dian J. Phys. **76A** (1), 65-68 (2002)

IJP A
an international journal

RF negative resistance and avalanche noise generation distributions along depletion zones of GaAs, InP, GaInAs and GaInAsP DDDs

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bstract : The RF negative resistance distribution and the avalanche noise generation profile have been computed for GaAs, InP, GaInAs and aInAsP double drift IMPATT diodes This gives the intensity of RF oscillation and noise generation within the individual space step of the depletion e of different diodes. A double peak nature of the negative resistance profile with peaks in the drift zones and near uniform noise generation within e avalanche zone have been obtained The GaInAs diode is expected to provide good RF performance due to its high value of diode negative resistance d low mean squared noise voltage

eywords Double drift diodes (DDD), IMPATT, avalanche noise

ACS Nos. 84 40.-x, 07 57 -c

. Introduction

he IMPATT (IMPact Ionization and Avalanche Transit Time) iodes are basically reverse biased *p-n* junctions, that operates nder avalanche breakdown condition leading to the generation f high frequency negative resistance in the microwave frequency inge The frequency of operation as well as the output power btained from the IMPATT devices have established these evices as the premier microwave and mm-wave devices. A ulsed power of 42 W at 96 GHz, 520mW at 217 GHz and a CW ower of 980mW at 100 GHz and 50 mW at 220 GHz are some of e milestone in the performance of IMPATT devices [1-3]. The dded favourable feature of IMPATT diode is that this devices an be fabricated from any base semiconductors which include inary, ternary and quaternary compounds. The widely different roperties of different semiconductors would result in widely ifferent values of ionization rates of carriers which in turn, vary e multiplication process along the depletion zone of diode ith different base materials. The authors have studied the nization processes of several semiconductors like GaAs, InP, aInAs and GaInAsP. The ionization process in a semiconductor etermines the amount of RF negative resistance generation nd the strength of avalanche noise source at a particular space oint of the depletion zone of the *p-n* junction, which can be used to compute the intensity of RF oscillations and amount of avalanche noise contribution from the referred space step.

Several types of *p-n* junction diode structures can operate to give RF oscillations at microwave frequencies. The conventional diode structures include flat profile single drift (SDD) having two structural forms n^+pp^+ and n^+np^+ and a double drift diode (DDD) with the structure n^+npp^+. The single drift diode has one avalanche zone and one drift zone in the low doped region. The DDD has two drift regions, one in *n*-region for drift of electrons and the other in *p*-region for drift of holes. Since both the charges undergo drift in respective *n/p* region, each of them contribute to RF power contrary to contribution from only one type of charge carrier in SDD. This fact leaves the DDD as one of the suitable premier structure which can provide higher efficiency and higher output power compared to those for SDD. The authors have considered double drift diode structure with the same base semiconductors as mentioned above.

2. Method

The one dimensional model of n^+npp^+ IMPATT double drift diode structure has been considered for the analysis. At first all the diode structures based on the above mentioned semiconductor materials are optimized to operate at an operating frequency of 60 GHz following a computer method for DC and

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high frequency analysis of the diode. The DC analysis was carried out by simultaneously solving the Poison's equation, carrier continuity equation and space charge equation for reversed bias p-n junction under avalanche breakdown condition by a double iterative computer method [4]. The values of electric field maximum near the junction and its location have been taken as parameters for iteration of the double iterative computer program framed for DC analysis. The device equations have been solved numerically with very small space step width and the iterations have been carried out till usual boundary conditions [4] are satisfied at the edges of the depletion zone. Each of the DDD has been optimized first for determining the optimized structural and operating parameters through several computer runs leading to realization of high value of device efficiency and localization of avalanche zone The boundaries of the depletion layer and of the avalanche zone/ drift zone are determined accurately from the final solution of the above said simulation program. The data from this analysis are taken as inputs for the high frequency analysis of the diode under small signal condition by solving second order device equations of R (device resistance) and X (device susceptance) through use of another double iterative numerical method which gives the microwave properties of the double drift diode (DDD) [5, 6]. This double iterative computer program involves iteration over the values of R and X at the left edge till the boundary conditions are satisfied at the right edge. The high frequency analysis gives the band width within which the diode can generate microwave negative resistance which leads to the generation of microwave oscillations and the optimum frequency (f_p) at which the diode conductance passes through the peak negative value. The ratio of RF voltage and the RF current ($\tilde{v}/\tilde{i}$) in every space step can be determined from the analysis which gives negative resistance generated within the particular space step The solution of high frequency analysis also gives the microwave negative resistance profile along the depletion zone of the diode.

