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Modeling of Surface Recombination in GaAlAs/GaAs HBT's

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Based on Spicer's unified defect model, both surface Fermi level pinning and surface recombination were newly introduced into a two-dimensional numerical model of GaAlAs/GaAs HBT's to theoretically investigate surface state effects on the device performance. It was shown that surface recombination was significant only at the boundary region between the intrinsic base and the extrinsic base. As a result, although current gain degrades with the existence of surface states, it does not depend on the spacing between the emitter and the base electrode edges.

I. Introduction

GaAlAs/GaAs heterojunction bipolar transistors (HBT's) have attracted much interest because of their possibility of high speed applications. In order to realize the full performance of intrinsic HBT's, however, various parasitic elements accompanying the extrinsic region must be removed. One of the most important problems is the recombination current in the extrinsic base region. It degrades current gain significantly[1-3]. In the previous paper, the above effect was theoretically investigated for HBT's with an ion-implanted extrinsic base region, using a two-dimensional numerical model[4]. The main origin of the excess base current in the extrinsic base region was considered to be ion-implantation damage. In mesa-type HBT's, on the other hand, the main origin of the excess base current is supposed to be surface recombination. Surface effects, such as surface Fermi level pinning and surface recombination, have been pointed out as important problems from the first stage of their development. However, the effects of the surface on device performance have remained not fully analyzed.

In this study, a simple model including both surface Fermi level pinning and surface recombination is proposed, and the model is introduced into a two-dimensional numerical model of GaAlAs/GaAs HBT's[4] in order to theoretically investigate the effects of the surface on device performance.

II. Model and Device Structure

A surface model developed in this study is based on Spicer's unified defect model[5]: i.e. two defect states associated with either a missing cation (a donor state 0.925eV below the conduction band edge) or an anion (an acceptor state 0.8eV above the valence band edge) are assumed in order to represent surface Fermi level pinning in GaAs. It is also assumed that these states act as a recombination center[6].

Then, Poisson's equation, including the spatial variation of the dielectric constant ε and various deep levels, is written as

$$\mathrm{div}(\varepsilon \,\mathrm{grad}\Psi) = -q(N_D{}^+ - N_A{}^- + N_{TD}{}^+ - N_{TA}{}^- + p - n)$$

where $N_{TD}{}^+$ is the density of the ionized donor type recombination center, i.e. the density of a positively charged recombination center emitting electron, and N_{TA}^- is the density of the ionized acceptor type recombination center, i.e. the density of a negatively charged recombination center capturing electron.

N_{TD}^+ and N_{TA}^- are expressed as

$$N_{TD}^+ = \frac{(1/c_{pD})n_{TD}+(1/c_{nD})p}{(1/N_{TD}c_{pD})(n+n_{TD})+(1/N_{TD}c_{nD})(p+p_{TD})}$$

$$N_{TA}^- = \frac{(1/c_{pA})n+(1/c_{nA})p_{TA}}{(1/N_{TA}c_{pA})(n+n_{TA})+(1/N_{TA}c_{nA})(p+p_{TA})}$$

where N_{TD} and N_{TA} denote the densities of the donor and acceptor type recombination centers, respectively, and c_{nD}, c_{pD}, c_{nA} and c_{pA} are the electron and hole capture rates for each center. n_{TD} is the density of electrons that would be in the conduction band if the electron Fermi level was located at the position of the donor type recombination center. p_{TD}, n_{TA}, and p_{TA} have similar meanings.

The recombination rate R can be expressed as

$$R = \frac{pn - n_i^2}{\tau_p(n+n_i)+\tau_n(p+n_i)} + \frac{pn - n_i^2}{(1/N_{TD}c_{pD})(n+n_{TD})+(1/N_{TD}c_{nD})(p+p_{TD})} + \frac{pn - n_i^2}{(1/N_{TA}c_{pA})(n+n_{TA})+(1/N_{TA}c_{nA})(p+p_{TA})}$$

The first term expresses conventional Schokley-Read-Hall type recombination through a neutral recombination center located at the intrinsic Fermi level. The second and the third terms denote recombination through the donor and acceptor type surface recombination centers, respectively.

The life times of the electron(τ_n) and the hole(τ_p) were assumed to be 10^{-9}s for the bulk semiconductor[7]. For the surface states, the values of the density and capture rates were estimated as follows.

