Effect of tunneling current on the noise characteristics of a 4H-SiC Read Avalanche diode

Deepak K. Karan, Pranati Panda, and G. N. Dash†

School of Physics, Sambalpur University, Jyoti Vihar, Burla, Sambalpur – 768 019 (Odisha), India

Abstract: Noise characteristics of a Read Avalanche diode are analyzed by incorporating the tunneling mechanism of the electron into the avalanche mechanism. Analytical expressions are presented for the mean square noise voltage and noise measure in MITATT (mixed tunneling and avalanche transit time) mode operation. A wide band gap semiconductor (4H-SiC) based MITATT diode is considered to study the effect of tunneling on the noise characteristics and negative conductance. While exhibiting enough potential for 4H-SiC to be used as a terahertz source of power in the MITATT mode, our results record a noise measure of 35.18 dB at a frequency of 1.5 THz.

Key words: MITATT; 4H-SiC; noise

DOI: 10.1088/1674-4926/34/1/014001 **EEACC:** 2520

1. Introduction

During the last decade SiC has emerged as an excellent semiconductor for high power device applications due to its wide band gap, induced superior electrical characteristics, high thermal conductivity and large carrier velocity. The material is being extensively explored for wide ranging applications starting from simple MOS devices[1] to high voltage devices[2] and hybrid electric vehicles[3]. The availability of a large number of poly-types of the material (SiC) has further extended its range of applicability. A comparative account of high frequency and noise characteristics of IMPATT (impact avalanche transit time) diodes based on different polytypes of SiC has been reported by Panda and Rao[4]. Some other reports present terahertz and mm-wave properties of a SiC based IMPATT diode[5, 6]. However, reports on noise in a SiC IMPATT diode are not available in published literature, except that of Pattanaik *et al.*[7]. This report, while presenting noise properties of a 6H-SiC IMPATT diode did not take the effect of tunneling current into account.

Noise study in IMPATT diodes initiated with the classic reports of Hines[8] and Gummel and Blue[9]. These reports did not consider the MITATT mode for their analysis. Dash *et al.* published the first report on noise simulation in a MITATT diode[10]. Later an analytical model for noise theory in a Read-type MITATT diode was also reported by Dash and his group[11]. They considered a narrow band gap material combination of $InAs/InAs_{0.88}Sb_{0.12}$[11]. The purpose of this paper is to consider a wide band gap material of SiC for application as a Read type MITATT diode with particular emphasis on the noise characteristics of the diode. Out of the numerous polytypes of SiC only 4H-SiC and 6H-SiC substrates are commercially available. 4H-SiC is the most widely explored material[1, 2, 4, 5] for high power devices because its carrier mobility is substantially higher compared to 6H-SiC. In addition the more isotropic nature of electrical properties makes 4H-SiC more attractive for power device applications. We have therefore chosen the 4H polytype of SiC for this analysis. Analytical expressions for mean square noise voltage and noise measure of a Read type avalanche diode in MITATT mode are presented following our method[11] and they are used to analyze the effect of tunneling current on the noise characteristics of the diode. The results so obtained reveal that 4H-SiC has enough potential to fulfill the necessity of a mixed mode THz microwave source.

2. Theory

We have considered a Read-type diode model for our mixed mode analysis. This is a high-frequency negative resistance diode embodying an inductively reactive multiplying region which is a uniformly high-field generation region of width x_g followed by a drift region in which the charge carriers drift for half a period of oscillation. The drift region is a generation free low-field region of width x_d. The carriers generated in the generation region are injected into the drift region where they travel with a constant saturated drift velocity v_d. During the impact ionization process noise is produced as it is a noisy process. In this analysis tunneling is assumed to be a quiet process.

The total noise current density J_n in this diode is composed of three components.

(1) J_{no}, the noise current density arising from the critical field necessary to maintain a steady avalanche.

(2) J_{ne}, the noise current density induced by the AC (noise) field caused by J_{no}.

(3) J_{nd}, the displacement noise current density arising out of the time variation of the noise electric field.

Thus the noise current density in the generation region is given by

$$J_n = J_{no} + J_{ne} + i\omega\epsilon E_{gn}. \tag{1}$$

where E_{gn} is the amplitude of the AC noise field in the generation region, ω the angular frequency of the AC, and ϵ the permitivity of the semiconductor.

