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Heavy Doping Effects on Bandgap and Minority Carrier Transport for AlGaAs/GaAs HBT's

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Bandgap narrowing in heavily doped p-type GaAs is estimated by photoluminescence measurement. Measured values agree well with the theoretical results. Monte Carlo simulation of minority-electron transport demonstrates that electron-hole scattering and hole-plasmon scattering play an essential role in heavily doped p-GaAs. Theoretical calculations on heterojunction bipolar transistors (HBT's) show that these heavy doping effects are substantial and must be considered when analyzing or designing HBT's with heavily doped base layers.

1. Introduction

AlGaAs/GaAs heterojunction bipolar transistors (HBT's) have recently demonstrated high speed capabilities and appear promising for high frequency and logic applications. For an HBT, the operating speed can be greatly improved by reducing the electron transit time through the device, as well as the base-resistance collector-capacitance product. In conventional molecular beam epitaxy (MBE), beryllium (Be) is commonly used as a p-type dopant. A maximum doping level of $2x10^{20}$ cm^{-3} has been achieved by growth at a low substrate temperature.[1)] However, a further increase of the hole concentration is difficult in Be-doped GaAs, because of thermal diffusion and interstitial incorporation of Be.

Recently, we have obtained heavily carbon (C) doped GaAs with a carrier concentration up to $1.5x10^{21}$ cm^{-3} by metalorganic molecular beam epitaxy (MOMBE).[2-4)] At these high doping levels bandgap narrowing, hole plasmon scattering and Auger recombination will strongly affect the performance of HBT's. In this paper we present experimental results and theoretical calculations of these heavy doping effects and their consequences on the performance of HBT's.

2. Optical properties and bandgap narrowing

The photoluminescence (PL) of Be and C-doped GaAs were measured at 4.2K. The effective bandgap narrowing was estimated using these luminescence spectra in the same way as reported in Ref. 7, and the results are plotted in Fig. 1. In this figure, the effective bandgap narrowing of Zn-doped[5-8)] GaAs are also plotted. Note that the measured bandgap narrowing of Zn, Be and C-doped GaAs all appear to be consistent with one another.

Next we calculated the effective bandgap narrowing as a function of impurity concentration. The calculations are based on the density of states functions resulting from the work of Kane[9)] and Morgan.[10)] The screening length is a critical parameter in this theory and we adopted the same screening length function as that used in Ref. 11. The solid lines in Fig. 1 are the theoretically calculated hole concentration dependence of the effective bandgap narrowing. The calculated values for the bandgap narrowing show good agreement with the values derived from the PL measurements.

3. Minority carrier transport

The transport of minority electrons has been investigated using Monte-Carlo methods. In addition to the standard scattering mechanisms, electron-hole scattering,[12] hole-plasmon scattering[13] and screened LO phonon scattering[13] were taken into account in the heavily doped p-GaAs. The electron scattering rate as a function of the electron energy are plotted in Figs. 2(a) and 2(b) for doping levels of 10^{20} cm^{-3} and 10^{21} cm^{-3}, respectively. At these high doping levels, the LO phonon scattering does not contribute to the electron energy relaxation because LO phonons are strongly screened by hole plasmons. Instead the electron-hole scattering and the hole-plasmon scattering play an essential role at hole concentrations larger than 1×10^{19} cm^{-3}.

The drift velocities of electrons injected into heavily doped p-GaAs as a function of the applied electric fields are plotted in Fig. 3. At low fields the electron-hole scattering has the same angular distribution as impurity scattering, and has the same effect on the electron mobility as doubling the doping level. Consequently, the minority-electron mobilities are smaller than those of majority electrons. The minority-electron mobilities estimated from Fig. 3 are in good agreement with the values previously

