The noise power Tradeoff of Poly SiC Ka Band of IMPATT diodes

J.Banejee, K.Roy, M.Mitra

Abstract— The Noise properties and performance of SiC-based DDR IMPATT diode at Ka Band frequency has been investigated through modeling and simulation technique. SiC-based IMPATTs with its different poly types (3C, 4H, and 6H) are modeled, designed and a comparative study among three are presented in this paper. A noise analysis model was also developed to compare the noise characteristics of 3C, 4H and 6H SiC-based IMPATTs. The results show that 3C-SiC based IMPATTs have better power delivery capability whereas 4H SiC-based IMPATTs are less noisy. An iterative method has been used to obtain the noise power tradeoff of these devices. It has been found that 4H SiC can generate 115.4 mW output power with 16.89 dB noisemeasure at 34 GHz. This device model has been designed in this work.This results also show the effect of negative conductance on the noise performance of the device. It is also found that 4H SiC based IMPATT has minimum shot noise ratio. Results of the analysis presented in this paper will be useful to find out a noise power tradeoff for different poly SiC based IMPATTs at Ka band frequencies.

Index Terms— Noise Power tradeoff in IMPATT, Poly SiC IMPATT, Avalanche noise of SiC IMPATT, Ka band IMPATT, DDR IMPATT noise, Low noise IMPATT, Avalanche Noise of negative resistance device.

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1 INTRODUCTION

Over the years it is being found that Impact Avalanche Transit Time (IMPATT) diodes became most powerful solid state sources in the mm-wave and sub-mm wave frequencies. These devices are now used as transmitter in radars, as a source in the missile seeker head and in many others mm-wave civilian and military applications, which includes communication. To get higher efficiency and power output different structures like SDR, DDR, DAR, lo-high-lo, etc. were proposed and developed by different scientists over the years. Then the IMPATT development started with different semiconductor materials like GaAs, InP, GaN, SiC etc. along with Silicon to achieve higher efficiency, power output and frequency range. But one of the main drawback of this type of diode is it's noisy "[1]" characteristics. Since the noise sets a lower limit to the microwave signals to be amplified, hence a Noise-Power tradeoff is necessary before reaching to any conclusion. Avalanche noise is the dominating noise effect of IMPATT operation. This is a form of noise that is generated when a junction diode is operated close to the point of avalanche breakdown. This occurs in semiconductor junctions when the carriers in a high voltage gradient develop sufficient energy to dislodge additional carriers through physical impact. Due to avalanche breakdown avalanche noise is more for IMPATT comparing with unipolar device like MOSFET.

This noise- power tradeoff of IMPATT device is not properly discussed in the literature still now. Noise behavior of different semiconductor based IMPATT was discussed in the previous work of the authors. It was found that SiC has minimum noise measure "[2]". In this paper noise performance of different poly SiC-IMPATT like 3C SiC, 4H SiC, 6H SiC has been obtained.A Noise-Power tradeoff "[3]" of these devices are also found using a computer based iterative method. So, this paper will be useful for the fruitful operation of the IMPATT device.

2 SIMULATION METHODOLOGY

The devices were designed following an IMPATT mode DC simulation method. The different noise parameters such as noise measure, shot noise ratio are also computed. In Figure 1. a DDR structure "[4]" of IMPATT is shown. W is the total width of the depletion layer. xo is the position of maximum electric field. D.C analysis of the DDR structure were carried out by solving Poission's equation "[5]" including mobile space charge in the depletion layer of the diode.

Poission's equation is given as,

$$\frac{dE}{dx} = (N_D - N_A + p(x) - n(x)) \qquad (1)$$

At each point in the depletion layer simultaneous solutions of

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Poisson equation is used. The field boundary conditions are given by,

E(-x1) = 0 and E(+x2) = 0.

Then small signal analysis is carried out by solving the following second order differential equation.

$$\frac{d^2R}{dx^2}+(\alpha_n-\alpha_p).\frac{dR}{dx}-2.r_n.(\frac{\omega}{v'}).(\frac{dX}{dx})+(\frac{2\alpha'}{v'^2}-H).R-2\alpha'(\frac{\omega}{v'}).X-(\frac{\omega}{v'})=0 \qquad (2)$$

and

$$\frac{d^2X}{dx^2}+(\alpha_n-\alpha_p).\frac{dR}{dx}-2.r_n.(\frac{\omega}{v'}).(\frac{\omega}{dx})+(\frac{\omega}{v'^2}-H).X-2\alpha'(\frac{}{v'}).R+(\frac{\omega}{v'^2}.)=0 \qquad (3)$$

where R, X are the resistance and reactance values, α, α_n, α_p ionization coefficients and H is a function of electric field.

