Noise Performance of IMPATT Diode Oscillator at Different mm-Wave Frequencies

S. J. Mukhopadhyay, R. Dhar, and Aritra Acharyya

Abstract The performance of noise of Silicon (Si) DDR (Double Drift Region) IMPATT (Impact Ionization Avalanche Transit Time) devices at different millimeter-wave frequencies is studied and presented in this article. The motivation behind this study is to see how the device operates at high frequencies. The temperature for the system has been kept constant at 300 K. Double iterative method has been used for the simulation. The noise measure and the noise spectral density at the desired window frequencies has been studied, analyzed and presented in this article. The direct dependence of noise on frequency has not been presented in any previous work; however, the dependence of ionization on frequency has been presented in some articles which have been described here. The authors here have tried to provide a dependence of noise performance on the operating frequency based on the given literature and simulated results. Simulated results show that the noise measure improves significantly with increase in frequency and the device thus proves to be more effective in use at higher frequencies. Different doping and structural parameters for the Si IMPATTs at different operating frequencies have been reported and used in the present work.

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1 Introduction

IMPATTs are high frequency generators and amplifier devices with frequencies ranging from a few gigahertz to several hundred gigahertz. IMPATTs have proven to be the most popular in military, defense, and radar applications, as well as non-military ones. IMPATTs have to be mounted on resonators to be used for sustainable use; otherwise they cannot be used for very high power applications. In DDR IMPATTS both the holes and electrons have different individual drift regions which help in more power handling and more efficient operations. The theory and development of SDR and DDR IMPATTs over the years presented in Refs. [1–5], have made it possible for the devices to be used for high power RF applications.

Although IMPATTs are very useful devices, their main drawback is that they are very noisy devices with noise measures ranging between 30 and 60 dB or even more—a cause for decrease in their efficiency. The main source of noise in these devices is the avalanching process which includes the collision of electrons in a very thin avalanche region leading to the generation of Electron–Hole-Pairs or EHPs. There are a lot of other noises too like the shot noise, Johnson noise, etc., but their effect is suppressed by the avalanching noise. The avalanching region in IMPATT devices plays a very important role in determining the noise performance of the devices [6–8].

In this article, we have presented the noise performance on Si DDR IMPATTs over a range of different window frequencies at mm-wave. Gummel and Blue [9] have presented a small signal theory on the avalanche noise of these devices. They contemplated field-dependent charge carrier ionization rates in their model, which assumed that electron and hole drift velocity is saturated and independent of the electric field even at the depletion layer's boundaries. In their simulation with realistic diodes they have shown that IMPATT devices can achieve 20–30 dB Noise Measures using different current densities from 100 to 1000 A/cm^2, parasitic resistances of 0 and 1 Ω and frequencies ranging from 7 to 40 GHz. Hines [10] has on the other hand presented the large signal noise properties along with the frequency conversion effects in IMPATT devices for the X-band frequencies. The same motivation has been used in this article with much higher frequency ranges starting from 94 GHz to nearly 400 GHz, with a constant parasitic capacitance of 1.5 Ω. Frequency up-conversion at the test frequencies can affect the noise performance of these devices. Moreover the temperature is kept fixed at 300 K which is one of the idealities that we have considered here. Moreover, the high noise measures in the devices can affect the sustainability of the frequency output with considerable amount of power. Thus, noise performance of these devices at these frequencies is very necessary to study.

Since the noise depends on the ionization of the device at the junction, the way by which ionizations depend on the frequency of operation is an important aspect to study. Earlier [11, 12] the authors verified the following relation,

$$W = \frac{0.37 v_{sn}}{f_d}, \tag{1}$$

where W is the width of depletion layer, v_{sn} is the saturation drift velocity of the electrons and f_d is the design frequency.

