Relaxation of electrons within AlAs barriers studied by hot electron spectroscopy

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Abstract

We have investigated electron transport through AlAs barriers by incorporating them as emitter barriers in a tunnelling hot electron transfer amplifier structure. Hot electron spectroscopy reveals that only about 1\% of the tunnelling electrons are collected close to their injection energy in contrast to an otherwise identical structure with an Al\textsubscript{0.5}Ga\textsubscript{0.5}As barrier where the fraction is 30\%. Moreover, three or four peaks could be clearly resolved in the broad background of scattered electrons in the device with the AlAs barrier which do not occur at simple multiples of the LO phonon energies. The observation of real space transfer of electrons into one of the X-point subbands below the emitter Fermi energy under hydrostatic pressure clearly indicates that these peaks are due to electrons which relax down through the ladder of X-point subbands in the barrier before being emitted into the base layer. © 1999 Elsevier Science B.V. All rights reserved.

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The understanding of carrier transport processes in thin indirect AlAs tunnel barriers is of great technological importance for optimising full device capabilities. These materials are frequently used in resonant tunnelling and single-barrier tunnelling diodes due to the good ideality of their characteristics at high temperatures. The importance of the X-point minima of AlAs barriers in the transport process was first demonstrated by Mendez et al. [1]. This was followed by several reports of transport studies on double-barrier resonant tunnelling diodes [1,2] and single-barrier diodes under hydrostatic pressure [2–7] providing clear evidence for X-point related carrier transport via elastic and phonon-related processes. In all these studies the relative positions of the band edges were inferred from simple current–voltage measurements. Recently evidence for the population of several X-point subbands during transport through an AlAs barrier was established by electroluminescence [7]. We have studied the transport processes occurring in 15 nm undoped AlAs tunnel barriers by incorporating them into the emitter barrier of a hot electron transistor and performing hot electron spectroscopy [8] on the carriers which have travelled through the AlAs emitter barrier.
Our transistors are based on the tunnelling hot electron transfer amplifier (THETA) proposed and demonstrated by Heiblum et al. [9]. A schematic conduction band profile of the AlAs emitter barrier transistor is shown in Fig. 1. The basic structure of the transistor is composed of three n⁺-doped GaAs regions separated by AlₓGa₁₋ₓAs potential barriers of 15 and 100 nm, thickness respectively, with the central n⁺-GaAs layer being thin enough (50 nm) to allow quasi-ballistic transport. The novelty of our structure lies in making the thin injection barrier from AlAs (x = 1) while the second direct collector barrier is used to perform a spectral analysis of the injected carriers which traverse the very thin base layer quasi-ballistically. For this purpose the collector barrier is linearly graded from x = 0.1 to 0.3 on the base side in order to reduce quantum mechanical reflection and to provide a voltage-dependent barrier height. Upon biasing the collector barrier acts as a high-pass energetic filter for the incident electrons and it can be shown that the number of collected electrons per unit energy, \( n(E_Z) \propto dI_c/dV_{CB} \), where \( E_Z \) is the energy of the electron associated with its momentum normal to the barrier, \( I_c \) is the collector current and \( V_{CB} \) the base-collector bias [8].

We have compared two types of device which are identical except for the composition of the 15 nm AlₓGa₁₋ₓAs emitter barrier; one where transport is expected to be dominated by the X-point (x = 1) and a second more conventional (x = 0.5) case where \( \Gamma \)-point transport should dominate. The device structures were grown by MBE on (1 0 0) n⁺-GaAs substrates. The collector was contacted from the rear of the substrate with a standard AuGe/Ni alloy. Since a shallow ohmic contact technology was not available we have defined three parallel 30 µm × 10 µm emitter mesas (see inset Fig. 1), the outer two of which are used as base contacts in a three-point geometry to electrically eliminate series resistance introduced due to the presence of the emitter barrier in common-base.
mode [10]. These emitter/base contacts were formed by annealing a Ge (22.5 nm)/Au (45 nm)/Ti (15 nm)/Au (150 nm) multilayer at 350°C for 10 s. A shallow selective wet etch was then used to cut through the emitter electrode between the pads followed by a deep etch to define the overall transistor structure. A 500 nm Si₃N₄ dielectric layer was then deposited over the whole chip and holes lifted off over the contact pads. Finally large areas Cr (20 nm)/Au (200 nm) were evaporated to facilitate wire bonding.

