Evidence of Hot-Electron Transfer into an Upper Valley in GaAs

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The measurement of current transport due to ballastic, quasimonoenergetic, hot electrons injected into thin layers of GaAs indicates that some electrons transfer into the first satellite valleys (L valleys). Applying hydrostatic pressure, which changes the relative energies of the valleys, results in a corresponding shift of the electron energy for which transfer is evident. Transfer of $\simeq 25\%$ at atmospheric pressure was estimated for a transit time of 0.03 ps. We have also measured the conduction-band discontinuity between GaAs and AlGaAs and find it to be insensitive to hydrostatic pressure.

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The importance of the transfer mechanism in which hot electrons scatter into the upper valleys in GaAs became apparent after the discovery of the Gunn effect.[1,2] For some time, the responsible satellite valleys were not correctly identified.[3] Only ten years later, when Aspnes published the correct order for the conduction valleys in GaAs,[4] were the L valleys thought to be involved in the observed differential negative resistance that results in the Gunn effect. Such Γ-to-L scattering may be important in other GaAs devices. The L-valley minima are about $E_{\Gamma L}=0.3$ eV above the bottom of the Γ or the (000) conduction-band minimum,[5-7] an energy difference that is less than the voltage commonly used in high-speed GaAs devices. Since the density-of-states effective mass of the electrons in the L valleys is more than eight times larger than the equivalent mass in the Γ valley ($m_L=0.56m_0$, $m_\Gamma=0.067m_0$,[5,8] where m_0 is the free-space mass of the electron), their mean free path and mobility are much lower, mainly because of a higher scattering rate. Thus, Γ-to-L scattering would lead to decreased performance of GaAs devices.

When device dimensions become very small and transit times through GaAs layers are less than 0.1 ps, one may ask whether a significant number of electrons that have sufficient energy will still be able to transfer into the satellite valleys. Here we report evidence for transfer, of otherwise Γ ballistic electrons, into the L valleys in 300-Å thin GaAs layers. We substantiate our hypothesis further by changing the energy of the L valleys relative to the Γ valley minima by applying hydrostatic pressure, and observing the corresponding change in the electrical characteristics.

Our experiments were performed with tunneling hot-electron transfer amplifier (THETA) devices.[9] These structures have been used before as energy spectrometers,[10-12] and led to the observation of ballistic (collisionless) transport in GaAs.[12] Briefly, the THETA device is a three-terminal structure composed of n-type doped emitter, collector, and a thin base (Fig. 1). The emitter and its barrier are constructed from a thin, undoped-AlGaAs layer (100 Å thick and AlAs concentration of 32% in the alloy), sandwiched between two degenerately doped GaAs layers. When one GaAs layer is negatively biased with respect to the other, electrons tunnel from one side of the barrier to the other and emerge into the positively biased GaAs layer with an energy, above the Fermi level ζ in the base, approximately equal to eV_{BE}, and with a half maximum total-energy breadth of about 40 meV.[9] The positively biased GaAs layer (base) is made very thin to allow the injected hot-electron beam to traverse it without energy loss or momentum change, namely

