# III-V Nitride based Solid State p-i-n Switch for Application in Millimeter Wave Secure Communication

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## ABSTRACT
This paper presents a new monolithic gallium nitride based p-i-n diode model which enhances the power handling capacity and bandwidth in millimeter wave (MMW) communication. The proposed model is simulated at bias current of 2 milliampere in 1.24 ohm series resistance to obtain insertion loss, isolation and return loss. Transit time analysis is also required to improve the performance of the switch and all these simulated results are compared to the standard measured value. A series connected Single Pole Single Throw (SPST) switch is implemented using p-i-n diode to get low insertion loss, low return loss and better isolation at high frequency. This radio frequency switch is more useful to deliver the radio frequency signal from one transmitter to N- number of receiver at 90 gigahertz frequency through 18 gigahertz frequency.

## Keywords
GaN, p-i-n diode, effective diffusion length, stored charge, intrinsic impedance, switching speed, return loss, insertion loss, isolation, stored charge transfer function

## 1. INTRODUCTION
The p-i-n diode is fabricated with highly doped p+, n+ regions and a lightly doped i region (Figure 1) which plays crucial role to operate radio frequency signal as a switch. The 'ON' and 'OFF' state of the switch is maintained by changing its impedance with changing the frequency using the non linear model which is compared to the equivalent small signal model (Figure 2) of p-i-n diode. This high frequency non linear model is controlled by the lead inductance ($L_S$), series resistance ($R_S$), junction capacitance ($C_J$) and junction resistance ($R_J$) of the p-i-n diode. The radio frequency characteristics of solid state switches are analyzed and implemented at high frequency from very beginning using low band gap materials such as silicon, gallium arsenide but these materials cannot play an effective role in millimeter wave communication for its electrical property. The based materials silicon and gallium arsenide of p-i-n diode are replaced by the most promising wide band gap material gallium nitride which provides several advantages such as high break down voltage, high operating frequency and high power handling capacity in millimeter wave communication. The high breakdown voltage (200-300V) of the switch determines the range of frequency and voltage in which it can be used without any distortion [2]. In wireless communication this solid sate switches are placed at the transmitter and receiver end to handle the high power and high frequency [3]. At high frequency this type of radio frequency switch is more reliable compare to MEMS switch for its longer carrier life time. At 2 milliampere forward bias current, this solid state switches offers insertion loss ~ 0.5dB, isolation ~ 65dB and return loss ~ 0.85dB. The intrinsic region of this radio frequency switch stores more charge (~ 16.8 pF) which reduce its impedance at high frequency [4]. The switching speed is also improved in satellite communication using this radio frequency switch [5]. Looking at these points in the present paper, the wide band gap gallium nitride material is considered as the base material of the p-i-n switch. The results are compared with another WBG material (3C-SiC) based p-i-n diode.

## 2. THEORY
The p-i-n diode is a 2-terminals solid state device which finds application at high frequency as a RF switch. At forward bias the switch acts as a variable resistor in different RF frequencies. At time of propagation this property of the switch changes the phase of the RF signal .The variable resistance [6] of this RF switch can be expressed as-

$$R_S = R_i + R_C + R_J \text{..........} (1)$$

where $R_i$ is the intrinsic resistance of the i region. $R_C$ is the contact resistance and $R_J$ is the junction resistance. Intrinsic resistance of p-i-n switch can be derived as -

$$R_i = \left( W^2 / 2 I_f \mu_{eff} \tau \right) \text{..........} (2)$$

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The intrinsic resistance ($R_I$) is the function of the effective carrier mobility ($\mu_{eff}$), carrier life time (τ), forward bias current ($I_f$) and the width ($W$) of the i region (Figure 1).

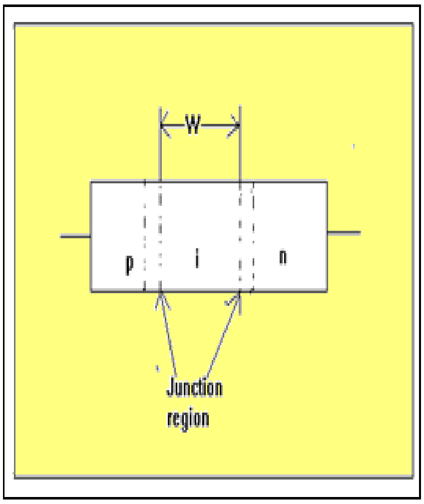


**Figure 1. Structure of p-i-n switch**

The lead resistance ($R_S$) and inductance ($L_S$) have the contribution to the contact resistance which is associated in series as shown in figure 2.