These two equations are solved by Runge Kutta Method at the following boundary conditions. The boundary conditions are given by the following equations:

at, x = 0,

$$\frac{\delta R}{\delta x}+(\frac{\omega X}{v_{ns}}) = -(\frac{1}{v_{ns}.\varepsilon}) \qquad (4.a)$$

$$\frac{\delta X}{\delta x}+(\frac{\omega R}{v_{ns}}) = 0 \qquad (4.b)$$

at, x = W,

$$\frac{\delta R}{\delta x}+(\frac{\omega X}{v_{ps}}) = (\frac{1}{v_{ps}.\varepsilon}) \qquad (4.c)$$

$$\frac{\delta X}{\delta x}+(\frac{\omega R}{v_{ps}}) = 0 \qquad (4.d)$$

Where,

$v' = (v_{ns}.v_{ps})^{1/2}$, $\alpha' = (\alpha_n . v_{ns} + \alpha_p . v_{ps})/(2. v')$, $r_n = (v_{ns} - v_{ps})/ (2. v')$.

The RF power output PRF"[3]"from the device can be obtained and can be expressed as:

$$P_{RF}=V_{RF}^2.|G|.\frac{A}{2} \qquad (5)$$

Where, V_{RF} is the amplitude of the RF swing. $V_{RF} = V_B/2$ is considered for 50% modulation index value. A is the area of the diode and –G is the negative conductance "[4], [6]" of the diode. The dc to mm-wave conversion efficiency "[1]" is calculated from the approximate formula,

$$\eta(\%)=\frac{V_D\times100}{\pi.V_B} \qquad (6)$$

Where, V_D=voltage drop across the drift region. Also $V_D = V_B - V_A$, where V_A = voltage drop across the avalanche region, and V_B = breakdown voltage.

The breakdown voltage is calculated "[7]" by integrating the spatial field profile over the total depletion layer width.

$$V_B=\int_0^W E.dx \qquad (7)$$

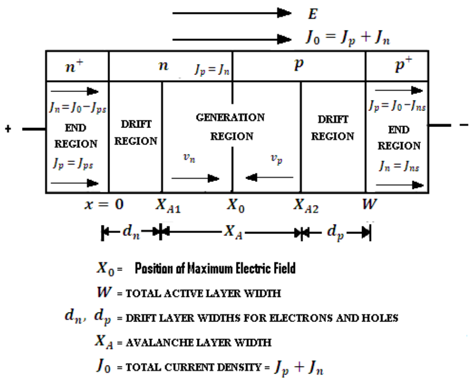

Fig. 1 The Active Layers of a Reverse Biased p-n junction

Then noise analysis is obtained by carrying out the following noise parameters.

Noise Measure is a measure of avalanche noise "[10],[11],[12] "can be given by definition

$$M = \frac{\langle V^2 \rangle}{-4.K.T.R.df} \qquad (8)$$

$\frac{\langle V^2 \rangle}{df}$ is the mean square noise voltage per band width (noise spectral density) which can be computed from the following equation (eqn. 9) given below :

$$\frac{\langle V^2 \rangle}{df} = (\frac{2.q}{J_0.A}).\frac{(1+\frac{W}{x_A})^2}{\alpha'^2} \qquad (9)$$

W and x_A are the depletion and avalanche region width respectively. Jo is the D.C current density, A is the area of the diode .K is Boltzmann constant T is temperature in Kelvin. (-R) is the real part of the device impedance and α` is the normalized ionization coefficient.

Noise parameters for shot noise is also obtained. Shot noise is associated with a discrete structure of electricity and the individual carrier injection through the *pn* junction. Shot noise has to be proportional to the current and any deviation from this relation can be used to evaluate parasitic leaking resistances. It can be used for diagnosis of photodiodes, Zener diodes, avalanche diodes.