2 Simulation Methods

In Ref. [13] the computer simulation of noise characteristics of the IMPATT diodes has been reported. Along with it in Refs. [14, 15] the small signal noise analysis and intrinsic noise theories have been reported for IMPATT devices. In Ref. [14] the IMPATT device used is a SDR or Single Drift Region type while the one that we have used in our study is a DDR or Double Drift Region type whose structure is shown in Fig. 1. In this figure, W = Wn + Wp represents the total active region of the diode. The region denoted by x_A represents the avalanching region of the diode. The $J_0$is the total current density of the diode and it flows from the N-side to the P-side. Vp and Vn represent the drift velocities of the holes and electrons, respectively. x_0 is the center of the diode and it is considered that that the avalanching process starts at that point. Table 1 depicts the parameters used for the simulation purpose.

In a DDR diode, the regions are structured as p^+p-nn^+; there are two separate drift regions for the holes and electrons. An elemental current di_c in the avalanche region over a small region dx is given by,

$$di_c = (\alpha_p I_p + \alpha_n I_n)dx \tag{2}$$

where $\alpha_{p,n}$ are the hole and electron ionization coefficients and $I_{i,n}$ are the average hole and electron currents. Thus the mean-square of this current can be written as,

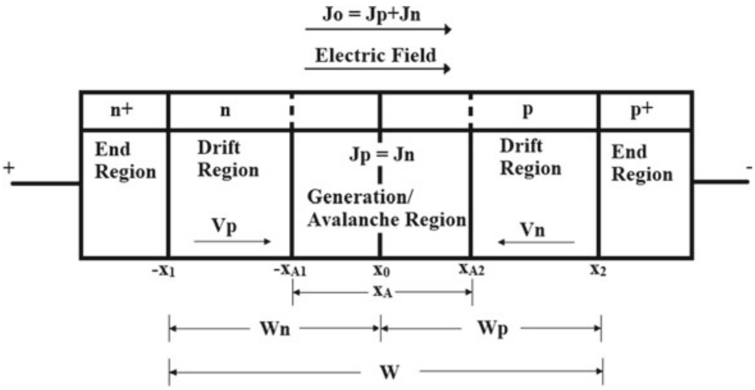

Fig. 1 1-D diagram of a Si DDR IMPATT

Table 1 Structural and doping parameters for Si for different operating frequencies

Operating frequency (GHz)	Wn (um)	Wp (um)	N_D (× $10^{23}/m^3$)	N_A (× $10^{23}/m^3$)	Nn+ (× $10^{26}/m^3$)	Np+ (× $10^{26}/m^3$)
94	0.32	0.30	1.50	1.55	5.0	2.7
140	0.28	0.245	1.80	2.10	6.2	3.5
220	0.18	0.16	3.95	4.59	7.5	4.7
300	0.132	0.112	6.00	7.32	9.0	5.9

$$< di_c^2 >= 2qdi_c df = 2q(\alpha_p I_p + \alpha_n I_n)dxdf \tag{3}$$

The open-circuit mean-square noise voltage $<v^2>$ can be computed by integrating the mean square current given in (3) against the absolute square of the transfer impedance, as given by the following relation,

$$< v^2 > /df = 2q \int |Z_t(x, \omega)|^2 (\alpha_p I_p + \alpha_n I_n)dx \tag{4}$$

The terminal noise voltage at a particular frequency ω is obtained by integrating the noise electric field over the whole space charge region,

$$v_t(x, \omega) = \int\limits_{x=0}^{x=W} e_n(x, \omega)dx \tag{5}$$

The transfer impedance is measured by dividing the noise voltage by the noise current generated due to the noise source,

$$Z_t(x, \omega) = \frac{v_t(x, \omega)}{i_n(x, \omega)} \tag{6}$$

Thus by substituting Eq. (6) in Eq. (4), we can finally get the value of $<v^2>$.

