

Optimized Ion Implantation Profiles for the p-n Junction Using Forth Moment Approach for Application in High Frequency VLSI Circuits

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ABSTRACT

The ion implantation based impurity doping profile across a p-n junction can be represented accurately using Pearson's fourth moment approach. The high-frequency characteristics of the reverse biased p-n junction (IMPATT diodes) are computed using different ion implantation profiles. It has been observed that the microwave properties of IMPATT diodes are very sensitive to the change in doping profiles. The optimized ion implantation profiles are suggested for different frequency bands to fabricate the reverse biased p-n junction for application in high-frequency circuits.

Keywords: \mathcal{H}_∞ control, Time-varying delay, Fuzzy systems, Linear Matrix Inequality (LMI).

1. INTRODUCTION

Ion Implantation is an important and effective technology for the fabrication of modern advanced electronic and optical devices. A highly energetic beam of the desired ion is made to strike and penetrate into the target (silicon) wafer to cast a well-defined p-n junction, having an appropriate doping profile. Many experimental reports are available on the fabrication of ion-implanted silicon p-n junction [1-3] as well as MOS devices. Despite the rapid advancement of p-n junction (mainly IMPATT - IMPact Avalanche Transit Time devices) modeling in the recent years, some fundamental problems, viz., profile studies are not adequately undertaken, though they appear important in fabrication of semiconductor devices. Many authors assume it as an exponential at the junction, which does not match exactly with the

experimental profiles [e.g. 4, 5]. The exponential profile is close to the profile obtained from diffusion technology [6]. However, the profile obtained from ion implantation technology deviates much more from the generally assumed exponential profile. The authors have determined the exact profile and have studied the characteristics of IMPATT devices using diffusion technology under limited source and infinite source [e.g. 6]. The results show that the device characteristics vary a lot with the change in fabrication parameters. Similarly, the authors have attempted for ion implantation profiles studies for IMPATT devices in their earlier work [7, 8] using an approximated two moments Gaussian distribution (third moment approach) which failed to incorporate the large tailing characteristics and as a result was not suitable to obtain the proper profile in IMPATT devices. This can be accurately represented only by using a fourth moment approach [9]. Therefore, the analyses reported so far for ion implantation profiles appear to be inadequate for characterization of reverse biased p-n junctions which can be used in VLSI devices for the fabrication of high frequency oscillators and fast operating switches. The model thus used here is an attempt to overcome the inadequacy of our earlier model by considering the profile shape factors which account for the exponential tail at the end and broadening at the top of the profile. The implantation profile can be approximated as Pearson's distribution with four-moment approach, which exactly fits with experimental data [9]. Thus, the objective of this report is to generate and optimize ion-implanted double drift p-n junction profiles to realize optimum RF power and efficiency at high frequency for use in VLSI Circuits. It is also well known that diodes with ion implantation profiles generate more noise [3]. In addition impact ionization itself is the main source of noise in IMPATT diodes [10]. Noise generation and its impact on IMPATT diode performance is therefore one of the vital area of study for ion implanted p-n junctions to determine its full device potential as signal generator. The main focus of this study will therefore be the optimization of ion implantation profile which will not only provide maximum power and efficiency but will generate less noise. However, it is difficult to achieve both at the same time. Thus a noise-power

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trade-off is needed for different ion implantation profiles. It is to be noted here that our earlier work had not taken into account the noise-power trade off study which plays an important role in determining the potential of device characteristics. The results of such study along with optimized ion implantation parameters for different frequency bands are presented in this paper.

