Appl. Phys. A 28, 195–204 (1982)

Applied Physics A Solids and Surfaces

Velocity Auto-Correlation and Hot-Electron Diffusion Constant in GaAs and InP

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Received 29 October 1981/Accepted 30 November 1981

Abstract. Auto-correlation functions of the fluctuations in the electron velocities transverse and parallel to the applied electric field are calculated by the Monte Carlo method for GaAs and InP at three different values of field strength which are around three times the threshold field for negative differential mobility in each case. From these the frequency-dependent diffusion coefficients transverse and parallel to the applied field and the figure of merit for noise performance when used in a microwave amplifying device are determined. The results indicate that the transverse auto-correlation function $C_t(s)$ falls nearly exponentially to zero with increasing interval s while the parallel function $C_p(s)$ falls sharply, attains a minimum and then rises towards zero. In each case a higher field gives a higher rate of fall and makes the correlation functions zero within a shorter interval. The transverses diffusion coefficient falls monotonically with the frequency but the parallel diffusion coefficient generally starts with a low value at low frequencies, rises to a maximum and then falls. InP, with a larger separation between the central and the satellite valleys, has a higher value of the low frequency transverse diffusion coefficient and a lower value of its parallel counterpart. The noise performance of microwave semiconductor amplifying devices depends mainly on the low frequency parallel diffusion constant and consequently devices made out of materials like InP with a large separation between valleys are likely to have better noise characteristics.

PACS: 72, 72.70, 85.60

Gunn diodes and FETs made with gallium arsenide are being extensively used for microwave generation and amplification. An important parameter of performance of these devices is their inherent noise a large part of which is thermal noise. The diffusion coefficient is a measure of the low-frequency component of thermal noise. Since the devices operate at high fields it is the hot-electron diffusion coefficient which is relevant. Hot-electron diffusion coefficient may be accurately calculated by the Monte Carlo technique. In the method commonly employed for this purpose the displacement of the electron is computed over a sampling time and the diffusion coefficient is computed by using its relation with the variance of the displacement. The hot-electron diffusion coefficient of GaAs has been calculated using this technique by Fawcett and Rees [1] and others [2–6]. Experimental results are also available for the hot-electron diffusion coefficient of GaAs [7]. But the agreement between theory and experiment is not very good.

Like GaAs, InP also shows negative differential mobility and it has been considered for the substitution of the former. Some studies [8] have also indicated lower noise in InP devices. Diffusion coefficient calculations

0721-7250/82/0028/0195/$02.00

were performed for InP [9], but experimental results on the same are not available in the literature.

The diffusion coefficient is frequency-dependent and its values at different frequencies give the noise power spectrum. The frequency-dependent diffusion coefficient may be determined from the spectrum of the current pulses. Such calculations have been reported for InP [9] and some interesting features are exhibited by the frequency-diffusion coefficient characteristics. However, no such studies are yet reported for GaAs.

The present authors reported in an earlier paper [10] a method for the calculation of the velocity-correlation functions and the frequency-dependent diffusion-coefficient from Monte Carlo simulation of the electron trajectory. The method was illustrated taking the example of InSb. It has now been used to study the characteristics of GaAs and InP at 300 K. The results of these studies are presented in this paper.

1. The Method

Although the method of computation is given in detail in [10], a brief summary is included here for the sake of completeness.

In a semiconductor block of length L, cross-sectional area A, and electron-density N, the spectral density of noise current in the direction α is [11]

$$S_{\Delta I}(\omega)=\frac{4e^2AN}{L}D_\alpha(\omega), \tag{1}$$

where

$$D_\alpha(\omega)=\int_0^\infty C_\alpha(s)\cos\omega s\,ds \tag{2}$$

and

$$C_\alpha(s)=L_{t_{T\to\infty}}\frac{1}{T}\int_0^T \Delta v_\alpha(t)\cdot\Delta v_\alpha(t+s)dt. \tag{3}$$

In (2) and (3) $\Delta v_\alpha(t)$ represents the fluctuations in the carrier velocity in the direction α, $C_\alpha(s)$ being the auto-correlation function of this fluctuation and $D_\alpha(\omega)$ the frequency-dependent diffusion coefficient in the direction α.

In order to obtain the auto-correlation function by using (3) the trajectory of a single electron is computed by Monte-Carlo simulation and the instants of collision, the initial velocity components after each collision and the average acceleration during each intercollision period is stored in the computer. From the stored data $C_\alpha(s)$ is determined using analytic expressions for the velocities inbetween two collisions. Averaging over nearly 50,000 real collisions is necessary to get satisfactory convergence of the values of the auto-correlation functions $C_t(s)$ and $C_p(s)$ in the directions transverse and parallel, respectively, to the applied electric field. From these functions the frequency-dependent diffusion coefficients $D_t(\omega)$ and $D_p(\omega)$ are obtained by (2).

2. Physical Parameters

Results are given for each material for three values of the applied electric field about three times the threshold field for the negative differential mobility, as devices made with these materials are usually operated near this values. The values of the field strength are given in Table 1.

Transport calculations have been reported in the literature for these two materials [1–6, 12–17]. Values of physical constants other than those related to the energy band structure are nearly the same in the published works, but there is no unanimity in the values of the energy-band parameters used by different authors. In the case of gallium arsenide in the earlier works a two-valley model, assuming a separation of 0.36 eV between the Γ and the X valley was used. The L valley was assumed to be much higher and of no consequence. A different model in which the L valley is separated from the Γ valley by nearly 0.3 eV and the X valley by nearly 0.5 eV has been in vogue since the publication of Aspnes' work [18]. The intervalley coupling constants are still unknown and are being discussed in the literature. Similar controversy exists also for the band structure of InP particularly for the intervalley deformation potential constants. It is not possible to resolve these controversies unambiguously and select values of physical parameters which will withstand all criticism. The values of the drift velocity obtained by the different authors are not, however, significantly different even though there is a difference in the values of the constants. It has been reported that the value of the diffusion coefficient is more sensitive to the value of the deformation potential constants. The difference, however, is mostly significant near the threshold field, whereas for the fields of our interest the difference is not that prominent.