† Corresponding author. Email: gndash@ieee.org
Received 23 June 2012, revised manuscript received 5 August 2012

2.1. Noise current densities

The noise current density at any point x in the drift region is given by

$$J_{\mathrm{n}}(x)=(J_{\mathrm{no}}+J_{\mathrm{ne}})\mathrm{e}^{-\frac{\mathrm{i}\omega x}{v_{\mathrm{d}}}}+\mathrm{i}\omega\epsilon E_{\mathrm{dn}}(x). \quad (2)$$

where $E_{\mathrm{dn}}(x)$ is the amplitude of the AC noise field in the drift region.

Here J_{ne} can be viewed as a small-signal fluctuation over the DC value J_{o} and hence can be obtained by solving Read's equation for mixed mode operation which is given by

$$\frac{\tau_{\mathrm{g}}}{2}\frac{\mathrm{d}}{\mathrm{d}t}J_{\mathrm{c}}(t)=[\alpha_{\mathrm{eff}}(t)x_{\mathrm{g}}]J_{\mathrm{c}}(t)+J_{\mathrm{T}}(t), \quad (3)$$

where $\tau_{\mathrm{g}}=x_{\mathrm{g}}/v_{\mathrm{d}}$, $J_{\mathrm{c}}(t)=J_{\mathrm{o}}+J_{\mathrm{ne}}\mathrm{e}^{\mathrm{i}\omega t}$ and α_{eff} is an effective value of the ionization coefficient of the carriers. α_{eff} is defined as the value of the ionization coefficient, equal for both types of carriers which will generate the same J_{o} in the generation region as the actual carriers with different (experimentally determined) values of ionization coefficients for electrons and holes. Thus the use of α_{eff} removes, to a large extent, the inaccuracy arising out of the assumption of equal ionization coefficients for electrons and holes in Read's equation. A method to determine α_{eff} has been described by Elta and Haddad[12] which is used here. The expression for α_{eff} is given by

$$\alpha_{\mathrm{eff}}=\frac{J_{\mathrm{dc}}-J_{\mathrm{s}}-qx_{\mathrm{g}}G_{\mathrm{T}}}{J_{\mathrm{s}}x_{\mathrm{g}}}. \quad (4)$$

The tunneling current can be expressed as

$$J_{\mathrm{T}}(t)=qx_{\mathrm{g}}G_{\mathrm{T}}(t). \quad (5)$$

The tunneling generation rate G_{T} is a function of the generation region electric field E_{g}. The expressions of $G_{\mathrm{T}}(E)$[12] and E_{g} are given by

$$G_{\mathrm{T}}=A_{\mathrm{T}}E_{\mathrm{g}}^{2}\mathrm{e}^{(-B_{\mathrm{T}}/E_{\mathrm{g}})}, \quad (6)$$

$$E_{\mathrm{g}}=E_{\mathrm{go}}+E_{\mathrm{gn}}\mathrm{e}^{\mathrm{i}\omega t}, \quad (7)$$

where E_{go} is the DC electric field, and A_{T} and B_{T} are constants dependent on the material parameters of the semiconductor.

Thus the time dependence of α_{eff} and G_{T} may be expressed as

$$\alpha_{\mathrm{eff}}(t)=\alpha_{\mathrm{eff}}(E_{\mathrm{go}})+\alpha'_{\mathrm{eff}}E_{\mathrm{gn}}\mathrm{e}^{\mathrm{i}\omega t}, \quad (8)$$

$$G_{\mathrm{T}}(t)=G_{\mathrm{T}}(E_{\mathrm{go}})+G'_{\mathrm{T}}E_{\mathrm{gn}}\mathrm{e}^{\mathrm{i}\omega t}, \quad (9)$$

where the primes over α_{eff} and G_{T} denote their field derivatives. Substituting $J_{\mathrm{c}}(t)$, $\alpha_{\mathrm{eff}}(t)$ and $G_{\mathrm{T}}(t)$ into Eq. (3) and removing the DC part, an expression for J_{ne} can be obtained as

$$J_{\mathrm{ne}}=\frac{2x_{\mathrm{g}}E_{\mathrm{gn}}(\alpha'_{\mathrm{eff}}J_{\mathrm{o}}+G'_{\mathrm{T}}q)}{\mathrm{i}\omega\tau_{\mathrm{g}}+2(1-\alpha_{\mathrm{eff}}x_{\mathrm{g}})}. \quad (10)$$