The "shot-noise ratio" defined as the mean-squared current of the equivalent parallel current generator, normalized to the shot noise "[3]" associated with the dc current shown in figure 4:

$$R = \frac{\langle i^2 \rangle}{2.q.I_{dc}.df} \qquad (10)$$

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$<i^2>/df$ is the mean square noise current per bandwidth.
I_{dc} is the D.C bias current and q is the charge of electron.

4 RESULTS AND DISCUSSIONS

Three different types of poly SiC DDR IMPATT structures-3C SiC, 4H SiC, 6H SiC are analyzed. The output power and noise measure are generated by these devices, obtained using a computer iteration method.

TABLE 1.
Materials parameters.

Material Parameters	3C SiC	4H SiC	6H SiC
Electron mobility (μ_n) (m^2 V-1s-1)	0.075	0.10	0.04
Hole mobility (μ_p) (m^2 V-1s-1)	0.004	0.01	0.01
V_{ns}	10^5	$8x10^4$	$0.6x10^5$
V_{ps}	$0.75x10^5$	$8x10^4$	$0.76x10^5$
ε_r	11.8	10.89	11.76

* Vns and Vps are saturation velocity of electron and hole respectively and ε_r is the relative dielectric constant of the material.

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The output power and noise measure "[2], [8], [9]" is carried out at Ka Band .The output power is shown in the figure 2 and other simulated results are obtained shown in Table 2.

TABLE 2.
Simulated material parameters

Parameters	3C SiC	4H SiC	6H SiC
Breakdown Voltage(V_B)	417.71 (V)	538.60	536.38
Efficiency (η %)	26.42	24.33	24.36
Doping concentration of n region (m^{-3})	1×10^{23}	1.2×10^{23}	1.2×10^{23}
Doping concentration of n region (m^{-3})	1×10^{23}	1.2×10^{23}	1.2×10^{23}
Width of n epi-layers, Wn (micrometer)	1.5	1.55	1.55
Width of p epi-layers, Wp (micrometer)	1.501	1.556	1.556
Area of the diode (m^2)	4 x 10^{-10}	4 x 10^{-10}	4 x 10^{-10}

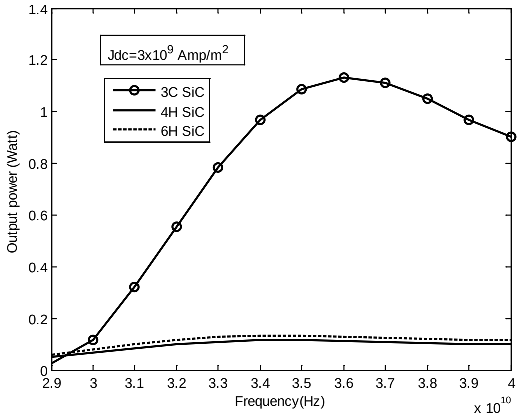

Fig 2. Variation of output power with frequency at Ka Band of different poly SiC Band.

The noise measure is also carried out for different poly-SiC and shown in the figure below (Fig.3).

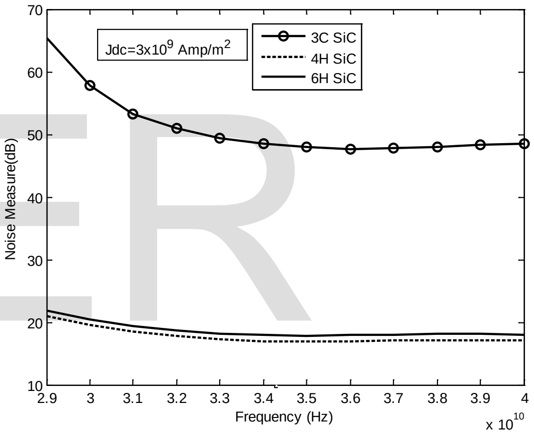

Fig 3. Variation of noise measure with frequency at Ka Band of different poly SiC

It is observed from above figures that 3C SiC produces 1.132 Watt output power but it generates minimum noise measure 47.7 dB at 36 GHz. So, due to high noise 3C SiC is not suitable for practical operation. But 4H SiC and 6H SiC will be better solutions as these can generate more than 100 miliwatt output power and produces noise measure below 20 dB at Ka band.

