Noise Performance of Millimeter-wave Silicon Based Mixed Tunneling Avalanche Transit Time (MITATT) Diode

Aritra Acharyya, Moumita Mukherjee and J. P. Banerjee

Abstract—A generalized method for small-signal simulation of avalanche noise in Mixed Tunneling Avalanche Transit Time (MITATT) device is presented in this paper where the effect of series resistance is taken into account. The method is applied to a millimeter-wave Double Drift Region (DDR) MITATT device based on Silicon to obtain noise spectral density and noise measure as a function of frequency for different values of series resistance. It is found that noise measure of the device at the operating frequency (122 GHz) with input power density of $10^{9}$ W/mm$^2$ is about 35 dB for hypothetical parasitic series resistance of zero ohm (estimated junction temperature = 500 K). Results show that the noise measure increases as the value of parasitic resistance increases.

Keywords—Noise Analysis, Silicon MITATT, Admittance characteristics, Noise spectral density.

I. INTRODUCTION

The rapid development of the process technology of IMPATT device and fine line lithography have made possible the fabrication of this device having narrow depletion layer width working at high frequency mm-waves. IMPATTs are already established as powerful and efficient sources in various communication systems operating in millimetre-wave and submillimetre-wave bands of frequency. The millimeter-wave and submillimetre-wave frequencies have many fold advantages such as increased resolution, higher penetrating power through cloud, dust, fog etc, requirement of low power supply voltage and reduced system size [1-3]. Several window frequencies are observed in the millimetre-wave frequency range (30-300 GHz) such as 35, 94, 140, 220 GHz. A lot of research interest has therefore aroused to design and develop IMPATT diodes in MITATT modes at window frequencies, capable of delivering appreciable amount of millimeter wave power of the order of watts. Further sharp decrease of DC to RF conversion efficiency of the device at higher mm-wave frequencies of operation can be compensated by using impurity bumps in the depletion layer of flat profile structures leading to quasi Read hi-lo and lo-hi-lo devices [4]. The incorporation of impurity bump in the depletion layer of IMPATTs leads to constriction of avalanche zone and simultaneous increase of the breakdown field to very high values in the range of $6 \times 10^7$ V/m to $10 \times 10^7$ V/m [5]. Higher RF power output can be obtained from IMPATTs based on wider bandgap materials such as SiC, GaN and InP [6-8] as compared to those based on Silicon. Some theoretical studies on the RF performance of heterojunction IMPATTs based on III-V and IV-IV semiconductors as reported in the literature [9-11] show that heterojunction devices are suitable for generation of high millimeter wave power along with high conversion efficiency.

The IMPATT devices are inherently noisy due to the statistical nature of carrier generation by impact ionization. Tager [12] reported an approximate expression for the small signal noise spectrum in 1965. Later in the year 1966, Hines and Blue [13] proposed a small signal theory for noise analysis of IMPATT device assuming equal carrier ionization rates for electrons and holes. One pioneering work on small-signal noise analysis of IMPATT diode was reported by Gummel and Blue [14], for arbitrary doping profile and realistic values of the ionization rates as a function of electric field. Many other researchers like Haus et al [15], Kuvas [16] carried out significant works on the noise analysis of IMPATT diode. Dash and Pati [17] developed a method of noise analysis in Mixed Tunneling and Avalanche Transit Time (MITATT) device on the framework of well-known double iterative field maximum simulation technique first reported by Roy et.al [18-19]. They estimated noise spectral density of symmetrically doped DDR structures and also high-low quasi Read structures of Si MITATTs based on the assumed junction temperature of 200°C. The effect of parasitic series resistance of the device was not considered in their method [17]. In the present paper the authors have adopted a similar approach to carry out the noise analysis of an asymmetrically doped flat-profile Si MITATT device on the framework of Gummel-Blue technique [14] where the effect of series resistance is taken into account.