The random multiplication of charge carriers in the avalanche process leads to the generation of avalanche noise along the depletion zone of the diode So the noise analysis of the diode has been considered in this study. Taking the DC data as input and considering the noise source at one space step at a time, the noise analysis has been performed, initiated from the left edge of the depletion zone of the diode. In the analysis the ac carrier continuity equation, the Poisson's equation and the current density equation are used to obtain two second order differential equations on the real and imaginary part of the noise electric field $e_R(x, x')$ and $e_X(x, x')$ [7] The equations are

$$D^2 e_R + (\alpha_n - \alpha_p)\, De_R - (2r_\_\, \omega/\bar{v})\, De_X +$$

$$\left\{(\omega^2/v^2) - H\right\} e_R - (2\alpha\omega/v)\, e_X$$

$$= 2r^+ q\gamma(x')/\bar{v}\varepsilon, \qquad \text{when } x = x'$$

$$= 0, \qquad \text{when } x \neq x'. \qquad (1)$$

$$D^2 e_X + (\alpha_n - \alpha_p)\, De_X - (2r_\_\, \omega/\bar{v})\, De_R +$$

$$\left\{(\omega^2/v^2) - H\right\} e_X + (2\alpha\omega/\bar{v})\, e_R = 0 \qquad ($$

with

$$H(x) = \left(2J_0/\bar{v}\varepsilon\right)\left(\delta\bar{a}/\delta E\right) + (\delta/\delta E)\,(a_p - a_n)\, D\, E_m$$

where the quantities $\bar{v}, \bar{a}, r_\_, r^+$ and D are defined as

$$v = (v_{sn} . v_{sp})^{1/2}, \quad \bar{a} = (a_n v_{sn} + a_p v_{sp})/2v,$$

$$r^+ = (v_{sn} + v_{sp})/2\bar{v}, \quad r_\_ = (v_{sn} - v_{sp})/2\bar{v}$$

and $D = \delta/\delta x$.

[Here, a_n (a_p) is the ionization rate of electron (hole), ω is angular frequency, v is the carrier velocity, v_{sn} (v_{sp}) is saturated drift velocity of electron (hole)].

It can be noted that $e_R(x, x')$ gives the noise field a when the noise source is located at x'. The eq. (1) and (2) on and e_X are solved simultaneously by the third double iterati algorithm subject to taking the proper boundary conditions [The boundary conditions are given as

$$\left\{(\delta e_R/\delta x) - (\omega/v_p)\, e_X\right\} = 0 \text{ and}$$

$$\left\{(\delta e_X/\delta x) + (\omega/v_p)\, e_R\right\} = 0 \text{ at the } p\text{-side of}$$

boundary $x = x_R$.

$$\left\{(\delta e_R/\delta x) + (\omega/v_n)\, e_X\right\} = 0 \text{ and}$$

$$\left\{(\delta e_X/\delta x) - (\omega/v_n)\, e_R\right\} = 0 \text{ at the } n\text{-side of}$$

boundary $x = x_L$

In this computer program, double iterations are carried on initial choice of e_R and e_X at the left edge till boundary conditi on right hand side is satisfied. The final solution gives the prof of the noise field (e_R and e_X). The integrated values of e_R and over the entire depletion region gives the terminal noise volt $V_R(x, x')$ and $V_X(x, x')$ due to noise source at x'. The profi of V_R and V_X can also be found out from this solution. Tak the injected current at x' as equal to $q.\gamma(x').A.dx'$, q bei the charge, A being the area of cross section of the device a γ being the strength of the noise source), the diode trans impedance and subsequently the mean squared noise volta $<V^2>/df$ have been calculated [7]. The method has be made accurate and realistic by considering the realistic impur profiles across the junction and by considering the realis variation of carrier ionization rates and drift velocities of differe semiconductor under consideration. The material parameters different semiconductors have been taken from the experimen orts. The authors have also obtained the RF negative istance distribution profile by determining $\tilde{e}/\tilde{i}$ at each lividual space step when the conditions for final solution of uble iterative computer method have been fulfilled at the imum frequency of operation. Similarly the noise distribution file could be computed by determining the $e_R \sim x$ profile en the noise source element has been located at any space p(x'). These distribution profiles while giving the integrated and noise parameters, can also give an in-depth derstanding regarding the device operation of different niconductor based *p-n* junction.

