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Hot electron transport in In (0·53) Ga (0·47) As

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Abstract. Monte Carlo results on the hot-electron transport coefficients of In (0·53) Ga (0·47) As are presented. The material parameters were selected by analysing the experimental hot-electron velocity-field characteristics and calculations were made by including all the relevant scattering mechanisms. Results are presented for the bulk drift velocity and diffusion coefficient and also for the velocity-field characteristics of submicron samples and 2 DEG.

Keywords. Hot-electron transport; Monte Carlo results; velocity-field characteristics; submicron transport; DEG transport.

1. Introduction

The ternary compound In (0·53) Ga (0·47) As has an energy band gap of 0·75 eV, which matches the 1·6 μm radiation at which the glass fibres have a low attenuation window. The material is also lattice-matched to InP and crystals of good quality may be grown by LPE, MBE or MOCVD. It was therefore developed to realise sources and detectors for communication systems working with 1·6 μm radiation.

It was, however, found, when good quality material became available, that it gave better performance characteristics for many devices which were earlier made with GaAs or InP. The number of devices which have been realised with In (0·53) Ga (0·47) As has been multiplying at a very rapid rate. A new device is reported almost every month. Performance characteristics of the InGaAs devices as reported in *IEEE Trans. Electron Device Lett.* (1987) are listed in table 1. It is evident from the reported results that In (0·53) Ga (0·47) As will be a serious competitor to GaAs and InP as the material for high-frequency and high-speed devices.

The author and his co-workers (Ahmed *et al* 1985; Nag *et al* 1986, 1987; Bose and Nag 1988) have in this context, studied the material by applying the Monte Carlo technique to assess theoretically its performance vis-a-vis that of GaAs and InP. The results of these studies are reviewed in this paper.

2. Velocity-field characteristics

The calculation of transport coefficients requires the knowledge of the physical parameters related to the energy band structure, coupling constants for the scattering mechanisms, and of the mass density, phonon spectrum and dielectric constant. Some of these parameters have been determined by experiments, some have been calculated and some others are estimated by interpolation using the values for GaAs and InAs. The parameters (Nag 1984) selected for the calculations are given in table 2. It is necessary to check if these parameters give acceptable results. For this purpose, the velocity field characteristics were first calculated with

Table 1. In (0·53) Ga (0·47) As devices*.

Device	Reporting month	Performance characteristic	Reference
SISFET	January	$g_t = 250$ (300 K) $f_t = 15$	Feuer *et al* (1987)
MODFET	March	$g_t = 17{\cdot}8$ (300 K) $= 89$ (77 K)	Lee *et al* (1987)
HPT	April	$G > 150$ $B = 14$	Campbell *et al* (1987)
HBT	May	$G > 100$	Lee *et al* (1987)
DHBT	June	$G > 275$	Nottenburg *et al* (1987)
SAGM-APD	July	$\tau = 14$	Tsang *et al* (1987)
JFET	August	$g_t = 553$	Albreeht and Lauterbach (1987)
MODFET	September	$g_t = 271\text{–}197$	Kuo *et al* (1987)
HEMT	September	$g_t = 240$ (300 K) $= 340$ (88 K)	Kuroda *et al* (1987)
MISFET	September	$f_t = 45$	Gardner *et al* (1987)
MISFET	November	$g_t = 152$ $f_t = 50$	de Alamo and Mizutani (1987)
Photodiode	December	$\tau = 0{\cdot}025$	Zebda *et al* (1987)

Symbols: g_t – transconductance in m s/mm; f_t – cut-off frequency in GHz; G – gain; B – bandwidth in GHz; τ – rise time in ns.
*Source: *IEEE Trans. Electron Devices Lett.* **8** (1987).

Table 2. Physical constants of In (0·53) Ga (0·47) As.