Rest of the paper is organised as follows. In the next section the DC and small-signal simulation method of the MITATT device is described. Results and discussions are provided in later section. Finally a conclusion is provided at the end of the paper.

II. DC AND SMALL-SIGNAL SIMULATION METHOD

The authors have adopted a double iterative field-maximum method [5, 18-19] to study the MITATT mode operation of the device. MBE growth technique for development of $p-n$
junction in included in the present modeling. At mm-wave region, since the device is operated at a higher bias current density, the junction temperature of the device increases above the room temperature. Thus the authors estimated the rise in junction temperature considering the effect of $p^-$ and $n^+$ contact metals. For this purpose a one dimensional heat-flow analysis of IMPATT device is carried out [20]. It is found that the device junction temperature at $94$ GHz rises to $500$ K. Thus the authors have designed the device at $500$ K to study the avalanche noise in W-band IMPATT device. Another consequence of high current operation is that the mobile space charge may degrade the performance seriously. The authors have optimized the bias current by several computer runs to minimize the effect of mobile space charge.

One-dimensional model of a reverse biased $p^+pn^+$ DDR IMPATT device is shown in Fig. 1. In Fig. 1, $x_{L}/x_{R}$ is the position where the electron energy in the valence/conduction field associated with the impurity space charge [14], the device junction temperature rises to $94$ GHz and $500$ K. Thus the authors estimated the rise in junction temperature considering the effect of mobile space charge. The authors have optimized the bias current by several computer runs to minimize the effect of mobile space charge.

The total current density is the sum of conduction and displacement currents,

$$J = J_x + J_p + \frac{\partial}{\partial t}(\xi_p) = q(v_p + v_n) + \frac{\partial}{\partial t}(\xi_p)$$  \hspace{1cm} \text{(3)}$$

Where, $J_p = qv_p p$ = hole current density and $J_n = qv_n n$ = electron current density. Equations (1) and (3) is solved for

$$\frac{d\xi_p}{dx} = \frac{q}{\epsilon} \left[ N_{p} - N_{A} + p(x) - n(x) \right] \hspace{1cm} \text{(1)}$$

Where, $N_D = $ Ionized donor density, $N_A = $ Ionized acceptor density, so $qN_{ dop} = q\left(N_D - N_A\right) =$ net impurity space charge, $p(x)$ and $n(x)$ are hole and electron densities respectively. $\xi_p$ is the portion of the electric field caused by the space charge of the mobile carriers, thus $\xi_p$ is the total electric field minus the field associated with the impurity space charge [14],

$$\xi_p = \xi - \frac{q}{\epsilon} \left[ N_{dop} \right] dx \hspace{1cm} \text{(2)}$$

Fig. 1 One-dimensional model of a reverse biased IMPATT Diode [Showing the Tunnelling Positions of Electrons and Holes].

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Carrier Continuity equations in MITATT mode of operation can be written as,

$$\frac{\partial}{\partial t} \xi_p = \left( \frac{1}{q} \frac{\partial}{\partial x} \xi_p \right) + G_{np}(x) + G_{n+p}(x) + \gamma_p(x) + U_p \hspace{1cm} \text{(6)}$$

$$\frac{\partial}{\partial t} \xi_n = \left( \frac{1}{q} \frac{\partial}{\partial x} \xi_n \right) + G_{np}(x) + G_{n+p}(x) - \gamma_n(x) - U_n \hspace{1cm} \text{(7)}$$

Fig. 1 One-dimensional model of a reverse biased IMPATT Diode [Showing the Tunnelling Positions of Electrons and Holes].