We have chosen the constants for our calculations in accordance with Kratzer and Frey (Model C) [17] for GaAs and Herbert et al. [14] with unscreened pseudopotential for InP. These values may have to be revised when all the up-to-date experimental results are reviewed, but we believe that the general conclusions of our paper will not be significantly affected by such revision. The values of the various physical constants used in our calculations are given in Table 1.

Table 1. Physical parameters used for Monte Carlo simulation

Parameter	Valley	Unit	GaAs	InP
Energy separation	$\Gamma - \mathrm{L}$	[eV]	0.3	0.6
between valleys	$\Gamma - \mathrm{X}$	[eV]	0.48	0.8
Effective mass of electron				
m_c^*, m_D^*	Γ	m_e	0.063	0.08
m_c^*	L	m_e	0.128	0.4
m_D^*	L	m_e	0.244	
m_c^*, m_D^*	X	m_e	0.58	0.4
Intervalley phonon energy,	$\Gamma - \mathrm{L}$	[eV]	0.0278	0.00681
and coupling constant		[10^8 eV/cm]	10	1.4
	$\Gamma - \mathrm{L}$	[eV]	–	0.0336
		[10^8 eV/cm]	–	13.7
	$\Gamma - \mathrm{X}$	[eV]	0.0299	0.00845
		[10^8 eV/cm]	10	0.75
	$\Gamma - \mathrm{X}$	[eV]	–	0.0336
		[10^8 eV/cm]	–	12.54
	L – X	[eV]	0.0293	0.00681
		[10^8 eV/cm]	5	1.94
	L – X	[eV]	–	0.0336
		[10^8 eV/cm]	–	8.4
	L – L	[eV]	0.0290	0.0336
		[10^8 eV/cm]	10	5.6
	X – X	[eV]	0.0299	0.02396
		[10^8 eV/cm]	7	9.9
Nonpolar optic phonon	L	[eV]	0.0343	0.0422
energy, and coupling constant		[10^8 eV/cm]	3	6.7
Polar optic phonon energy	All	[eV]	0.03536	0.0422
Static dielectric constant			12.90	12.35
Optical dielectric constant			10.92	9.52
Acoustic deformation	Γ	[eV]	7	7
potential	L	[eV]	2.24	12
	X	[eV]	3	12
Nonparabolicity	Γ	[eV^{-1}]	0.610	0.635
	L	[eV^{-1}]	0.461	0
	X	[eV^{-1}]	0.204	0
Velocity of sound		[10^5 cm/s]	5.24	5.13
Density		[gm/cm^3]	5.36	4.79
Appl. electric		[kV/cm]	8	20
field strength		[kV/cm]	10.5	30
		[kV/cm]	12.5	40

3. Results

The results of the calculations are presented in Figs. 1–4 (Figs. 1 and 2 for GaAs and Figs. 3 and 4 for InP) and Tables 2 and 3.

Figures 1 and 3 depict, against the interval s, the auto-correlation function $C_t(s)$ and $C_p(s)$ of the fluctuations in the transverse and parallel components of electron-velocity for the three values of the applied electric field. The origin of the curves for $C_t(s)$ is shifted to the right to prevent overlapping with the curves for $C_p(s)$.

Figures 2 and 4 show the variation of the diffusion constants $D_t(\omega)$ and $D_p(\omega)$ in the directions transverse and parallel, respectively, to the field against frequency.

Tables 2 and 3 record the numerical values of some of the relevant quantities for each material for the different applied fields. Table 2 covers the parameters related to the velocity-field characteristics while Table 3 covers those related to the fluctuations in the velocity. The results indicate that the general nature of variation of the calculated quantities for the two materials is the same and similar to InSb, as reported in [10]. These general features are discussed first.

3.1. Auto-Correlation Function, Transverse

Figures 1 and 3 show that the auto-correlation function of fluctuation in the transverse component of electron-velocity $C_t(s)$ falls nearly exponentially with s.

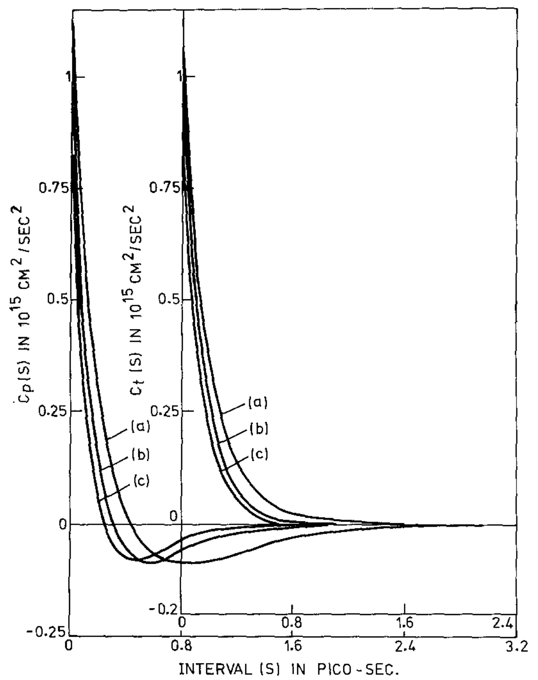

Fig. 1a–c. Transverse and parallel auto-correlation functions $C_t(s)$ and $C_p(s)$ in n-GaAs for different electric fields. (a) 8 kV/cm, (b) 10.5 kV/cm, (c) 12.5 kV/cm