The noise measure (M_N) is given by the following expression,

$$M_N = \frac{\langle v_n^2 \rangle /df}{4k_B T_j(-Z_R - R_S)}, \tag{7}$$

3 Results and Discussion

The entire simulation has been done in MATLAB environment at different window or operating frequencies of 94 GHz, 140 GHz, 220 GHz and 300 GHz, respectively, and the following results have been obtained. The results show that the Noise Measure decreases with the frequency which is shown by the following figures. It is noted that in all the figures the least measure of noise is not perfectly placed at the respective window frequencies but with a little offset from them. The reason is justified by the non-ideality of the diodes.

Figure 2 shows the noise measure at a window frequency of 94 GHz and the noise measure is around 36.36 dB at a frequency of 117 GHz.

Figure 3 shows the noise measure at a window frequency of 140 GHz and the noise measure is around 19.72 dB at a frequency of 218 GHz.

Figure 4 shows the noise measure at a window frequency of 200 GHz and the noise measure is around 11.16 dB at a frequency of 270 GHz.

Figure 5 shows the noise measure at a window frequency of 300 GHz and the noise measure is around 0.64 dB at a frequency of 117 GHz. Thus it can be seen that with the increase of operating frequencies the noise measure reduces significantly to less than 1 dB at around 300 GHz, which is shown in the following Fig. 6.

The validation for decrease in noise figure with frequency can be explained by the works done in Refs. [11, 12]. There it has been shown that as we increase the operating frequency the depletion width decreases and hence the avalanching process confines to a very small region. As a result, the collision between the ions decreases and hence the noise measure reduces significantly. Thus at high frequencies, it can be concluded that the diode can be used much more efficiently but at even higher frequencies the depletion width will reduce so much that the ionization will cease to occur, rendering the diode to be absolutely useless as there will be no production of power at any frequency.

The values of all the noise measures at different operating frequencies are given in Table 2.

