Theoretical Comparison of Electron Real Space Transfer in Classical
and Quantum Two-Dimensional Heterostructure Systems

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Abstract

We present a comparison of the effect of real space transfer on the
electron drift velocities in both classical heterostructure systems, those in
which spatial quantization effects do not occur, and in two-dimensional
heterostructure systems using an ensemble Monte Carlo simulation. The
calculations for the two-dimensional system are based on a first principles
formulation of electron transport in a triangular quantum well system using
an ensemble Monte Carlo code tailored to include the basic physics of two-
dimensional systems. In addition, we present an analysis, again based on a
complete ensemble Monte Carlo simulation, of real space transfer from
classical systems, ones in which no two-dimensional gas is formed at the
heterointerface. Electron drift velocities within the classical system
greater than that possible in the constitutive bulk materials are thwarted by
either real space transfer out of the high mobility material into the adjacent
low mobility material or k-space transfer within the narrow gap material itself. In contrast, higher electron drift velocities than that achievable in the bulk occur in a system in which two-dimensional effects are present. In this case, when the electrons are confined within the two-dimensional gas, their corresponding drift velocities are somewhat larger than within the bulk three-dimensional system. We conclude that in electronic devices in which the electric field is applied parallel to the heterostructure layers, that the highest electron velocities are achieved for transport within the two-dimensional gas. In structures in which either a two-dimensional system is not present or the carriers all reside outside of the quantized states, the electron drift velocity is always less than the corresponding velocity in the bulk material due to the combined actions of real space and k-space transfer.
1. Introduction

The high electron mobility transistor (HEMT) [1,2] is the leading candidate for high speed digital and microwave device applications. The device delivers significant current without sacrificing speed by spatially separating the current carrying electrons from their donor atoms via modulation doping [3]. At present, the vast majority of HEMTs studied have been made using the GaAs/AlGaAs material system. Though the performance of these devices exceeds that of comparable conventional MESFET structures, improved operation is frustrated by the occurrence of the persistent photoconductivity effect (PPC) and the collapse of the drain I-V characteristic which appear within high Al content heterostructures. Persistent photoconductivity and the I-V drain collapse can be avoided by using AlGaAs layers with less than 20% Al mole fraction content. However, real space transfer effects [4] become significant at small conduction band edge discontinuities reducing overall device performance.

These inherent limitations of GaAs/AlGaAs HEMTs prompted the development of strained layer, Ga$_{0.85}$In$_{0.15}$As/GaAs pseudomorphic structures [5] and Ga$_{0.85}$In$_{0.15}$As/Al$_{0.15}$Ga$_{0.85}$As devices [6]. The particular advantage of the pseudomorphic HEMTs is that a low Al content AlGaAs modulation doped structure can be used while a large conduction band edge discontinuity is retained. Therefore, the persistent photoconductivity effect, as well as the I-V drain current collapse, can be avoided. Nevertheless, real space transfer effects can occur in the pseudomorphic devices leading to a significant decrease in the electron drift velocity.

In order to assess the limitations on the performance of HEMTs posed by real space transfer, it is necessary to study the transport properties of the
two-dimensional electron gas formed at the heterointerface. In this paper we present a first principles formulation of the electronic transport in a triangular quantum well system using an ensemble Monte Carlo code tailored to include the basic physics of two-dimensional systems. Our aim is to examine the physics of electronic transport in a two-dimensional Ga$_{0.85}$In$_{0.15}$As/Al$_{0.15}$Ga$_{0.85}$As heterostructure in order to assess the inherent limitations of this system in HEMT-like structures due to real space transfer. In addition, we present a comparison of real space transfer effects within classical systems, ones in which no two-dimensional gas is formed at the heterointerface. On the basis of this comparison, it is found that the steady state electron drift velocity can significantly exceed the corresponding bulk drift velocity when two-dimensional effects are present, while in a strictly classical system, no such enhancement is observed.

Below, two sets of calculations are presented. The first set is for a strictly classical system, as shown in Figure 1, in that the layer widths are assumed large and the doping concentration sufficiently small that two-dimensional effects do not appear. Lateral transport of the electrons in the direction parallel to the heterostructure interface is analyzed in which both the velocity-field characteristic and the threshold for real space transfer out of the narrow gap material into the wide band gap layers are determined. Calculations under these conditions are presented for both the GaAs/AlGaAs and GaInAs/AlGaAs material systems. Results are included for the GaAs/AlGaAs system in order to check with previously published results. Hence, the GaAs/AlGaAs calculations serve as a convenient control on both the classical and two-dimensional GaInAs/AlGaAs calculations. In addition, the velocity-field characteristic of a quasi-two-dimensional electron gas at a
Ga$_{0.85}$In$_{0.15}$As/Al$_{0.15}$Ga$_{0.85}$As heterointerface is determined as sketched in Figure 2. Two-dimensional effects are fully included into the Monte Carlo code and the effects of both real space transfer and transfer out of the two-dimensional system into the bulk are explored. All of the calculations are performed assuming a lattice temperature of 300 K.