The avalanche process can be considered as combination of a noiseless generation rate $G_A$ (given by (8)) and a noisy generation rate $\gamma$ = $\gamma_p$ = $\gamma_n$.

$$G_A(x) = \alpha_n(x)v_n(x)h(x) + \alpha_p(x)v_p(x)p(x) \hspace{1cm} \text{(8)}$$

$\alpha_n$ and $\alpha_p$ are electron and hole ionization rates. $v_n$ and $v_p$ are respective saturated drift velocities. $U_n$ and $U_p$ are the recombination rates of the 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. So, the carrier continuity equation in the presence of noise in MITATT mode can be written as,

$$\frac{\partial}{\partial t}(\xi_p + \xi_n) + \frac{\partial}{\partial x}(J_p + J_n) = 2(G_A(x) + \gamma(x)) + G_{np}(x) + G_{n+p}(x) \hspace{1cm} \text{(9)}$$

In this analysis the tunneling generation rate for electrons $[G_{np}(x)]$ is obtained from quantum mechanical considerations as reported in [23-24]. Thus,

$$G_{np}(x) = a_p \zeta_p^2(x) \exp \left( -\frac{b_p}{\zeta(x)} \right) \hspace{1cm} \text{(10)}$$

Where the coefficients $a_p$ and $b_p$ are given by,

$$a_p = \frac{q^2}{8\pi^2 h^2} \left( \frac{2m}{E_g} \right)^{\frac{3}{2}} \hspace{1cm} \text{(11)}$$

$$b_p = \frac{1}{2\hbar^2} \left( \frac{m^* E_g}{2} \right)^{\frac{3}{2}} \hspace{1cm} \text{(12)}$$

The symbols used in equations (10), (11) and (12) carry their usual significance. The tunneling generation rate for holes can be obtained from Fig. 1. The phenomenon of tunneling is instantaneous and the tunnel generation rate for holes is related with that for electrons i.e. $G_{np}(x) = G_{np}(x')$. The tunnel generation of an electron at $x'$ is simultaneously associated with the generation of a hole at $x$, where $(x - x')$ is the spatial separation between the edge of conduction band and valence band at the same energy. If $E$ is the measure of
energy from the bottom of the conduction band on the n-side and the vertical difference between \( x \) and \( x' \) is \( E_\text{g} \). \( x' \) can be easily obtained from Fig. 1 as [5],

\[
x = x \left(1 - \frac{E_x}{E}\right)^\frac{1}{2} \quad \text{for} \ 0 \leq x \leq x_j \tag{13}
\]

\[
x = W - x' \left(1 + \frac{E_x}{E_b - E}\right)^\frac{1}{2} \quad \text{for} \ x_j \leq x \leq W \tag{14}
\]

The hole generation rate due to tunneling is zero in the region defined by \( 0 \leq x \leq x_j \) (Fig. 1) as electrons in the valence band have no available states in the conduction band for tunneling. Similarly, non-availability of states in the conduction band for tunneling to take place in the region \( x_j \leq x \leq W \) (Fig. 1) makes no contribution of tunnel generated electrons in this region [5]. The expressions for electron and hole current densities are given by,

\[
J_p = q\nu_p v_p \left(\frac{\partial n}{\partial x}\right), \quad J_n = q\nu_n v_n \left(\frac{\partial p}{\partial x}\right)
\]

Where \( D_n \) and \( D_p \) are the diffusion constants of electrons and holes respectively. In this analysis diffusion current components are very much smaller than drift components are neglected for simplicity, as in this case \( \nu \) and \( D \) are constants.

The following equations can be formed by using the relations \( J_n = q\nu_n v_n \) and \( J_p = q\nu_p v_p \), the steady-state carrier continuity equations are written as [5],

\[
\frac{\partial J_n(x)}{\partial x} = \mu_n q \left(\frac{\partial n}{\partial x}\right) + \sigma_q \frac{\partial J_n(x)}{\partial x} - \phi_q \frac{\partial J_n(x)}{\partial x} + qG_n(x), \tag{17}
\]

\[
\frac{\partial J_p(x)}{\partial x} = -\mu_p q \left(\frac{\partial p}{\partial x}\right) - \sigma_q \frac{\partial J_p(x)}{\partial x} + qG_p(x) - \phi_p \frac{\partial J_p(x)}{\partial x}. \tag{18}
\]