Physical constant	Γ Valley	L valley	X valley
Number of valleys	1	4	3
Effective mass ratio	0·042 (95 K) 0·03745 (300 K)	0·26	0·54
Nonparabolicity factor $(\mathrm{eV})^{-1}$	1·167	0·59	0·65
Valley separation from Γ valley (eV)	—	0·55	0·67
Polar optic phonon energy (eV)	0·0345	0·0345	0·0345
Acoustic phonon deformation potential (eV)	9·2	9·2	9·2
Alloy scattering potential (eV)	0·42	0·42	0·42

Intervalley transition	Coupling constant in units of 10^8 eV/cm	Phonon energy in eV
Γ–L	10	0·027
Γ–X	10	0·0299
L–L	10	0·0290
L–X	9	0·0293
X–X	9	0·0299

Mass density – 5·469 (g/cm^3), sound velocity – $4{\cdot}7 \times 10^5$ (cm/s);
High-frequency dielectric constant – 11·34;
Low-frequency dielectric constant – 13·88;
Lattice constant – $5{\cdot}86 \times 10^{-8}$ cm.

these parameters and compared with the experimental results, which were obtained earlier by Windhorn *et al* (1982) by using the microwave time-of-flight technique.

The calculated values are presented in figure 1 along with the experimental

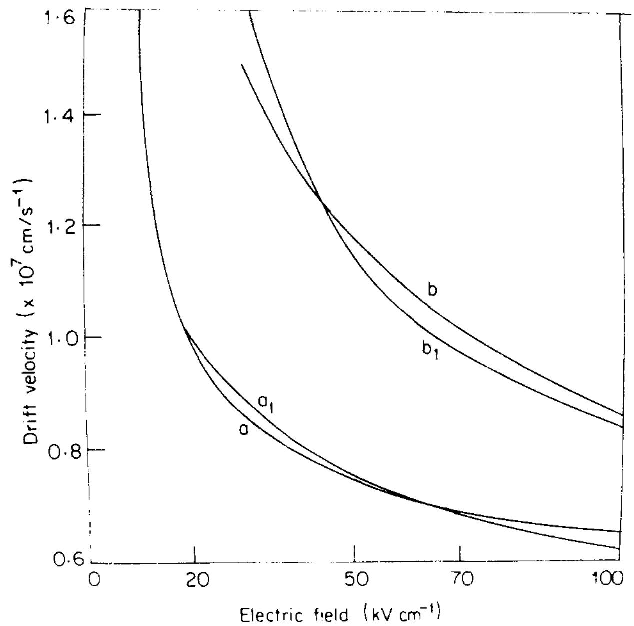

Figure 1. Velocity-field characteristics for bulk In (0·53) Ga (0·47) As at 300 K (a, a) and 95 K (b, b). a, b-theoretical, a, b,-experimental.

results. It is seen that the calculated values agree very closely with the experiments.

Low-field mobility, peak velocity and threshold field for negative differential velocities were also calculated for the temperatures of 300 and 95 K. The values are respectively 13,770 cm^2/V.s, $2{\cdot}83 \times 10^7$ cm/s, 3·1 kV/cm and 31,770 cm^2/V.s, $4{\cdot}25 \times 10^7$ cm/s, 2·5 kV/cm. The values for 300 K are nearly the same as those obtained from experiments (Kowalsky *et al* 1984). The values for 95 K could not, however, be checked as experimental results are not available.

3. Hot-electron diffusion coefficient

The diffusion constant for high fields was obtained by using the following relations.

$$c(s) = (1/T) \int_0^T [v(t) - \bar{v}]\,[v(t+s) - \bar{v}]\,dt, \tag{1}$$

$$\bar{v} = (1/T) \int_0^T v(t)\,dt, \tag{2}$$

$$D(\omega) = \int_0^\infty c(s) \cos \omega s\,ds, \tag{3}$$

where $c(s)$ is the autocovariance coefficient of velocity fluctuations, $\bar{v}$ the average velocity, t the time, s the time interval, T the sampling time and $D(\omega)$ the diffusion coefficient for the frequency ω.

The values of velocity were recorded in the Monte Carlo simulation at some chosen intervals. The covariance coefficient was computed by using the recorded values of velocity and the diffusion coefficient from the values of $c(s)$ by using (3).