The Monte Carlo model including the details of the two-dimensional transport physics used in the calculations is discussed in Section 2. The classical two-dimensional calculations are presented in Section 3 for both material systems. The results for the two-dimensional velocity-field calculations in the GaInAs/AlGaAs heterostructure system are discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. Model Description and Calibration

The calculations presented herein are based on an ensemble Monte Carlo model using analytically derived band structures for both constituent materials in the heterostructure system. All of the principle scattering mechanisms involving electron-phonon interactions and impurity scattering are included in the analysis. The electron drift velocities are calculated based on both the gradient of the E of k relation, as well as on power balance; in steady state, the energy gain from the field must equal that lost to the phonons. The simulation is performed under constant field conditions and steady state convergence is readily obtained when the energy gain from the field is balanced by that lost to the phonons. The GaInAs material parameters used in the calculations are obtained from interpolating over the binary system parameters given by Adachi [7]. The GaAs and AlGaAs parameters are from a recent work [8]. The interface boundary condition is treated using a strictly classical model; electrons incident onto the interface from within
the narrow gap semiconductor layer whose energies are less than the potential discontinuity are specularly reflected. Similarly, electrons whose energies exceed the potential barrier height are assumed to have a 100% transmission probability from one layer into the next. No reflections arising strictly from quantum mechanical effects are considered. Of course, there is a finite probability that the electrons will be reflected at this interface each time they approach it. Nevertheless, the effect of reflections has been neglected here for simplicity.

As a built-in control on our calculations, we first determine the electron drift velocity in bulk $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ in order to compare to existing experimental measurements [9-11]. The calculated values are plotted with the experimental measurements in Figure 3 over a wide range of applied electric fields. The agreement between the two is almost exact. The parameters used in the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ calculations are compiled in Table I. Using these parameters and a similarly derived set for bulk GaAs [8], the material parameters for the 15% In, InGaAs composition can be found. Each parameter is determined based on the interpolation methods of Adachi [7,12]. The number of equivalent valleys for the X and L satellite minima are taken as 3 and 4, respectively, since it is assumed that the valleys lie at the edge of the Brillouin zone. Therefore, only half of each valley is included within the first Brillouin zone. It is important to note that by first comparing our calculations to available experimental measurements, both in the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ system and in bulk GaAs [8], that a built-in control has been created for the $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ calculations.

The material parameters for the $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ system are determined similarly through interpolations of the GaAs and $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}$ parameters.
Again, no experimental measurements of the bulk drift velocities exist in the 15% Al alloy composition. Therefore, the best approach is to first compare to existing experimental measurements, determine a material parameter set, and then interpolate these parameters to obtain a corresponding set for a different alloy composition. The material parameters for both alloys, \( \text{In}_0.15\text{Ga}_{0.85}\text{As} \) and \( \text{Al}_{0.15}\text{Ga}_{0.85}\text{As} \) are collected in Tables II and III, respectively.

The narrow band gap layers in the classical calculations are chosen to be nearly intrinsic, no intentional impurities are present. However, the AlGaAs layers are assumed doped to \( -1.0 \times 10^{17} \text{ 1/cm}^3 \). Therefore, within the AlGaAs layers impurity scattering is also included in the analysis, as well as all of the relevant phonon scattering mechanisms present.

The treatment of the two-dimensional transport physics is accomplished as follows. The two-dimensional system is defined as the triangular-like quantum well formed at the GaInAs/AlGaAs interface bordered by the conduction band edge discontinuity on one side and the band bending on the other side as shown in Figure 2. When the electron has an energy less than the well height, which we define as the band bending, it is considered to be within the two-dimensional system. Once within the triangular quantum well, the electron's motion is subject to the physics of the two-dimensional system; the \( y \) direction is quantized, the scattering mechanisms are described using a two-dimensional formulation, and the energy depends upon which subband the electron enters.

For simplicity, we include only two subbands in the quantum well whose energies are calculated using the results of Stern and Das Sarma [13]. Since the intervalley separation energies for the L and X minima exceed the well
depth, the subbands are assumed to form only in the gamma minimum and the L and X valleys are treated as three-dimensional states. The electron's energy when it lies within the two-dimensional gas is simply given then as,

$$E = E_i + \frac{k^2 (k_x^2 + k_z^2)}{2m}$$

where $E_i$ is the subband energy and the quantization is taken to be in the $y$ direction. Therefore, the electron $k$-vector has components only in the $x$ and $z$ directions, and its motion can only change in these directions in accordance with the action of the applied electric field.