A defect density of $\sim 10^{13}\mathrm{cm}^{-2}$ is required[8], in order to pin the surface Fermi level at the position of the defect states. Since the density of the surface atoms is of the order of $10^{15}\mathrm{cm}^{-2}$, the defect density of $10^{13}\mathrm{cm}^{-2}$ is considered to be realistic[9]. Then, each kind of surface state was assumed to be uniformly distributed to a depth of 5 Å from the surface with a density of $N_{TD}=N_{TA}\equiv N_T=2\mathrm{X}10^{20}\mathrm{cm}^{-3}$.

Typical capture cross sections σ for the bulk recombination centers in GaAs are known to range from $\sim 10^{-21}$ to $\sim 10^{-15}\mathrm{cm}^2$ at room temperature[9]. In the present study, the largest value of σ, $10^{-15}\mathrm{cm}^2$, was assumed. Considering that the thermal velocities of the carriers, v_{th}, are equal to $\sim 10^7$cm/s and that $c=\sigma v_{th}$, the capture rate of electrons and holes were assumed to be $c_{nD}=c_{pD}=c_{nA}=c_{pA} \equiv c=10^{-8}\mathrm{cm}^3/\mathrm{s}$. The same assumptions were introduced for the GaAlAs surface.

The above assumptions mean that the intrinsic surface recombination velocity S_0 is equal to $2\mathrm{X}10^5$cm/s. Comparing Henry's result of $S_0=4\mathrm{X}10^5$cm/s obtained for a GaAlAs pn diode[10], these assumptions are considered to be realistic.

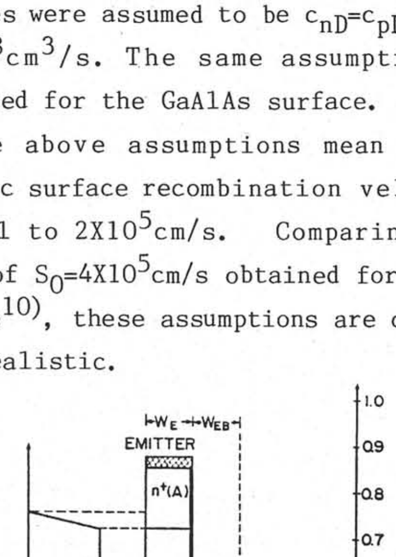

Fig.1. Typical device structure of HBT analyzed in this study.

Table I Parameters for Structure I

Layer		Doping (cm^{-3})	Thickness (μm)
Emitter :	n^+(A)	5×10^{18}	0.13
	n (B)	3×10^{17}	0.22
Base :	p^+(C)	5×10^{18}	0.1
Collector :	n (D)	5×10^{16}	0.4
	n^+(E)	2×10^{18}	0.1

The physical parameters used in this work are the same as those used in the previous work[4].

The analyzed mesa-type HBT is shown in Fig.1. The structural parameters are listed in Table I. The emitter width (W_E) was fixed to be 1.0µm. The spacings between the emitter pattern edge and the base electrode edge (W_{EB}) were 0.1, 0.2, 0.5, 1.0, and 2.0µm. Surface defect states were introduced into the region marked with bold lines in Fig.1.

III. Results and Discussions

Figure 2 shows the I-V characteristics calculated for W_{EB}=1.0µm. When the surface states are introduced, J_B is seen to increase due to the recombination current at the surface of the extrinsic base.

Figure 3 shows h_{FE} as a function of W_{EB}.

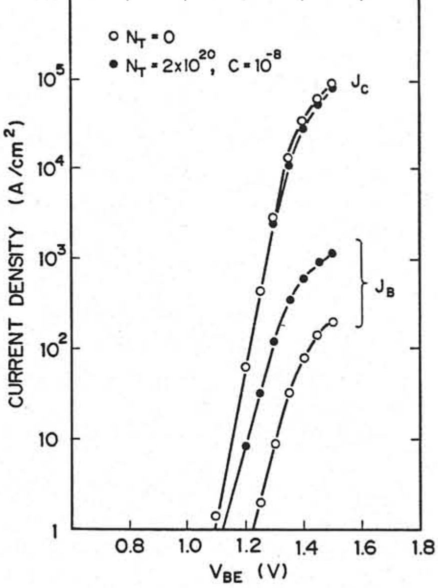

Fig.2. I-V characteristics calculated for W_{EB}=1.0µm structure.

