as compare to Si IMPATT. The main reason for the low noise behavior of GaAs for a given electric field is the same value of the electron and hole ionization rates. Whereas, in Si the ionization rates are quite different. It may be mentioned here, the high power generation mechanism is such that if we wish to get more output power then we are supposed to get more noise.

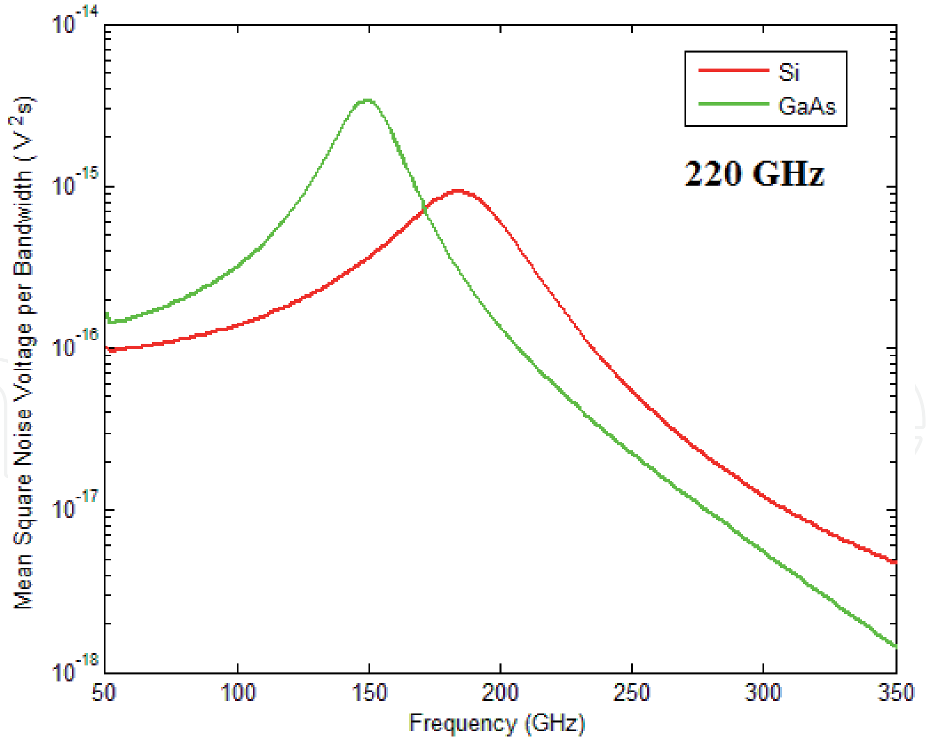

Figure 8.
Variation of mean square voltage per bandwidth with frequency for IMPATT DDR operating at 220 GHz.

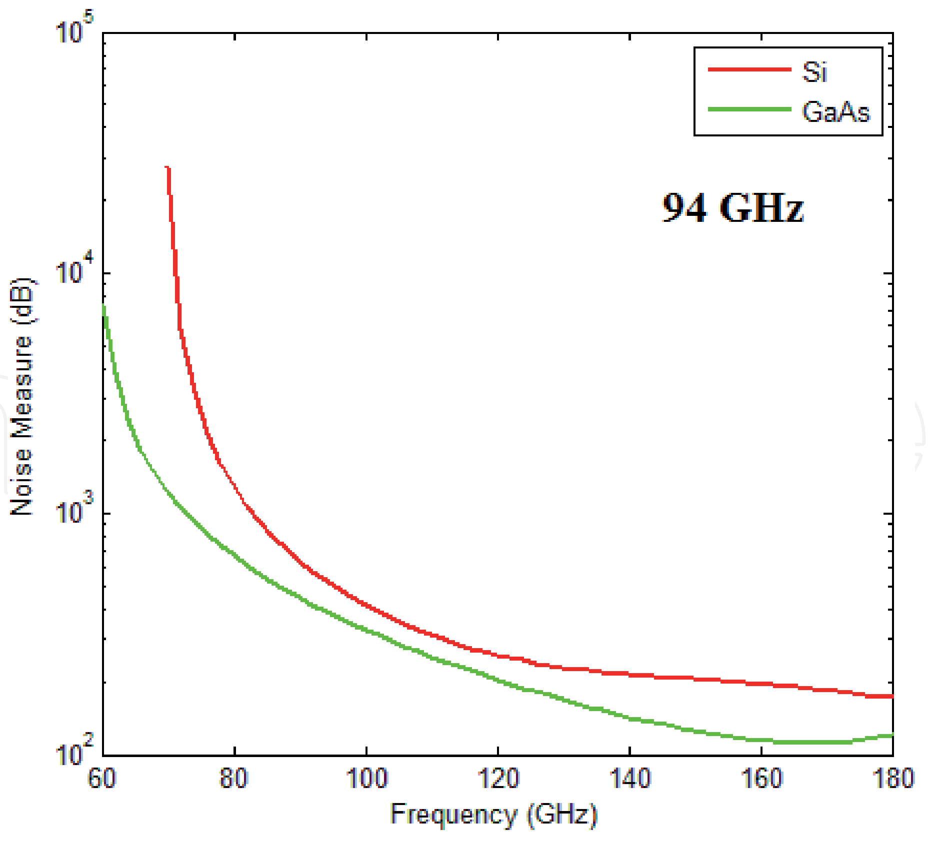

Figure 9.
Variation of noise measure with frequency for DDR IMPATT diodes operating at 94 GHz.