Within the two-dimensional system, the electron's motion is subject to various two-dimensional scattering mechanisms, particularly, polar optical phonon, acoustic phonon, alloy, and ionized impurity scatterings. Each of these scattering agents is treated in the Monte Carlo simulation. The alloy scattering potential is chosen to be 0.55 eV similar to that used by Yoon et al. [14]. The overall scattering rates in each case are calculated using the approach of Yoon et al. [14] with the trial wavefunctions of Yamaguchi [15]. Both intra and interband scatterings are treated. The final state of the electron after the scattering event is found in a similar way to that for the bulk systems [16] except that only the $k_x$ and $k_z$ components change in accordance with the physics of the scattering event. This approach is similar to that of Tomizawa et al. [17].

The coupling of the two-dimensional system to the bulk, in this case, the three-dimensional bulk GaInAs, is accomplished through polar optical phonon scatterings. At electron energies near the top of the quantum well, the electron can scatter to three-dimensional states within the bulk GaInAs.
Similarly, the electron can enter the quantum well system from the bulk via polar optical phonon emission events. The extent to which the electron transfers from the quantum system to the bulk and vice versa depends upon the relative strength of the polar optical scattering within the two and three-dimensional systems. Upon reaching an energy greater or equal to the well height, the electron can scatter either within the two-dimensional system as before or into the three-dimensional system via polar optical scatterings.

The actual mechanism by which the carrier scatters between the two and three-dimensional systems is as follows. If the carrier is initially within the two-dimensional system, near the top of the quantum well, it can scatter either according to the two-dimensional scattering rates present [14] or into the three-dimensional bulk system. It is assumed that the matrix element dictating the transition into the three-dimensional system is equivalent to that of the bulk system. In other words, the initial and final states are assumed to be three-dimensional-like. Similarly, the matrix element governing the transitions from the three-dimensional system into the two-dimensional system is equivalent to the corresponding two-dimensional polar optical scattering mechanisms. At present, we do not incorporate a mixed two to three-dimensional state matrix element in treating the scattering rate between the two systems. A more complete model will be presented in which this limitation will be addressed.

In addition to scatterings, the electrons can transfer between the two and three-dimensional systems via drifting upwards or downwards in energy. At electron energies greater than that corresponding to the band bending of the quantum well, the electrons are treated as in the bulk three-dimensional system. Upon drifting to lower energies, those below the band bending of the
well, the electrons are assumed to transfer to the two-dimensional states. Though this approach is somewhat artificial, the net result is physically correct; when the electrons are at energies below the top of the well, they are treated as belonging to the two-dimensional system.

Once within the three-dimensional bulk GaInAs, the electrons can be further heated to sufficiently high energy at which real space transfer into the neighboring AlGaAs layer can occur. This is of great importance in analyzing the behavior of HEMT-like devices.

The band bending due to the effects of modulation doping is included as well in the simulation. Hence, our two-dimensional heterostructure calculations include the effects of both the longitudinal applied electric field, as well as the transverse field due to the band bending. However, at present we do not perform a self-consistent calculation; the fields are assumed constant throughout the entire simulation. Currently, our computing facilities are not adequate for a self-consistent analysis. Future work using a Cray XMP will address this issue. Nevertheless, much of the essential physics of transport in a two-dimensional heterostructure system can be determined with our present model.

In summary then, our treatment of the two-dimensional system includes the full details of all of the relevant scattering mechanisms which provide for intra and interband scatterings, as well as a coupling to the bulk system. The actual simulation of the electron while within the two-dimensional quantum well is similar to that in the bulk except that only the $k_x$ and $k_z$ components change in accordance with the applied electric field and that the energy is found using Eq. (1).
3. Classical Real Space Transfer Calculations

We first present calculations of the lateral electron drift velocity in a simple AlGaAs/InGaAs/AlGaAs layered structure in order to study real space transfer in the absence of quantum confinement effects. The structure, as shown in Figure 1, consists of a 200 Å wide In$_{0.15}$Ga$_{0.85}$As layer enclosed on either side by a 5000 Å wide Al$_{0.15}$Ga$_{0.85}$As layer. In order to ascertain the effect of real space transfer on the overall carrier velocity, the corresponding bulk InGaAs and AlGaAs electron drift velocities are presented along with the real space transfer results in Figure 4. At low applied electric field strengths, the carriers remain within the InGaAs layer and the drift velocity approaches the bulk InGaAs result. As the electric field increases, the electrons begin to transfer to the lower mobility AlGaAs layer. Notice that throughout the full range of applied electric field strengths that the electron drift velocity in the multilayered system is intermediate between that of the constitutive bulk materials as is expected. The peak electron drift velocity in the multilayered device occurs at roughly 3.25 kV/cm. At this field strength, essentially 20% of the electrons have transferred to the AlGaAs layers, as can be seen from inspection of Figure 5. Further inspection of Figure 5 indicates that real space transfer between the two layers occurs prior to k-space transfer in the In$_{0.15}$Ga$_{0.85}$As. This is not too surprising since the conduction band edge discontinuity is assumed to be 0.27 eV [6] while the $\Gamma$–L valley separation in the InGaAs is 0.368 eV.