2. METHOD

The n^+npp^+ Double Drift Region (DDR) device can be fabricated by implantation of boron ions into an n^+n substrate, or by implanting antimony or phosphorus ions into a p^+p substrate. Since n^+n substrates with any specific doping value are easily available, the authors have considered only boron implantation into n^+n wafer. A silicon crystal can be driven amorphously to a depth of about $0.6\mu\text{m}$ by bombarding it at room temperature with $10^{16}\text{Si}^+ \text{ ions}/\text{m}^2$ at an energy of 300 keV [11]. If a conventional silicon doping species, such as boron or antimony is then implanted into the amorphous layer, and the sample is suitably annealed, an impurity distribution that is asymmetrical would result [11]. The conventional annealing technique would substantially modify the implanted profile through diffusion. Thus we suggest the use of flash lamp annealing technique for a very short period to keep the change in profile negligible. This profile was earlier approximated as the combination of two half Gaussian distributions that join at a modal projected range (which is usually called the third moment approach) [7, 8]. However, this approximation can not generate the tail region of the profile that is obtained from the experimental results. Using fourth moment approach i.e using Pearson's distribution formula however, the exact doping profile matching with the experimental results can be obtained [9]. Hence the authors have used the Pearson's fourth moment approach to determine the ion implantation doping profile for different values of energy and dose. An expression for the boron implanted profile using Pearson's fourth moment approach can be written as [9]

$$\ln \left(\frac{f(x-R_p)}{f_0} \right) = \frac{1}{2b_2} \ln \{ b_0 + b_1(x-R_p) + b_2(x-R_p)^2 \} - \frac{\frac{b_1}{b_2} + 2b_1}{\sqrt{(4b_0b_2 - b_1^2)}} \tan^{-1} \left(\frac{2b_2(x-R_p) + b_1}{\sqrt{(4b_0b_2 - b_1^2)}} \right)$$

Where a, b_0, b_1, b_2 , and A are constants based on four moments of Pearson profile,

$$\begin{aligned} a &= -\gamma\sigma_p(\beta+3)/A \\ b_0 &= -\sigma_p^2(4\beta-3\gamma^2)/A \\ b_1 &= a \\ b_2 &= -(2\beta-3\gamma^2-6)/A \\ A &= 10\beta-12\gamma^2-18 \end{aligned}$$

$f(x-R_p), f_0$ along with ion implanted dose (ϕ) gives the distribution of implanted dopant concentration $N(x)$ for particular implanted energy (E) and dose (ϕ) [9]. R_p, σ_p, γ , and β are projected range,

standard deviation, skewness and kurtosis respectively. The values of R_p, σ_p, γ , and β are taken from Ref. [9] which agree with the experimental values for the energy range considered here. Since p-type dopants are implanted into n-type substrate, the net doping at any point is given by $N_e(x) = |N_D - N(x)|$, which is determined from the computer program (N_D is the concentration of n-type dopants). The point where $N_D = N(x)$ is also determined and is designated as the junction point. The regions of p-side and n-side beyond the required width can then be lapped out. In order to generate a given profile, the authors have used double doses successive ion implantation. We have used two different energy and dose values to make the p-side to be reasonably flat, so that a good device performance could be obtained. Sets of different values of energy and dose have been used to generate different shapes of the ion implantation profiles. It may be noted here that the junction points are different for different energy combinations. However, the locations of junctions are shown at the same point in figure 1 to make it convenient for numerical analysis of the diode. These generated profiles are then used as input in a separate program [6, 12] to determine the device characteristics such as breakdown voltage (V_B), drift region voltage drop (V_D) and device efficiency ($\eta = V_D/\Pi V_B$). The high frequency analysis of the p-n junction under reverse biased conditions is carried out by solving the device A.C. equations on diode resistance (R) and diode reactance (X) following a modified Runge Kutta method [6, 12]. The high frequency properties, e.g. diode negative resistance ($-Z_R$), optimum frequency (f_p) corresponding to peak diode negative conductance ($-G_p$), quality factor ($Q = |B/G|$) and band width (BW - showing the frequency range for negative conductance), are also determined from the high frequency analysis. The details of the simulation procedure are described earlier in Ref. [12]. Then using the procedure described in Ref. [13], the RF power generated from the device was computed from the diode negative conductance for a known area of the diode. The accuracy of predicting diode characteristics was enhanced by considering the presence of diffusion and tunneling currents [14]. The model considers the latest reported values of material parameters and their realistic variations with electric field and temperature which are presented in Ref. [15].