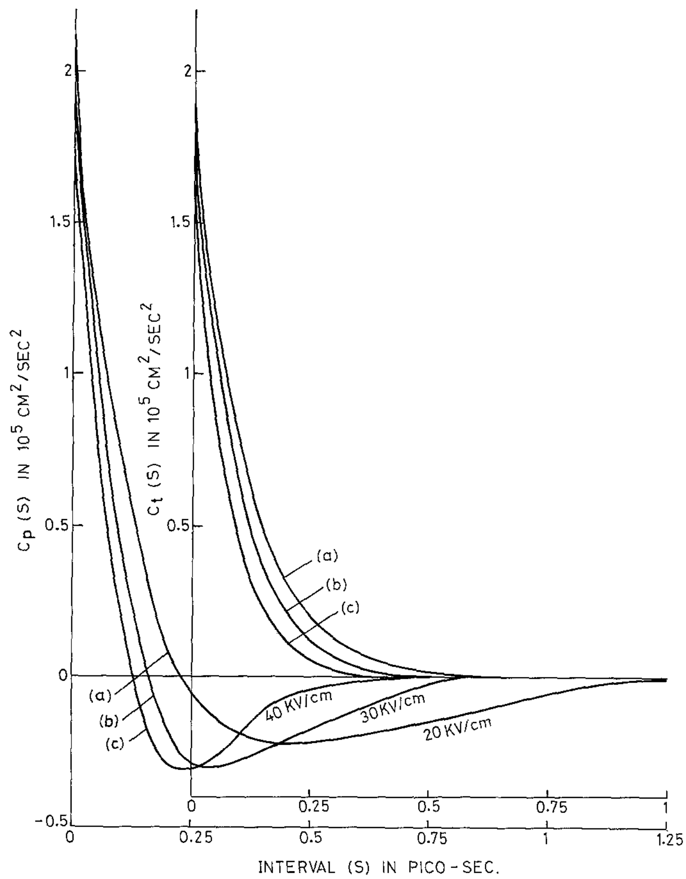

Fig. 3a–c. Transverse and parallel auto-correlation functions $C_t(s)$ and $C_p(s)$ in n-InP for different electric fields. (a) 20 kV/cm, (b) 30 kV/cm, (c) 40 kV/cm

In a logarithmic plot of $C_t(s)$ versus s most of the points lie on a straight line except that $C_t(0)$ is well above the straight line but the points following it sharply approach the straight line reaching it within a small value of s. For the fields of 8 kV/cm and 10.5 kV/cm in GaAs the points at higher values of s are found to lie on a second straight line of smaller slope. The correlation time τ_c given by the slope of the straight lines are recorded in Table 3. The exponential fall of $C_t(s)$ with s was explained in [10] on the basis of the variation of the transverse velocity $v_t(t)$ with time. The explanation is repeated here with special reference to InP. Figure 5a shows versus time the calculated values of a transverse component of electron velocity $v_t(t)$ in InP for a field of 40 kV/cm. It is assumed that $v_t(t)$ is nearly constant between successive collisions. The auto-correlation function $C_t(s)$ for such a function is proportional to $\exp(-s/\tau_c)$ if (i) the probability that the electron does

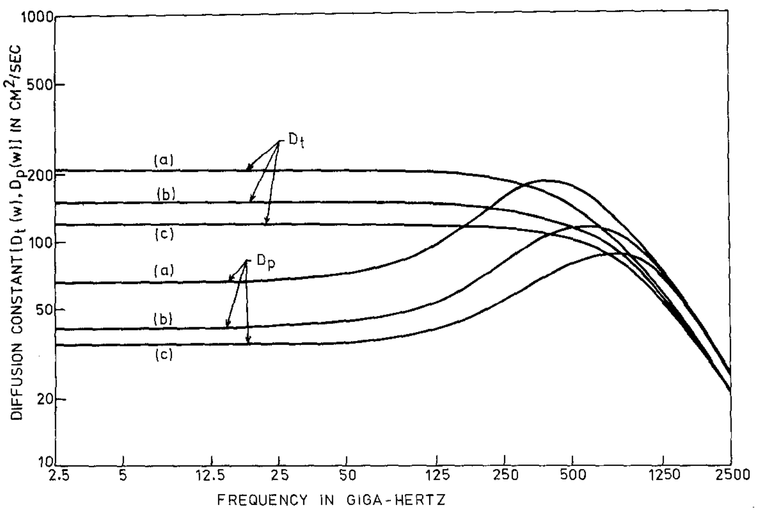

Fig. 2a–c. Transverse and parallel diffusion constants $D_t(\omega)$ and $D_p(\omega)$ versus frequency for n-GaAs at different electric fields. (a) 8 kV/cm, (b) 10.5 kV/cm, (c) 12.5 kV/cm

