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$Ga_{0.47}In_{0.53}As$—The material for high-speed devices

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Abstract. Electron transport properties of $Ga_{0.47}In_{0.53}As$ are reviewed. The available physical constants of the material and results on electron mobility in bulk materials, 2 DEG systems and under hot-electron conditions are presented. Applications of the material in the construction of FET's and photo-conductive detectors are briefly discussed.

Keywords. Ternary alloy semiconductor; electron mobility; FET; photodetector.

1. Introduction

The speed of semiconductor logic devices and the limiting frequency of operation of amplifying devices are ultimately limited by the material properties. Silicon may be used in comparatively low-speed and low-frequency devices. But, for the realisation of higher speeds and higher frequencies, compound semiconductors, particularly gallium arsenide, have been found to be more suitable. Intensive search is also being carried out for growing materials with still better properties. One line of work has been concerned with ternary and quaternary alloys of III–V and II–VI compounds. The search has yielded one ternary alloy of GaAs and InAs which has electron mobility and saturation velocity higher than that of GaAs. The particular alloy, $Ga_{0.47}In_{0.53}As$, is lattice-matched to InP. Good crystals of this material have been grown by various techniques and devices have also been fabricated which appear to justify some of the expectations. These results achieved through intensive work over the last five years or so are reviewed in this paper.

2. Physical constants

In the early stages of work on $Ga_{0.47}In_{0.53}As$, the various material constants were estimated from the knowledge of the values of the constants for the constituent binaries. The interpolation formulae and the values of the constants obtained by applying these formulae are presented in table 1. The GaAs values are indicated by subscript A and those for InAs by subscript B. Experimental values of many of the physical constants have, however, become available during the course of the last few years. The energy band gap has been studied by Antypas and Moon (1973), Moon *et al* (1974), Takeda *et al* (1976), Nahory *et al* (1978), Yamazoe *et al* (1978), Pearsall (1980), Porod *et al* (1982), Ohno *et al* (1981), Chen and Kim (1981) and Wicks *et al* (1981) and Bhattacharya *et al* (1983). There is general agreement for the room temperature value of 0·75 eV for the direct band gap. The temperature dependence in the earlier studies

Table 1. Physical constants of $Ga_{0.47}In_{0.53}As$.

Physical constant symbol (Unit)	Interpolation formula	Values for		Values for $Ga_{0.47}In_{0.53}As$	
		GaAs	InAs	Interpolated	Experimental
Lattice constant a (Å)	$0.47a_A + 0.53a_B$	5·642	6·058	5·862	—
Effective mass ratio m^*	$\left(\frac{0.47}{m_A^*} + \frac{0.53}{m_B^*}\right)^{-1}$	0·068	0·023	0·033	0·042(0 K)
Band gap E_g (eV)	$0.47E_{gA} + 0.53E_{gB}$	1·522	0·410	0·93(0 K)	0·75(300 K)
Temperature coeff. of band gap α_T (10^{-4} eV/K)	$0.47\alpha_{TA} + 0.53\alpha_{TB}$	−3·95	−3·5	−3·71	−3·26 −2·3
Longitudinal elastic constant C_l ($N m^{-2}$)	$0.47C_{lA} + 0.53C_{lB}$	14·5	10·3	12·3	—
Static dielectric constant K_s	$(K_s - 1)/(K_s + 2) = 0.47(K_{SA} - 1)/(K_{SA} + 2) + 0.53(K_{SB} - 1)/(K_{SB} + 2)$	13·18	14·55	13·88	—
High frequency dielectric constant K_α	$(K_\infty - 1)/(K_\infty + 2) = 0.47(K_{\alpha A} - 1)/(K_{\infty A} + 2) + 0.53(K_{\alpha B} - 1)/(K_{\alpha B} + 2)$	10·9	11·8	11·34	—
Longitudinal optic phonon temperature (K)	—	—	—	—	400
Mass density ρ (gm/cm^3)	$(0.47\rho_A + 0.53\rho_B)$	5·31	5·61	5·469	—
Piezoelectric coupling constant C_{pz}	$0.47C_{pzA} + 0.53C_{pzB}$	0·052	0·0168	0·033	—
Γ-X valley separation (eV)	—	—	—	1	—
Γ-L valley separation (eV)	—	—	—	—	0·55
Spin-orbit splitting (eV)	—	—	—	—	0·379
Acoustic phonon deformation potential constant E_1 (eV)	$(0.47E_{1A}^2 + 0.53E_{1B}^2)^{1/2}$	12	5·8	9·2	—