Results and discussion

uble drift n^+npp^+ diode structures have been optimized for eration in *V*-band with optimum frequency of operation around GHz. The optimization has been carried out through several mputer runs. The punch through factor (PTF) value, the ation of field maximum, and the location of peak of the negative istance profile are taken as guiding parameters for optimization ocess. A diode is optimized if the PTF value remains around , the field maximum is located closer to the junction and the gative resistance peak remains near the centre of the drift ne The diodes have been analysed by taking GaAs, InP, lInAs and GaInAsP as the base materials and the mm- wave well as noise properties of the diodes have been computed llowing the method as outlined above. The optimized design ameters of the semiconductors have been given in Table 1 d some of the microwave and noise characteristics like values peak diode negative resistance ($-Z_{Rp}$), peak negative nductance ($-G_p$), optimum operating frequency (f_p) and peak an squared noise voltage $<V^2>/df$ are given in the Table-2.

ble 1. Optimised design parameters of IMPATT diodes of different terials for *V*-Band Operation (60 GHz), current density $J = 1\ 0 \times 10^8$ A/

Materials	GaAs	InP	GaInAs	GaInAsP
Width (nm)				
n side	700	520	580	680
p-side	700	520	580	680
Doping (10^{22}/m^3)				
n-side	5 0	8 4	4 0	5 9
p-side	4.8	8 4	4 0	5 9

ble 2. Microwave and noise characteristics of diodes of different terials at optimum operating frequency 60 GHz.

terial	Peak Negative conductance ($-G_p$) (10^6 S/m^2)	Total negative resistance ($-Z_{Rp}$) ($10^{-9}\Omega$m^2)	Mean Squared noise voltage $<V^2>/df$ (10^{-15} v^2 s)
As	8.73	16 1	1.75
P	9.01	9.9	2.03
InAs	13.4	16.5	0 46
lnAsP	8.43	14.3	3.49

The negatic resistance distribution profile and the avalanche noise generation profile for GaInAs and InP DDDs have been shown in Figure-1 and Figure-2 respectively. The variation of $-Z_{Rp}$ and $<V^2>/df>$ with frequency for the GaInAs diode are shown in Figure-3.

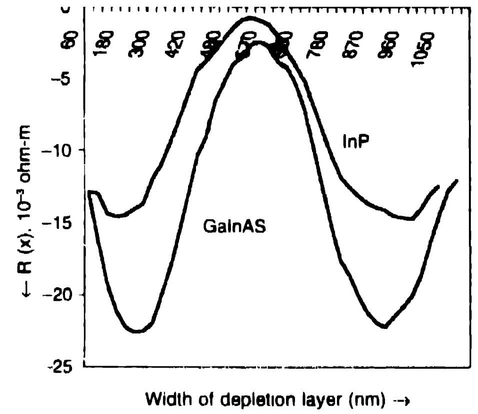

Figure 1. Plot of negative resistance distribution profile, $R(x) \sim x$ of GaInAs and InP diode at operating frequency 60 GHz

It can be seen from Figure-1 that the negative resistance distribution profile has a double-peak nature (in negative scale) with the peaks located in the center of the drift zone. The diode negative resistance is mostly generated in drift region as the total phase delay (transit time delay + avalanche phase delay) attains value between $\pi/2$ to $3\pi/2$.