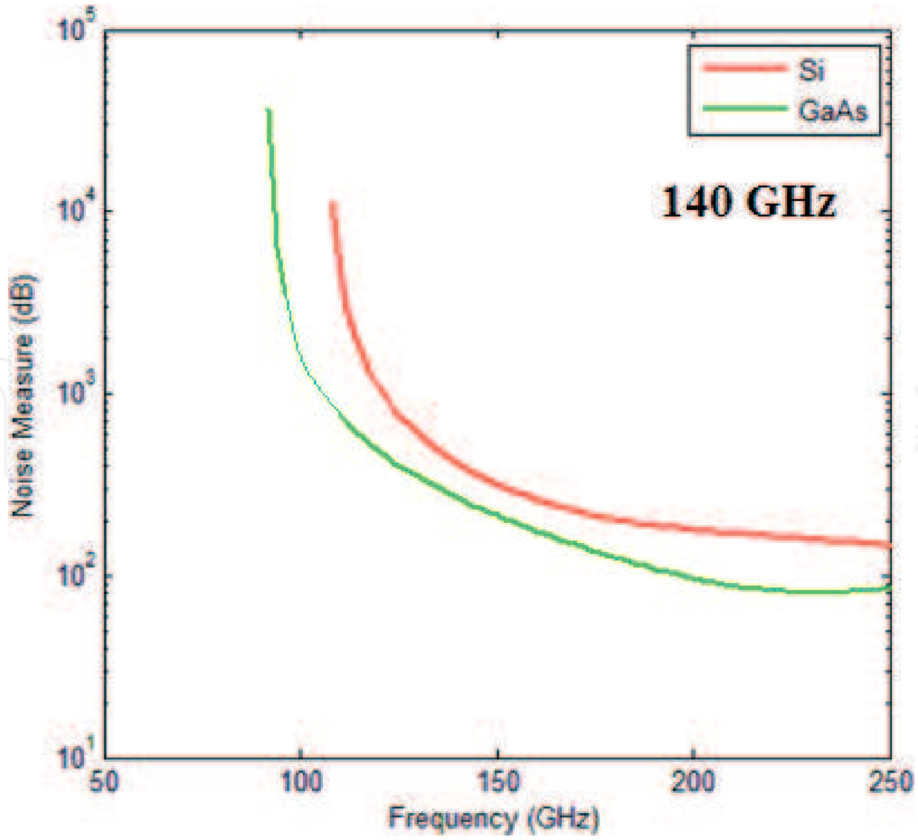

Figure 10.
Variation of noise measure with frequency for DDR IMPATT diodes operating at 140 GHz.

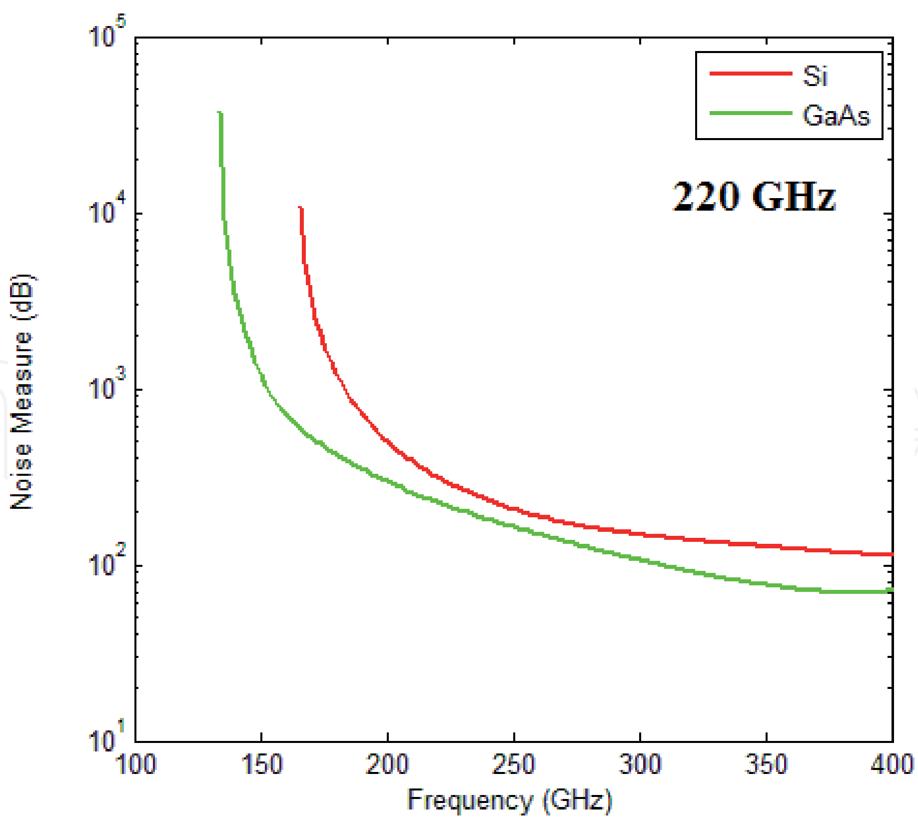

Figure 11.
Variation of noise measure with frequency for DDR IMPATT diodes operating at 220 GHz.

4. Conclusion

The small signal characteristics of DDR IMPATTs based on GaAs designed to operate at mm-wave window frequencies such as 94 GHz, 140 GHz, and 220 GHz are presented in this chapter. Both the DC and Small signal performance of the IMPATT diode based on GaAs are investigated by simulation technique. The results show that the DDR IMPATTs based on GaAs are most suitable device for generation of RF power with maximum conversion efficiency up to 220 GHz. However, at higher mm-wave frequencies, the DDR IMPATTs based on GaAs surpass the other semiconductor material for IMPATT not only for frequencies below 94 GHz but also above 94 GHz. Thus, GaAs is a vibrant base semiconductor for IMPATT diodes at the both microwave and mm-wave frequencies and also for higher mm-wave frequencies greater than 94 GHz. It is worthy indication of the future of communication technology.

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