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Energy Transport Modeling of Graded AlGaAs/GaAs HBTs: Importance of Giving Adequate Transport Parameters

K. Okada, A. Nakatani and K. Horio

Faculty of Systems Engineering, Shibaura Institute of Technology
307 Fukasaku, Omiya 330, Japan (TEL:81-48-687-5813, FAX:81-48-687-5198)

AlGaAs/GaAs HBTs have received great interest for applications to high-speed and high-frequency devices and ICs. Since nonequilibrium carrier transport becomes important in the HBTs, carrier energy must be considered in the modeling of them. For this purpose, an energy transport model that uses hydrodynamic equations derived from the Boltzmann equation is attractive and has been applied to AlGaAs/GaAs HBTs [1],[2] as well as GaAs MESFETs and Si MOSFETs *etc.*. In the HBTs, material parameters should depend on material composition as well as carrier energy and the doping densities. However, up to now, methods of giving parameters in the transport equations were too rude. In [1], a constant value of energy relaxation time was assumed, and in [2] parameters for GaAs at a certain doping density were also assumed for all x in $Al_xGa_{1-x}As$. So, in this work, a method of giving composition-, doping-, and energy-dependent transport parameters is proposed, and successfully applied to the simulation of AlGaAs/GaAs HBTs.

Here, we consider AlGaAs/GaAs HBTs where Al composition x changes from 0.3 to 0 in the emitter and/or base regions, as shown in Fig.1. #1 is a graded-base structure, and #2 is a graded-emitter structure. If we now treat an equivalent one-valley model where an upper and a lower valleys are considered, we must give transport parameters (such as average electron mobility μ_n, energy relaxation time τ_w and upper valley fraction F_U) as functions of Al composition x, electron energy w_n and doping density N. To do this, we first evaluate the transport parameters (by Monte Carlo method) as a function of w_n for some representative x (0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3) and N. Fig.2 shows such examples. Once these are available as fit curves or tables for several given N, parameters for any x between 0 and 0.3 can be obtained as functions of w_n and N by linear extraporation method. It should be noted that there is one problem in the linear extraporation method when we determine electron energy at thermal equilibrium: w_{n0} for every x. Careless determination by $w_{n0} = w_{n01} + (x - x_1)(w_{n02} - w_{n01})/(x_2 - x_1)$ leads to a great fluctuation of electron temperature T_{n0} at zero bias. Instead, by combining an equation: $w_{n0} = (3/2)kT_{n0} + F_{U0}\Delta_{LU}$ (Δ_{LU}: valley energy separation) and a relation between w_{n0} and F_{U0} (determined by the linear extraporation), we can obtain constant T_{n0} throughout the device.

Next we describe calculated examples of device characteristics. Fig.3 shows cutoff frequency f_T - collector current density I_C curves for graded-base HBT (#1) calculated by using various kinds of parameters. In the case using GaAs parameters for all x (GaAs Parameters) where N dependence is considered, f_T is estimated rather higher than that obtained by considering x dependence of transport parameters (AlGaAs Parameters). This is because electron-velocity overshoot in the base region is overestimated as seen in Fig.4. If the N dependence is also neglected (GaAs: 2×10^{17} cm^{-3}), the deviations become much larger. In the case using constant τ_w of 1 psec, the electron velocity profile in the base region deviates much from those obtained by using Monte Carlo parameters, and f_T is estimated lower. So, we can say that to use reasonable transport parameters is important to estimate the characteristics of graded-base HBTs adequately.

Fig.5 shows f_T - I_C curves for graded-emitter HBT (#2) calculated by using two kinds of parameters. As expected, deviation between the two characteristics is not so large. However, it is unexpected that in the case using AlGaAs parameters, f_T is estimated higher in relatively low current region. This is because in the case using AlGaAs parameters, the emitter resistance is higher and the potential drop becomes remarkable in the $Al_{0.3}Ga_{0.7}As$ emitter as well as in the graded emitter region (Fig.6), which leads to a higher effective field at the graded emitter region near the base and a higher electron velocity around the emitter-base junction (Fig.7). So, the base delay time becomes shorter and f_T is estimated higher in this current region.

In conclusion, we have developed an energy transport simulation method for graded AlGaAs/GaAs HBTs, which uses Al composition-, doping-, and energy-dependent transport parameters estimated by Monte Carlo method. This approach can also be applied to other devices that have position-dependent band structures.

[1] K.Horio, Y.Iwatsu and H.Yanai, *IEEE Trans. Electron Devices*, vol.36, pp.617-624, 1989.

[2] A.Azoff, *IEEE Trans. Electron Devices*, vol.36, pp.609-616, 1989.