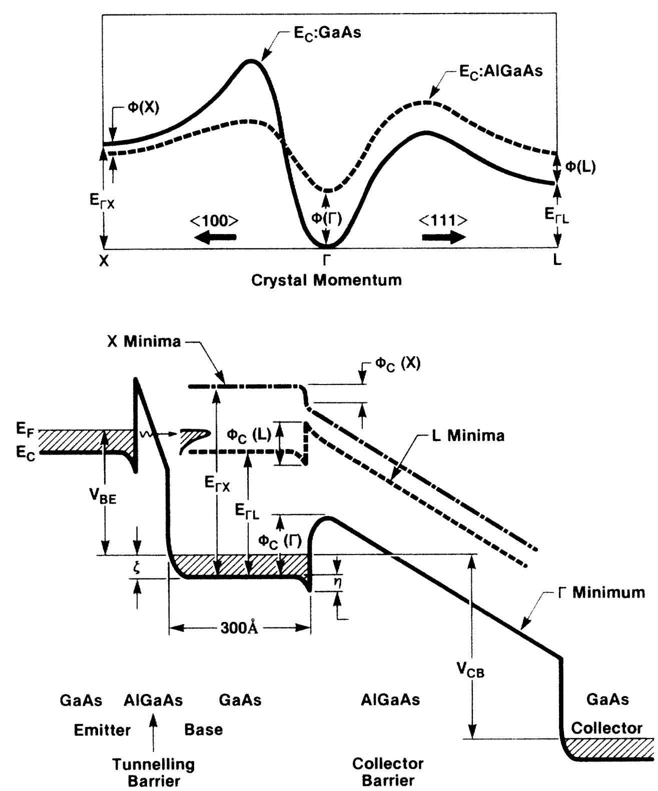

FIG. 1. The relative arrangement of the conduction bands in GaAs-AlGaAs heterojunction vs crystal momentum, at the top. At the bottom, the different bands in the THETA device are displayed vs position. The device is biased as in the experimental procedure. The various barrier heights Φ's, band splittings E's, ζ, and η are shown.

TABLE I. A summary of the nominal device parameters. Also included are the calculated and measured different collector barrier heights.

Sample	Nominal % of AlAs in collectors	Collector width (Å)	Collector grading (Å)	Base doping (cm^{-3})	300 Å (200 Å) base Fermi level (meV)	V_{tr} $V_{CB}=0.2$ V (mV)	$\Phi_C(\Gamma)$ (meV)	$\Phi_C(L)$ (meV)	$\Phi_C(X)$ (meV)
NH330	32	1000	100	1.5×10^{18}	81 (87)	270	300	75	−15
NH346	16	1200	60	1×10^{18}	65 (71)	290	140	25	−40
NH378	32	600	200	8×10^{17}	56 (62)	315	335	110	−20

ballistically. The base is followed by a collector barrier, which is made of a thicker AlGaAs layer, and a subsequent n-type doped GaAs layer as a collector electrode. The thick AlGaAs barrier prevents the equilibrium electrons in the base from tunneling into the collector but allows the collection of the incoming ballistic electrons, provided $eV_{BE}+\zeta \geqslant \Phi_C(\Gamma)$, where $\Phi_C(\Gamma)$ is the collector barrier height for Γ electrons. To minimize quantum-mechanical reflections from the collector barrier, the AlGaAs is graded as shown in Fig. 1. A detailed description of the fabrication procedure is given by Heiblum *et al.*[11] The parameters characterizing each device structure are given in Table I. The values of the Fermi level are calculated for 300- and 200-Å base widths (due to partial depletion with biasing).

We have shown previously that a substantial fraction of the injected electrons traverse the base ballistically.[12] Figure 2 shows the differential transfer ratio,

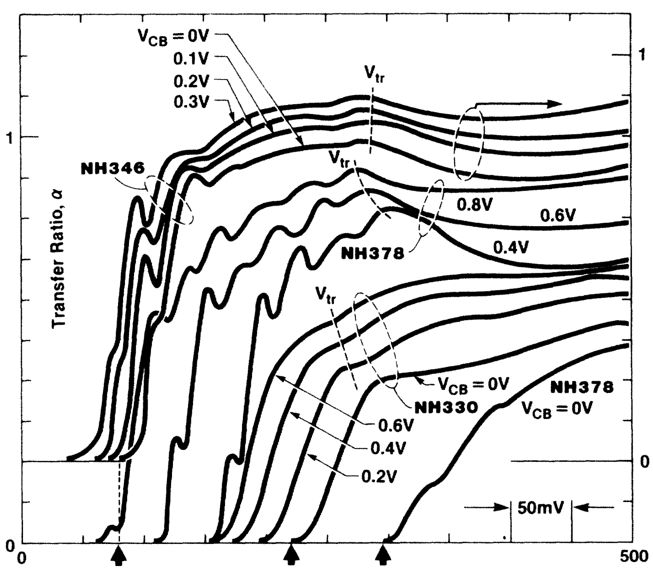

FIG. 2. The differential transfer ratio $\alpha = dI_C/dI_E$ vs the injection voltage V_{BE} for the three THETA devices measured at 4.2 K. For each curve the parameter is the base-collector voltage V_{CB}. As V_{CB} increases, the onset of α decreases to lower injection energies. The arrows mark the barrier height above the Fermi level in the base for each structure. Note the weak dependence of V_{tr} on V_{CB}.

