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Electroluminescence of Electrons Ballistically Injected and Emitting Phonons in the P-Type Base of AlGaAs/GaAs Heterojunction Bipolar Transistor Structures

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We have investigated the transport behavior of high-energy ballistic electrons in the base of Npn-$Al_xGa_{1-x}As$/GaAs heterojunction bipolar transistors (HBT) with an abrupt emitter-base heterojunction. The observed electroluminescence spectra show several high-energy peaks that are associated with ballistic electrons and with LO-phonon emissions. By varying the emitter-collector voltage, the neutral base width can be modulated, leading to a change in spatial electron distributions and thus determining the ballistic mean free paths.

1. Introduction

Hot electron luminescence of optically [1] and electrically [2,3] excited electrons has been measured to study hot electron transport in III-V semiconductors. In N-AlGaAs/p-GaAs diodes, electron injection from N-AlGaAs to p-GaAs over the conduction band discontinuity ΔE_c at the heterointerface can generate ballistic electrons which was confirmed from electronluminescence (EL) measurements, and these measurements were used to evaluate ΔE_c[2]. Longitudinal-optical (LO) phonon emission replicas from high energy electrons have also been observed. In a diode structure, however, the distribution profile of electrons does not change in space and a large number of relaxed electrons remain in p-GaAs layer.

We report on the observation of ballistic electrons in the base of $Al_xGa_{1-x}As$/GaAs HBT structures. In the transistor structures we designed, the base doping level is low (~10^{17} cm^{-3}) in order to decrease the electron-hole interactions, and the lightly doped base combined with a heavily doped collector can change the neutral base width. Measured EL spectra exhibit high-energy peaks corresponding to ballistic electrons with LO-phonon emission. Ballistic mean free path of electrons, on the order of 130 nm for $Al_{0.3}Ga_{0.7}As$/GaAs HBTs at about 20 K, is obtained from the intensity variation of the ballistic (0-LO phonon emission) peak.

2. Experimental

The AlGaAs/GaAs HBT structures used in this work were prepared with MBE grown epitaxial layers. Two kinds of structures with different emitter AlAs mole fractions x of 0.3 and 0.55 were built, which have different ΔE_cs. They are denoted as HBT30 ($Al_{0.3}Ga_{0.7}As$/GaAs) and HBT55 ($Al_{0.55}Ga_{0.45}As$/GaAs). The base region was lightly doped to suppress electron-hole scattering. The layer structures are shown in Table 1. The n-type dopant was Si and the p-type dopant was Be. Transistors were fabricated in a double-mesa structure with emitter/base junction areas of 9x9 μm^2 and 50x4 μm^2 for HBT30 and HBT55, respectively. The base contact region was fabricated by diffusing Zn into the extrinsic base area. The base contact metal was non-alloyed Pt/Ti/Pt/Au, and the emitter and collector contact metals were alloyed Au/Ge/Ni.

For EL measurements, HBTs were set in a cryostat and the device temperatures were kept at about 20K. Electrical bias was applied with a base current

		HBT30			HBT55		
Layer	Material	Doping (cm^{-3})	Thickness (nm)	AlAs (%)	Doping (cm^{-3})	Thickness (nm)	AlAs (%)
E-cap	n-GaAs	4x10^{18}	150		4x10^{18}	150	
E-grading	N-AlGaAs	4x10^{18} - 1x10^{17}	30	3-30	4x10^{18} - 1x10^{17}	30	3-55
Emitter	N-AlGaAs	1x10^{17}	30	30	1x10^{17}	30	55
Spacer	u.d.-GaAs	-	5		-	-	
	p^+-GaAs	-	-		1x10^{19}	5	
Base	p -GaAs	2.5x10^{17}	240		1x10^{17}	230	
Collector	n -GaAs	4x10^{18}	500		4x10^{18}	500	

Table 1. $Al_xGa_{1-x}As$/GaAs HBT layer structures.