(Pearsall 1980) was given as

$$E_g(T) = 0.812 - 3.26 \times 10^{-4}T + 3.31 \times 10^{-7}T^2,$$

whereas, more recently it has been given as (Towe 1982)

$$E_g(T) = 0.821 - 2.3 \times 10^{-4}T - 2.39 \times 10^{-7}T^2.$$

The band gap has also been evaluated by a modified virtual crystal approximation by Porod *et al* (1982) and Porod and Ferry (1983). They obtain a value of 0·75 eV for the band gap. Values of the Γ-*L* separation were obtained as 0·51 eV and that of *X*-*L* separation 0·12 eV. A value of 0·55 eV ± 0·05 eV for the Γ-*L* separation was also obtained experimentally by Cheng *et al* (1982).

The effective mass of the band edge electrons in the Γ-valley has been measured by Brendeck *et al* (1979), Nicholas *et al* (1980) and Guldner *et al* (1982). All the different techniques, cyclotron resonance, Shubnikov-de Haas, magneto-phonon and interband magneto-absorption, have been used. There has been some discrepancy in the reported values which has been explained by Nicholas *et al* (1980) as being due to a mistake in the interpretation of resonance peaks. The presently accepted value is 0·041 m_0 at near-helium temperature. The effective mass has also been calculated by Guldner *et al* (1982) by the k.p method using the values of the momentum matrix element and the spin-orbit splitting. The calculated value is 0·0385 m_0 and is about 6% smaller than the experimental value.

The spin orbit splitting has been measured by Yamazoe *et al* (1981) to be 0·379 eV and it differs by about 50 MeV with the earlier value obtained by Perea *et al* (1980).

The lattice vibration spectrum has been studied by Brodsky and Lucovsky (1968), Yamazaki *et al* (1980), Pinczuk *et al* (1978), Nicholas *et al* (1980) and Pearsall *et al* (1979) by Raman scattering and Portal *et al* (1978) by magnetophonon resonance.

The spectra have two different modes corresponding to GaAs and InP. The LO mode frequency corresponding to GaAs is 278 cm^{-1} and the mode is split off by about 15 cm^{-1}. The mode corresponding to InAs has frequencies around 230 cm^{-1} with very little separation between the LO and TO mode. However, the ratio of the mode intensities for the two kinds of modes is about 1·5 : 0·25 (Yamazaki *et al* 1980) and effectively one kind of optic phonons with effective temperature 400 K are assumed to be active.

Experimental values for all the other constants are not, however, reported as yet and all the calculations of the phenomenological parameters have to be made by using the interpolated values. It may, however, be noted that the interpolated values for constants are in fair agreement with experimental values wherever available. Acceptance of the interpolated values for constants whose experimental values are not available is not, therefore, likely to introduce much error.

3. Electron mobility

Electron mobility in $Ga_{0\cdot47}In_{0\cdot53}As$ has values higher than in GaAs and InP, the materials which were so far considered to have better properties than Si for high frequency applications. This was evident from the measurements of mobility for the bulk materials carried out by Abrahams *et al* (1959), Conrad *et al* (1967), Wagner (1970), and Dzahakhutashivili *et al* (1971). However, the material is mostly used in epitaxial form in devices and studies over the past few years have been concentrated on epitaxial layers grown by the various techniques, VPE (Katoda *et al* 1974), LPE (Pearsall 1980; Claxton *et al* 1982), MBE (Massies *et al* 1982; Cheng *et al* 1981) as well as MOCVD (Razeghi *et al* 1982; Duchmin *et al* 1981; Cho 1983). There is fairly good agreement between the results obtained by different workers. We present first these experimental results.