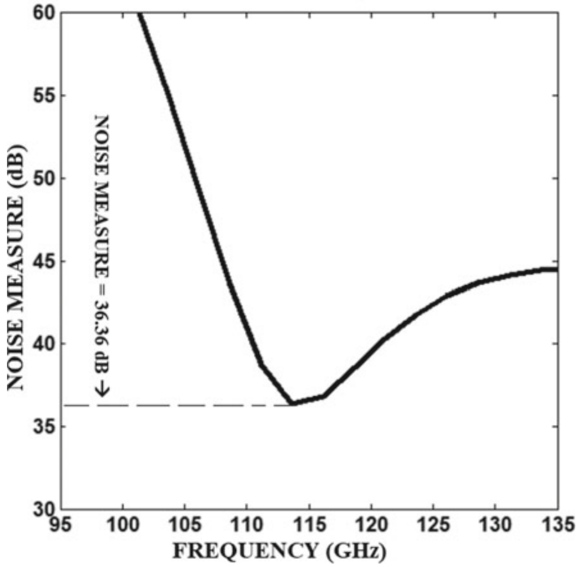

Fig. 2 Noise measure versus frequency at 94 GHz atmospheric window frequency

Fig. 3 Noise measure versus frequency at 140 GHz atmospheric window frequency

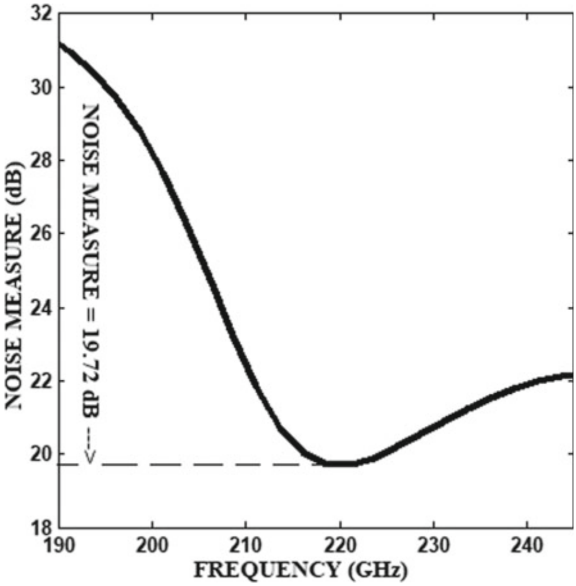

Fig. 4 Noise measure versus frequency at 200 GHz atmospheric window frequency

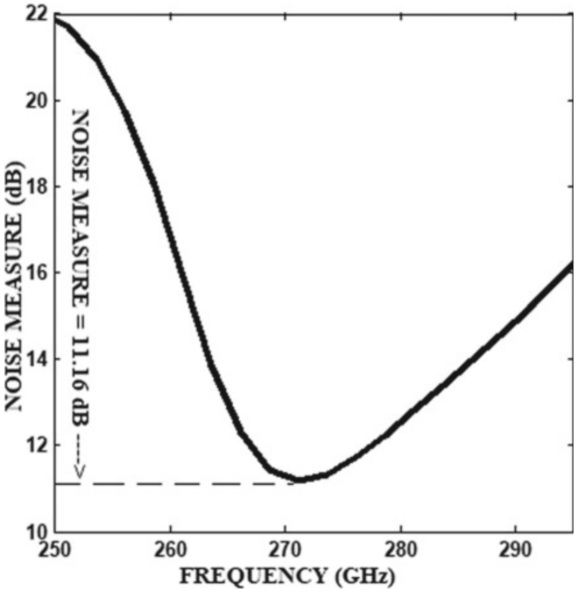

Figure 7 shows the noise spectral density over the desired operating frequency range. The points where the NSD takes the dip in the curve, are the points of desired frequency. The Noise Measure is then measured taking the values of NSD at those points.