The following equations can be formed by using \( J = J_n + J_p = \text{Constant} \) and \( P(x) = J_p / J_n(x) \) in equations (17) and (18),

\[
\phi(x) = \phi_0 + \phi_1 \frac{\partial J(x)}{\partial x} = \phi_0 + \phi_1 \left[\frac{\partial J_n(x)}{\partial x} + \frac{\partial J_p(x)}{\partial x}\right]
\]

\[
\phi(x) = \phi_0 + \phi_1 \frac{\partial J(x)}{\partial x} = \phi_0 + \phi_1 \left[\frac{\partial J_n(x)}{\partial x} + \frac{\partial J_p(x)}{\partial x}\right]
\]

Now \( p - n \), i.e. the mobile space-charge concentration at any space point can be obtained from (17) and (18) as,

\[
q\frac{\partial (p - n)}{\partial x} = \mu_n q \left(\frac{\partial n}{\partial x}\right) + \sigma_q \frac{\partial (p - n)}{\partial x} - \phi_q \frac{\partial J_n(x)}{\partial x} - \phi_p \frac{\partial J_p(x)}{\partial x} + qG_n(x) + qG_p(x) + \frac{2q}{\eta} J(x)
\]

\[
\phi(x) = \phi_0 + \phi_1 \frac{\partial J(x)}{\partial x} = \phi_0 + \phi_1 \left[\frac{\partial J_n(x)}{\partial x} + \frac{\partial J_p(x)}{\partial x}\right]
\]

Where, \( K \) is a correction factor whose value depends on the type of the semiconductor base material. In the case on Si, variation of drift velocity for electrons and holes with electric field has form [25],

\[
\nu_{x,p} = \nu_{x,p} \left[1 - \exp \left(-\frac{\mu_n \xi}{\nu_{x,sp}}\right)\right]
\]

For which the correction factor is given by,

\[
K = \frac{J_p \mu_p}{\nu_p} \left(1 - \frac{J_p}{\nu_p} \right) \frac{J_n \mu_n}{\nu_n} \left(1 - \frac{J_n}{\nu_n} \right)
\]
the small signal analysis. The depletion layer edges of the device are fixed from the DC analysis and taken as the starting and end points for the small signal analysis. Two second order differential equations are formed by resolving the diode impedance $Z(x, \omega)$ into its real part $R(x, \omega)$ and imaginary part $X(x, \omega)$ [5, 19] given by,

$$\frac{\partial^2 R}{\partial x^2} + [\alpha_e(x) - \alpha_p(x)] \frac{\partial R}{\partial x} - 2r_e \left( \frac{\omega \tau_e}{v} \right) \frac{\partial X}{\partial x} + \left[ \frac{\alpha_p}{v} - H(x) - \frac{q_e}{\varepsilon_e} \left( \frac{G_e(x) + G_i(x)}{2} \right) \right] R - 2r_e \left( \frac{\omega \tau_e}{v} \right) X - 2r_e \left( \frac{\omega \tau_e}{v} \right) \frac{\partial X}{\partial x} = 0 \tag{27}$$

$$\frac{\partial^2 X}{\partial x^2} + [\alpha_e(x) - \alpha_p(x)] \frac{\partial X}{\partial x} - 2r_i \left( \frac{\omega \tau_i}{v} \right) \frac{\partial R}{\partial x} + \left[ \frac{\alpha_p}{v} - H(x) - \frac{q_e}{\varepsilon_e} \left( \frac{G_e(x) + G_i(x)}{2} \right) \right] X + 2r_i \left( \frac{\omega \tau_i}{v} \right) R + \left( \frac{\omega \tau_i}{v} \right) \frac{\partial X}{\partial x} = 0 \tag{28}$$