3.1 *Low-field experiment*

The temperature dependences of mobility as obtained by Takeda *et al* (1976) and Massies *et al* (1982) are illustrated in figure 1. Figure 2 illustrates the electron concentration dependence of mobility at 300 K and 77 K over the concentration range 10^{16}–10^{18} for materials grown by LPE and 10^{16}–$10^{19}/cm^3$ for MBE materials. Mobility values for MOCVD samples, also shown in figure 2, are lower. Studies have also been made of the effect of lattice mismatch and layer thickness on the mobility in MOCVD materials by Razeghi *et al* (1982). Lattice mismatch reduces the mobility for values of $\Delta a/a > \pm 5 \times 10^{-3}$. Electron mobility in high purity LPE materials with impurity concentrations of the order of $10^{14}/cm^3$ over the temperature range 10–300 K has been recently reported by Rao and Bhattacharya (1983) and Bhattacharya *et al* (1983). These are also presented in figure 1. It should be noted that the highest values of mobility so far reported are 1·2 and 6 $m^2/V.S.$ respectively at 300 K and 77 K.

3.2 *Low-field theory*

The electron mobility in ternary semiconductors was studied in detail by Harrison and Hauser (1976). The study was based on interpolated values of most of the physical constants. Reasonable agreement was found between theory and experiment by assuming an impurity concentration equal to the electron concentration and adjusting effectively the alloy scattering potential. Later studies by Adams *et al* (1980) showed a strong component in the mobility which varies with temperature as $T^{-1/2}$. Such a

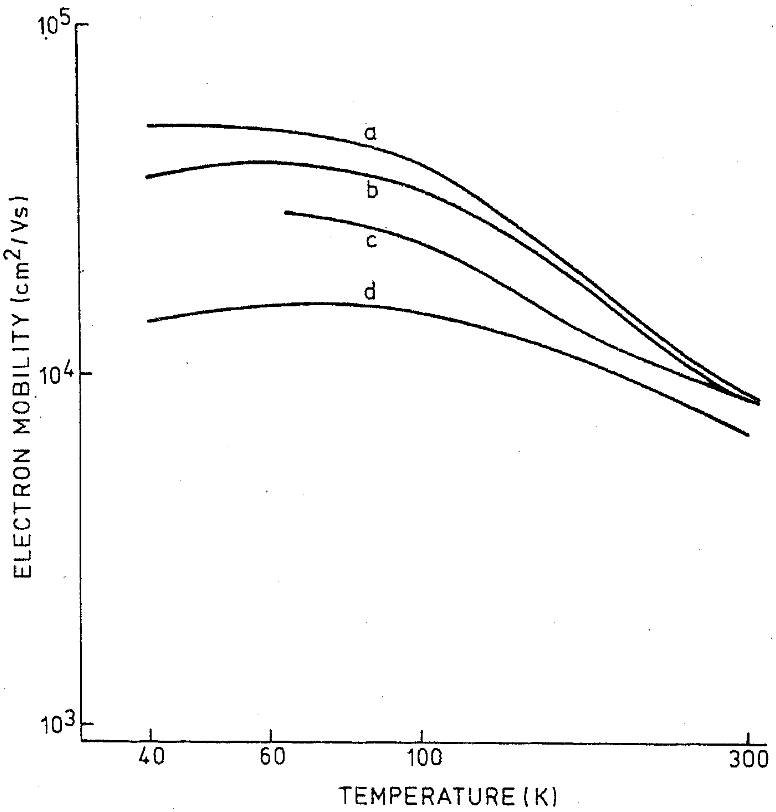

Figure 1. Electron mobility at temperatures between 40 and 300 K. **a.** Bhattacharya *et al* (1983); **b.** Cho (1983); **c.** Takeda *et al* (1976); **d.** Rao and Bhattacharya (1983).