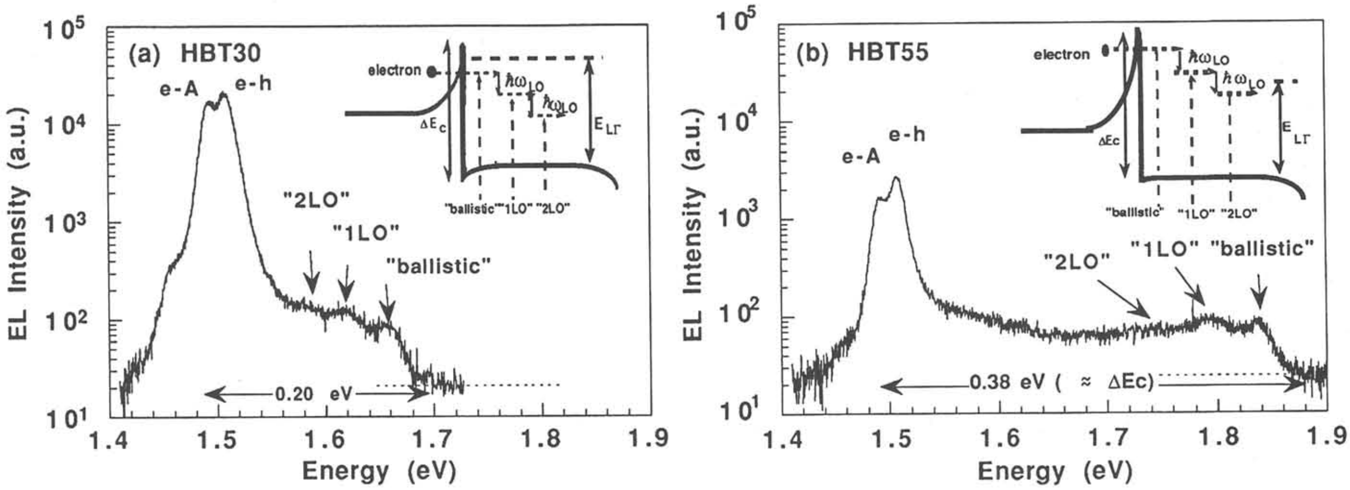

Fig. 1 Electroluminescence spectra for HBT30 (a) and HBT55 (b). The transistor bias conditions were I_B = 10 μA and V_{CE} = 1.2 V for HBT30, and I_B = 2 μA and V_{CE}=1.9 V for HBT55. "Ballistic", "1LO", and "2LO" denote recombinations emitting zero, one and two LO-phonons, respectively. Insets show schematics of high energy electron EL in HBTs.

I_B and an emitter/collector voltage V_{CE} (common-emitter configuration). Radiation from the HBTs was collected using a microscope and focused on to a monochromator. A photomultiplier with a GaAs photocathode and a conventional photon counting system was used.