An expression for J_{no} is obtained following the procedure of Hines[3] as

$$J_{\mathrm{no}}=\sqrt{\frac{2qJ_{\mathrm{o}}B}{\omega^{2}\tau_{x}^{2}A}}, \quad (11)$$

where q is the electronic charge, B is the band width, A is the area of the diode, and τ_{x} is the time between successive collisions. The noise voltage drop V_{dn} in the drift region is obtained by integrating $E_{\mathrm{dn}}(x)$ for the drift region

$$V_{\mathrm{dn}}=\frac{J_{\mathrm{n}}x_{\mathrm{d}}}{\mathrm{i}\omega\epsilon}+(J_{\mathrm{ne}}-J_{\mathrm{no}})x_{\mathrm{d}}\frac{1-\mathrm{e}^{\mathrm{i}\theta_{\mathrm{d}}}}{\omega\epsilon\theta_{\mathrm{d}}}, \quad (12)$$

where $\theta_{\mathrm{d}}=\frac{\omega x_{\mathrm{d}}}{v_{\mathrm{d}}}$ is the transit angle for the drift region.

2.2. Short-circuit noise current

Under short-circuit conditions we have,

$$V_{\mathrm{dn}}+E_{\mathrm{gn}}x_{\mathrm{g}}=0. \quad (13)$$

Now V_{dn} from Eq. (12) can be substituted into Eq. (13) to get an expression for the short-circuit noise current J_{n}. However, before this, in order to eliminate E_{gn}, Equation (10) is substituted into Eq. (1) and an expression for E_{gn} is obtained as

$$E_{\mathrm{gn}}=\frac{J_{\mathrm{n}}-J_{\mathrm{no}}}{x_{\mathrm{g}}}\frac{R_{\mathrm{g}}+\mathrm{i}\omega L_{\mathrm{g}}}{1-(\omega^{2}/\omega_{\mathrm{g}}^{2})+\mathrm{i}\omega C_{\mathrm{g}}R_{\mathrm{g}}}, \quad (14)$$

where the equations for resistive and reactive components of impedance of the generation region obtained from small-signal solution of Read's equation in mixed mode are used[12] i.e.

$$R_{\mathrm{g}}=\frac{1-\alpha_{\mathrm{eff}}x_{\mathrm{g}}}{\alpha'_{\mathrm{eff}}J_{\mathrm{o}}+G'_{\mathrm{T}}q}, \quad (15)$$

$$L_{\mathrm{g}}=\frac{\tau_{\mathrm{g}}}{2(\alpha'_{\mathrm{eff}}J_{\mathrm{o}}+G'_{\mathrm{T}}q)}, \quad (16)$$

$$C_{\mathrm{g}}=\frac{\epsilon}{x_{\mathrm{g}}}. \quad (17)$$

Also, we defined $\omega_{\mathrm{g}}=1/\sqrt{L_{\mathrm{g}}C_{\mathrm{g}}}$ in Eq. (14). Now the E_{gn} in V_{dn} can be eliminated by substituting Eq. (14) into Eq. (1) and obtaining an expression for J_{ne} as

$$J_{\mathrm{ne}}=\frac{J_{\mathrm{n}}-J_{\mathrm{no}}}{1-(\omega^{2}/\omega_{\mathrm{g}}^{2})+\mathrm{i}\omega C_{\mathrm{g}}R_{\mathrm{g}}}. \quad (18)$$

Substituting Eq. (12) into Eq. (13) and making use of Eqs. (14) and (18) we obtain an expression for the short-circuit noise current J_{n} following some algebra

$$J_{\mathrm{n}}=J_{\mathrm{no}}\frac{Z_{\mathrm{g}}}{Z_{\mathrm{d}}}\left[1+\frac{x_{\mathrm{d}}\sin\theta_{\mathrm{d}}}{x_{\mathrm{g}}\theta_{\mathrm{d}}}-\frac{\mathrm{i}x_{\mathrm{d}}(\cos\theta_{\mathrm{d}})}{x_{\mathrm{g}}\theta_{\mathrm{d}}}\right], \quad (19)$$

where the generation region (Z_{g}) and drift region (Z_{d}) impedances are given by

$$Z_{\mathrm{g}}=\frac{R_{\mathrm{g}}+\mathrm{i}\omega L_{\mathrm{g}}}{1-(\omega^{2}/\omega_{\mathrm{g}}^{2})+\mathrm{i}\omega C_{\mathrm{g}}R_{\mathrm{g}}}, \quad (20)$$

$$Z_{\mathrm{d}}=\frac{1}{\mathrm{i}\omega C_{\mathrm{d}}}+\frac{1}{1-(\omega^{2}/\omega_{\mathrm{g}}^{2})+\mathrm{i}\omega C_{\mathrm{g}}R_{\mathrm{g}}}\frac{1-\mathrm{e}^{-\mathrm{i}\theta_{\mathrm{d}}}}{\omega c_{\mathrm{d}}\theta_{\mathrm{d}}}, \quad (21)$$

where $c_{\mathrm{d}}=\frac{\epsilon}{x_{\mathrm{d}}}$. The diode impedance $Z_{\mathrm{D}}=Z_{\mathrm{g}}+Z_{\mathrm{d}}$.

