Effect of substrate-epitaxy interface doping profile on the series resistance and mm wave performance of Si IMPATT diode

P De

Department of Physics, Gobardanga Hindu College, University of Calcutta, P O Khantura, 743 273

E-mail: pdeghc@yahoo.co.in

Received 26 August 2006; accepted 22 August 2007

The effect of abrupt and exponential type of doping profiles in the transition region of epitaxy-substrate interfaces (nn++ and pp++) on the parasitic resistance and mm wave properties of double drift region low-high-low (n++nn+npp+pp++) Si IMPATT diode suitable for 35 GHz window frequency have been simulated. The results show that the negligible width of the nn++ (0.016 μm) and pp++ (0.015 μm) substrate-epitaxy interface regions over the total depletion layer width of 2.0 μm with realistic exponential doping gradient rather than its hypothetical abrupt nature, severely degrade the maximum avalanche region breakdown field at the junction, negative resistance, negative conductance as well as the power conversion efficiency; in other way increasing simultaneously the value of drift region electric field, punch through condition and the series resistance of the diode.

Keywords: Substrate-epitaxy interface, Series resistance, IMPATT diode

1 Introduction

In recent years, design optimization of low-high-low (lhl) double drift region (DDR) mm wave IMPATTs are being carried out for improving the output power for both CW and pulsed mode of operations at 35 GHz window, as these devices play important role in guided missiles, missile tracking radar systems and short-range mm wave communications. The doping density, doping profile and the bias current1,2 play major role in determining the field profile, efficiency and series resistance of the diode. In most of the cases, the fabricated diode exhibited lower efficiency than its designed value and may suffer serious burnout problem. Also the nature of the actual electric field profile at breakdown and under oscillatory condition is not perfectly known. For the optimized structures, the doping level and thickness of the epitaxial layer are normally so chosen that the depletion layer edges at breakdown are situated near the epitaxy-substrate (nn++) interface to reduce the punch through and the parasitic series resistances contributed by any undepleted high resistivity epi-layer as shown in Fig. 1. The series resistance mainly determines the serious power losses in IMPATTs. The measurement of this crucial parameter in case of double drift high power Read like structure3 is significant. For this the author considered here lhl DDR structure yielding narrow avalanche region and uniform drift region.

The previous studies4-6 on the DDR lhl structures were mainly concentrated over the p-n junction depletion layer considering the abrupt nature of the substrate-epitaxy transition region doping profile (dotted line in Fig. 2). The doping profile at the nn++ and pp++ substrate-epitaxy interfaces are not abrupt

Fig.1 — Electric field distributions indicating (i) punch through condition, (ii) exact type and (iii) undepleted zone in the depletion region of IMPATT Diodes
for realistic fabrication (solid line in Fig. 2) and therefore, its gradient would give rise to a detrimental effect on the dc and RF properties. But investigations on the series resistance and negative resistance properties incorporating the exponential type of the substrate-epitaxy interface doping profile of mm wave IMPATT structures are not readily available in the published literatures.

Previous works\textsuperscript{7,8} in the mm wave range generally shows a punch through condition (as shown in Fig. 1) of the diode due to the requirement of narrow depletion width. Therefore, in the mm wave frequency band the effect of the substrate region exponential doping profile will be significant for the DDR structure having narrow depletion layer width, high doping level and subjected to a high bias current density. In that case, the high space charge effect and the high punch through condition may lead to an increase of series resistance of the diode\textsuperscript{9}. The present analysis indicates that the consideration of substrate-epitaxy region exponential doping profile degrade the dc and mm wave properties along with an increase in crucial series resistance of Si IMPATT diode.

2 Computer Analysis

In the computer analysis, one dimensional p-n junction diode equations (Poisson’s equation and the continuity equation) considering the mobile space charge effect have been solved satisfying appropriate boundary conditions using a double iterative computer method\textsuperscript{8}. Experimental values of the ionization rates\textsuperscript{10}, field dependent drift velocities and mobilities\textsuperscript{11} of the charge carriers have been used. The diode structure has been designed considering the electron and hole depletion layer width approximately by the equation\textsuperscript{12} $W_{n,p} = 0.37v_{sn,sp}$, where $v_{sn,sp}$ are the saturation drift velocities of the electron and hole, respectively. The lattice temperature under the operating condition of the diode\textsuperscript{13} has been considered to be 200°C. The current multiplication factors have been considered to be same for both the carriers\textsuperscript{12} and have been kept fixed at 10\textsuperscript{6} that correspond to negligible reverse saturation current. Realistic exponential doping functions\textsuperscript{13,14} at the p-n junction as well as those at $n^+n$ or $p^+p$ substrate-epitaxy interface regions are incorporated in this analysis and are shown in Fig. 2. The small signal admittance and the negative resistance values are simulated following the Gummel-Blue method\textsuperscript{7,15}. The value of series resistance has been estimated using formula of Adlerstein et al\textsuperscript{16-18}.