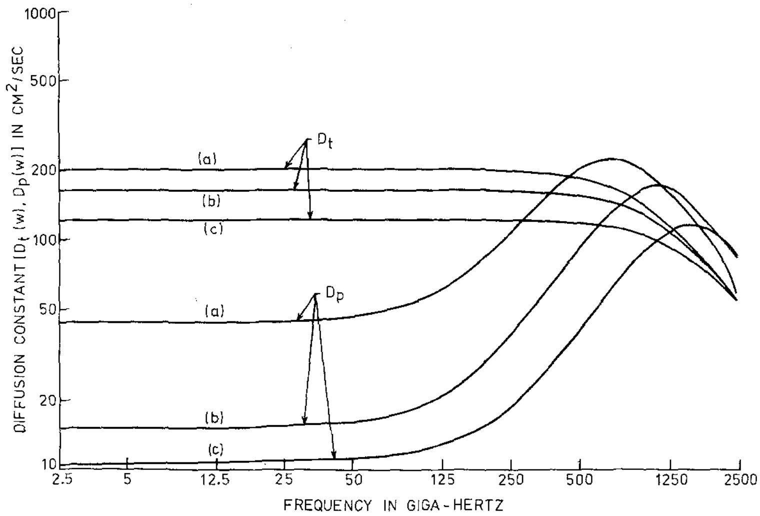

Fig. 4a–c. Transverse and parallel diffusion constants $D_t(\omega)$ and $D_p(\omega)$ versus frequency for n-InP at different electric fields. (a) 20 kV/cm, (b) 30 kV/cm, (c) 40 kV/cm

Table 2. Results on parameters related to velocity-field characteristics

Parameters (Material / Field)	Unit	GaAs 8 kV/cm	GaAs 10.5 kV/cm	GaAs 12.5 kV/cm	InP 20 kV/cm	InP 30 kV/cm	InP 40 kV/cm
Drift velocity	[10^7 cm/s]	1.50	1.45	1.43	1.83	1.36	1.15
		(1.35	1.15	1.10)[7]	(1.5	1.15	1.0)[12a]
		(1.4)[2]	–	–	(1.7	1.15	0.88)[12b]
					(1.75	1.25	1.1)[14a]
					(1.55	1.1	0.9)[14b]
					(1.8	1.25	–)[15]
		(1.6	1.4	1.3)[17b]	(2.09	1.39	1.0)[26]
		(1.58	1.45	1.35)[17c]	(1.9	1.39	1.16)[27]
		(1.25	1.15	1.1)[6a]	(2.23)[24]	–	–
		(1.4	1.15	1.05)[12]	(2.23	1.8)[25a]	
		(1.2)[6b]	–	–	(2.09)[25b]		
					(–	0.80	0.82)[28]
Population in valleys	Γ [%]	39.83	29.22	24.06	79.29	65.50	55.13
		(55.0	48.0	40.0)[17b]	(63.0	45.0	38.0)[12a]
					(80.0	72.0	65.0)[12b]
	L [%]	60.12	70.60	75.39	20.69	34.45	44.70
		(45.0	52.0	59.0)[17b]	(37.0	55.0	62.0)[12a]
					(20.0	28.0	35.0)[12b]
	X [%]	0.05	0.18	0.55	0.02	0.05	0.17
		(0	0	1)[17b]	(0	0	0)[12a, b]
Chord mobility	[cm^2/Vs]	1875	1381	1144	915	453	288
Differential mobility	[cm^2/Vs]	−345	−141	−49	−1013	−294	−147

Results quoted from the literature are given in parenthesis. The super scripts give the reference number.

6a: Ref. [6] (1st reference); 6b: Ref. [6] (2nd reference, with parameter of 6a); 6c: Ref. [6] (2nd reference, with parameters of Ref. [16])

12a: Ref. [12] (with unscreened pseudopotential); 12b: Ref. [12] (with screened pseudopotential)

17b: Ref. [17] (Model B); 17c: Ref. [17] (Model C)

not suffer a collision up to time t is proportional to $\exp(-t/\tau_c)$, and (ii) the velocity immediately after the collisions has a Gaussian distribution [19]. In this case τ_c is the correlation time.

The nearly exponential nature of the $C_t(s)$ curves indicate that the two conditions mentioned above are reasonably satisfied in the cases under consideration. The departure from linearity for small values of the interval s may be attributed to the presence of more than one valley and the consequent multiplicity of scattering processes with a wide range of scattering probabilities.

Table 3. Results on parameters related to velocity fluctuations

Parameter	Material / Field / Unit	GaAs 8 kV/cm	GaAs 10.5 kV/cm	GaAs 12.5 kV/cm	InP 20 kV/cm	InP 30 kV/cm	InP 40 kV/cm
Mean square velocity fluctuation:							
Transverse $\langle v_t^2 \rangle$	$[10^{14}\,cm^2/s^2]$	10.71	8.87	8.90	18.88	18.35	16.99
Parallel $\langle (\Delta v_p)^2 \rangle$	$[10^{14}\,cm^2/s^2]$	11.36	9.00	8.98	21.28	20.53	18.05
Correlation time τ_c	$[10^{-12}\,s]$	0.197; 0.613	0.151; 0.730	0.135	0.110	0.100	0.075
Interval s for:							
(a) $C_t(s) = 0$	$[10^{-12}\,s]$	1.60	1.56	1.48	0.65	0.55	0.44
(b) $C_p(s) = 0$							
(i)	$[10^{-12}\,s]$	0.40	0.30	0.26	0.23	0.16	0.12
(ii)	$[10^{-12}\,s]$	2.28	2.04	1.10	2.13	0.80	0.81
$\langle v_t^2 \rangle \cdot \tau_c$	$[cm^2/s]$	210.9	133.9	120.2	207.7	183.5	127.4
Low frequency diffusion coefficient Transverse $D_t(0)$	$[cm^2/s]$	207.8 (190 (178	152.7 150 125	112.5 140)[6a] 100)[1]	203.0 (194.5	164.0 160.0	122.6 120.0)[9]
Parallel $D_p(0)$	$[cm^2/s]$	65.8 (300 (150 (100 (300 (160 (300 (140)[6b] (60)[6c]	41.3 225 60 55 225 125 200	33.8 190)[5] 45)[6a] 40)[1] 190)[7] 110)[2] 175)[3]	43.0 (72.0	15.0 34.5	10.7 21.8)[9]
Max. value of $D_p(\omega)$	$[cm^2/s]$	184.7	116.0	86.6	221.0 (250.0	169.0 200.0	116.7 130)[9]
Freq. for $[D_p(\omega)]_{max}$	[GHz]	400	600	800	700 (600*	1100 1000**	1500 1700)[9]
Fig. of merit for noise performance (i) $D_p(\omega)/V_d$	$[10^{-7}\,cm]$	43.87	28.48	23.64	23.50	11.03	9.30
(ii) $D_p(\omega)/\|\mu_d\|$	[V]	0.191	0.293	0.690	0.0424	0.0510	0.0728