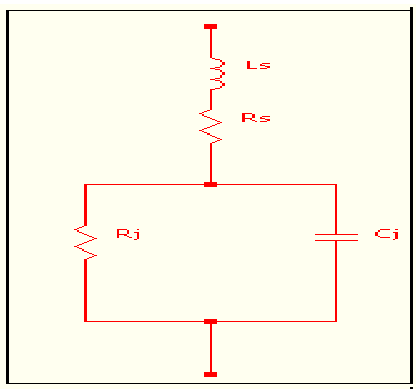


**Figure 2. Small signal equivalent model of p-i-n switch**

Therefore it is important to give an effort to keep $R_S$ and $L_S$ at lower value for low insertion loss and high isolation when the device is connected as a switch. It can be written as-

$$R_C = (r_p + r_{cp}^{+}) + (r_n + r_{cn}^{+}) \ldots\ldots\ldots(3)$$

Where $r_p$, $r_n$ are the resistances of p+ and n+ regions but $r_{cp}^{+}$ and $r_{cn}^{+}$ are the resistance of p+ and n+ metal contact respectively.

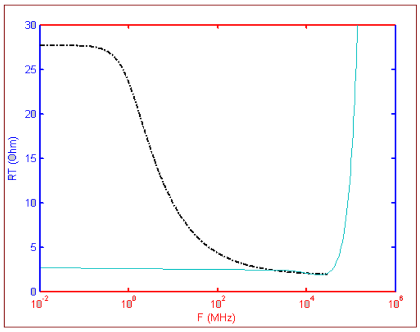


**Figure 3. Total resistance of p-i-n diode at 2mA forward current**

The frequency dependence junction resistance $R_j(f)$ of p-i-n diode can be expressed as a function of forward bias current to explain its application as a switch at high frequency regime by author et.al. [5]. To define $R_j(f)$ as function of forward bias current, it has been considered junction temperature. It may be expressed as-

$$R_j(f) = \frac{2}{I_f}\ln\left(\frac{I_f}{I_s}\right)\beta\tanh\left(\frac{W}{2L}\right)\cos(\phi-\theta/2)\ldots\ldots(4)$$

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Where

$$a = \frac{\omega}{2L}\left[1+(\omega\tau)^2\right]^{0.25}\cos\left(\frac{\theta}{2}\right)$$

$$b = \cot\left(\frac{\theta}{2}\right)$$

$$\beta = \left[\{\coth(a)(1+\cot^2(b))\}^2 + \{\cot(b)(1-\coth^2(a))\}^2\right]^{0.5} \Big/ \left[1+(\omega\tau)^2\right]^{0.25}\left[\coth^2 a + \cot^2 b\right]$$

$$a = \frac{\omega}{2L}\left[1+(\omega\tau)^2\right]^{0.25}\cos\left(\frac{\theta}{2}\right)$$

$$b = \cot\left(\frac{\theta}{2}\right)$$

$$\phi = \tan^{-1}\left[\{\cot(b)(1-\coth^2(a))\} \Big/ \{\coth(a)(1+\cot^2(b))\}\right]$$

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$$\theta = \tan^{-1}(\omega\tau)\ldots\ldots\ldots(5)$$

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$R_j$ depends on diffusion length *(L)*, i region width *(W)*, forward bias current ($I_f$) and reverse saturation current ($I_s$). The diffusion length *(L)* depends on the carrier lifetime (*τ*) and the effective diffusion constant ($D_{eff}$) of i- region and it is written as-

$$L = \sqrt{D_{eff}\tau}\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

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$I_f$ relates the stored charge (Q) as-

$$Q = I_f\tau\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

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Transit time *(τ)* of a radiofrequency switch is also an important parameter to determine the operating frequency *($f_0$)* of the switch which is inversely proportional to the transit time and it can be expressed as –