3. Results and Discussions

3.1 Electroluminescence spectra

Typical EL spectra for HBT30 and HBT55 are shown in Figs. 1(a) and 1(b), respectively. In these spectra, the two main EL peaks at 1.511 eV (e-h) and 1.492 eV (e-A) correspond to a band-to-band electron-hole and a band-to-acceptor (Be) recombination, respectively. Also, there are several small peaks above 1.55 eV having an equal interval of 35-40 meV between them. The highest energy peak is likely due to the radiative recombination of the ballistic electrons. The subsequent lower-energy peaks are associated with multiple LO-phonon emissions because the energy separation is close to LO-phonon energy $\hbar\omega_{LO}$ = 36 meV. The ELs from the high-energy electrons appear at 1.69 and 1.88 eV for HBT30 and HBT55, respectively. For HBT55 the energy separation of this energy to the accepotor level (1.492 eV) is consistent with the conduction band discontinuity ΔE_c at the emitter-base junction of 0.38 eV, which means the conduction band is almost flat in the base at the emitter-base junction. As shown schematically in the insets, electrons in the Γ-valley of the $Al_{0.3}Ga_{0.7}As$ emitter are injected into the Γ-valley of the GaAs base in HBT30. On the other hand, in HBT55, X-valleys lie lowest in the $Al_{0.55}Ga_{0.45}As$ emitter and X-valley electrons have possibility to be transferred to the L-valleys and Γ-valley of the GaAs base, where $\Delta E_c(Al_{0.55}Ga_{0.45}As) \approx 0.4$ eV, $\Delta E_{\Gamma\text{-}L}$ (GaAs) ≈ 0.3 eV and $\Delta E_{\Gamma\text{-}X}$ (GaAs) ≈ 0.5 eV. Here, a recombination contributed from L-valley electrons is not efficient because it is indirect recombination. In addition, electron transfer from the L-valley to the Γ-valley is a very slow process [4]. Consequently, the "ballistic" peak in HBT55 correspond to the electrons injected from the X-valley of the $Al_{0.55}Ga_{0.45}As$ emitter directly into the Γ-valley of the GaAs base.

The electron temperature T_c of quasi-thermalized carriers is obtained from the high energy tale of the band-to-band luminescence. T_c is calculated to be 80 K in HBT30 and 150 K in HBT55. In HBT55, since electrons may also populate in the L-valley as described above, the value of T_c here is not exactly correct. But the much higher T_c here reflects the higher injection energy compared to the case of HBT30.

3.2 Base width modulation

The neutral base width W_B was modulated by controlling the emitter/base voltage V_{CE} at a constant base current I_B. Here W_B values were calculated using the depletion layer approximation. The variation in luminescence spectra are shown in Figs. 3 (a) and (b) for HBT30 and HBT55, respectively. The spectral intensities are normalized by collector current I_C in order to compare them at an equal electron injection. In addition, they are divided by the energy dependent recombination probability of band-electrons and holes at the acceptor energy level, which is represented as $P_r(E_c) = \{1+ m_e(E_c-E_g-E_A)/m_h/E_A\}^{-4}$, where E_c, E_c and E_A are the energies of electrons from the band edge, of band gap at the base, and of the acceptor level [5].

In both HBT30 and HBT55, two distinct peaks corresponding to "ballistic" and "1LO", and weak "2LO" peaks can be seen. The full width at half maximum (FWHM) for ballistic peaks is about 26 meV for HBT30 and becomes wider for "1LO" peaks, which are wider than the calculated value of 6meV. These broadening are assumed to be due to electron-hole interaction. FWHM for HBT55 is broader (≈40 meV) than for HBT30. In HBT55, electrons are transferred from the X-valley of the emitter to the Γ-valley of the base with phonon emission process, which could be a reason for the large