The boundary conditions for $R$ and $X$ are given by: [n side & p side respectively]

$$\frac{\partial R}{\partial x} + \frac{\omega X}{v_n e} = \left( \frac{1}{v_n q} \right) \text{ and } \frac{\partial X}{\partial x} - \frac{\omega R}{v_n e} = 0 \text{ at } x = 0 \tag{29}$$

$$\frac{\partial R}{\partial x} + \frac{\omega X}{v_p e} = \left( \frac{1}{v_p q} \right) \text{ and } \frac{\partial X}{\partial x} + \omega R = 0 \text{ at } x = W \tag{30}$$

$$Z(x) = R(x) + i X(x)$$

A double-iterative simulation scheme is used to solve those equations simultaneously by satisfying the boundary conditions. The device negative resistance ($-G$), Susceptance ($B$) and the quality factor ($Q_p$) of the device are evaluated by using the following relations:

$$-G(\omega) = \frac{Z_p}{(Z_p^2 + Z_x^2)} \tag{32}$$

$$Q_p = \frac{-B(\omega)}{G_p} \text{ at peak frequency} \tag{34}$$

It may be noted that both $-G$ and $B$ are normalized to the area of the diode. At the resonant frequency of oscillation, the maximum RF power output ($P_{RF}$) from the device is calculated by using the following expression:

$$P_{RF} = \frac{1}{2} V_{RF}^2 G_p A \tag{35}$$

Where, $V_{RF}$ is the amplitude of the RF swing ($V_{RF} = V_B/2$, assuming 50% modulation of the breakdown voltage $V_B$), $G_p$ is the diode negative conductance at the operating frequency and $A$ is the junction area of the diode (junction diameter of the device is taken as 35 $\mu$m [29] for W-band IMPATT device).

The present method is free from any simplifying assumptions and it takes into account the MBE grown realistic doping profiles, recently reported values of material parameters of silicon [27] at 500 K and the effect of mobile space charge [21-22].

III. NOISE SIMULATION METHOD

The random nature of the impact ionization process is the main source of noise in avalanche transit time device. This random impact ionization process gives rise to fluctuations in the DC current and DC electric field. These random fluctuations in the DC values of current and electric field appear as small-signal components to their DC values even when no voltage variation has been applied at the diode. Open circuit condition with no applied small-signal voltage is considered for the noise analysis in MITATT mode of the device. Expressing small-signal AC field, $e = e_r + ie_i$, two second order differential equation s are formed for real and imaginary parts of the noise field following standard procedure [17] the second order differential equations for real and imaginary parts of the noise field are obtained as,

$$D^2 \frac{d^2 e_r(x, x)}{dx^2} + [\alpha_e(x) - \alpha_p(x)] D e_r(x, x) - \frac{2q_e \omega}{v} D e_i(x, x)$$

$$+ \left[ \frac{q_e}{\varepsilon_e} H(x) - \frac{q_e}{\varepsilon_e} \left( G_e(x) + G_i(x) \right) \right] e_r(x, x) - 2q_e \frac{\omega}{v} e_i(x, x) = \frac{2q_e \gamma(x)}{v} \tag{36}$$

$$D^2 \frac{d^2 e_i(x, x)}{dx^2} + [\alpha_e(x) - \alpha_p(x)] D e_i(x, x) + \frac{2q_e \omega}{v} D e_r(x, x)$$

$$+ \left[ \frac{q_e}{\varepsilon_e} H(x) - \frac{q_e}{\varepsilon_e} \left( G_e(x) + G_i(x) \right) \right] e_i(x, x) - 2q_e \frac{\omega}{v} e_r(x, x) = 0 \tag{37}$$

Where, $\gamma(x) = \alpha_e(x) \frac{e_r(x, x)}{e_i(x, x)} + \alpha_p(x) \frac{e_i(x, x)}{e_r(x, x)}$. Boundary conditions at n$^+$ and p$^+$ p junctions are given by,

$$\left[ -\frac{\omega \tau_l}{v_n} \right] e(x, x) = 0 \text{ at } x = 0 \tag{38}$$
\[ \frac{i\omega}{v_p} + D \] \text{e}^{\left(x, x'\right)} = 0 \quad \text{at} \quad x = W \quad (39)

The noise electric field distribution along the depletion layer can be obtained by solving (36) and (37) subject to boundary conditions, (38) and (39), following the process described in [17].