$$f_0 = 1/2\tau \qquad (8)$$

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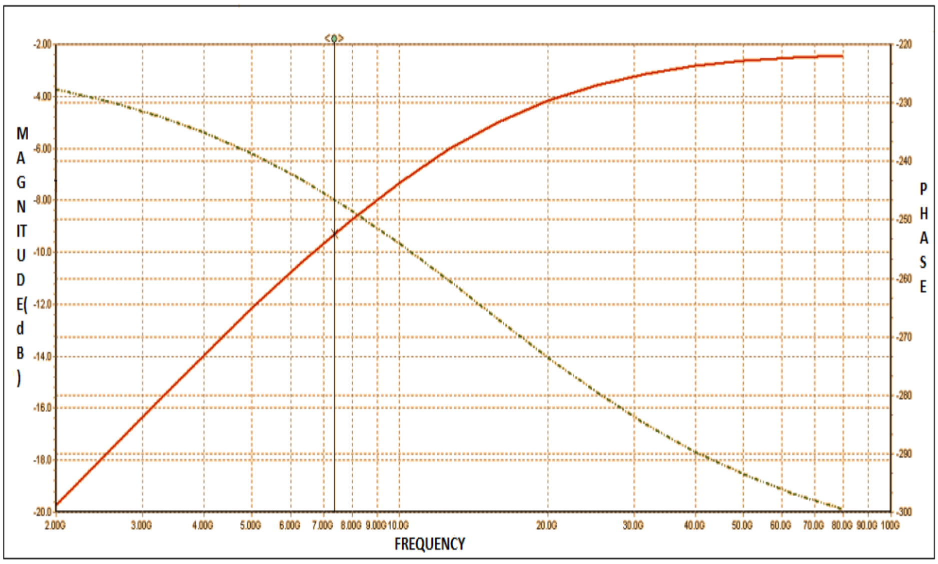


**Figure 4. Frequency response plots of return loss (S11) and phase of p-i-n switch**

The application of the device at high frequency requires higher breakdown voltage to handle high power. The WBG semiconductor (GaN) shows high breakdown voltage. The break down voltage of p-i-n switch is given by-

$$V_b = \int_0^W E(z)\,dz \qquad (9)$$

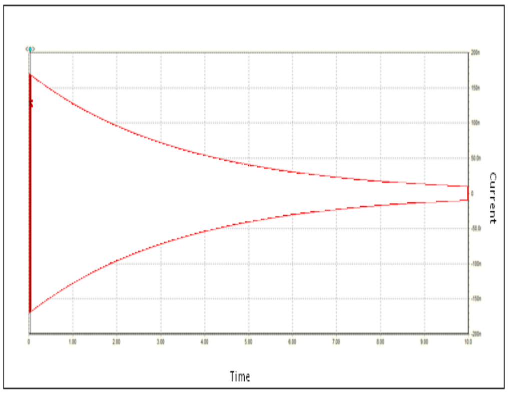


**Figure 5. Transit time analysis of p-i-n switch**

where *E (z)* is electric field constant and z represents the width of i region. *E (z)* is also constant in the depletion region and zero in the diffusion region. Using the Gauss's law the electric field is given by [7]-

$$E(z) = zN_i q/\varepsilon \qquad (10)$$

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Where ε is the relative permittivity of GaN and *Ni* represents the ionized donor atoms which distribute the charge in the lightly doped n region or i-region.

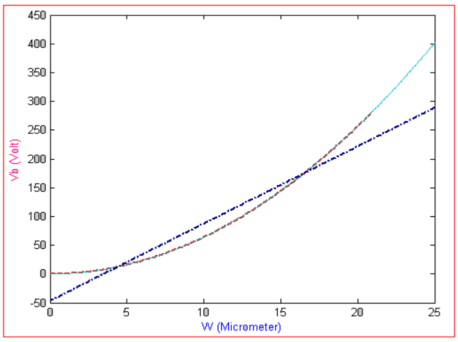


**Figure 6. Break down voltage for GaN p-i-n switch**

The transfer function is also used to measure the efficiency of RF switch. The i-region of p-i-n switch plays the key role in the development of RF switch.

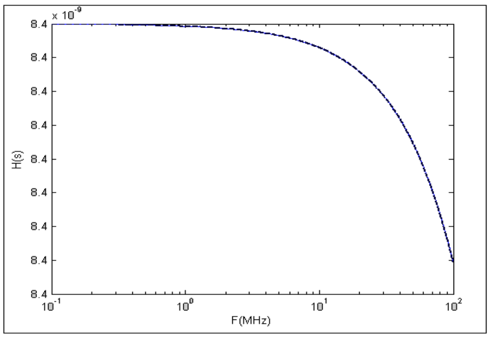


**Figure 7. Transfer function of GaN p-i-n diode**

The stored charge-current transfer function in the i-region can be written as -

$$H(s) = Q(s)/I(s) \qquad (11)$$

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$$I(s) = \frac{x_m}{L}\sqrt{1+s\tau}\,\frac{\tau}{1+s\tau}\coth\left[\frac{x_m}{L}\sqrt{1+s\tau}\right] \ldots (12)$$

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The location *($x_m$)* of the minimum stored charge in the i region can be expressed as-

$$x_m = W/2\left[1+\frac{2L}{W\sqrt{1+s\tau}}\tanh^{-1}\left(\frac{b-1}{b+1}\tanh\left(\frac{W\sqrt{1+s\tau}}{2L}\right)\right)\right] \ldots (13)$$

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Where *b* is defined as the ratio of electron to hole mobility *($\mu_n/\mu_p$)*.