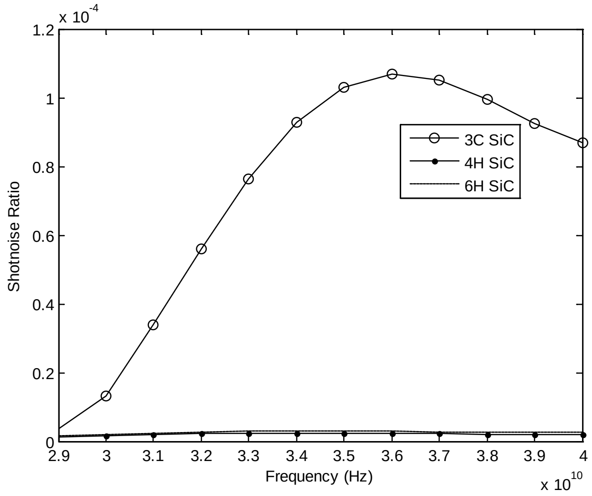

Fig 4. Variation of shot noise ratio of different poly SiC IMPATT at Ka Band.

It is observed that 4H SiC and 6H SiC-IMPATT has low noise measure and shot noise ratio comparing with 3C SiC structure.So, The noise performance and output power generation"[13]" of 4H SiC and 6H SiC are shown in the figures 5, 6 and Figure 7, 8.

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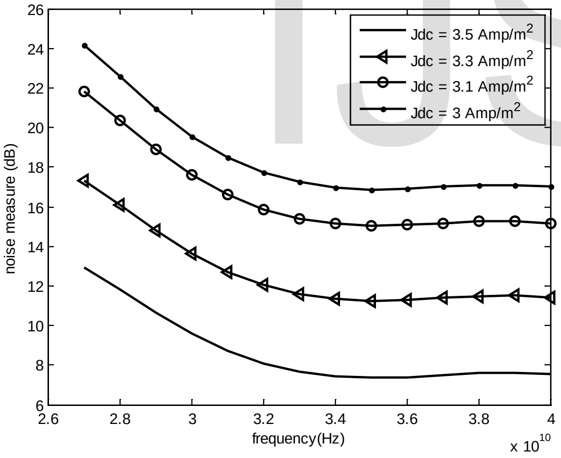

Fig 5. Variation of Noise Measure with frequency of 4H SiC

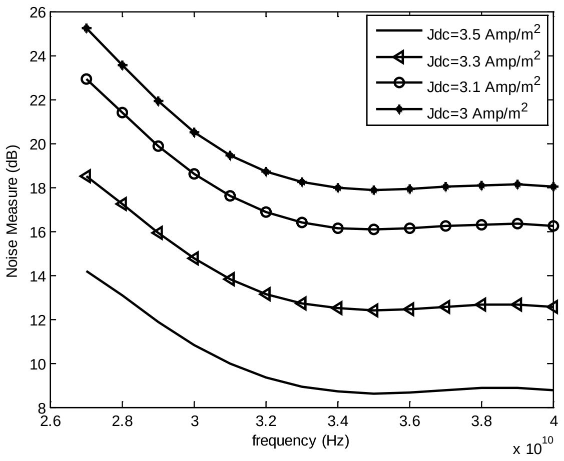

Fig 6. Variation of Noise Measure with frequency of 6H SiC

It is seen from Figure 5 and Figure 6 Noise Measure decreases with increasing current density at Ka band. It is also observed that 4H SiC produces only 7.383 dB noise measure and 6H SiC produces 8.685 dB noise measure at 34 GHz at DC current density Jdc= 3.5×10^9 Amp/m^2. These results show remarkably low noise of IMPATT operation.