From inspection of Figure 5, we conclude that for the device geometry chosen in the In$_{0.15}$Ga$_{0.85}$As/Al$_{0.15}$Ga$_{0.85}$As system, that real space transfer becomes significant at applied electric fields in excess of 4 kV/cm prior to intervalley transfer in the bulk GaInAs. Additionally, the electrons, upon
transferring into the AlGaAs layers, transfer to the L valley in significant numbers at applied fields greater than 7 kV/cm. This is as expected since, as the field increases, the electrons undergo k-space transfer within each respective layer.

Similar calculations are performed for a GaAs/AlGaAs multilayered structure where quantum confinement effects are neglected assuming both 32 and 45% Al composition. The steady state electron drift velocity in these structures, as well as the calculated bulk GaAs and bulk AlGaAs drift velocities are presented in Figures 6 and 7, respectively. The material parameters used in these calculations have been presented elsewhere [8]. The conduction band edge discontinuity in this system has been chosen as 62% of the band gap difference in accordance with recent photoluminescence experiments [18,19]. As can be readily seen from Figure 6, the electron drift velocity at low applied fields approaches that for bulk GaAs, while at higher fields it approaches the bulk AlGaAs. As before, the drift velocity in the real space transfer structure always lies between the two limits of the bulk GaAs and bulk AlGaAs values.

Comparison of Figures 8 and 9 indicates that real space transfer dominates the transport physics in a 32% Al composition sample, while k-space transfer within the GaAs layer occurs first in the 45% sample. This is readily understood by recognizing that the conduction band edge discontinuity is significantly larger between the GaAs and Al0.45Ga0.55As layers than between the GaAs and Al0.32Ga0.68As. The values chosen here, 0.348 and 0.247 eV for the 45 and 32% Al composition heterostructures, respectively, lie above and below the corresponding Γ-L valley separation energy in GaAs (taken here as 0.284 eV [8]). Therefore, it follows that real space transfer will
occur before k-space transfer in the 32% Al sample since the threshold energy is less. Inspection of Figure 6 indicates that the peak drift velocity occurs at ~3.25 kV/cm, less than that for k-space transfer alone, 3.75 kV/cm [8].

Conversely, k-space transfer occurs more readily than real space transfer in the 45% Al device. In fact, in this structure the effects of real space transfer are not significant (less than 20% transfer into the AlGaAs) until the applied field becomes much larger, > 10 kV/cm, well above the threshold field for k-space transfer of 3.75 kV/cm (typically defined as the applied field which corresponds to the peak drift velocity). The velocity-field relation for the real space transfer device closely follows that for the bulk GaAs throughout most of the applied field range considered here. It is interesting to note that the electrons occupy the L and X valleys upon transferring into the AlGaAs layers. This follows immediately since for a 45% Al composition, AlGaAs becomes an indirect semiconductor [20]. Owing to the much larger density of states within the L and X valleys, the vast majority of the transferred electrons reside within the satellite valleys rather than the central, Γ valley.

In the 32% Al composition case, upon transferring from the GaAs into the adjacent AlGaAs layers, the electrons first enter the central or Γ valley. At higher applied electric field strengths, the electrons heat up in each layer and subsequently transfer into the higher energy L valleys. Therefore, the Γ valley dominates the transport physics when real space transfer occurs throughout the low field range. When either the conduction band edge discontinuity becomes much larger than the Γ-L valley separation energy or the applied electric field strength is large, significant transfer to the L valleys occurs.
The GaAs/AlGaAs real space transfer calculations can be compared to previous Monte Carlo studies [21]. The previous studies did not include the L valley in the AlGaAs nor the X valleys in either material system as is done here. Therefore, the previous work does not include the effects of k-space transfer in the surrounding AlGaAs layers. Nevertheless, reasonable agreement is obtained between the results presented here and those of Glisson et al. [21]. Comparing our calculations for a 32% Al composition real space transfer device (which has a heterostructure potential edge discontinuity of \( \sim 0.24 \) eV) to those made by Glisson et al. [21] for a system in which the potential discontinuity is 0.20 eV, both the peak drift velocity and the onset of the negative differential resistance agree reasonably well. We found that the peak drift velocity is roughly \( 1.7 \times 10^7 \) cm/sec while Glisson determined it to be \( \sim 1.6 \times 10^7 \) cm/sec. The threshold field, 2.4 kV/cm, found by Glisson et al. [21], is somewhat lower than that found here, 3.25 kV/cm, but this is most likely due to the different potential discontinuities chosen between the two studies.