Table 1. Percentage of tunneling current, mean-square noise voltage, noise measure and negative conductance for different values of x_g/W.

x_g/W (%)	J_T/J_o (%)	f_g (GHz)	$\langle V_n^2\rangle/B$ ($V^2\cdot$s)	f_p (THz)	$\langle V_n^2\rangle/B$ ($V^2\cdot$s)	NM (dB)	G_D (S/m^2)	f_l (THz)	NM (dB)
25	0.76	179	2.16×10^{-11}	0.9	3.129×10^{-19}	36.74	1.537×10^{8}	10.40	11.08
20	1.9	189	3.56×10^{-12}	1.0	2.848×10^{-19}	36.46	1.941×10^{8}	10.20	10.59
15	6.1	210	8.24×10^{-13}	1.2	2.635×10^{-19}	36.24	2.623×10^{8}	10.10	9.78
10	31.71	270	2.92×10^{-13}	1.5	2.368×10^{-19}	35.18	4.719×10^{8}	10.05	7.67

2.3. Mean square noise voltage and noise measure

The open circuit noise voltage V_n can now be obtained as,

$$V_n = J_n Z_D. \tag{22}$$

However, the quantity which is of more interest in noise study is the mean square noise voltage per unit bandwidth which can be derived as

$$\langle V_n^2\rangle/B = \frac{2qJ_o}{\omega^2\tau_x^2 A}|Z_g|^2\left|1+\frac{x_d\sin\theta_d}{x_g\theta_d}-\frac{\mathrm{i}x_d(1-\cos\theta_d)}{x_g\theta_d}\right|^2. \tag{23}$$

Another important quantity of interest for noise study is the noise measure (NM) defined as

$$\mathrm{NM} = \frac{\langle V_n^2\rangle/B}{4kT[-\mathrm{Real}(Z_D)]}. \tag{24}$$

Equations (23) and (24) have been used to study the effect of the tunneling current on the noise characteristics of the 4H-SiC Read diode.

3. Results and discussion

The material parameters for 4H-SiC used in this study are taken from the NSM archive[13]. The diode structural and operating parameters which are kept fixed are taken as $W = 2.0\ \mu$m, $J_0 = 3\times10^8$ A/m^2 and $A = 10^{-10}$ m^2. However, x_g and $x_d = W - x_g$ are taken as being variable. x_g/W varied from 10% to 25% and the electric field in the generation region E_{go} required to generate J_o is computed in each case by an iterative sub program. The percentage of tunneling current, mean-square noise voltage, noise measure and negative conductance are estimated in each case. The results are presented in Table 1.

A detailed account of noise data is given in Table 1. The noise data are presented at three different frequencies namely: $f_g = \omega_g/2\pi$, the frequency at which a resonance like peak in the $\langle V_n^2\rangle/B$ curve (Fig. 1) appears, f_p, the frequency corresponding to the maximum value of diode negative conductance and f_l, the frequency at which the noise measure shows a minimum. Table 1 shows that as the generation region width is narrowed down from 25% to 10% the percentage of tunneling current in the SiC read diode increases from 0.76% to 31.71% with a consequent decrease in $\langle V_n^2\rangle/B$ at f_g by 2 orders of magnitude. Since the diode negative conductance peaks at f_p, the diode operation is set around this frequency and therefore the noise data at f_p are very important. The mean square noise voltage and the noise measure at f_p for different values of x_g/W can be seen from Table 1. Both $\langle V_n^2\rangle/B$ and the noise measure decreases, even at f_p, when the tunneling current is increased by reducing the generation region width. However, it is interesting to note that the negative conductance increases with an increase in the tunneling current. The noise measure shows a minimum of 35.18 dB for an optimum frequency of 1.5 THz. This will permit tunneling assisted control of noise in the SiC MITATT diode. The minimum noise-measure at f_l for different values of x_g/W is also shown in Table 1. The noise measure steadily decreases with the increase in the tunneling current. A minimum noise measure of 7.67 dB at 10.05 THz is noteworthy.