Insertion losses *(IL)*, isolation *(ISO)* and return loss are also important parameter to analyze the performance of p-i-n switches. Insertion loss may be occurred when the switch is 'ON' where as isolation is referred when the switch is 'OFF' and the return loss is measured when RF signal reflects back from output port of the switch to the input port of the switch.

$$ISO = 10\log_{10}[1+(X_c/2Z_0)^2] \ldots\ldots\ldots\ldots (15)$$

The RF switch is connected in series SPST configuration to analyze its insertion loss, isolation and return loss. In series connected RF switches, the insertion loss and isolation are expressed as-

$$IL = 20\log_{10}[1+R_s/2Z_0] \ldots\ldots\ldots\ldots (14)$$

$$ISO = 10\log_{10}[1+(X_c/2Z_0)^2] \ldots\ldots\ldots\ldots (15)$$

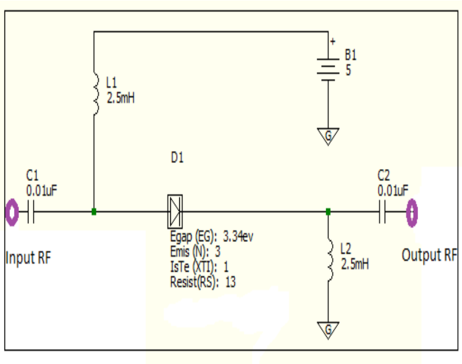


**Figure 8. Series connected SPST MMW switch at 2mA forward bias current**

In p-i-n switch, IL depends on series resistance where as ISO depends on junction capacitance and both of these depends on the characteristic impedance *(Zo)*.The return loss of the switch is taken by analyzing the S11 parameter of the RF switch.

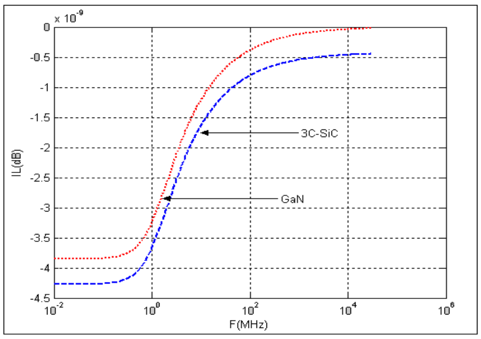


**Figure 9. Insertion loss of p-i-n diode at 2mA forward current for series connection**

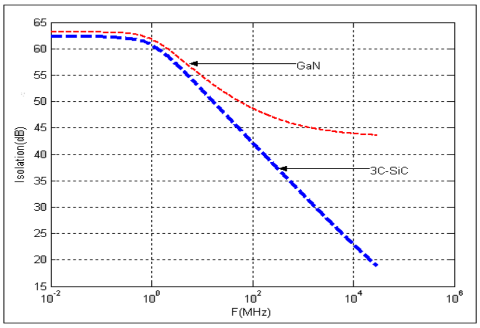


**Figure 10. Isolation of p-i-n diode at 2mA forward current for series connection**

## 3. RESULT AND ANALYSIS

The resistance and phase of p-i-n switch are estimated at 2mA forward bias current in fig.2 & fig.3. Here the analysis of resistance and phase are done using WBG semiconductor (GaN) which offers better application at higher frequencies and high RF power. To control the high RF power it requires high breakdown voltage of p-i-n switch. Fig.5 shows that GaN based p-i-n switch offer high breakdown voltage at 4 pm width of the i- region. The operating frequency of p-i-n switch also plays an important role to handle the high RF frequencies. This p-i-n switch puts forward high operating frequency which is determined with help of the transit time analysis (fig.4). The i- region stored charge transfer function and measured with the help of equations (11)-(13). Fig.5 shows that in the i- region, less charge is stored at low frequencies but stores more charge at high frequencies. The insertion loss of series connected GaN based SPST switch is less compared to another series connected 3C-SiC based SPST switch (fig.8). Isolation is also better for GaN p-i-n switch (fig.9) because of its high junction capacitance and return loss of this switch (fig.3) is also less compare to other radiofrequency switches.

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