Finally, it is interesting to compare the peak electron drift velocities in the real space transfer devices of Figures 6 and 7. Notice that the peak drift velocity is much larger in the 45% Al composition device than in the 32% Al composition sample. The threshold field for negative differential resistance is also slightly higher within the 45% composition than within the 32% composition. These results are consistent with recent calculations obtained in bulk material [8] in which it was determined that both the peak steady state drift velocity and the threshold field are directly related to the degree of confinement of the electrons within the central valley. The degree of confinement depends, in turn, upon the efficiency of the phonon cooling.
mechanisms (in bulk III-V compounds, the predominant phonon scattering agents are polar optical phonons) and the intervalley separation energies or, as in the case of real space transfer, the conduction band edge discontinuity between the two material systems. Therefore, if the conduction band edge is increased significantly, the electrons are more strongly confined within the higher mobility GaAs layer and subsequently achieve a higher peak velocity.

Similar physics has been found recently in the study of ballistic transport in hot electron transistors [22,23]. High carrier velocities can be achieved, in general, by confining the carriers within the low effective mass \( \Gamma \) valley. In the systems discussed above, longitudinal carrier transport in a heterostructure system, high electron drift velocities are thwarted either by real space transfer out of the high mobility narrow gap layer or by \( k \)-space transfer to the low mobility satellite valleys. In either case, velocities greater than that within the constitutive bulk material cannot be attained.

For systems in which the field is applied perpendicular to the heterostructure system, in order to attain high carrier speeds, paradoxically, it is more advantageous for the carriers to be accelerated "uphill," against the built-in heterostructure potential, than "downhill," where the electrons gain energy from the heterostructure potential [23]. The electrons lose their excess kinetic energy by moving against a built-in potential, due either to heterostructure potential steps [23], or a graded band gap layer, etc., such that they remain confined within the \( \Gamma \) valley. In this way, \( k \)-space transfer to the low mobility satellite valleys is defeated, preserving the high velocities present within the central valley. Interestingly, much higher drift velocities can be attained over longer distances from that achievable in the corresponding bulk material [23]. The general conclusion then, based on the
calculations presented here and in References 22 and 23, is that when the electrons are confined within the \( \Gamma \) valley, the peak steady state drift velocity increases.

4. Calculations in Two-Dimensional Heterostructure Systems

The electron drift velocity as a function of applied electric field at 300 K in a heterostructure in which two-dimensional quantum confinement effects are present is plotted in Figure 10. The calculations are performed using the treatment of the two-dimensional effects described in Section 2 above. Therefore, the calculations detail the additional effect of the presence of the two-dimensional triangular well on the electron drift velocity. It is important to note that the calculated electron drift velocity exceeds that of the bulk In\(_{0.15}\)Ga\(_{0.85}\)As at low electric fields, < 1.0 kV/cm. Inspection of Figure 10 also indicates that the electron mobility is greater in the heterostructure system at low applied fields than within the bulk system. At all higher fields investigated thereafter, the electron drift velocity in the heterostructure lies below that attainable in bulk In\(_{0.15}\)Ga\(_{0.85}\)As.

The high electron drift velocity at low applied longitudinal electric fields is due to transport within the two-dimensional system as is readily seen from Figure 11. The electrons virtually all transfer out of the two-dimensional system at field strengths above 1 kV/cm after which the transport is dominated by three-dimensional effects. The electrons remain predominantly within the InGaAs and experience k-space transfer at higher electric fields consistent with that found above in the classical case.

Notice that the effects of real space transfer are less important in this structure than in the classical structure. This is most probably due to the
choice of geometries in the two devices. In the structure containing two-dimensional effects, the InGaAs is bordered only on one side by AlGaAs (which is the typical device geometry used in pseudomorphic HEMTs), while in the classical calculations the InGaAs layer is bordered on both sides by AlGaAs.

The two-dimensional calculations of the electron drift velocity shown in Figure 10 are in good qualitative agreement with the experimental measurements of Hong et al. [24] even though the choices of material composition is somewhat different. Self-consistent treatment of the electric fields, both the applied longitudinal and that due to the band bending at the heterointerface, has been neglected here due to computational limitations. A future work will address this issue as well as fully probe the physics of a pseudomorphic GaInAs/AlGaAs HEMT structure.

5. Conclusions

We have presented a series of "computer experiments" of electron real space transfer in both strictly classical, where no quantum confinement effects are present, and in two-dimensional heterostructure systems. The classical real space transfer calculations are made using both GaAs/AlGaAs and GaInAs/AlGaAs material systems, while the two-dimensional heterostructure simulations are applied to only GaInAs/AlGaAs pseudomorphic layers. The classical calculations are performed using an ensemble Monte Carlo solution of the semiclassical Boltzmann Transport Equation. A built-in control on the calculations is provided by first comparing the calculated steady state bulk electron drift velocities to existing experimental data. Further comparison is made to previous real space transfer calculations [21] using the GaAs/AlGaAs calculations and reasonable agreement is found. Based on the bulk electron drift velocity calculations, a full material parameter set can be
attained. If necessary, interpolations are performed between different compositions in order to determine a reliable parameter set in a composition that has not yet been experimentally probed. Therefore, the effects of real space transfer are completely isolated since the only difference between the real space transfer calculations and the constituent bulk materials is the presence of the heterostructure.