The distribution of the diffusion impurity density\textsuperscript{3,14} (solution of Fick’s diffusion equation) is given as:

$$N(x) = N_0 \left[ 1 - \frac{2}{\sqrt{\pi}} \int_{0}^{x} e^{-\lambda^2} d\lambda \right]$$

where $\lambda = \frac{x}{2\sqrt{Dt}}$

$N(x,t)$ is the density of the diffusion impurity, $x$ the distance counted from the surface into the bulk of the material, $t$ the time and $D$ is the diffusion constant of the impurities. For most of the practical purposes, the approximate formula\textsuperscript{14} of $N(x)$ is given by:

$$N(x) = N_o \left[ -(1.08\lambda + 0.78\lambda^2) \right]$$

Therefore, the distribution of the doping profile in the depletion region has been considered as follows:

For the $p$ side

$$N(x) = \begin{cases} N_A[\exp(-x/s)-1] & \text{for } 0<x<w_1 \\ N_{ahi} & \text{for } w_1<x<w_2 \\ N_{alo} & \text{for } w_2<x<w_p \\ N(x) = N_o[\exp(-1.08\lambda-0.78\lambda^2)] & \text{for } p^+p \text{ interface} \end{cases}$$

For the $n$ side

$$N(x) = \begin{cases} N_D[1-\exp(x/s)] & \text{for } 0<x<-w_1 \\ N_{ahi} & \text{for } -w_1<x<-w_2 \\ N_{alo} & \text{for } -w_2<x<-w_n \\ N(x) = N_o[\exp(-1.08\lambda-0.78\lambda^2)] & \text{for } n^+n \text{ interface} \end{cases}$$
The width of the different doping levels and doping densities are presented in Table 1. The required doping level is less in case of exponential type of the substrate-epitaxy interface doping profile, compared to its abrupt type for the same operating frequency (Table 1).

### 3 Results and Discussion

The dc electric field profiles of Si lhl DDR structures are shown in Fig. 3. Where, the dotted curve represents the field profile with the effect of abrupt type of doping profile in the substrate-epitaxy interface region, while the solid curve is due to the account of very thin exponential type of doping profile in the same region. The solid curve indicates that the maximum field at the avalanche center decreases and the drift region field increases due to the exponential nature of doping profile of the \( n^{+}n \) and \( pp^{+}p \) interfaces. It is also clear that the field value at the \( nn^{++}n \) and \( pp^{++}p \) substrate-epitaxy interfaces increases with the above effect, indicating higher punch through condition of the IMPATT diode which may lead to higher reverse saturation current.

The field profile and the avalanche region voltage drop give good indications about lhl diode. The avalanche and the drift region voltages are \( V_A \) and \( V_D \), respectively and are presented in Table 2. The results show that the ratio of the \( V_A \) to \( V_D \) increases remarkably from 1.21 to 3.16 due to the exponential type of the substrate-epitaxy region doping profile. As a result, the power conversion efficiency (\( \eta \)) estimated from the Scherfetter and Gummel formula increases drastically from 14.4 to 7.62 due to this effect.

The negative resistivity profiles in the depletion region shown in Fig. 4, are good indicators about the contribution of its drift and avalanche layer. Where the solid curve is the result of exponential type and the dotted curve is as a result of abrupt nature of substrate-epitaxy interface doping profile of the spatial variation of resistivity in the depletion region. The profiles have been computed at the same current density \( 2 \times 10^7 \text{ A.m}^{-2} \) at the corresponding optimum frequencies of 34 and 32 GHz, respectively as presented in Table 3. The negative resistance value mostly arises from the drift region, and a remarkable deviation occurs in the drift region. The peak value of negative resistance is higher on the \( n \) side than on the \( p \) side, because the electron ionization rate is higher.
Table 3 — Small signal properties of Si LHL DDR IMPATTs at 35 GHz window
Considering substrate-epitaxial doping profile

<table>
<thead>
<tr>
<th></th>
<th>Abrupt</th>
<th></th>
<th>Exponential</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( f_p )</td>
<td>(-G_p)</td>
<td>( B_p)</td>
<td>((-R_p))</td>
</tr>
<tr>
<td>GHz</td>
<td></td>
<td>(10^5) (\Omega) (\text{m}^{-2})</td>
<td>(10^3) (\Omega) (\text{m}^{-2})</td>
<td>(\Omega)</td>
</tr>
<tr>
<td>32</td>
<td>15.05</td>
<td>86.4</td>
<td>1.0</td>
<td>0.07</td>
</tr>
</tbody>
</table>

than that of hole in Si. From the conductance versus susceptibility plots (G-B plots) as shown in Fig. 5, it indicates that the exponential realistic substrate-epitaxy interface region doping profile decreases the value of the maximum negative conductance but increases the corresponding center frequency \( (f_p) \). This is due to the high field value of the drift region as a result of exponential type substrate-epitaxy interface region doping gradient.

The values of \((f_p)\), corresponding maximum negative conductance \((G_p)\), susceptance \((B_p)\), negative resistance \((R)\) and the values of series resistances \((R_s)\) are presented in Table 3. The value of \(f_p\) increases from 32 to 34 GHz; the value of \(R\) decreases from -1.0 to -0.6 \(\Omega\); the value of \(G_p\) decreases from \(-15.05\times10^5\) to \(-11.41\times10^5\) \(\text{mho.m}^{-2}\) and the value of \(B_p\) increases from \(86.4\times10^5\) to \(97.25\times10^5\) \(\text{mho.m}^{-2}\).

As a result, the increase in the value of series resistance is from 0.07 to 0.1 \(\Omega\) due to a change from abrupt to exponential type of doping profile in the substrate-epitaxy interface region.

4 Conclusion

The present simulation indicates that the incorporation of an exponential and realistic doping profile rather than its abrupt type in the substrate-epitaxy interface region gives rise to an increase in series resistance also with overall degradation in the dc and mm wave performance of IMPATT device. Thus the present analysis may be applied to explain the low power availability from IMPATTs compared to its designed value as well as to explain its serious burnout problem. Thus, the investigations carry some significance as a precautionary step for the design optimization of high power IMPATT diode structure.

Acknowledgement

The author acknowledges University Grants Commission, New Delhi, for Post-Doctoral Research Award and financial support.
References
10 Grant W N, *Solid State Electronics*, 16 (1973) 1189.