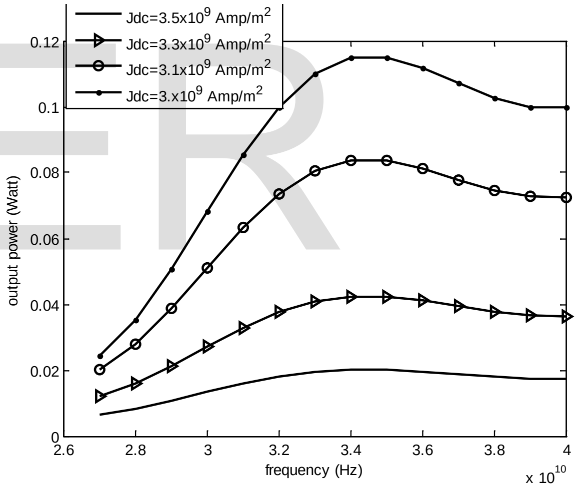

Fig 7. Variation of output power with frequency of 4H SiC

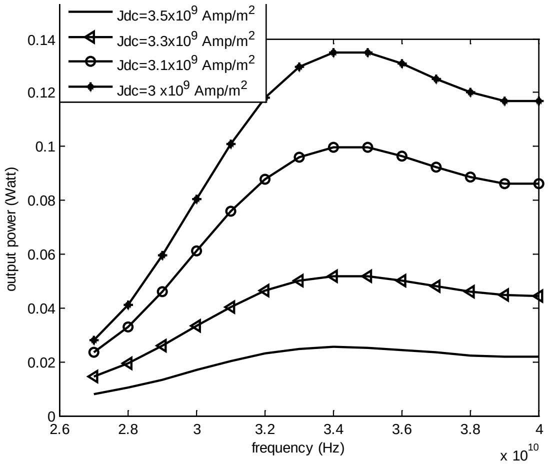

Fig 8. Variation of output power with frequency of 6H SiC

It is observed from above plots that output power decreases with increasing Jdc. It is also observed that at J_{dc} = 3.5x10^9 Amp/m^2 Peak output power obtained for 4H SiC IMPATT is only 20.38 miliwatt and 6H SiC generates 25.51miliwatt. Though 4H SiC gives outstanding noise performance at J_{dc} = 3.5x10^9 Amp/m^2, it will not be applicable due to low output power generation. Then it is observed again from above plot, A device is modeled which generates more than 100 mW power and minimum noise measure. It is obtained at J_{dc} = 3 x10^9 Amp/m^2 at which 4H SiC IMPATT generates noise measure 16.89 dB and 6H SiC produces 17.95 dB, and both of these diodes produces more than 100 mW power. From this two 4H SiC IMPATT is chosen for comparatively better noise performance at Ka band.

TABLE 3.
Simulated noise parameters

Material		4H SiC		6H SiC	
Frequency (GHz)	Current Density (J_{dc}) (Amp/m^2)	Peak Output Power (mW)	Noise Measure (dB)	Peak Output Power (mW)	Noise Measure (dB)
34	3.5x 10^9	20.38	7.383	25.51	8.685
34	3.3x 10^9	42.67	11.29	51.95	12.48
34	3.1x10^9	84.13	15.06	99.74	16.16
34	3x 10^9	115.4	16.89	135	17.95
34	2.9x 10^9	155.4	18.71	179.4	19.73
35	2.5x 10^9	424.4	25.82	465.1	26.57

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Other parameters of the device are also obtained at Ka band given below.