In the classical calculations presented herein, the velocity field characteristics are consistent with those for bulk material; as the degree of confinement of the electrons within a high mobility region increases, the peak steady state drift velocity as well as the threshold electric field increases. The electrons are confined by the combined action of phonon cooling effects and the potential barrier formed by the conduction band edge discontinuity. In the GaAs/AlGaAs real space transfer devices, phonon cooling effects are identical between different Al composition structures, hence the calculations probe the effects of the band edge discontinuity on the overall carrier drift velocity.

It is found that the electron drift velocity within a heterostructure which shows no quantum confinement effects and in which the field is applied parallel to the heterostructure direction, never exceeds the corresponding drift velocity within the bulk narrow gap material. The action of real space transfer or k-space transfer collectively act to limit the maximum achievable drift velocity in these structures.

When two-dimensional quantum confinement effects are present, the electron drift velocity can exceed the corresponding three-dimensional bulk drift velocities if the vast majority of the carriers are confined to the quantum states. At higher fields, at which the concentration of carriers
within the two-dimensional levels becomes depleted, the electron drift velocity again becomes less than that of the corresponding narrow gap bulk layer. Therefore, high electron drift velocities in heterostructure systems in which the field is applied laterally cannot be attained except at very low fields or temperatures. We conclude, based on our model of transport in a two-dimensional heterostructure system, that the high speed advantages of devices which utilize lateral transport in two-dimensional heterostructure systems arises predominantly from other effects than from improvements in the carrier saturation drift velocities. This finding is consistent with numerical simulations of HEMT devices in which it is found that both velocity overshoot and lower access source resistance are most important in improving device speed [24,25].

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References


Figure Captions

Figure 1: Schematic drawing of the device structure used for simulating the effects of real space transfer in a classical system; no two-dimensional effects are assumed to be present.

Figure 2: Schematic drawing of the device structure used for calculating the transport properties in a quantum two-dimensional system. Only two subbands are included in the analysis.

Figure 3: Comparison of calculated and experimental measurements of the steady state electron drift velocities in bulk In$_{0.53}$Ga$_{0.47}$As as a function of applied electric field.

Figure 4: Calculated electron drift velocity in bulk In$_{0.15}$Ga$_{0.85}$As, Al$_{0.15}$Ga$_{0.85}$As, and in a real space transfer device made from these material systems. The AlGaAs layer is taken to be doped to $1.0 \times 10^{17}$ cm$^{-3}$ in both the real space transfer device and in the bulk calculation.

Figure 5: Electron valley occupancy as a function of applied electric field for the InGaAs/AlGaAs real space transfer device.

Figure 6: Calculated steady state electron drift velocity in bulk GaAs, bulk Al$_{0.32}$Ga$_{0.68}$As, and in a real space transfer device made from these material systems. The AlGaAs layer is assumed to be doped at $1.0 \times 10^{17}$ cm$^{-3}$ in both the real space transfer device and in the bulk AlGaAs case.

Figure 7: Calculated steady state electron drift velocity in bulk GaAs, bulk Al$_{0.45}$Ga$_{0.55}$As, and in a real space transfer device made from these material systems. The AlGaAs layer is assumed to be doped
at \(1.0 \times 10^{17} \text{ } \text{1/cm}^3\) in both the real space transfer device and in the bulk AlGaAs case.

**Figure 8:** Electron valley occupancy as a function of applied electric field in the Al\(_{0.32}\)Ga\(_{0.68}\)As/GaAs real space transfer device.

**Figure 9:** Electron valley occupancy as a function of applied electric field in the Al\(_{0.45}\)Ga\(_{0.55}\)As/GaAs real space transfer device.

**Figure 10:** Electron drift velocity as a function of applied electric field at 300 K in a two-dimensional heterostructure In\(_{0.15}\)Ga\(_{0.85}\)As/Al\(_{0.15}\)Ga\(_{0.85}\)As system. The AlGaAs layer in the heterostructure system is assumed to be doped at \(1.0 \times 10^{18} \text{ } \text{1/cm}^3\) consistent with most HEMT-like structures.