As mentioned earlier we have also addressed the noise study of the ion-implanted diodes in this paper which, to the author's knowledge, is the first report of such study. The high-frequency noise theory [10, 15] developed earlier for this type of study was used for this purpose. The most important parameter for noise analysis is the noise-measure (NM) [10]. The simulation scheme used here [15] is capable of estimating the same. The authenticity of the model developed has been tested earlier by compar-

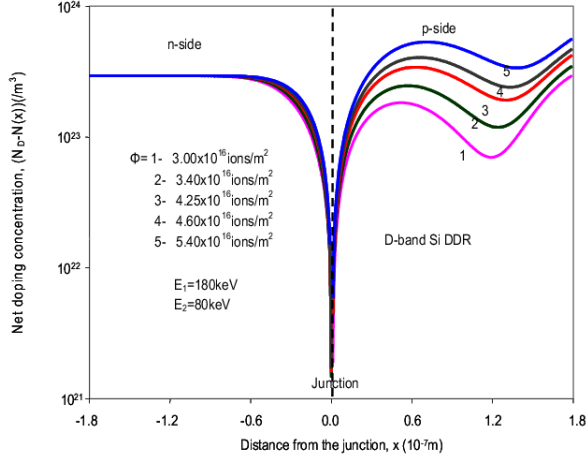


Fig.1: Doping profiles for different doses for a particular combination of energy values

ing with experimental results [10, 12, 15, 16]. This model proves to be useful for computer simulation and CAD from the viewpoint of device design and fabrication and therefore, can be useful to the VLSI technologists as the first hand tool for the fabrication purpose. Important results obtained from these studies are presented in the next section. All the results and figures are drawn by taking realistic variations of drift velocities with electric field, realistic variation of ionization rates in Si with electric field at 200°C [16]. The carrier diffusion constants in Si have been taken from experimental data which is mentioned in [16].

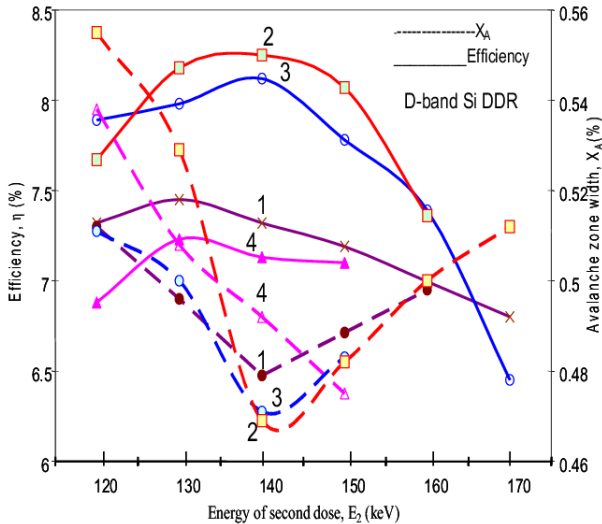


Fig.2: Efficiency (η) and Avalanche Zone Width (X_A) versus energy of the second dose (E_2) for $E_1 = 160 \text{ keV}$ at D-band. The curves are 1. $\phi = 4.6 \times 10^{16} \text{ ions/m}^2$, 2. $\phi = 4.8 \times 10^{16} \text{ ions/m}^2$, 3. $\phi = 5.0 \times 10^{16} \text{ ions/m}^2$, 4. $\phi = 5.2 \times 10^{16} \text{ ions/m}^2$

Table 1: Optimized design parameters for different bands

Frequency band	W_n (nm)	W_p (nm)	N_p (10^{23} m^{-3})	J_0 (10^8 A/m^2)
W	300	300	1.75	3.5
D	180	180	2.95	7.0
G	140	140	4.70	10.0