Calculated values of diffusion coefficient are plotted in figure 2 against electric field normalised by the threshold field for negative differential resistance. The transverse diffusion coefficient shown by the dotted line is larger than those of

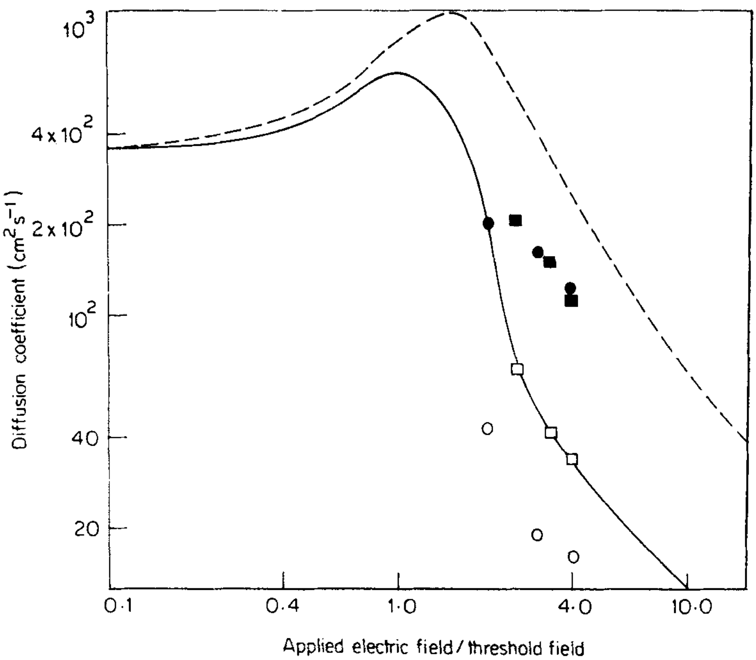

Figure 2. High-field transverse and parallel diffusion ($D_\perp$, $D_\parallel$) coefficients at 300 K for In (0·53) Ga(0·47) As, GaAs and InP. (Solid line—$D_\parallel$ for In(0·53)Ga(0·47)As; broken line—$D_\perp$ for In(0·53)Ga(0·47)As; □—$D_\parallel$ for GaAs; ■—$D_\perp$ for GaAs; ○—$D_\parallel$ for InP; ●—$D_\perp$ for InP.

GaAs (indicated by closed circles) and of InP (indicated by closed squares). On the other hand, the parallel coefficient is nearly the same as those of GaAs (indicated by open squares), but larger than those of InP (indicated by open circles). The diffusion coefficient is a measure of the noise performance of the devices made with the material. The present results indicate that the performance of In(0·53) Ga(0·47) As would be similar to that of GaAs, but poorer than InP.

4. Submicron transport

Transport characteristics for submicron samples were calculated by simulating the electron trajectory in short samples. Electrons were injected in the simulation from one end of the sample by assuming that they obey a Maxwellian distribution at the lattice temperature before injection. The velocity of the simulated electron was recorded at intervals of 0·04 ps, till it reached the end of the sample. The average velocity of the electrons during the flight was calculated by using the relation

$$v(t) = \sum_{i=1}^{N} v_i(t)/N, \tag{4}$$

where $v_i(t)$ is the velocity of the electron at any time t after injection and N the total number of simulated electrons.

The average velocity was found to increase with time and attain steady values after about 1 ps. The velocity showed overshoot for fields larger than the threshold