**Figure 11:** Electron occupancy of the two-dimensional system, bulk InGaAs, and AlGaAs layers as a function of applied electric field strength.
### Table I. In$_{0.53}$Ga$_{0.47}$As

#### Bulk Material Parameters

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#### Valley Dependent Parameters

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<td>1.02</td>
</tr>
<tr>
<td>Optical Phonon Energy (eV)</td>
<td>---</td>
<td>0.0327</td>
<td>0.0327</td>
</tr>
<tr>
<td>Number of Equivalent Valley</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Intervalley Deformation Potential (eV/cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>from $\Gamma$</td>
<td>0</td>
<td>$1 \times 10^9$</td>
<td>$1 \times 10^9$</td>
</tr>
<tr>
<td>from $X$</td>
<td>$1 \times 10^9$</td>
<td>$9 \times 10^8$</td>
<td>$9 \times 10^8$</td>
</tr>
<tr>
<td>from $L$</td>
<td>$1 \times 10^9$</td>
<td>$1 \times 10^9$</td>
<td>$9 \times 10^8$</td>
</tr>
<tr>
<td>Intervalley Phonon Energy (eV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>from $\Gamma$</td>
<td>0.0</td>
<td>0.03</td>
<td>0.0299</td>
</tr>
<tr>
<td>from $X$</td>
<td>0.0299</td>
<td>0.0293</td>
<td>0.0299</td>
</tr>
<tr>
<td>from $L$</td>
<td>0.03</td>
<td>0.029</td>
<td>0.0293</td>
</tr>
</tbody>
</table>
Table II. \( \text{In}_{0.15}\text{Ga}_{0.85}\text{As} \)

### Bulk Material Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Constant (cm)</td>
<td>5.71 \times 10^{-8}</td>
</tr>
<tr>
<td>Longitudinal Phonon Energy (eV)</td>
<td>0.0329</td>
</tr>
<tr>
<td>Sound Velocity (cm/sec)</td>
<td>4.92 \times 10^5</td>
</tr>
<tr>
<td>Low-Frequency Dielectric Constant</td>
<td>12.96</td>
</tr>
<tr>
<td>High-Frequency Dielectric Constant</td>
<td>10.97</td>
</tr>
<tr>
<td>Density (g/cm^3)</td>
<td>5.394</td>
</tr>
</tbody>
</table>

### Valley Dependent Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \Gamma )</th>
<th>( L )</th>
<th>( X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Mass (( m^*/m_0 ))</td>
<td>0.0556</td>
<td>0.2543</td>
<td>0.4665</td>
</tr>
<tr>
<td>Nonparabolicity (eV^{-1})</td>
<td>0.829</td>
<td>0.260</td>
<td>0.068</td>
</tr>
<tr>
<td>Energy Band Gap (eV)</td>
<td>1.19</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Valley Separation (eV)</td>
<td>---</td>
<td>0.368</td>
<td>0.63</td>
</tr>
<tr>
<td>Optical Phonon Energy (eV)</td>
<td>---</td>
<td>0.03385</td>
<td>0.03385</td>
</tr>
<tr>
<td>Number of Equivalent Valley</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

**Intervalley Deformation Potential (eV/cm)**

<table>
<thead>
<tr>
<th></th>
<th>( \Gamma )</th>
<th>( L )</th>
<th>( X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>from ( \Gamma )</td>
<td>0</td>
<td>1 \times 10^9</td>
<td>1 \times 10^9</td>
</tr>
<tr>
<td>from ( X )</td>
<td>1 \times 10^9</td>
<td>9 \times 10^8</td>
<td>9 \times 10^8</td>
</tr>
<tr>
<td>from ( L )</td>
<td>1 \times 10^9</td>
<td>1 \times 10^9</td>
<td>9 \times 10^8</td>
</tr>
</tbody>
</table>

**Intervalley Phonon Energy (eV)**

<table>
<thead>
<tr>
<th></th>
<th>( \Gamma )</th>
<th>( X )</th>
<th>( L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>from ( \Gamma )</td>
<td>0.0</td>
<td>0.030</td>
<td>0.0299</td>
</tr>
<tr>
<td>from ( X )</td>
<td>0.0299</td>
<td>0.0293</td>
<td>0.0299</td>
</tr>
<tr>
<td>from ( L )</td>
<td>0.030</td>
<td>0.029</td>
<td>0.0293</td>
</tr>
</tbody>
</table>
### Table III. Al$_{0.15}$Ga$_{0.85}$As

#### Bulk Material Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Constant (cm)</td>
<td>5.6533 x 10$^{-8}$</td>
</tr>
<tr>
<td>Longitudinal Phonon Energy (eV)</td>
<td>0.0352</td>
</tr>
<tr>
<td>Sound Velocity (cm/sec)</td>
<td>5.327 x 10$^5$</td>
</tr>
<tr>
<td>Low-Frequency Dielectric Constant</td>
<td>12.43</td>
</tr>
<tr>
<td>High-Frequency Dielectric Constant</td>
<td>10.51</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>5.12</td>
</tr>
</tbody>
</table>