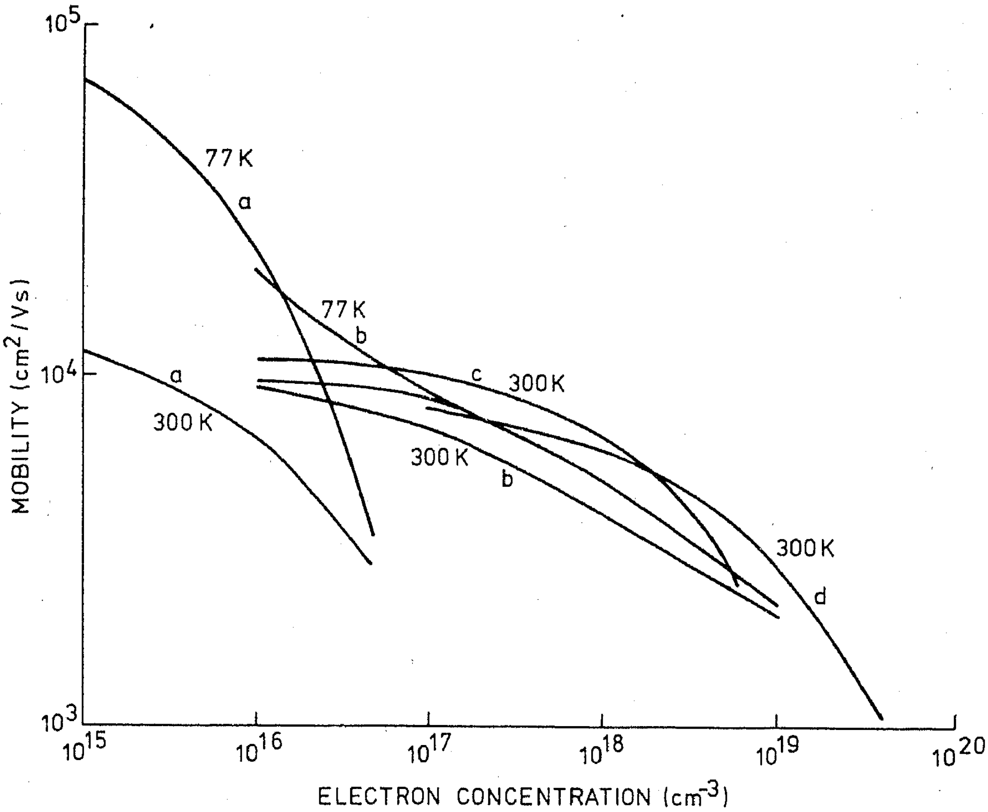

Figure 2. Electron mobility for electron concentrations between 10^{15} and $10^{20}\ cm^{-3}$. **a.** Razeghi *et al* (1982); **b.** Cho (1983); **c.** Pearsall (1980); **d.** Clanton *et al* (1982).

variation with T may be due to either space charge, cluster or alloy scattering. Adams *et al* (1980), however, studied the pressure dependence of mobility and established that this temperature dependence may be interpreted to be mostly due to alloy scattering.

Electron mobility in degenerate materials has been analysed and reasonable agreement was again found between theory and experiment, by assuming a compensation ratio of about 5. Experimental values of mobility for electron concentrations of about $10^{19}/cm^3$ were also found to be in good agreement with theoretical calculations of Takeda and Sasaki (1980).

In spite of the agreements reported by various workers there is still scope for a detailed examination of the low-field electron mobility. The electron mobility in ternary materials like $Ga_{0.47}In_{0.53}As$ is strongly affected by alloy scattering. Till today, the alloy scattering potential ΔU in this material and the exact form of alloy scattering potential are not known (Nishinaga and Hiramatsu 1983; Hiramatsu and Nishinaga 1983). In earlier studies, experimental data have been fitted by choosing different values of ΔU, in the range 0·66–0·42 eV. The volume of scattering potential discontinuity is also an unknown quantity and it also depends on the magnitude of ordering. The agreement so far reported has also been based on calculations using interpolated values of physical constants. Considering the importance of $Ga_{0.47}In_{0.53}As$ it would be useful to evaluate the various low-field transport coefficients using recent values of physical constants for different impurity concentrations and for different strengths of alloy scattering.

3.3 *Hot-electron mobility*

Hot-electron velocity-field characteristics have been studied both experimentally and theoretically. The characteristics for fields below the threshold value were obtained at 300 K by Sasaki (1977), Houston *et al* (1978) and Marsh *et al* (1980) from conventional experiments. The characteristics are shown in figure 3. The threshold field for negative resistivity obtained in different experiments lies between 2·7 and 4·6 kV/cm. The peak velocity for electrons has also been obtained by studying the minority carrier transport in *p*-type materials (Degani *et al* 1981) and from the study of field effect transistors (Bandy *et al* 1981). The results of the former experiment are also included in figure 3. It was observed that v_{peak} is about $2{\cdot}6 \times 10^7$ cm/sec and the threshold field is larger than 7 kV/cm. Experiments with FET gave a value of $2{\cdot}95 \times 10^7$ cm/sec for v_{peak}.