$\alpha = dI_C/dI_E$, where I_C and I_E are the collector and emitter currents, respectively, as a function of the injection energy measured at 4.2 K for three different device structures, all with 300-Å base width. As a result of the ballistic transport, the value of V_{BE} for which α begins to increase significantly (the onset of α) for $V_{CB}=0$ (marked by the arrows in Fig. 2) plus the Fermi-level height, ζ, gives $\Phi_C(\Gamma)$. As measured, the barrier heights are not strictly proportional to the AlAs concentration,[13] most probably because of the negative charges often found in the AlGaAs.[14] An independent determination, obtained by measurement of activation energies for thermionic emission over the collector barrier, confirmed the $\Phi_C(\Gamma)$ values. Application of a voltage V_{CB} to each device (collector positive with respect to base) lowers the collector barrier heights as seen by the shift of the onset of α to lower values of V_{BE}.

A common feature seen in all devices is an initial rapid increase in the transfer ratios, followed by a saturation. The rapid increase is related to the narrow spread in the energy of normal motion of the ballistic electrons, as they are raised by V_{BE} above $\Phi_C(\Gamma)$. The slow increase that follows results from the collection of lower-energy quasiballistic electrons (those electrons that have lost some energy during transfer). However, as seen in Fig. 2, when V_{BE} approaches 0.3 V, α unexpectedly decreases before rising again later. We term the value of V_{BE} for which α reaches a maximum V_{tr}. As seen in Fig. 2, the value of V_{tr} is similar in all the devices, and is only weakly dependent on V_{CB}. The exact location of V_{tr} is somewhat complicated by the quasiperiodic structure which modulates α, particularly at 4.2 K. Preliminary calculations suggest that this structure results from the interference in the thin base due to quantum-mechanical reflections from the potential barriers which define the base. We believe that the characteristic behavior of α near V_{tr} results from the transfer of some of the ballistic electrons into the L valleys in the base. The small band bending at the base near the collector barrier ($\eta = 8$–15 meV and few tens of angstroms wide) will tend to lower V_{tr} for some of the ballistic electrons which transfer, resulting in a slightly broader maximum and accounting partly for the small reduction in V_{tr} as V_{CB} increases. Above the threshold V_{tr}, the quasiperiodic structure in α vanishes because of the damping of the coherent motion of the ballistic electrons, which results from the transfer into L valleys.

The coupling between Γ states and the L valleys is expected to be via the 26-meV longitudinal-acoustic and 30-meV longitudinal-optical phonons at the (111) Brillouin-zone edge,[15] if we assume that the coupling in GaAs is similar to that in Ge.[16] Therefore, the threshold for the intervalley scattering of the ballistic electrons is expected to be higher than the valley splitting $E_{\Gamma L}$, by some 26–30 meV plus approximately the width of the energy distribution, leading to $E_{\Gamma L} \simeq V_{tr} + \zeta - (0.03\text{–}0.04)$ eV. Using V_{tr} and ζ of Table I leads approximately to $E_{\Gamma L} \simeq 0.29$ eV in all the devices, which is in close agreement with the published data.[5-7] Note that we do not rule out the possibility that the intervalley transfer probability may include non-phonon-assisted components, i.e., impurity scattering.

Why does α decrease after partial transfer into L valleys occurs? The fraction of the electrons that transfer should diffuse toward the collector while staying in quasithermal state in the L valleys with an expected lifetime of about $1-2$ ps.[17] The L electrons will, however, encounter a collector barrier $\Phi_C(L)$ in the AlGaAs, as shown in Fig. 1 and estimated in Table I. For the estimates we have used the known $E_{\Gamma L}$ in AlGaAs[5] and our determined $E_{\Gamma L} = 0.29$ eV in GaAs. At 77 K the barriers, $\Phi_C(L)$, are sufficiently high to prevent collection. Since $\Phi_C(L)$ in NH378 is much larger than that in NH346, the reduction in its α for $V_{BE} > V_{tr}$ is the greatest (about 20%). In the case of NH330, where the doping density is the highest and α is the smallest, only about a third of the injected electrons are ballistic (compared to about three-quarters in the other two devices, as measured by the spectroscopy method described in Ref. 12). Here, as the injection energy eV_{BE} increases, the decrease in α is obscured by the increased collection of the relatively large number of lower-energy quasiballistic electrons.