Results quoted from the literature are given in parenthesis. The superscripts give the reference number 6a, 6b, and 6c are the same as in Table 2. * at 15 kV/cm; ** at 25 kV/cm

For higher fields $C_t(s)$ has a higher rate of fall, i.e. smaller correlation time and becomes zero in a shorter interval. The decrease in the correlation time results from the increase in the rate of scattering due to the increase in average electron energy in the higher fields. Though the mean-square velocity does not change appreciably with the field, the higher population in the upper valey indicates the higher average energy at higher fields. These quantities (mean square velocity and relative population in valleys) are given in Tables 3 and 2, respectively.

3.2. Auto-Correlation Function, Parallel

Figures 1 and 3 show that with increasing interval s the auto-correlation function of the fluctuations in the parallel component of the electron velocity $C_p(s)$ falls sharply to zero, becomes negative and finally approaches zero. The existence of negative values of $C_p(s)$ was explained in [10] to be due to inter-collision periods during which the fluctuation changes from negative to positive values due to its nearly linear increase with time. Figure 5b shows the calculated values of $\Delta v_p(t)$ under the same conditions and over the same period as Fig. 5a. It is clearly seen from the figure that the long flights of the electrons in the Γ valley make large negative contributions to the auto-correlation function $C_p(s)$. These long flights, however, are not so dependent on intervalley scattering, as was suggested by Fawcett and Rees [1]. Checking on 1000 consecutive collisions in InP it was found that in some cases the long flight starts with an intervalley transfer to the central valley, but there are very few cases in which it ends with a return of the electron to the upper valley. The duration of the long flights thus varies

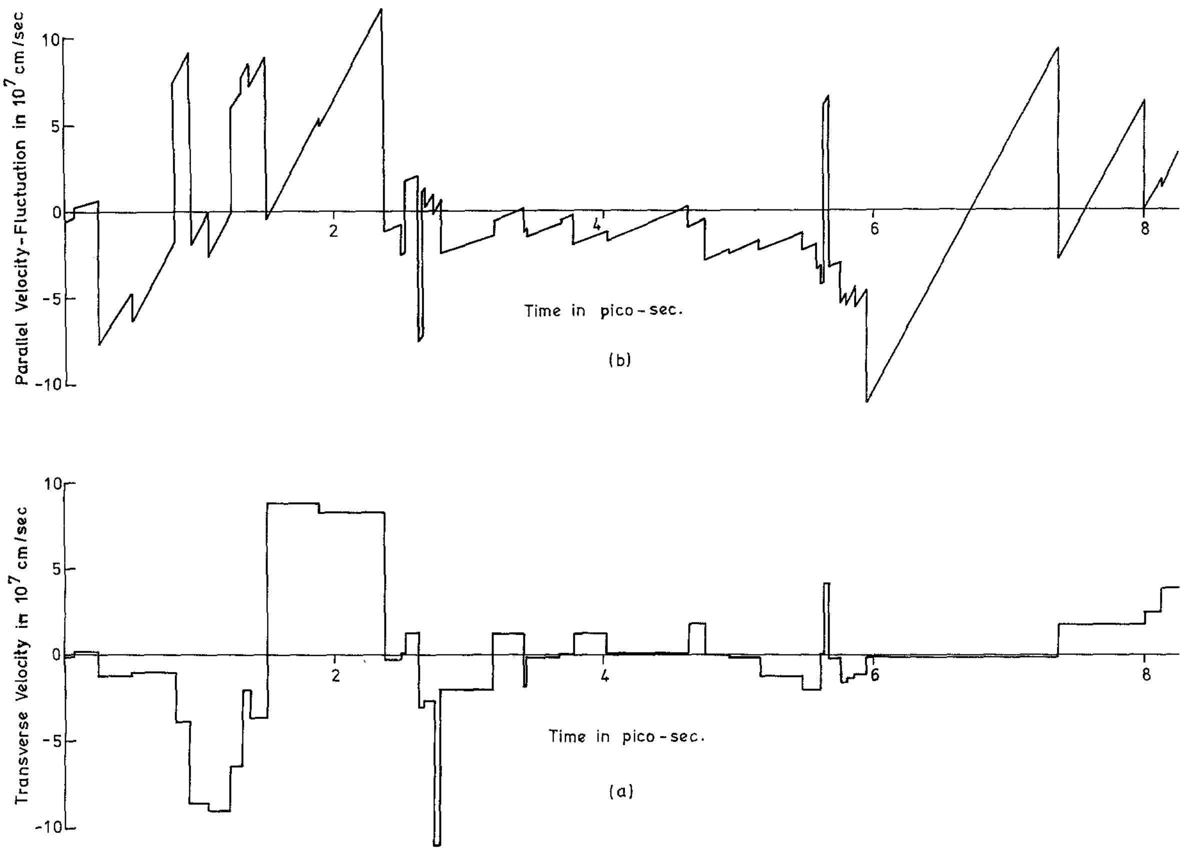

Fig. 5. A sample of transverse velocity and parallel velocity fluctuation versus time in n-InP for an electric field of 40 kV/cm

widely and it seems that no particular value may be ascribed to it for the purpose of calculating the frequency at which the spectral density and the diffusion coefficient $D_p(\omega)$ is maximum, as has been done by Hill et al. [9].