The velocity-field characteristics for fields upto about 150 kV/cm have been obtained by Windhorn *et al* (1982) using the microwave time-of-flight technique of Evans and Robson (1974) over the temperature range 95–385 K. The characteristic for 300 K and 95 K are included in figure 3.

Energy loss rate under hot electron conditions has been studied by Shah *et al* (1980). It was concluded that the energy loss rate is smaller than in GaAs by a factor of about 3, and the energy of the phonon responsible for this loss is 34 meV.

Velocity-field characteristics for 300 K upto a field of about 16 kV/cm was computed by the Monte-Carlo method by Littlejohn *et al* (1977, 1978) for $Ga_{0{\cdot}5}In_{0{\cdot}5}As$. The threshold field and the peak velocities obtained in these calculations are respectively about $2{\cdot}2 \times 10^7$ cm/sec and 4 kV/cm, which are close to the experimental values. The velocity for post-threshold fields is, however, significantly smaller than that of Windhorn *et al* (1982). The characteristics has also been computed by Marsh (1982) using more recent values of the physical constants and including the effect of clustering. The velocities for pre-threshold fields were found to be in excellent agreement with experiments but the threshold field was around 3·2 kV/cm, about 10% higher than some experiments. It should be noted that in all these calculations the estimated values

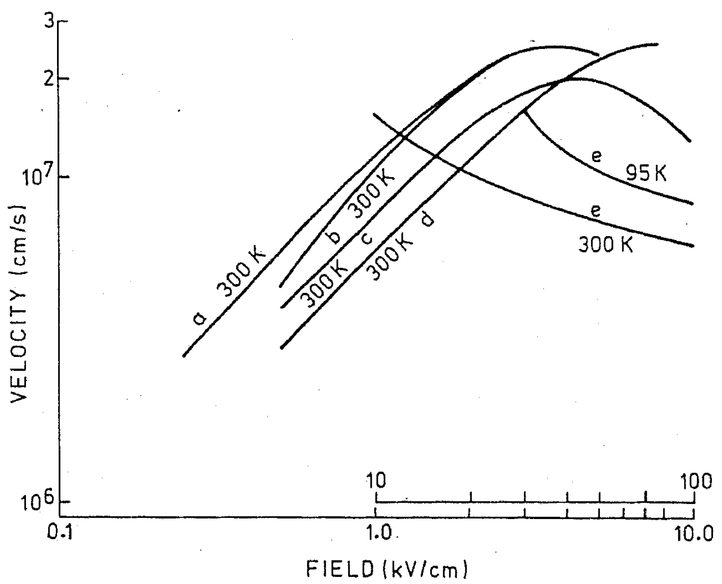

Figure 3. Electron velocity at field between 100 V/cm and 100 kV/cm. **a.** Marsh *et al* (1980); **b.** Marsh (1982); **c.** Littlejohn *et al* (1978); **d.** Degani *et al* (1981); **e.** Windhorn *et al* (1982).

were used for the band parameters for the L and X valleys and for the intervalley coupling constants. These parameters affect more significantly the post-threshold values and as experimental values of velocity are now available for such fields, Monte-Carlo calculations covering the high-field region would be very fruitful for judging the correctness of the estimated values of the parameters.

3.4 *Mobility in 2 DEG systems*

Electron mobility in two-dimensional systems has been studied by Drummond *et al* (1982), Guldner *et al* (1982) and Katalsky *et al* (1982). Drummond *et al* (1982) studied two types of systems undoped $Ga_{0.47}In_{0.53}As$ on doped $Al_{0.48}In_{0.52}As$ and doped $Al_{0.48}In_{0.52}As$ on undoped $Ga_{0.47}In_{0.53}As$ grown by MBE, with 80 Å thick undoped $Al_{0.48}In_{0.52}As$ spacer. The mobility-temperature curves obtained by them are shown in figure 4. Guldner *et al* (1982) on the other hand produced 2 DEG by growing with MOCVD