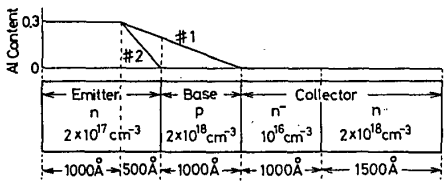

Fig.1 Device structure considered in this study.

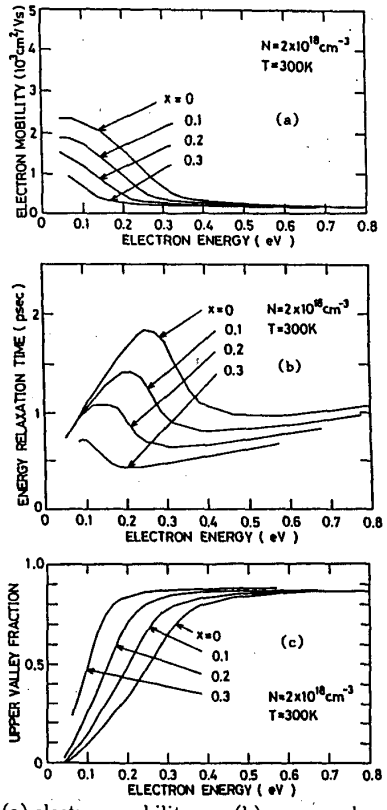

Fig.2 (a) electron mobility μ_n, (b) energy relaxation time τ_w, and (c) upper valley fraction F_U versus electron energy w_n curves as a parameter of x in $Al_xGa_{1-x}As$, calculated by a Monte Carlo method. The energy difference between upper and lower valleys Δ_{LU} and upper-valley effective mass m_U are set to $0.284 - 0.605x$ (eV) and $0.23m_0$, respectively.

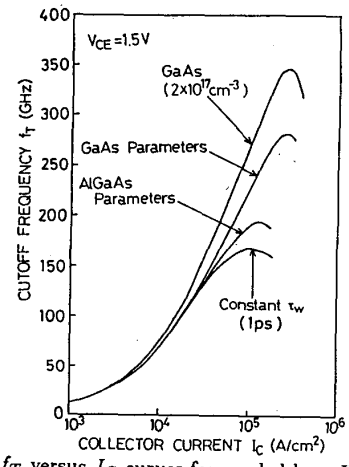

Fig.3 f_T versus I_C curves for graded-base HBT calculated by using various parameters.

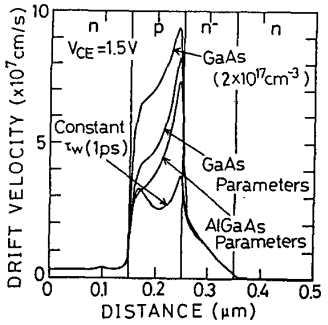

Fig.4 Average electron velocity versus distance curves calculated by using various parameters, corresponding to Fig.3. $I_C = 10^5$ A/cm^2.

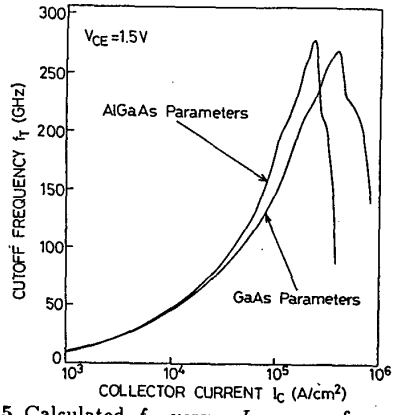

Fig.5 Calculated f_T versus I_C curves for graded-emitter HBT.

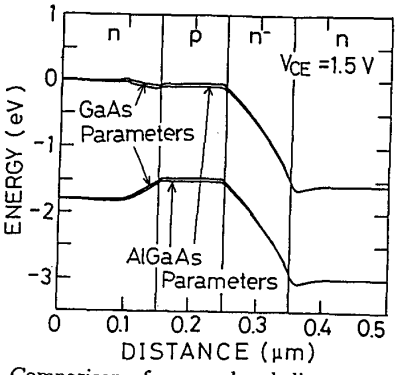

Fig.6 Comparison of energy band diagrams calculated by using different parameters, corresponding to Fig.5. $I_C = 2 \times 10^5$ A/cm^2.

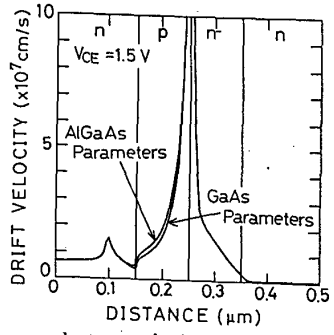

Fig.7 Average electron velocity versus distance curves, corresponding to Fig.6. $I_C = 2 \times 10^5$ A/cm^2.