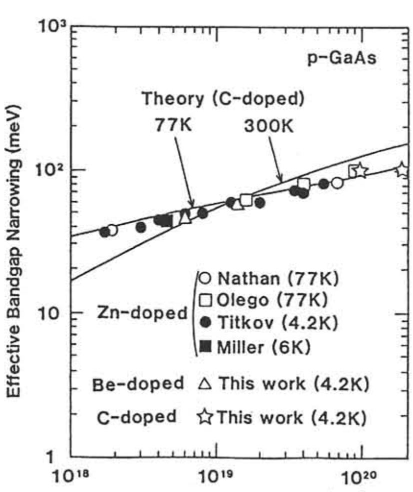

Fig.1 Effective bandgap narrowing as a function of hole concentration estimated from PL measurement. The solid lines are the theoretically calculated hole concentration dependence of the effective bandgap narrowing.

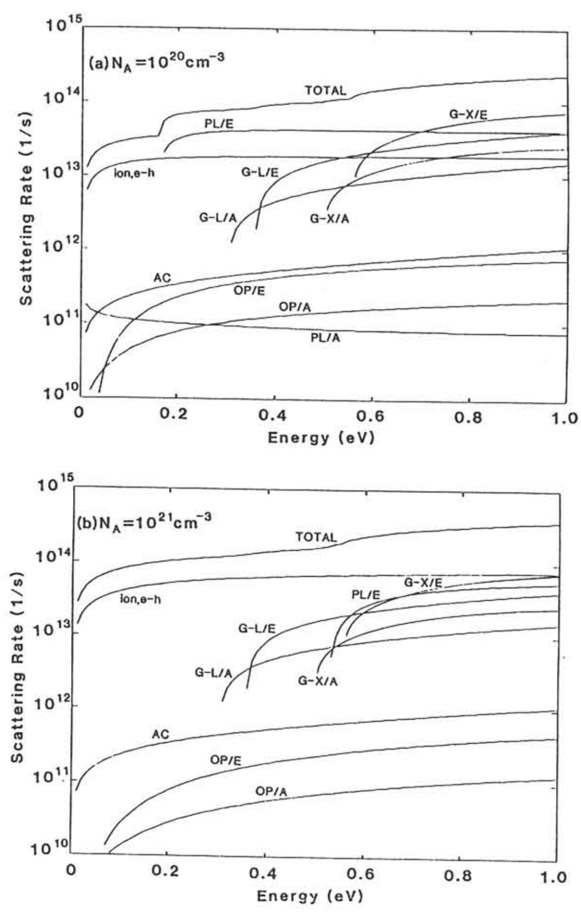

Fig.2 Scattering rates of an electron in the central valley of GaAs with a carrier concentration of (a) 10^{20} cm^{-3} and (b) 10^{21} cm^{-3}. ion: ionized impurity scattering, e-h: electron-hole scattering, AC: acoustic phonon scattering, OP: optical phonon scattering, G-L: Γ-L intervalley scattering, G-X: Γ-X intervalley scattering, PL: hole-plasmon scattering, /E: emission, /A: absorption.

calculated[14,15] for hole concentration between 10^{17} and 10^{19} cm^{-3}. At a hole concentration of $1x10^{21}$ cm^{-3}, the minority-electron mobility is determined to be 300 cm^2/Vs.

As the electric field is increased, the rate at which electrons lose energy through hole-plasmon scattering increases. At hole concentrations between 10^{19} and 10^{20} cm^{-3}, this leads to the retention of electrons in the central valley. As a result, negative differential resistance does not appear at electric fields up to 10 kV/cm. On the other hand, at hole concentration of $1x10^{21}$ cm^{-3}, the plasmon energy becomes larger than the Γ-L valley separation of 0.33 eV. Consequently, even at low electric fields most electrons transfer to the upper valleys before they lose energy through hole-plasmon scattering.