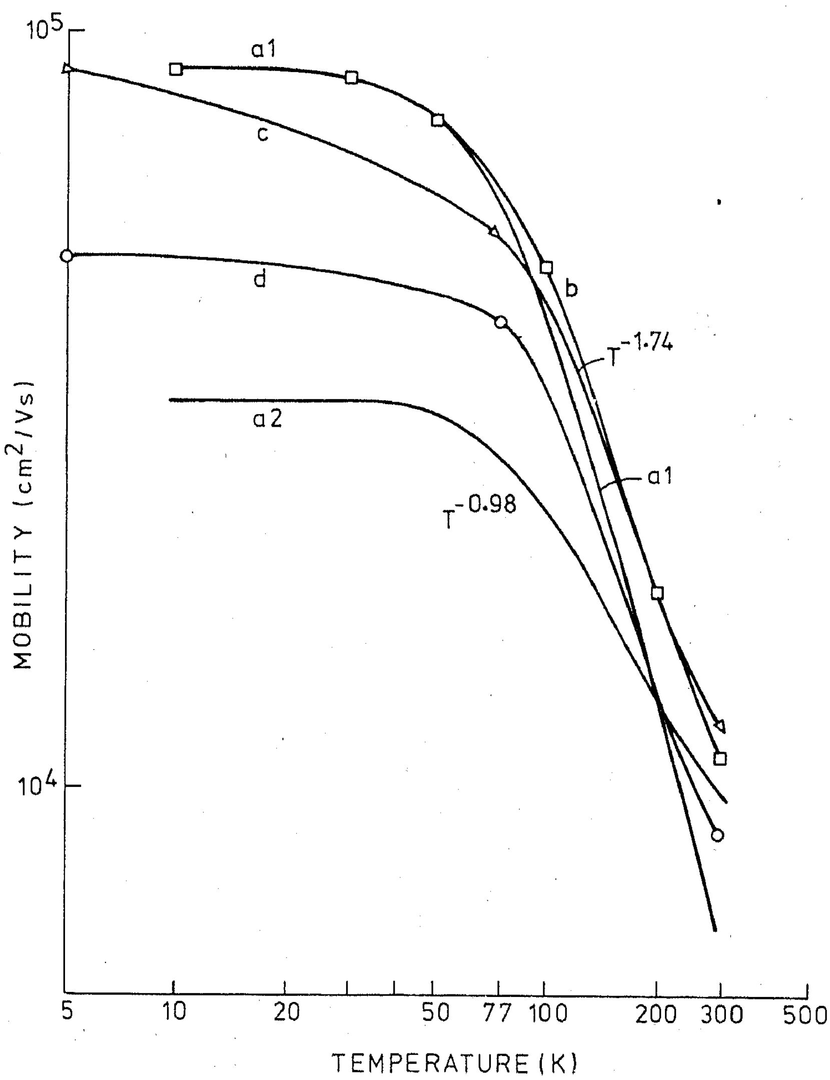

Figure 4. Electron mobility in 2 DEG systems at temperatures between 5 and 300 K. **a1.** Drummond *et al* (1982) AlInAs on GaInAs. **a2.** Drummond *et al* (1982) GaInAs on AlInAs; **b.** Kastalsky *et al* (1982); **c.** Razeghi *et al* (1982); **d.** Guldner *et al* (1982).

technique $Ga_{0\cdot47}In_{0\cdot53}As$ on InP. The mobilities determined by them for 300, 77 and 4·2 K (0·88, 4·2, 5·1) are also shown in figure 4. In addition to mobility, the effective mass and the electron concentration were also determined from cyclotron resonance and Shubnikov-de Haas effect. The effective mass ratio was 0·047 ± 0·0001 and the electron density $4\cdot3 \times 10^{-11}$ cm^2. The increased value of the effective mass has been ascribed to non-parabolicity. Electron mobility obtained by Razheghi *et al* (1982) using hetero-junction structure were different for different layers of $Ga_{0\cdot47}In_{0\cdot53}As$ grown on InP. The highest values obtained by them for a thickness of 0·6 μm are shown in figure 4 (1·2, 5·5, 9). On the other hand for superlattice quantum well structures the values were (0·76 and 1·8). Kastalsky *et al* (1982) studied mobility using the same structure as used by Drummond *et al* (1982). The mobility temperature curve obtained by them are shown in figure 4, which is almost identical to that of Drummond *et al* (1982).