In this analysis tunneling is assumed as a quiet or noiseless process. The avalanche process can be considered as a combination of a noiseless generation rate \( G_a \) and a noise generation rate \( \gamma \). An element of current \( dJ_n \) generated in the interval \( dx' \) around \( x' \) due to a noise generation source \( \gamma(x') \) located at \( x' \) in the depletion layer.

\[ dJ_n = q \gamma(x) dx \quad (40) \]

From the theory of shot noise the element of mean-square noise current \( d\langle i_n \rangle \) in a frequency interval \( df \) contributed by \( dJ_n \) is obtained,

\[ d\langle i_n \rangle = 2q \gamma(x) A \langle \gamma(x) \rangle dx \quad (41) \]

Where, \( A \) is the junction area of the device. By integrating \( e(x,x') \) with respect to \( x \) within the whole depletion layer the terminal voltage \( V_T(x') \) produced by \( \gamma(x) \) can be obtained as,

\[ V_T(x') = \int_{0}^{W} e(x,x') dx \quad (42) \]

Thus the transfer impedance can be defined as,

\[ Z_T(x') = \frac{V_T(x')}{I_{\text{average}}(x')} \quad (43) \]

Where, \( I_{\text{average}}(x') = A dJ_n \) is the average current generated in the interval \( dx' \). The mean-square noise voltage can be found as,

\[ \langle v_{n, z}^2 \rangle = 2q \gamma(x) A \int_{0}^{W} \gamma(x) dx' \quad (44) \]

Mean-square noise voltage per bandwidth is called Noise Spectral Density \( \langle v_{n, z}^2 \rangle / df \text{ Volts}^2/\text{Sec} \). The quantity, which can appropriately asses the performance of the diode in an amplifier is called noise measure. Noise measure can be defined \([14, 28] \)

\[ M = \frac{\langle v_{n, z}^2 \rangle}{df} = \frac{4K_BT}{Z_R - R_p} \quad (45) \]

Where, \( K_B = \) Boltzmann Constant, \( T = \) Absolute Temperature, \( Z_R = \) Diode negative resistance, \( R_p = \) Positive parasitic series resistance associated with the diode.

**IV. RESULTS AND DISCUSSIONS**

A double iterative field maximum computer method is used by the authors where the basic device equations (e.g. Poisons Equation, Space Charge Equation and Current Continuity Equations) are solved simultaneously by considering the mobile space charge effect. An asymmetrically doped DDR MITATT diode is designed and optimized to operate near W-band. Structural and doping parameters of the diodes are tabulated in Table I and simulated DC and small-signal parameters are listed in Table II. Diode is assumed to operating in continuous wave (CW) mode. The impact ionization rates and carrier drift velocities and other material parameters for a semiconductor (silicon) are taken from recent reports [27] and incorporated in the analysis.

Doping profile of the diode is shown in Fig. 3. Fig. 4(a) and Fig. 4(b) show the electric field profile and \( P(x) \) profile of the diode for bias current density \( J_0 = 5 \times 10^8 \text{ Amp/m}^2 \). Small-signal conductance-susceptance plot and spatial variation of the negative resistivity (resistivity profile) (both for \( J_0 = 5 \times 10^8 \text{ Amp/m}^2 \)) are shown in Fig. 5 and Fig. 6 respectively.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode Structure</td>
<td>Flat-DDR</td>
</tr>
<tr>
<td>Base Material</td>
<td>Silicon</td>
</tr>
<tr>
<td>n-epitaxial layer thickness (( \mu )m)</td>
<td>0.3200</td>
</tr>
<tr>
<td>p-epitaxial layer thickness (( \mu )m)</td>
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</tr>
<tr>
<td>n-epitaxial layer doping concentration (( \times 10^{21} ) m(^{-3} ))</td>
<td>1.450</td>
</tr>
<tr>
<td>p-epitaxial layer doping concentration (( \times 10^{21} ) m(^{-3} ))</td>
<td>1.750</td>
</tr>
<tr>
<td>n+-substrate layer doping concentration (( \times 10^{26} ) m(^{-3} ))</td>
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</table>