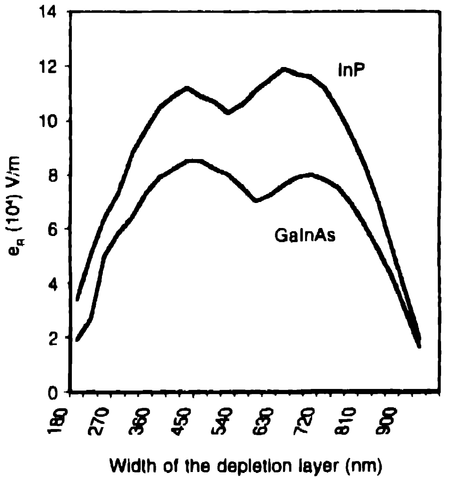

Figure 2. Variation of real part of the noise field with width of depletion layer (noise source at field maximum) of GaInAs and InP diode at operating frequency 60 GHz

The negative resistance peaks are located at space point where the total phase delay becomes π. Such condition is satisfied at appropriate space points in the *n* and *p* side drift zones, which in turn, lead to double negative resistance peak distribution profile of the DDDs. This nature is observed to be common to all the diodes under consideration. The location of the peak depending on the diode structural parameters could be brought to the center of the drift regions by optimization process which lead towards realisation of better microwave performance. The magnitude of the peak is found to be the highest for GaInAs diode compared to other diodes. The position of minima of $R(x)$ profile of the DDDs is observed to be near the junction plane. The the RF negative resistance contribution becomes higher within the entire depletion zone of GaInAs diode than the same for other diodes (Figure1). The integrated value of $\int R(x)dx = Z_R$ therefore becomes the highest for this diode indicating possible higher RF power generation for GaInAs diode.

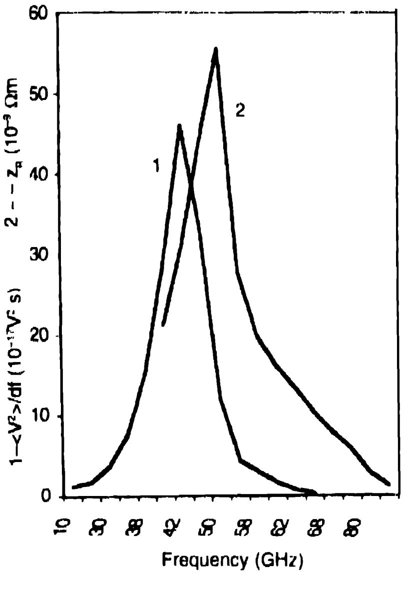

Figure 3. Variation of diode negative resistance Z_R and mean square noise voltage $<V^2>/df$ of GaInAs diode with frequency

In contrast to the $R(x)$ profile, the noise generation profile shows a near constant nature in the avalanche zone which rapidly falls to zero value as one enters the drift zone (Figure 2). The avalanche noise generation is confined to a narrow avalanche zone as the avalanche ionization process occurs mostly within this zone. The drift zone remains nearly free from carrier generation through impact ionization This explains nearly constant nature of avalanche noise generation in avalanche region. However, a small dip is observed near the junction plane. The small dip in the noise profile near the junction plane suggests the peak noise generation to take place at slightly away from the junction. This can be explained from the fact that the product of ionization rate and concentration of charge carriers $(\alpha_n.n)$ or $(\alpha_p p)$, maximises slightly away from the junction. The noise generation profile and the negative resistance profile hav been observed to be of same nature for all the semiconducto devices. However, the magnitude of the peak, minima and thei locations differ. The areas under the profiles give the net diod negative resistance and noise voltage. The negative resistanc is found to be the maximum and the noise voltage to be th minimum for GaInAs diode. The noise generation for GaInA diode is found to be lower within the entire depletion zon compared to InP and other DDDs.

Figure-3 shows the variations of $-Z_{Rp}$ and $< V^2 > /df$ wit frequency for GaInAs diode The value of $-Z_{Rp}$ peaks at 60 GH and mean squared noise voltage peaks at 42 GHz. This become a favourable parameter for device operation around 60 GHz a the value of $-Z_{Rp}$ is maximum at this frequency but noise i much lower to peak value. The values of $-Z_{Rp}$ and $< V^2 > /dj$ for different diodes have been given in Table-2. It can be see that the integrated value of RF diode negative resistance is th highest and the mean squared noise voltage is the lowest f GaInAs DDD as compared to other diodes.

4. Conclusion

Thus the paper provides a clear idea regarding signal and nois generation in different regions of the IMPATT diodes Th comparative account of RF and noise properties of diodes wi different semiconductors indicates the possible realisation the best microwave performance for the GaInAs double dr diode.

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