Hsieh *et al* (1983) studied the effect of spacer thickness and for the optimum thickness of 80 Å at 300 K and 120 Å at 77 K obtained the mobility values of 1·09 and 5·5 m^2/V sec. The corresponding values for GaAs-GaAlAs system are 0·679 and 9·55 m^2 V^{-1} sec^{-1}.

Electron mobility in 2 DEG $Ga_{0\cdot47}In_{0\cdot53}As$ has been theoretically computed by Basu and Nag (1983). The low temperature value is limited by alloy scattering. Since no definite value for alloy scattering potential has yet been established it was treated as an adjustable parameter and a value of 0·42 eV explained the experimental results.

4. Applications

Studies on the properties of $Ga_{0\cdot47}In_{0\cdot53}As$ have established that the electron mobility and the peak electron velocity in this material are higher than in GaAs. The material is, therefore, being tested for use in various devices. It should be noted that the energy band gap of $Ga_{0\cdot47}In_{0\cdot53}As$ (0·75 eV) is in the right range for its application in photodiodes and laser for the wavelength 1·65 μm, where the optical fibres have a low-loss window. Such diodes in various forms and lasers have been constructed and proved to be useful. We shall not review these devices here, but only those for which the high mobility is an advantage. We shall review the progress in two such devices namely the FET's and photoconductive detectors.

4.1 FET

Conventional techniques of Schottky FET's are not applicable to $In_{0\cdot53}Ga_{0\cdot47}As$ as the barrier height for such Schottky contacts is small (~ 0·2 eV) and gate leakage current, as a result, is large. Three kinds of techniques have been tried for increasing effectively the barrier height or reducing the leakage current. In one technique (Leheny *et al* 1980; Chen *et al* 1982), zinc was diffused on the surface to form a *p-n* junction gate, or a shallow junction with a *p*-layer was formed. In the second technique, a thin layer of InGaAsP (Bandy *et al* 1981) or $Al_{0\cdot48}In_{0\cdot52}As$ (Ohno *et al* 1980) was used on top of the $In_{0\cdot53}Ga_{0\cdot47}As$ layer. The third technique was to produce an insulated gate structure. For the insulator native oxide (Morgan and Frey 1978; Liao *et al* 1982), SiO_2 (Weider *et al* 1981) or Si_3N_4 (Liao *et al* 1981) was used. The transconductance is highest in the native oxide inversion mode (Liao *et al* 1981) FET's and a value of 33 ms/mm was realised. The oxide was grown by a plasma technique (Tell *et al* 1981). A gain of 12 dB at 8 GHz has also been reported for the FET's with top heterostructure (Bandy *et al* 1981).

4.2 *Photodetectors*

The high electron velocity in $Ga_{0.47}In_{0.53}As$ is useful in designing photodiodes with high operating speeds. For this purpose the structure is so constructed that the photons are absorbed in a region where electrons are minority carriers. This may be done by allowing the light to be absorbed in p^+ layer in a p^+nn^+ homojunction structure or using a heterojunction and allowing the light to be absorbed in the depletion region. The response time achieved by such construction is of the order of 100 psec.

The high velocity is more gainfully employed in photoconductive photodetectors which have both the advantages of low noise and large gain as compared to *p-n* or *p-i-n* photodetectors (low noise, no gain) and avalanche photodetectors (large gain, large noise). Such detectors have been studied by Gammel *et al* (1981), Klein *et al* (1981) and Degani *et al* (1981). The gain of the devices is determined by the ratio of life time and transit time. Using 3 μm long devices, a gain of 10 may be obtained. The response time may also be as low as 40 psec. In fact, the lowest limit for non-resonant absorption ($h\nu_{ex} > E_g$) is set by hot electron energy relaxation time (Bimberg 1982) to about 40 psec, which appears to have been already realised. The performance of the devices is in agreement with a saturation velocity around $2 \cdot 5 \times 10^7$ cm/sec. The noise behaviour, at present, is mostly limited by the states at the interface with the substrate, but is likely to improve with improvement in materials.

5. Conclusion

Experimental results on electron mobility in $Ga_{0.47}In_{0.53}As$ for bulk materials, 2 DEG systems and under hot electron conditions agree with theoretical expectations. The performance of FET's and photodetectors constructed with the material show that devices with high frequency of operation and small response time may be realised.

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