4. Static characteristics of HBT's

The static characteristics, including bandgap narrowing and Auger recombination, of HBT's with a base doping level of 10^{21} cm^{-3} were calculated. Bandgap narrowing was taken into account using the following expression:[7]

$$\Delta E_g=-2.2x10^{-8}(N_A)^{1/3} \qquad (1)$$

In addition to Shockley-Read-Hall (SRH) recombination, Auger recombination was also taken into account by the following:

$$R_A=(A_n n+A_p p)(pn-n_{ie}^2) \qquad (2)$$

SRH life time was assumed to be 1 ns and parameters A_n and A_p were taken to be $1x10^{-31}$ cm^6/s. This leads to a minority-electron lifetime of 9.9 ps in p^{++} GaAs with a hole concentration of 10^{21} cm^{-3}. The minority-electron mobility was estimated to be 300 cm^2/Vs from Monte Carlo simulation, which gives a minority-electron diffusion length L_n=880 Å.

The HBT structure parameters used in the simulation are shown in Table I. The base layer is heavily doped with C up to $1x10^{21}$ cm^{-3}. Fig. 4 shows the common-emitter current gain versus collector current density with the base width W_B as a parameter. The bandgap narrowing in the base increases the current gain by a factor of 10 for this doping level over what it would have been with no bandgap narrowing.

Table I Simulated HBT structure.

Layer	Thickness (Å)	Type	Doping (cm^{-3})	AlAs Fraction
Emitter	1200/300	n	$5x10^{17}$	0.3/0.3-0
Base	W_B	p^+	$1x10^{21}$	0
Collector	5000	n	$5x10^{16}$	0
Buffer	1500	n	$5x10^{17}$	0

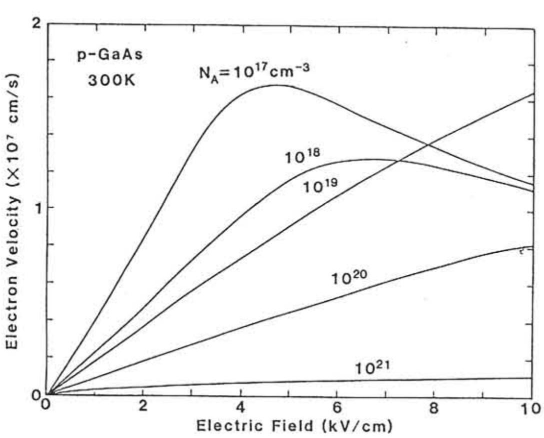

Fig.3 Drift velocity of minority-electrons as a function of the electric field in p-type GaAs.

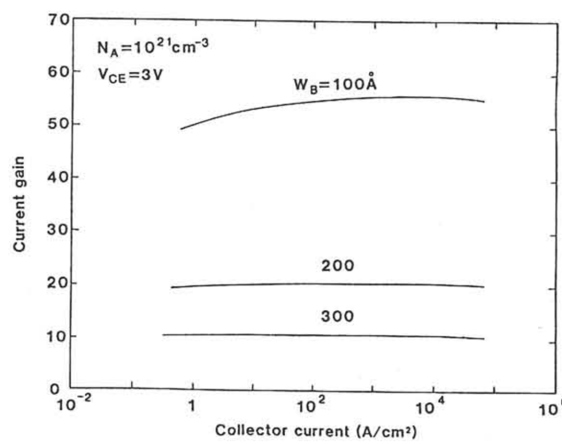

Fig.4 Common-emitter current gain versus collector current density with the base width W_B as a parameter.

However, Auger recombination increases the base current substantially, which decreases the current gain. From Fig. 4 it can be seen that, in order to obtain a current gain of 10 it is necessary to reduce the base width to less than 300 Å.

5. Conclusions

Bandgaps of heavily doped p-type GaAs were determined by PL measurement. Measured bandgap narrowing values agree well with the theoretical results. Moreover the transport of minority electrons was investigated using Monte Carlo methods. Electron-hole scattering and hole-plasmon scattering were shown to play an essential role in heavily doped p-GaAs. Based on these results, static characteristics of HBT's with base doping level of 10^{21} cm^{-3} were calculated. In order to obtain a current gain of 10 it was found necessary to reduce the base width to less than 300 Å.

Acknowledgment

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