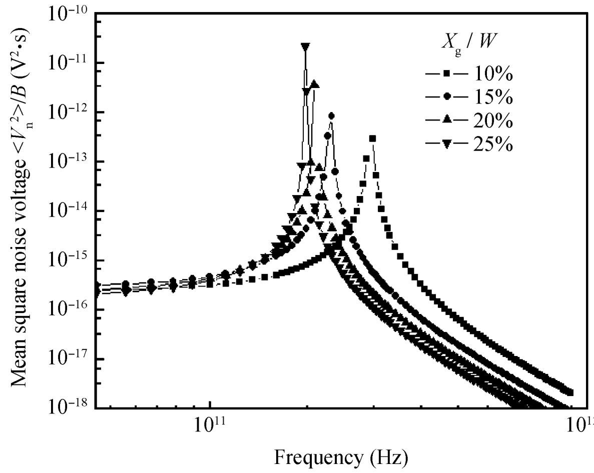

Fig. 1. Variation of mean square noise voltage per unit band width as a function of frequency for different values of x_g/W depicting the effect of the tunneling current.

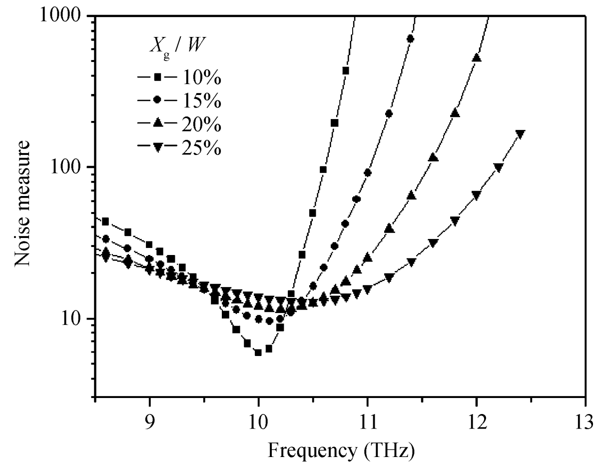

Fig. 2. Variation of noise measure as a function of frequency for different values of x_g/W depicting the effect of the tunneling current.

Figures 1, 2 and 3 show respectively the plots of mean-

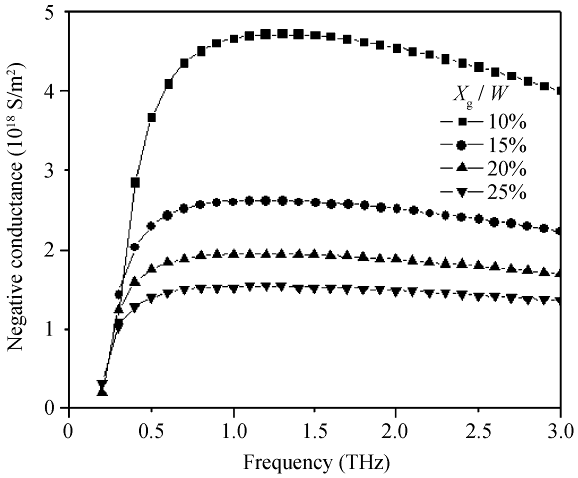

Fig. 3. Variation of device negative conductance as a function of frequency for different values of x_g/W depicting the effect of the tunneling current.

square noise voltage, noise measure and negative conductance as a function of frequency for different values of x_g/W. From Fig. 1 it is observed that as the frequency increases for a particular value of x_g/W, the mean square noise voltage shows a resonance like peak at a particular frequency known as the avalanche frequency. As x_g/W increases, the avalanche frequency gradually decreases. Also, it is clear that for an increase in tunneling current i.e. in MITATT mode operation, the frequency corresponding to the peak of the mean square noise voltage shifts to higher values. Further, this figure confirms the decrease in the mean square noise voltage with the increase in the tunneling current as noted from Table 1.

From Fig. 2 it is observed that as the frequency increases, for a particular value of the x_g/W, the noise measure shows a minimum at a particular frequency, f_l. As the x_g/W value increases, f_l gradually increases and the minimum value of noise measure increases. Also it is clear from the figure that f_l shifts towards the lower side as the tunneling current increases. From Fig. 3 it is observed that as the frequency increases (at a given x_g/W), the negative conductance first increases and after a particular frequency known as the optimum frequency, it decreases. The optimum frequency shows a trend of shifting towards the higher value with an increase of the tunneling of electrons. Moreover the negative conductance corresponding to the optimum frequency increases with a decrease of x_g/W and correspondingly an increase of tunneling current (as noted earlier). This can be understood in the following way.