Measurements were performed at ambient pressure in a cryo-cooler down to 8 K and under hydrostatic pressure down to 4.2 K in a liquid-helium cryostat. For the latter a Unipress self-clamping pressure cell with a 1 : 1 mixture of petroleum ether and transformer oil as pressure transmitting medium was used. A manganin wire gauge calibrated against an InSb sensor was used to monitor the pressure.

Fig. 2 shows \( \frac{I_C}{I_B} \) vs. \( V_{CE} \) and \( \left( \frac{1}{I_B} \right) \left( \frac{dI_C}{dV_{CE}} \right) \) vs. \( V_{CE} \) characteristics of both devices measured in common-emitter configuration. For the Al₀.₅Ga₀.₅As emitter barrier device (Fig. 2(a)) we estimate that about 30% of the injected electrons are collected with energy close to the injection energy within the large ‘ballistic’ peak in broad agreement with Refs. [9,10]. In the otherwise identical AlAs emitter barrier device (Fig. 2(b)) the ballistic peak is very small and only represents 1% of the injected current providing clear evidence for the dominance of inelastic processes during tunnelling. We also see a large background of scattered electrons which increases rapidly towards low energies and contains well-defined peaks. These are not present in the sample with the Al₀.₅Ga₀.₅As barrier indicating that their origin lies in the transport processes through the indirect AlAs barrier. When the peak widths and positions are analysed carefully using the correct lever rule for the collector high pass filter, they are found to be too narrow and too closely spaced to be consistent with any known phonon replicas of the main ballistic peak.

Since it is probable that these structures are related to X-point barrier subbands we have applied hydrostatic pressure which is known to reduce the \( \Gamma' \) (GaAs)–X(AlAs) conduction band offset at a rate of \(-12\) meV/kbar leaving the \( \Gamma' \) (GaAs)–\( \Gamma' \) (AlAs) conduction band offset unaffected [1]. Fig. 3 shows the common-emitter transconductance normalised by the injected current \( I_B \) under various pressures at an injection voltage of 300 mV. As the pressure

![Fig. 2](image1.png)  
**Fig. 2.** Common-emitter current–voltage and transconductance–voltage characteristics of (a) an Al₀.₅Ga₀.₅As and (b) an AlAs emitter barrier normalised by the base current measured at ambient pressure.

![Fig. 3](image2.png)  
**Fig. 3.** Common-emitter transconductance of the device with an AlAs emitter barrier normalised by the base current for different values of pressure \( (V_{BE} = 300\) mV).
increases the tiny quasi-ballistic peak near 0.27 V ($p = 1$ bar) diminishes at the expense of a second lower energy peak near 0.34 V which grows rapidly above 3.4 kbar. We attribute this to the real space transfer of electrons into one of the X-point bound states adjacent to the emitter Fermi band at this bias. This process will become dominant above pressures such that the top of the X-point barrier falls below the emitter Fermi level at this bias. These transferred electrons then can tunnel out at a well defined but lower energy.

Given that there is clear evidence for real space transfer of carriers into the barrier it seems likely that the normalised conductance peaks in the background of the scattered electrons of Fig. 2(b) correspond to electrons that have cascaded down the ladder of X-point subbands and subsequently been emitted into the base layer. We have calculated the positions of the X-point subbands for our biased 15 nm AlAs tunnel barrier using exact Airy function solutions of the Schrödinger equation with values for the band offsets and effective masses. Band bending at the interfaces has been accounted for using a classical solution of the Poisson equation in these regions [11]. The same Poisson solver has been used to calculate a lever rule of 7.7 for the forward biased collector barrier; i.e. an increase in $V_{CB}$ of 1 V lowers the barrier by $\frac{1}{7.7}$ V. Using our 7.7 lever rule we find reasonable agreement between the calculated spacing of first three longitudinal subbands and the experimentally measured spacing of the peaks in the scattered spectrum.

In conclusion we have used hot electron spectroscopy to demonstrate that the majority (99%) of carriers passing through a 15 nm AlAs potential barrier have suffered substantial inelastic scattering. We also see clear evidence of real-space transfer of electrons from the emitter electrode into X-point bound states in the barrier adjacent to the Fermi band. These electrons subsequently relax down through the ladder of X-point subbands and are re-emitted at these well-defined energies. We find reasonable quantitative agreement between the positions of peaks measured in the scattered electron distribution and the calculated energies of the lowest-energy longitudinal X-point subbands in the AlAs barrier.

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