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias Current Density, ( J_0 (\times 10^8 \text{ Amp/m}^2) )</td>
<td>5.0</td>
</tr>
<tr>
<td>Peak Electric Field, ( E_m (\times 10^7 \text{ Volts/m}) )</td>
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</tr>
<tr>
<td>Breakdown Voltage, ( V_B (\text{Volts}) )</td>
<td>20.88</td>
</tr>
<tr>
<td>Efficiency, ( \eta (%) )</td>
<td>9.34</td>
</tr>
<tr>
<td>Peak Operating Frequency, ( f_p (\text{GHz}) )</td>
<td>122</td>
</tr>
<tr>
<td>Peak Conductance, ( G_p (\times 10^7 \text{ S/m}^2) )</td>
<td>-6.4045</td>
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<tr>
<td>Peak Susceptance, ( B_p (\times 10^7 \text{ S/m}^2) )</td>
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<tr>
<td>Quality Factor, ( Q = \frac{\omega}{f_p} )</td>
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<tr>
<td>Negative Resistance, ( R_n (\times 10^3 \text{ Ohms/m}) )</td>
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<tr>
<td>RF Power Output, ( P_{so} (\text{Watts}) )</td>
<td>0.3490</td>
</tr>
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</table>

![Fig. 3 Doping Profile of the Si based DDR MITATT diode.](image-url)
density the mean-square noise voltage decreases in the low frequency region as well as near the resonant frequency. But in the case of MITATT mode of operation, it is seen that at the lower frequencies the variation of mean square noise voltage with DC current density is similar to the IMPATT mode. But unlike IMPATT mode, the peak of the spike increases as the operating current increases. It may be noted that as the operating current decreases (from $20 \times 10^8$ Amp/m$^2$ to $5 \times 10^8$ Amp/m$^2$) the percentage of tunneling generation rate to the avalanche generation rate increases (from 1.28% to 22.45%) as shown in Table III which causes the peak of the spike to decrease. This trend shows that in MITATT mode the noise voltage would be totally dependent on the ratio of the peak tunneling generation rate to the peak avalanche generation rate ($g_{Tpeak}/g_{Apeak}$) instead of total DC current unlike the case in pure IMPATT devices [17].

### Table III Simulated DC and Small-Signal Parameters

<table>
<thead>
<tr>
<th>Bias Current Density ($J_0 \times 10^8$ Amp/m$^2$)</th>
<th>Percentage of Tunneling Generation Rate ($g_{Tpeak}/g_{Apeak}$)</th>
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<tbody>
<tr>
<td>20</td>
<td>1.28</td>
</tr>
<tr>
<td>15</td>
<td>2.89</td>
</tr>
<tr>
<td>10</td>
<td>7.18</td>
</tr>
<tr>
<td>5</td>
<td>22.45</td>
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</table>

The Noise Measure versus frequency is plotted for DC current density, $J = 5 \times 10^8$ Amp/m$^2$ and various assumed values of parasitic positive series resistance for W-band Si DDR MITATT diode in Figure 8. It is clear that as the series resistance value increases Noise Measure also increases degrading the noise performance of the device. Figure 9 shows Noise Measure versus frequency curves for different current densities with $R_p = 0$ Ohm. As the current density increases the resonance frequency at which the Noise Measure is minimum increases, but the Noise Measure value at the corresponding resonance frequency decreases. These behaviors of the Noise Measure actually agree with results obtained by Gummel and Blue [14].
The investigations also show that the increase in the tunneling generation rate decreases the noise levels of MITATT diodes.

REFERENCES