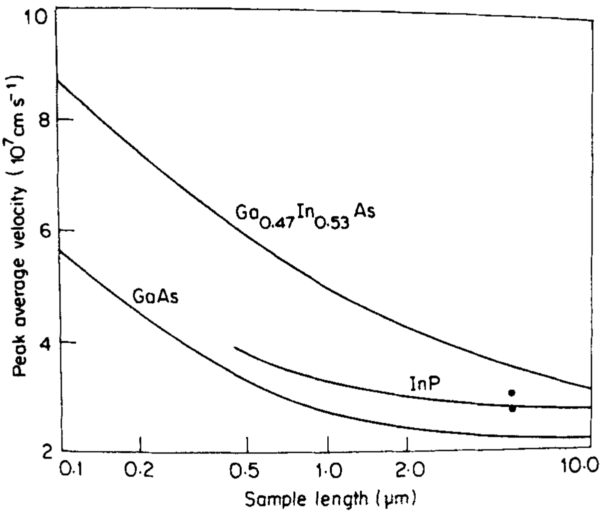

Figure 3. Peak average velocity in submicron samples for In (0·53) Ga (0·47) As, GaAs and InP.

field. The threshold field and the peak velocity was found to increase with decrease in the sample length. The parameter of interest in the application of the submicron samples to devices is the peak velocity. Peak velocity for different sample lengths is shown in figure 3. Similar results for GaAs and InP are also given for comparison. It is seen that In (0·53) Ga (0·47) As gives larger peak velocities than both GaAs and InP.

5. 2 DEG transport

A novel kind of field effect transistor is being currently studied, in which the conduction band bending near the surface adjacent to the gate in a heterostructure FET is so arranged that the bent band forms a quantum well. Electrons have freedom of motion parallel to the surface in such wells as the electron momentum perpendicular to the surface is quantized. Transistors have been constructed by using such heterostructures comprising a large and a small band gap material. The mobility of electrons in such 2 DEG transistors may be very high as large electron concentration may be realised in the undoped active layer by migration from the doped high band gap gate layer. A variation of the usual field-effect transistor structure is also being studied. A gate layer is used in these structures on both the surfaces of the active layer, so that a rectangular quantum well is formed. The carrier concentration may be made higher in such systems as carriers will migrate from both the gate layers and consequently the switching time may be made smaller.

Electron transport in rectangular quantum wells of In (0·53) Ga (0·47) As was studied by the Monte Carlo method, by including band nonparabolicity and considering acoustic phonon and polar optic phonon-scattering. Calculations were simplified by using the MCA approximation. Velocity-field characteristics for the temperature of 77 K are illustrated in figure 4 for well widths of 100 and 200 Å, for

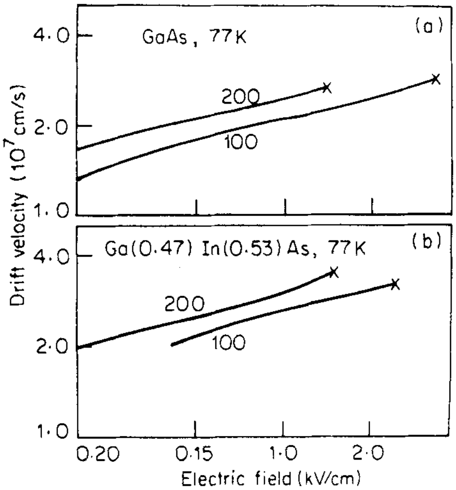

Figure 4. Velocity-field characteristics of In (0·53) Ga (0·47) As and GaAs in rectangular quantum wells for well widths of 100 and 200 Å.

which MCA approximation does not introduce an error of more than 15%. Calculated results for GaAs are also presented for comparison.

It is seen that the velocity rises sharply upto a field of about 500 V/cm and then it increases slowly and reaches a run-away condition. The peak value of stable velocity is $3{\cdot}3 \times 10^7$ cm/s for In (0·53) Ga (0·47) As compared to $2{\cdot}6 \times 10^7$ cm/s for GaAs. The velocity for In (0·53) Ga (0·47) As is also found to be higher than for GaAs at all fields.

6. Conclusion

Calculated results on hot-electron transport characteristics of In (0·53) Ga (0·47) As have been reviewed. It is found that the electron velocity is higher in In (0·53) Ga (0·47) As for the different kinds of device structures using bulk, submicron or 2 DEG systems. The noise performance is similar to that of GaAs but poorer than that of InP.

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