The basic philosophy in the proposition of a Read diode envisages a thin high field avalanche/generation region (with negligible drift time) followed by a low field drift region (with virtually no generation) where the carriers drift for half a cycle. Thus the performance of the diode (negative conductance and negative resistance which has a direct bearing on the power output) is expected to be better if the generation region becomes thinner (i.e. x_g/W decreases). But a thinner generation region is more prone to the tunneling of electrons whereby the tunneling component of the current increases with a decrease in x_g/W. However, the tunneling current suffers from a loss in the phase delay of $\pi/2$ which the avalanche component of the current acquires from the avalanche process. The net loss in the phase delay decreases the power output (at the optimum frequency corresponding to no or negligible tunneling). However, in order to gain the required phase (a total phase delay of π between the RF current and RF voltage is required for maximum negative resistance) the optimum frequency increases and the negative resistance/conductance regains some value at the new optimum frequency. The actual value is determined by two competing mechanisms: avalanche and tunneling. If tunneling dominates the value decreases. On the other hand if avalanche dominates the value increases as in the present case.

4. Conclusions

An analytical model is used to study the avalanche noise in a 4H-SiC Read type diode for mixed mode operation. SiC is a wide band gap semiconductor. Since the breakdown voltage is very high the avalanche mechanism is expected to dominate the operation of a SiC MITATT diode. Thus we see that even at a high tunneling current of 31% the noise measure remains quite high at 35.18 dB at a frequency of 1.5 THz. Further, with an increase in the tunneling current the decrease in noise measure is not significant. On the other hand, the tunneling current enhances the device negative conductance as seen from Table 1. This is a noteworthy feature.

Acknowledgement

The facilities extended through the DRS programme under SAP of UGC are acknowledged.

References

[1] Zhang C X, Zhang E X, Fleetwood D M, et al. effects of bias on the irradiation and annealing responses of 4H-SiC MOS devices. IEEE Trans Nucl Sci, 2011, 58: 2925

[2] Imhoff E A, Kub F J, Hobart K D, et al. High-performance smoothly tapered junction termination extensions for high-voltage 4H-SiC devices. IEEE Trans Electron Devices, 2011, 58: 3395

[3] Zhang H, Tolbert L M, Ozpineci B. Impact of SiC devices on hybrid electric and plug-in hybrid electric vehicles. IEEE Trans Industry Applications, 2011, 47(2): 912

[4] Panda A K, Rao V M. Modeling and comparative study on the high frequency and noise characteristics of different polytypes of SiC-based IMPATTs. IEEE Asia Pacific Microwave Conference, 2009: 1569

[5] Mukherjee M. Effects of punch-through on terahertz frequency characteristics of 4H-SiC based p^{++} p n n^{++} IMPATT devices. IEEE 4th International Conference on Computers and Devices for Communication, 2009: 1

[6] Tripathy P R, Mishra R K, Pati S P. MM-wave characteristics of SiC-based IMPATT oscillators. IEEE Applied Electromagnetics Conference, 2009: 1

[7] Pattanaik S R, Dash G N, Mishra J K. Prospects of 6H-SiC for operation as an IMPATT diode at 140 GHz. Semicond Sci Technol, 2005, 20: 299

[8] Gummel H K, Blue J L. A small signal theory of avalanche noise in IMPATTs. IEEE Trans Electron Devices, 1967, ED-14: 569

[9] Hines M E. Noise theory for the Read type avalanche diode. IEEE Trans Electron Devices, 1966, ED-13: 158

[10] Dash G N, Mishra J K, Panda A K. Noise in mixed tunneling avalanche transit time (MITATT) diodes. Solid State Electron, 1996, 39(10): 1473

[11] Dash G N, Mishra J K, Nayak S K. Tunneling assisted noise control in InAs/$InAs_{0.88}Sb_{0.12}$ Read Avalanche diode. IETE Tech Review, 1999, 16(2): 243

[12] Elta M E, Haddad G I. Mixed tunneling and Avalanche mechanisms in p–n junction and their effects on microwave transit time devices. IEEE Trans Electron Devices, 1978, ED-25: 694

[13] http://www.ioffe.ru/SVA/NSM/Semicond/SiC