The fraction of the electrons that transfer into the L valleys depends on the base transit time. We have estimated the transfer time using values of the Γ-to-L coupling obtained from nonlinear optical studies in GaAs, where the coupling is found to be $D_{\Gamma L} = 7.1 \times 10^8$ eV/cm.[18] For this value of coupling, the calculated scattering time in picoseconds is given by $0.033/(V_{BE} - V_{tr})^{1/2}$, where the V's are in volts. For $V_{BE} - V_{tr} = 0.1$ V and a transit time of 0.03 ps, we estimate that 25% of the ballistic electrons would be scattered to the L valleys. Note, however, that in our data, the differential transfer ratio does not reflect only the Γ-to-L transfer but also the rate of change of the emitter current with V_{BE}.

In order to study the intervalley transfer further, we have applied hydrostatic pressure in the range 0 to 11 kbar to the devices cooled to 77 K. It is known that for GaAs and AlGaAs under hydrostatic pressure the L valleys move up more slowly with respect to the valence-band edge than does the Γ minimum, effectively bringing Γ and L states closer together in energy. At 77 K the change in the energy separation is $\Delta E_{\Gamma L} \simeq -5$ meV/kbar.[19-21]

The α's measured at constant V_{CB} for different hydrostatic pressures are shown for NH378 in Fig. 3. Since the onset of α is seen to be pressure independent, $\Phi_C(\Gamma)$ does not change by more than 10 meV (our approximate resolution) under pressure. In the range where transfer occurs, V_{tr} gets smaller and the maximum value of α decreases as the pressure increases. The shift of V_{tr} is about 60 meV when the pressure rises from 0 to 11 kbar, as expected theoretically. The apparent decrease in α with pressure seems more than expected by a simple density-of-states argument, which should make its dependence proportional to $(eV_{BE} + \zeta - E_{\Gamma L})^{1/2}$. This effect and the gradual disappearance of a clear maximum could be related to the emitter current which changes its dependence on V_{BE} with pressure.

Increasing the injection energies above 0.5 eV, with or without applied pressure, does not show any indication of electron transfer into the X valleys with an energy $E_{\Gamma X} \simeq 0.48$ eV above the Γ minimum.[5] This can be understood when we realize that the X-valley minima in the AlGaAs collector barrier are lower than those in the GaAs, given by the calculated negative $\Phi_C(X)$ in Table I and shown schematically in Fig. 1. Therefore, there is no barrier for the collection of X-valley electrons.

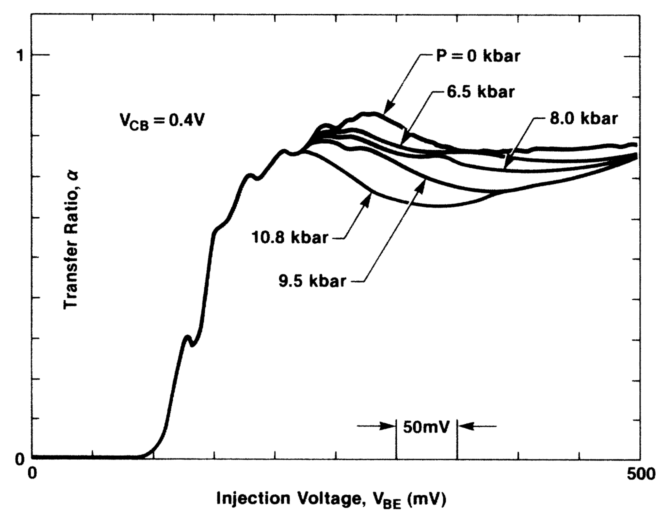

FIG. 3. The dependence of α on hydrostatic pressure for NH378. As the pressure increases, V_{tr} and the maximum of α decrease. Note that the onset of α, which determines $\Phi_C(\Gamma)$, is pressure invariant.

The existence of ballistic hot electrons in thin GaAs layers of a THETA device enables us to observe current transport effects associated with hot-electron transfer into the L valleys. The effect, observed even in layers as thin as 300 Å, with electron transit time as short as 0.03 ps, is consistent with phonon-assisted transfer. The transfer hypothesis was tested by application of hydrostatic pressure to the device structures. This led to transfer at lower injection energies, as expected. With our unique device structure the Γ-band discontinuity in the GaAs-AlGaAs heterojunctions was determined and found not to change from atmospheric pressure to 11 kbar.

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