3. RESULTS

The structural and operating parameters of the D-band diode considered in this paper are chosen as follows. An n^+n wafer of doping density is assumed. The n- and p-side widths (W_n and W_p respectively) are calculated following an approximate design criterion and are found to be 180 nm each. The operating current density (J_0) appropriate for D-band operation is taken as $7 \times 10^8 \text{ A/m}^2$. To realize the doping profile of the required dimension, first, an approximate value of the energy of the first dose (E_1) is chosen, keeping in mind the width requirement. Then, with a fixed value of energy (E_1), the energy of the second dose (E_2) and the dose amount (ϕ) are varied for a range of values. Further, for each set of energy E_1 and E_2 , the ion dose (kept same for both the energy values) is varied for a range of values and the device properties are computed in each case. The technique is then repeated for other frequency bands. For different frequency bands, different range of energy and ion dose are chosen, keeping in mind the width and net doping concentration requirement of the diode to operate in a given frequency band (table 1).

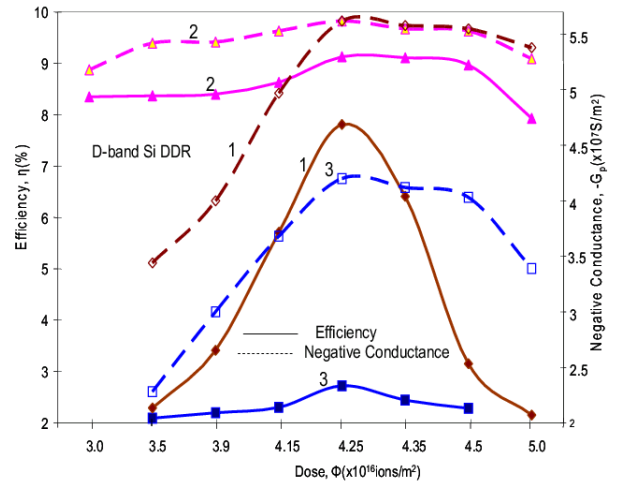


Fig.3: Efficiency (η) and Peak Negative Conductance ($-G_p$) versus dose (ϕ) for different values of E_2 and a fixed value of E_1 . The curves are 1. $E_1 = 180 \text{ keV}$ and $E_2 = 70 \text{ keV}$, 2. $E_1 = 180 \text{ keV}$ and $E_2 = 80 \text{ keV}$, 3. $E_1 = 180 \text{ keV}$ and $E_2 = 90 \text{ keV}$

The net doping concentration profiles obtained

from the D-band structure is presented in figure 1. The energy combination in this case is 180 keV and 80 keV. The different profiles were obtained by varying the ion dose from $3.0 \times 10^{16} \text{ ions/m}^2$ to $5.4 \times 10^{16} \text{ ions/m}^2$. These profiles are used as the input in our simulation program to compute different electrical properties of the device. From figure 1, it is seen that, with variation of ion dose (ϕ), the profile on p-side shows a considerable change whereas the same on the n-side records only a marginal variation increasing to a flat value quickly as one moves away from the junction. A flat doping profile has better device properties and hence we have tried to make the p-side as flat as possible. But from ion implanted p-n junction at such dimension, we see that flat doping profile can never be achieved in contrast to the earlier assumptions by many researchers. Nevertheless, the doping profile on p-side whose average value is close to the flat value on n-side is expected to give better results.

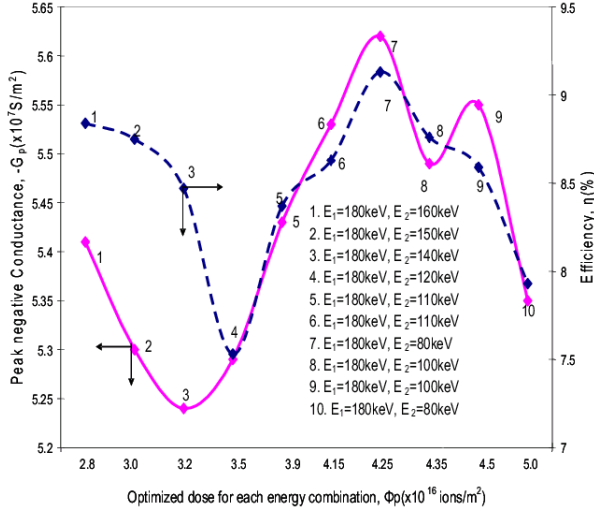


Fig.4: Variation of peak negative conductance and efficiency with optimized dose for different set of energy values at their optimum