For higher fields, $C_p(s)$ like $C_t(s)$ has a higher rate of fall with increase in s and becomes zero in a shorter interval. But in each case the mean-square value of the fluctuation $\Delta v_p(t)$ which is given by $C_p(0)$ is slightly greater than that of the transverse case, i.e. $C_t(0)$. This is in agreement with our earlier results for InSb [20]. The higher value of $C_p(0)$ is due to the presence of fluctuations in the convective motion of the electron in this case, in addition to the fluctuations due to the thermal motion which alone is present in the transverse direction [21].

The negative region of $C_p(s)$ which is a special feature of the parallel case, becomes more pronounced with an increase in the applied field, such that the minimum attains a more negative value. Also the minimum occurs at a lower value of s. This increase in the negative values with the field arise from the more frequent occurrence of long flights which make negative contributions to $C_p(s)$.

3.3. *Diffusion Coefficient at Low Frequencies*

The diffusion constants $D_t(0)$ and $D_p(0)$ were calculated from the computed values of $C_t(s)$ and $C_p(s)$ by using (2). It should be pointed that the correlation coefficients show irregular variations for large values of s. The variations are within 1% of their maximum values for $s=0$. This variation contributes an error in the calculated values of the diffusion constants. We estimate that the error arising from this source is less than 5% for $D_t(0)$ but it may be somewhat larger for $D_p(0)$ for some values of the field.

A comparison (Figs. 2 and 4, Table 3) of the low frequency diffusion coefficients $D_t(0)$ and $D_p(0)$ transverse and parallel, respectively, to the applied electric field shows that for each material studied $D_t(0)$ is greater than $D_p(0)$. With increase in the field strength both $D_t(0)$ and $D_p(0)$ decrease the fall being very marked in the case of $D_p(0)$ of InP.

These features of $D_t(0)$ and $D_p(0)$ are direct consequences of the nature of the variation of $C_t(s)$ and $C_p(s)$ with s. By (2) $D_t(0)$ and $D_p(0)$ are obtained by integrating the respective auto-correlation function over s. Further, for an exponentially falling $C_t(s)$ the corresponding $D_t(0)$ is $\langle[v_t(t)]^2\rangle \cdot \tau_c$ where τ_c is the correlation time [20]. The values of $\langle[v_t(t)]^2\rangle$ which is the same as $C_t(0)$, τ_c and their product are given in Table 3. The agreement with $D_t(0)$ is very significant. The lower values of $D_p(0)$ compared to $D_t(0)$ also follows from the nearly equal values of $C_p(0)$ and $C_t(0)$, sharper fall of $C_p(s)$ and the presence of negative values of $C_p(s)$. This anisotropy in the values of $D_t(0)$ and $D_p(0)$ is anticipated also from the nature of the variation of $v_t(t)$ and $\Delta v_p(t)$ with t, as shown in Fig. 5a and b. In a simple theory, if the individual electron trajectories are assumed to be uncorrelated, the diffusion constant is approximately given by

$$D \sim \left\langle \int_0^T [\Delta v(t)]^2 dt \right\rangle,$$

where T is the duration of the trajectory, and $\langle\,\rangle$ indicates average value. It is then evident from the shape of the trajectories shown in Fig. 5 that $D_p(0)$ will be smaller than $D_t(0)$ due to the predominence of triangular trajectories. However, the exact magnitude of the difference and the fact that the difference increases with the intervalley separation cannot be explained from these simple considerations. More detailed study is necessary for the clarification of this significant result.

The fall in the value of both $D_t(0)$ and $D_p(0)$ with increased field results from the higher rate of fall of $C_t(s)$ and $C_p(s)$. In the case of $D_p(0)$ the decrease is enhanced by the enlargement of the negative region of the $C_p(s)$ curve.

3.4. *Frequency-Dependence of Diffusion Coefficients*

The dependence of the diffusion coefficients $D_t(\omega)$ and $D_p(\omega)$ on frequency can be examined from Figs. 2 and 4. It is observed that $D_t(\omega)$ remains nearly constant at lower frequencies but falls monotonically at higher frequencies. As mentioned above, $D_p(\omega)$ has a much lower value than $D_t(\omega)$ at low frequencies. Initially $D_p(\omega)$ increases with frequency, reaches a maximum which is nearly equal to $D_t(0)$ and then falls with frequency. In the neighbourhood of the maximum and at higher frequencies $D_p(\omega)$ is greater than $D_t(\omega)$.

At any particular frequency within the entire range studied $D_t(\omega)$ has a lower value at a higher field. The dependence of $D_p(\omega)$ on the field, however, is more involved. For a higher field the low-frequency value of $D_p(\omega)$ and its maximum are lower, but the maximum occurs at a higher frequency. For frequencies near and beyond its maxima $D_p(\omega)$ at a higher field may have a higher value than that for a lower field.