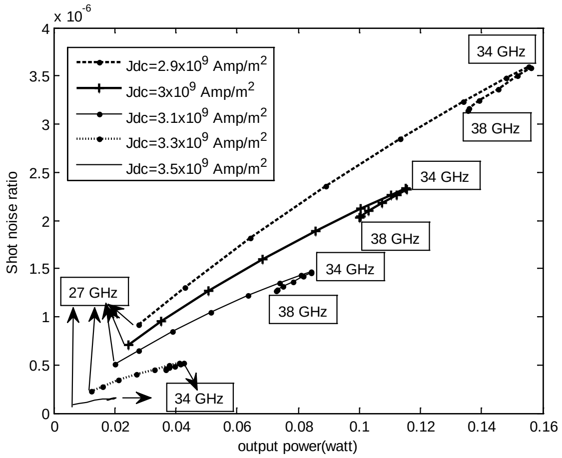

Fig 9. Variation of Shot noise ratio with output power of 4H SiC

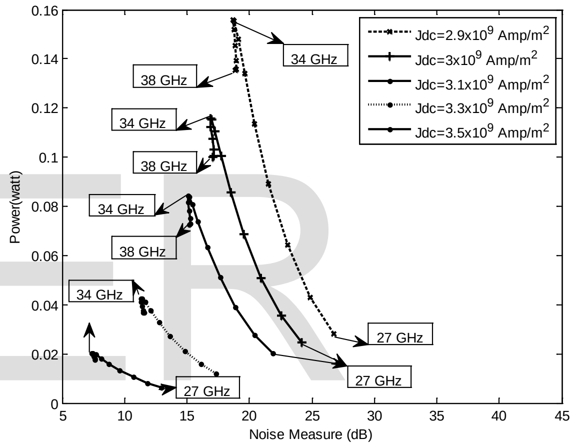

Fig 10. Variation of output power with noise measure of 4H SiC

Variation of shot noise with output power is shown in Figure 9. It is seen that shot noise is increased with increasing output power up to 34 GHz. Beyond 34 GHz power decreases but shot noise ratio is decreasing at higher rate comparing with the frequency below 34 GHz. It is seen interestingly that noise measure decreases with increasing output power below 34 GHz and beyond this frequency power is falling with increasing noise measure slowly. Negative conductance (-G) is a crucial factor for output power generation (eqn.5). It has also some effects on the noise behavior of IMPATT device.

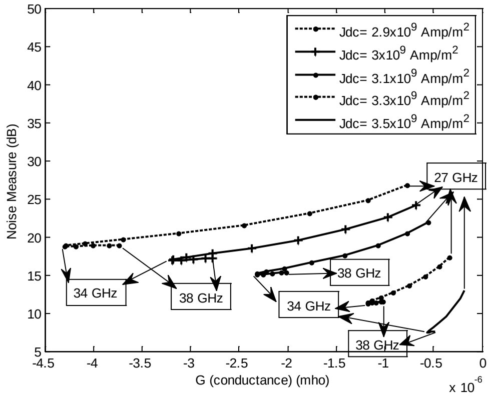

Fig 11. Variation of Noise Measure with conductance of 4H SiC

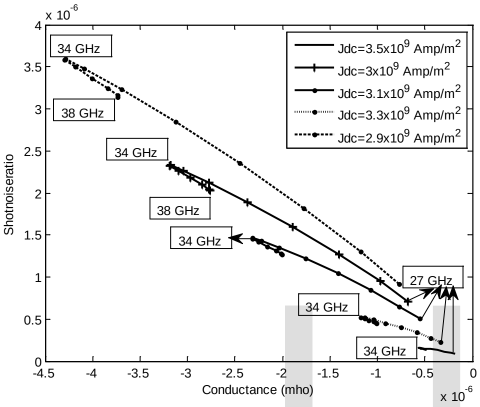

Fig 12. Variation of shot noise ratio with conductance of 4H SiC

Variation of noise measure is shown in Fig 11. It is observed that noise measure rapidly decreases with increasing negative conductance below 34 GHz and beyond 34 GHz noise measure increases slowly with increasing value of negative conductance. Variation of shot noise ratio is shown in Fig 12. It is observed that shot noise ratio increases with increasing negative conductance below 34 GHz and beyond 34 GHz shot noise ratio decreases slightly higher rate with decreasing value of negative conductance which shows the reverse characteristic of noise measure.

TABLE 4.
Simulated parameters of designed 4H SiC IMPATT

Material	4H SiC
DC Current Density (J_{dc}) (Amp/ m^2)	3x 10^9
Peak Quality Factor (Q_P)	13.97
Minimum Noise Measure (dB)	16.89
Peak Output Power (mw)	115.4
Peak Frequency (f_P)	34
Maximum Shot noise ratio	2.332x 10^{-6}

5 CONCLUSIONS

The noise performance at Ka band of different poly SiC (like 3C SiC, 4H SiC, 6H SiC) IMPATT has been studied in this paper. It is observed from the results that 4H SiC and 6H SiC produces low noise. It is also observed that 3C SiC produces more power than 4H SiC and 6H SiC based IMPATT. But 3C SiC produces much more noise than other two poly type. So, for the better noise performance 4H SiC and 6H SiC has been studied in details. The result shows 4H SiC produces minimum noise measure and shot noise ratio. It is also obtained that noise measure strongly depends on the DC bias current density and noise measure is directly proportional with DC bias current density. It is observed that output power is also directly proportional to noise measure. So, a noise power tradeoff is very crucial for this IMPATT device. It is obtained that 4H SiC generates 16.89 dB noise measure and 115.4 milliwatt power at 34 GHz at DC bias current density 3x10^9 Amp/m^2. This device is designed for its low noise generation and more than 100 milliwatt power generation at Ka band. It is emerged that 4H SiC based IMPATT is most powerful device comparing with other two poly SiC based IMPATTs for its low noise characteristics. A noise power tradeoff is also obtained for this diode at 34 GHz at Ka band.

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