Figure 2 shows the variation of efficiency and avalanche zone width for different values of dose (ϕ) and energy of the second dose (E_2) for a fixed value of energy E_1 . The figure shows that the efficiency first increases with increase in E_2 , attains a maximum value, and thereafter it decreases with increase in E_2 . The opposite trend is observed in case of avalanche zone width. Thus we observe that the efficiency maximizes and the avalanche zone width minimizes for a given set of values for E_2 and ϕ , which for the chosen E_1 (160 keV) are $E_2 = 140 \text{ keV}$ and $\phi = 4.8 \times 10^{16} \text{ ions/m}^2$. The values of E_2 and ϕ which optimize the device properties however change with change in E_1 as can be seen from figure 3. This figure shows the variations of device efficiency and peak device negative conductance as a function of ion dose ϕ , with E_2

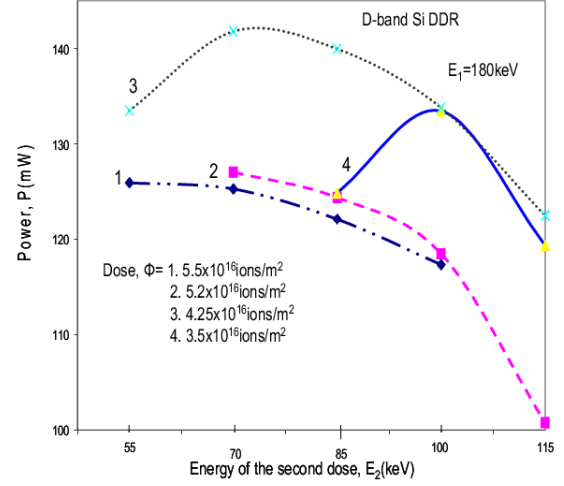


Fig.5: Power generated at different values of doses and energy of the second dose at a fixed value of energy E_1

Table 2: Suggested optimized ion-implantation parameters for different frequency bands

Frequency band	$E_1(\text{keV})$	$E_2(\text{keV})$	$\phi(\text{ions/m}^2)$
W	200	110	1.3
D	180	80	4.25
G	160	60	10.0

as a parameter for a fixed E_1 of 180 keV. From the figure it is clearly observed that the efficiency and the peak device negative conductance maximize for a different combination of E_2 and ϕ compared to the case of $E_1 = 160 \text{ keV}$. Several such optimum set of values for E_2 and ϕ are obtained by varying E_1 and the results are plotted in figure 4 which shows the final optimum combination parameters for D-band of operation. More power generation is an important factor in IMPATT devices. The power generated from such type of structures is hence computed and some of the results are presented in figure 5. Figure 5 also shows the existence of an optimized structure which generates maximum power compared to other structures. From all such study the optimized ion implantation parameters for the D-band are observed to be (respectively for E_1 , E_2 and ϕ) 180 keV, 80 keV and $4.25 \times 10^{16} \text{ ions/m}^2$ in contrast to our previous observation of 100 keV, 76 keV and $10.0 \times 10^{16} \text{ ions/m}^2$ [7]. There is a considerable variation in the values which thus signifies the importance of this study.

As mentioned earlier noise study forms an integral part of IMPATT device analysis. The appropriate quantity to assess the performance of the diode is the noise-measure [11]. Figure 6 shows the variation of the noise-measure with energy of the second dose at the design frequency for a fixed value of E_1 . It is seen that, for all the cases of dose values considered, the noise-measure decreases when the energy of the

second dose increases, attains a minimum and then increases with further increase in the dose energy. It is interesting to observe that the lowest minimum of noise measure corresponds to our earlier optimized dose and energy parameters. Thus we expect that these parameters may prove to be beneficial for the fabrication of double drift diodes based on boron impurities implantation into n^+n Si wafers. The study has been repeated for other bands and the results for W, D and G bands are presented in table 2.