The product of the frequency at which $D_p(\omega)$ is maximum and the interval for the first zero of $C_p(s)$ is fairly constant and lies in the range 0.16–0.21 (Table 3). Thus the frequency for $[D_p(\omega)]_{\max}$ is nearly inversely proportional to the interval for the first zero of $C_p(s)$. These characteristics of the frequency-dependence of $D_t(\omega)$ and $D_p(\omega)$ follow directly from the nature of variation of $C_t(s)$ and $C_p(s)$ with s and (2).

3.5. *Specific Features of the Materials*

GaAs. The field strength considered for GaAs are close to the region of saturation of the drift velocity V_d. This is evident from the small absolute values of the differential mobility and the high population of the L valley (Table 2). The mean-square velocities $\langle[v_t(t)]^2\rangle$ and $\langle[\Delta v_p(t)]^2\rangle$ lie in the range $9\text{–}11 \times 10^{14}\,\mathrm{cm^2/s^2}$. The correlation time τ_c obtained from the slope of the logarithmic plot of $C_t(s)$ against s are of the order of 0.1 ps. As mentioned earlier, two values of τ_c are obtained for field strengths of 8 kV/cm and 10.5 kV/cm. The auto-correlation functions $C_t(s)$ and $C_p(s)$ become zero for $s \geqq 1.1$ to 2.28 ps. Thus for determination of the low-frequency diffusion coefficients $D_t(0)$ and $D_p(0)$ from the variance of displacement sampling times greater than 11–28 ps, should be taken. This follows from our earlier finding that the diffusion coefficient is independent of the sampling time T if T is greater than 10 times the interval beyond which the auto-correlation function is zero [10]. $D_t(0)$ and $D_p(0)$ lie in the range 110–210 $\mathrm{cm^2/s}$ and 30–70 $\mathrm{cm^2/s}$, respectively, while the maximum value of $D_p(\omega)$ covers the range 80–190 $\mathrm{cm^2/s}$ which is quite close to the range of values of $D_t(0)$. The maxima of $D_p(\omega)$ occur in the frequency range 400–800 GHz.

Two figures of merit of a semiconductor amplifying device regarding its noise performance are given by $D_p(\omega)/V_d$ [22] and $D_p(\omega)/|\mu_d|$ [23], $D_p(\omega)$ being the diffusion constant at the operating frequency, V_d the drift velocity and $|\mu_d|$ the absolute value of the differential mobility at the applied field. In the microwave range the value of the first parameter for GaAs devices lies in the range $(20\text{–}50) \times 10^{-7}$ cm and for the second it covers the range 0.19–0.69 V.

The results obtained by us are compared with those available in the literature and quoted in Tables 2 and 3. The drift velocities calculated by us agree with those of Model C of [17], which was obtained from the same set of physical parameters. The figures for relative population of the valleys given in [17] are based on Model B and the agreement is not quite satisfactory. Our estimate of the sampling time (11–28 ps) for the determination of the diffusion coefficient has the same order of magnitude (3–10 ps), as reported by Fawcett and Rees [1], although their model is quite different from ours. There is good agreement in the values of $D_t(0)$. But our values of $D_p(0)$ are low compared to most of the other values; it agrees with that value of [6b] which is based on nearly the same set of parameters. Because of the wide difference with the experimental results of Ruch and Kino [7] we intend to repeat the calculations with a set of parameters that would result in better agreement with the experimental values.

InP. For the field strength considered for InP the majority of the electrons remain in the central valley and very few reach the X valley, the population in the L valley lies between 20% and 45%. The drift velocity varies from 1.15×10^7 to 1.83×10^7 cm/s. The chord mobility and the differential mobility cover the wide ranges of 280–915 cm^2/Vs and -1000 to -150 cm^2/Vs, respectively. The mean-square velocities $\langle[v_t(t)]^2\rangle$ and $\langle[\Delta v_p(t)]^2\rangle$ are in the neighbourhood of 2×10^{15} cm^2/s^2 and the correlation times lie in the range 0.75–1.1 ps. $C_t(s)$ and $C_p(s)$ become zero for intervals beyond 0.5 and 1 ps, respectively, and indicate a minimum sampling time of about 5 and 10 ps for the determination of the diffusion constant from the variance of displacement. The transverse and parallel diffusion constants lie in the range of 120–200 cm^2/s and 10–45 cm^2/s, respectively. The maximum of $D_p(\omega)$ at each field strength is nearly equal to the transverse diffusion coefficient $D_t(0)$ and occurs in the frequency range of 700–1500 GHz. The figures of merit for noise performance $D_p(\omega)/V_d$ and $D_p(\omega)/|\mu_d|$ in the microwave range lie between 9×10^{-7} and 24×10^{-7} cm and between 0.04 and 0.075 V, respectively.

Comparison with the experimental [24–28] and calculated values [9, 12–15] available in the literature and quoted in Tables 2 and 3 show that the agreement in the case of the drift velocity and the relative population in the valleys is quite good. Our results regarding the diffusion coefficients $D_t(\omega)$ and $D_p(\omega)$ and the variation of $D_p(\omega)$ with frequency are in fairly good agreement with those in [9] although the results have been obtained there by methods quite different from ours. Our estimate of the sampling time also agrees with the finding in [9] that $D_p(0)$ becomes independent of the sampling time T only if T is greater than 30 ps.

3.6. Comparison Between the Materials

A comparison of the results for these two materials reveals that for the field strength considered most of the electrons in GaAs are in the higher valley while in InP less than half are so transferred. This is due to the difference in the separation of the valleys (0.3 eV in GaAs and 0.6 eV in InP) in spite of the higher field applied in InP. This difference in the relative population of the valleys results in the lower mean-square velocity fluctuation in GaAs. It is observed that the correlation time is lower for InP while the transverse diffusion coefficient for both materials are nearly equal. This equality follows from the fact that $D_t(0)=\langle[v_t(t)]^2\rangle\cdot\tau_c$ and from the nature of the variation of these two quantities from one material to the other. The parallel diffusion coefficient $D_p(0)$ is lower for InP due to the greater prominence of the negative values of $C_p(s)$ for InP, which has a higher separation between valleys. The frequencies at which $D_p(\omega)$ becomes maximum are lower for GaAs.