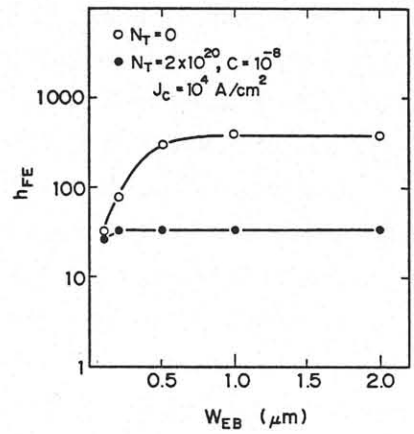

Fig.3. Calculated h_{FE} versus W_{EB} characteristics.

In case of no trap density N_T=0, h_{FE} degrades rapidly with a decrease in W_{EB} from 0.5µm. On the other hand, when $N_T=2X10^{20}cm^{-3}$ is assumed, h_{FE} is always limited to a small value of ~30, thereby showing no dependence on W_{EB}. The reason is discussed in the following.

A part of the electrons injected from the intrinsic base into the extrinsic base diffuses deeply in the extrinsic base bulk region, to reach the base electrode. This base electron current is enhanced when the base electrode is located close to the intrinsic base region. Thus, h_{FE} degrades with decreasing W_{EB}, in the case that the surface recombination current is negligibly small.

On the other hand, when the surface states exist, the situation is different.

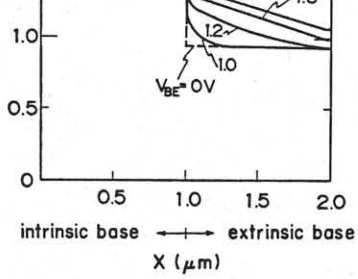

Fig.4. Conduction band edge profile along surface of extrinsic base.

Figure 4 shows the conduction band edge profile along the surface of the extrinsic base from the intrinsic region to the extrinsic region for the case of $N_T=2X10^{20}cm^{-3}$. When $V_{BE}=0V$, the surface Fermi level is pinned at the position of the donor type trap located at 0.925eV below the conduction band. In this situation, most of the acceptor type traps 0.8eV above the valence band emit electrons and are neutral, while about half of the donor type traps are ionized. Therefore, positive charges of $\sim 5X10^{12}cm^{-2}$ exist at the surface of the extrinsic base. When bias is applied, the acceptor type traps immediately capture the electrons to compensate for the positive charges of the donor type traps, so that pinning is gradually reduced.

Figure 5 shows electron density, hole density and recombination rate profiles along the surface of the extrinsic base. As was discussed already, pinning is removed with the injection of electrons. Since holes are injected into the region where pinning is removed, both the electron and hole densities at the boundary between the intrinsic base and the extrinsic base are larger than those at other surface regions of the extrinsic base. Thus, the rate of surface recombination has a sharp peak at the boundary between the intrinsic base and the extrinsic base as seen in Fig.5. This result is responsible for the independency of h_{FE} on W_{EB} (Fig.3), when $N_T=2X10^{20}cm^{-3}$ is assumed.

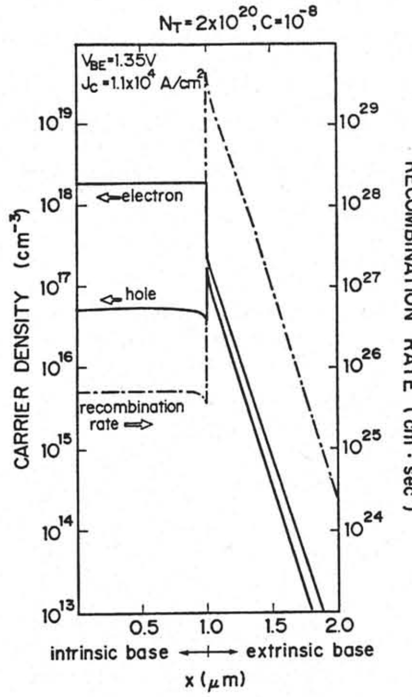

Fig.5. Electron density, hole density and recombination rate profiles along surface of extrinsic base.

IV. Conclusion

A new surface model of GaAs and GaAlAs was developed. The model was introduced into a two-dimensional numerical model of GaAlAs/GaAs HBT's, and the effects of the surface states on device performance were investigated for HBT's with a mesa-type extrinsic base. It was shown that current gain really decreases with the existence of the surface states. It was also shown that surface recombination was intensive only at the boundary region between the intrinsic base and the extrinsic base.

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