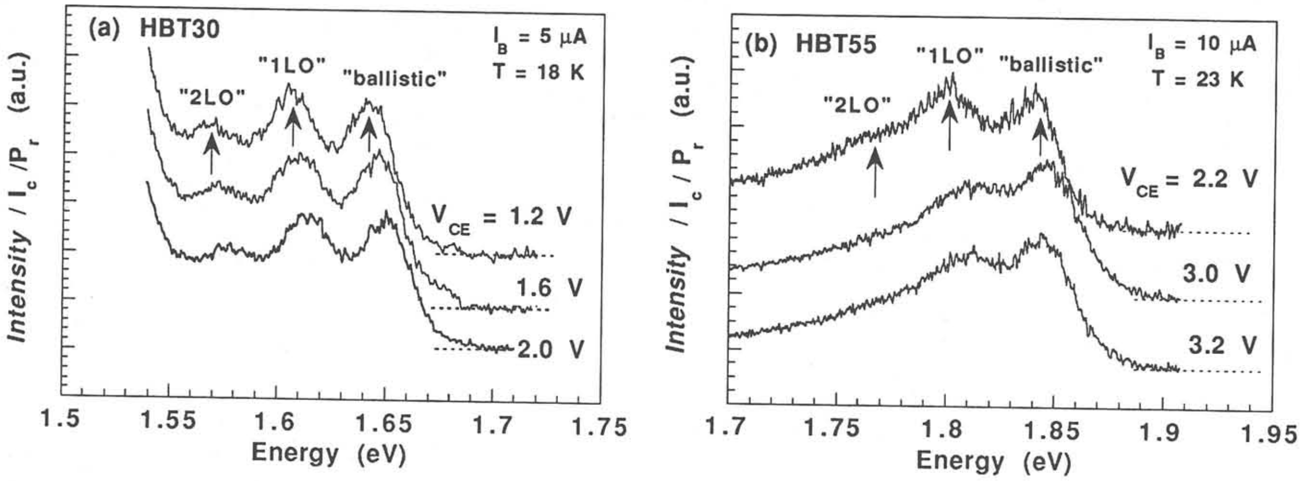

Fig. 2 Electroluminescence spectra in the high energy range for HBT30 (a) and HBT55 (b). For these measurement, I_B= 5 μA and V_{CE}= 1.2, 1.6, 2.0 V for HBT30, and I_B = 10 μA and V_{CE} = 2.2, 3.0, 3.2 V for HBT55.

FWHM. Although the ballistic peaks shift slightly to a higher energy with V_{CE} due to the increase in sample temperature, the shifts are very small (about 10 K) and are believed not to influence electron transport and recombination characteristics. The relative intensity of the "1LO" peak to the "ballistic" peak decreases with increasing V_{CE}, which is more evident in HBT55. This variation is explained by the reduction of the neutral base width W_B that results in less LO-phonon scattering events in the base. It is also found that "ballistic" peak intensity decreases with increasing V_{CE}. The ballistic mean free path (L_B) is then evaluated from these characteristics. Here, the spatial distribution of ballistic electrons is assumed to be $F(z) = F_0 \exp(-z/L_B)$, where F_0 is the population density of ballistic electrons at the emitter-base junction interface and z is the distance from the interface on the direction perpendicular to the junction plane. Figure 3 shows the

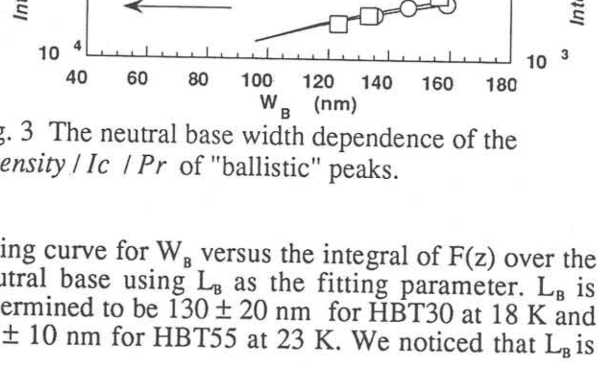

Fig. 3 The neutral base width dependence of the *Intensity / Ic / Pr* of "ballistic" peaks.

fitting curve for W_B versus the integral of F(z) over the neutral base using L_B as the fitting parameter. L_B is determined to be 130 ± 20 nm for HBT30 at 18 K and 20 ± 10 nm for HBT55 at 23 K. We noticed that L_B is comparable to W_B in the case of HBT55, which accounts for the fact that the intensity of "2LO" and other multiple phonon peaks (below ~1.8 eV) decreases in Fig. 2 (b).

4. Conclusions

In conclusion, we measured the electroluminescence of ballistic electrons injected into the base of AlGaAs/GaAs HBTs. The high-energy peaks are clearly separated and are associated with recombinations of ballistic electrons and with LO-phonon emissions. The ballistic mean free paths obtained by modulating the neutral base width are on the order of 130 nm in $Al_{0.3}Ga_{0.7}As$/GaAs at 18 K and of 20 nm in $Al_{0.55}Ga_{0.45}As$/GaAs structures at 23 K.

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