#### Valley Dependent Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Gamma$</th>
<th>$L$</th>
<th>$X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Mass ($m^*/m_0$)</td>
<td>0.074</td>
<td>0.231</td>
<td>0.421</td>
</tr>
<tr>
<td>Nonparabolicity (eV$^{-1}$)</td>
<td>0.624</td>
<td>0.638</td>
<td>0.344</td>
</tr>
<tr>
<td>Energy Band Gap (eV)</td>
<td>1.61</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Valley Separation (eV)</td>
<td>---</td>
<td>0.220</td>
<td>0.318</td>
</tr>
<tr>
<td>Optical Phonon Energy (eV)</td>
<td>---</td>
<td>0.03628</td>
<td>0.03628</td>
</tr>
<tr>
<td>Number of Equivalent Valley</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

**Intervalley Deformation Potential (eV/cm)**

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma$</th>
<th>$L$</th>
<th>$X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>from $\Gamma$</td>
<td>0.0</td>
<td>$9.25 \times 10^8$</td>
<td>$1.0 \times 10^9$</td>
</tr>
<tr>
<td>from $X$</td>
<td>$1.0 \times 10^9$</td>
<td>$9.0 \times 10^8$</td>
<td>$9.15 \times 10^9$</td>
</tr>
<tr>
<td>from $L$</td>
<td>$9.25 \times 10^8$</td>
<td>$9.25 \times 10^8$</td>
<td>$9.0 \times 10^8$</td>
</tr>
</tbody>
</table>

**Intervalley Phonon Energy (eV)**

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma$</th>
<th>$L$</th>
<th>$X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>from $\Gamma$</td>
<td>0.0</td>
<td>0.03202</td>
<td>0.03251</td>
</tr>
<tr>
<td>from $X$</td>
<td>0.03251</td>
<td>0.0320</td>
<td>0.03251</td>
</tr>
<tr>
<td>from $L$</td>
<td>0.03202</td>
<td>0.03125</td>
<td>0.0320</td>
</tr>
</tbody>
</table>
GaAs

or

In$_{0.15}$Ga$_{0.85}$As

GaAs

or

In$_{0.15}$Ga$_{0.85}$As

Al$_{0.32}$Ga$_{0.68}$As

or

Al$_{0.15}$Ga$_{0.85}$As

$\Delta E_c$

Figure 1
$\Delta E_c$ \\
Subband 2 \\
Subband 1 \\
Well Height \\
$V(y)$
Drift Velocity ($x 10^7 \text{cm/sec}$) vs. Electric Field (kV/cm).

- Marsh et. al.
- Calculation
- Windhorn et al.

$\text{In}_{0.53} \text{Ga}_{0.47}\text{As}$
Drift Velocity (x $10^7$ cm/sec)

- $\text{In}_{0.15}\text{Ga}_{0.85}\text{As Bulk}$
- $\Delta \text{In}_{0.15}\text{Ga}_{0.85}\text{As/Al}_{0.15}\text{Ga}_{0.85}\text{As (RSTD)}$
- $\square \text{Al}_{0.15}\text{Ga}_{0.85}\text{As Bulk}$

Electric Field (kV/cm)

Figure 4
(Swain et al.)
Figure 5

Al_{0.15}Ga_{0.85}As/In_{0.15}Ga_{0.85}As

- $\Gamma \rightarrow \text{In}_{0.15}\text{Ga}_{0.85}\text{As}$
- $L \rightarrow \text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$

- Total InGaAs
- Total AlGaAs
Drift Velocity ($\times 10^7$ cm/sec) vs. Electric Field (kV/cm)

- $\text{GaAs Bulk}$
- $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As/GaAs (RSTD)}$
- $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As Bulk}$
Drift Velocity (x10^7 cm/sec) vs Electric Field (kV/cm)

- ○ GaAs Bulk
- △ Al_{0.45}Ga_{0.55}As/GaAs (RSTD)
- □ Al_{0.45}Ga_{0.55}As Bulk

Figure 7
Figure 8

Al_{0.32}Ga_{0.68}As/GaAs
- Γ \rightarrow GaAs
- L \rightarrow Al_{0.32}Ga_{0.68}As

- Total GaAs
- Total AlGaAs

OCCUPANCY (%)

ELECTRIC FIELD (kV/cm)
Figure 9

Al\textsubscript{0.45}Ga\textsubscript{0.55}As/GaAs (RSTD)

- $\Gamma$ (GaAs)
- $L$ (AlGaAs)

- Dashed line: Total GaAs
- Dotted line: Total AlGaAs

OCCUPANCY (%) vs. ELECTRIC FIELD (kV/cm)
2.5

In 0.15 Ga 0.85 As Bulk

A A1 0.15

Ga 0.85 As /In 0.15 Ga 0.85 As

❑

Al 0.15 Ga 0.85 As Bulk

DRIFT VELOCITY (x 10^7 cm/sec)

10

12

14

16

18

20

ELECTRIC FIELD (kV/cm)

0

2

4

6

8

10

12

14

16

18

20

Figure 10

Bourne et al.