Noise Performance. The spectral density of noise current is directly proportional to the frequency-dependent diffusion coefficient (1). In semiconductor devices the noise power at the output depends on the noise current parallel to the applied field. So the noise performance of devices depends on the parallel diffusion coefficient $D_p(\omega)$ of the material. It is seen from Figs. 2 and 4 that at the microwave frequencies $D_p(\omega)$ is nearly the same as its low frequency value $D_p(0)$ and the frequencies at which $D_p(\omega)$ has high values are much above the microwave range.

Two figures of merit of the material used in amplifying devices have been defined as: (i) $D_p(\omega)/V_d$, and (ii) $D_p(\omega)/|\mu_d|$. A lower value of these figures indicates better noise performance. These figures of merit for the two materials at microwave frequencies are given in Table 3. It is seen that InP is expected to have a better noise performance than GaAs.

$D_p(\omega)$ increases with frequency and attains its maximum value at a frequency in the neighbourhood of 1000 GHz. The performance of devices made of these materials will thus be limited by their noise performance in the submillimeter range of wavelength.

4. Conclusion

An examination of the calculated values of the autocorrelation functions $C_t(s)$ and $C_p(s)$ and the frequency dependent diffusion coefficients $D_t(\omega)$ and $D_p(\omega)$ of the materials GaAs and InP leads to the following conclusions.

Both $C_t(s)$ and $C_p(s)$ fall with increasing interval s. The fall in $C_t(s)$ is nearly exponential but $C_p(s)$ falls at a rate higher than $C_t(s)$, attains a negative maximum and finally becomes zero. For a higher field both $C_t(s)$ and $C_p(s)$ fall more sharply than when the field is low.

The transverse diffusion constant $D_t(\omega)$ falls monotonically with frequency but the parallel diffusion constant $D_p(\omega)$ generally starts with a low value at low frequencies, rises to a maximum and then falls with increase in frequency. InP with a large separation between the central and the satellite valleys has a higher value of $D_t(0)$ and a lower value of $D_p(0)$.

At microwave frequencies $D_p(\omega)$ is nearly equal to $D_p(0)$. The noise performance of semiconductor devices for microwave frequencies depends on $D_p(\omega)$. Since InP has a lower $D_p(0)$ compared to GaAs devices made of InP are likely to have better noise characteristics when used as microwave amplifiers.

References

1. W.Fawcett, H.D.Rees: Phys. Lett. **29** A, 578 (1969)
2. P.N.Butcher, W.Fawcett, N.R.Ogg: Br. J. Appl. Phys. **18**, 755 (1967)
3. T.Ohmi, S.Hasuo: Proc. 1970 Int. Conf. Phys. Semicond. (U.S. Atomic Energy Commission, Cambridge 1970) p. 60
4. P.E.Bauhahn, G.I.Haddad, N.A.Masnari: Electron. Lett. **9**, 460 (1973)
5. M.Abe, S.Yanagisawa, O.Wada, H.Takanashi: Appl. Phys. Lett. **25**, 674 (1974)
6. J.Pozela, A.Reklaitis: Solid State Commun. **27**, 1073 (1978); Solid State Electron. **23**, 927 (1980)
7. J.G.Ruch, G.S.Kino: Phys. Rev. **174**, 921 (1969)
8. B.K.Ridley: J. Appl. Phys. **48**, 754 (1977)
9. G.Hill, P.N.Robson, W.Fawcett: J. Appl. Phys. **50**, 356 (1979)
10. M.Deb Roy, B.R.Nag: Appl. Phys. A **26**, 131 (1981)
11. K.M.van Vliet: Solid State Electron. **13**, 649 (1970); J. Math. Phys. **12**, 1998 (1971)
12. W.Fawcett, D.C.Herbert: J. Phys. C **7**, 1641 (1974)
13. W.Fawcett, G.Hill: Electron. Lett. **11**, 80 (1975)
14. D.C.Herbert, W.Fawcett, C.Hilsum: J. Phys. C **9**, 3969 (1976)
15. T.J.Maloney, J.Frey: J. Appl. Phys. **48**, 781 (1977)
16. M.A.Littlejohn, J. R. Hauser, T.H.Glisson: J. Appl. Phys. **48**, 4587 (1977)
17. S.Kratzer, J.Frey: J. Appl. Phys. **49**, 4064 (1978)
18. E.Aspnes: Phys. Rev. B **14**, 5331 (1976)
19. S.Goldman: *Information Theory* (Prentice-Hall, New York 1962)
20. M.Deb Roy, B.R.Nag: Int. J. Electron. **48**, 443 (1980)
21. B.R.Nag, P.N.Robson: Phys. Lett. A **43**, 507 (1973)
22. B.Kallaback: Electron. Lett. **9**, 11 (1973)
23. H.W.Thim: Electron. Lett. **7**, 106 (1971)
24. H.Tlam, G.A.Acket: Electron. Lett. **7**, 722 (1971)
25. G.H.Glover: Appl. Phys. Lett. **20**, 244 (1972)
26. P.M.Boers: Electron. Lett. **7**, 625 (1971)
27. L.D.Neilsen: Phys. Lett. A **38**, 221 (1972)
28. B.A.Prew: Electron. Lett. **8**, 592 (1972)

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