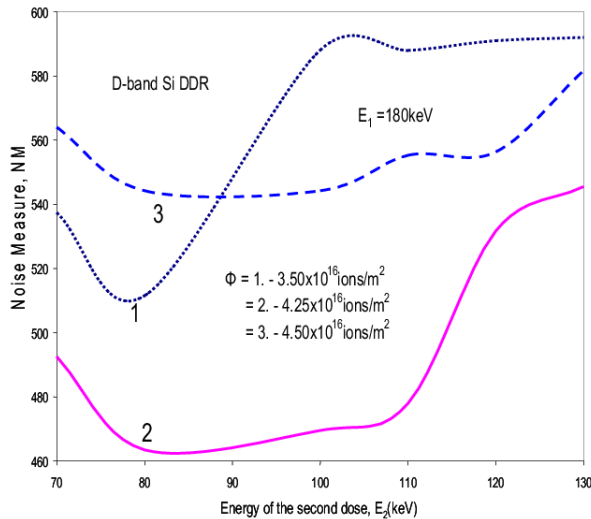


Fig.6: Noise Measure at design frequency for different ion implantation parameters

The optimization of ion-implantation parameters can be explained from doping profiles (figure 1) and electric field profiles (figure 7). From figure 1, it can be seen that for very low values of the ion dose, the doping profile on the p-side shows sharp troughs and crests, which gradually flattens with increase in dose value. However, for very large value of ion dose, the average doping value on the p-side becomes much larger than that on the n-side. For a particular value of ion dose, the doping profile on the p-side becomes relatively flat (curve 3 in figure 1) and possesses an average value nearly equal to that on the n-side. Such a profile is thus expected to give better microwave performance. This is because the stiff rise in doping profile on the p-side for high values of ϕ would lead to a sharp reverse field gradient within the depletion zone. This would leave a sizeable length of undepleted p-zone, as the electric field value would fall to zero at a shorter distance from the junction. Similarly, for very low values of ion dose, the doping profile is observed to have deeper troughs. This would reduce the field gradient causing substantial amount of punch-through field at the end of the p-side depletion layer. This has been reflected in figure 7. The undepleted portion of active layer would provide positive series resistance [17] for high values of ϕ , and the punch through field profile with a knee would cause

an extended avalanche region for low values of ϕ . In both these cases, the device properties would show degraded microwave performance.

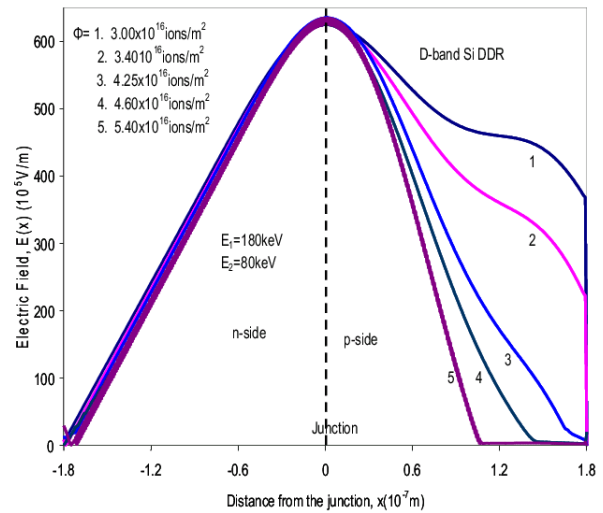


Fig.7: Electric field profiles for D-band SiDDR for different values of doses

4. CONCLUSION

A method to realize ion-implantation impurity profiles using fourth moment approach for a p-n junction and to use it as an IMPATT diode has been developed. The microwave as well as noise properties of different structures were studied extensively. The existence of an optimum set of ion implantation parameters is observed. The optimized parameters for a D-band Silicon diode are observed to be $E_1 = 180 \text{ keV}$, $E_2 = 80 \text{ keV}$, and $\phi = 4.25 \times 10^{16} \text{ ions/m}^2$. The results may prove to be useful for the fabrication of silicon double drift region (DDR) diode.

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