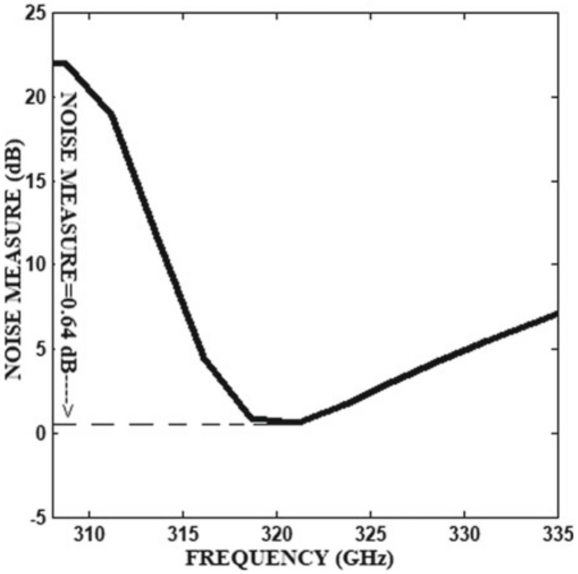

Fig. 5 Noise measure versus frequency at 300 GHz

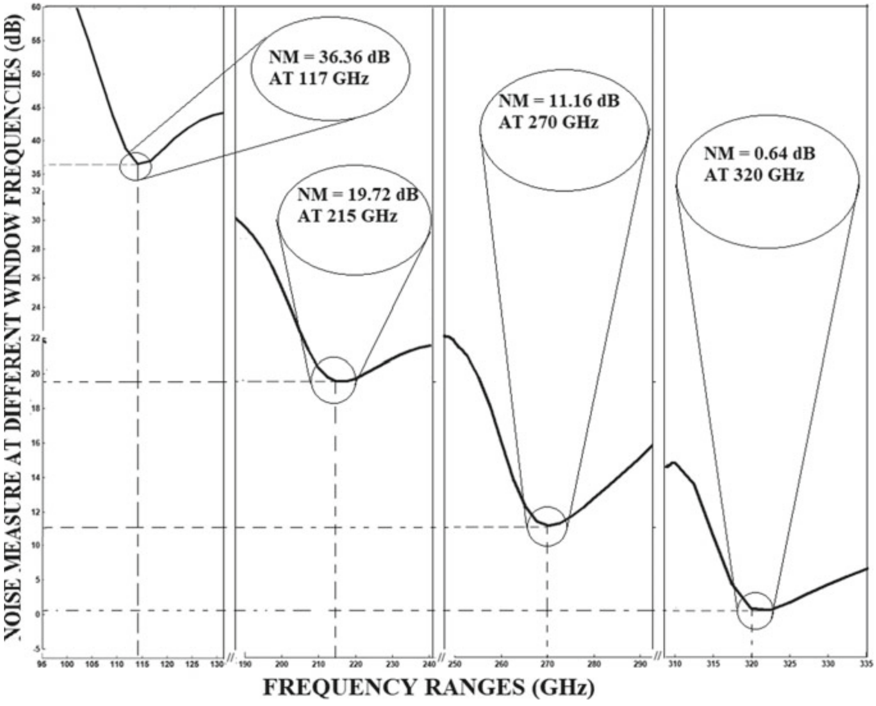

Fig. 6 Noise measure versus frequency for progressive atmospheric window frequencies

Table 2 Window frequencies and the respective noise measures

Window frequency (GHz)	Noise measure (dB)
94	36.36
140	19.72
200	11.16
300	0.64

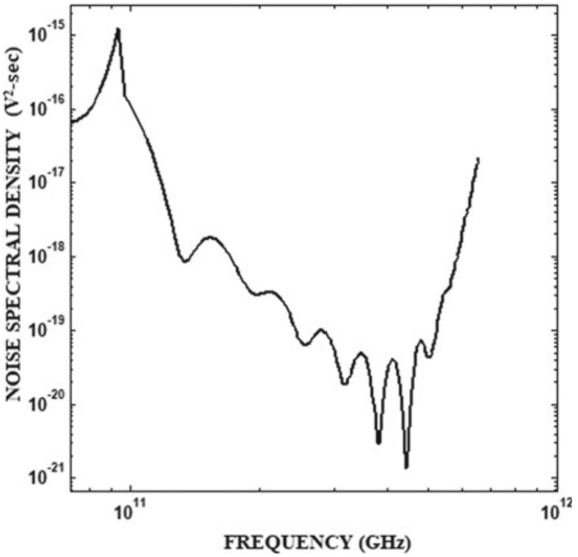

Fig. 7 Noise spectral density versus frequency for the whole operating frequency range

Z_R is the frequency dependent thing in the relation. The negative resistance is obtained from the Conductance-Susceptance curve or the G-B curve. The point of frequency where the lowest conductance is achieved is considered the operating frequency. The negative resistance is obtained from the inversion of the conductance value. Hence, the lowest conductance turns into the highest negative resistance at the desired frequency. Hence the value of the noise measure decreases with increase in negative resistance. According to the results shown above it can be assumed that increase in frequency leads to the increase in negative resistance which in turn leads to the decrease in Noise Measure.

Moreover at higher frequencies, according to Eq. 1, we find that as the operating frequency increases, the depletion width of the diode decreases, hence the space width for the noise to generate decreases, thus this also acts as a method of decreasing Noise Measure at higher frequencies.

4 Summary

After obtaining all the results we can conclude that operating the IMPATT Diodes at higher frequencies can help in reduction of the noise measures of the device, thus effectively improving the noise performance of the device. As discussed above, one of the reasons for reduction in Noise Measure at higher frequencies is the reduction of depletion width at high frequencies. The reduction in the depletion region also leads to the decrease in ionization and thus that may affect the performance of the device. The power handling capacity of the device reduces due to decrease in ionization which is not a property for IMPATT Diodes. Thus in order to achieve optimum performance from the device the trade-off between power and noise must be considered carefully. Thus to achieve a good balance between power and noise, the device must be carefully fabricated using proper structural and doping parameters required for the device to perform at that desired operating frequency.

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