Polaron pinning effects in superlattices at high electric and magnetic fields

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Abstract

Current–voltage characteristics of GaAs/AlAs superlattices have been measured using long-pulsed magnetic fields up to 37 T applied parallel to the growth axis. In the region of Wannier–Stark localisation a combined Wannier–Stark Landau ladder of states is obtained and a number of resonant features corresponding to inter-well transitions are observed. At low magnetic fields, their voltage positions increase with magnetic field. However at magnetic fields above about 18 T, their voltage positions become independent of magnetic field owing to a pinning effect associated with polaronic coupling to the longitudinal-optic phonon mode.

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Superlattices have been the subject of much interest from the scientific and engineering communities owing to their applications in microwave and laser structures [1,2]. Many of these applications work in the Wannier–Stark localisation regime, in which a strong applied electric field breaks the miniband into a ladder of states localised in consecutive quantum wells of the superlattice. Under such conditions, a variety of transport mechanisms may be possible. Application of a strong magnetic field can greatly modify the transport mechanisms. For example, in the presence of a magnetic field applied perpendicular to the layers of the superlattice, one possible mechanism is inter-Landau level hopping [3,4] in which an electron changes Landau level index whilst tunnelling between quantum wells.

In this contribution, electrical conduction through n-GaAs/AlAs superlattices is investigated using pulsed magnetic fields up to 37 T applied parallel to the growth axis of the superlattice. A large number of features are observed in the current–voltage characteristics. Possible origins of these features are considered.

The device studied was grown by molecular beam epitaxy on an n+ substrate. It consists of an undoped, nineteen period GaAs/AlAs superlattice with a nominal period \( d = 14 \) nm determined by X-ray scattering. This is separated from n-doped contact layers by undoped spacer layers. The material was processed into circular mesas of 100 µm and 200 µm diameter and ohmic contacts were made to the top layer and substrate. Each current–voltage characteristic was measured...
in a period of 400 μs at the peak of a long magnetic field pulse. During this time the magnetic field varied by less than 0.1 T.

Fig. 1 shows current–voltage, $I(V)$, characteristics in magnetic fields applied parallel to the growth axis. Note the strong suppression of the current at all voltages above 0.1 V. The behaviour of the $I(V)$ characteristic in the miniband conduction regime below 0.1 V is discussed elsewhere [5]. At relatively low magnetic fields ($<15$ T) the resonant features in the $I(V)$ characteristics evolve with increasing magnetic field in a complicated way. Some, such as the peak at 0.4 V, appear independent of magnetic field up to about 5 T. (Note that this peak is strongly quenched above 5 T.) However, most of the features are quite strongly dependent on the magnetic field $B$, especially for $10 \, T < B < 18 \, T$. At higher magnetic fields the $I(V)$ characteristics become simpler with a relatively small number of features, several of which are almost independent of magnetic field, as indicated by arrows on Fig. 1.

A strong electric field $F$ applied to a superlattice transforms the miniband states into a set of localised Wannier–Stark states associated with each quantum well. When a magnetic field is also applied parallel to $F$, the energies $e$ of the states in the $p$th quantum well are fully quantised into discrete levels according to the relation $e = (n + 1/2)\hbar \omega_c - eFd\!p$, where $\hbar \omega_c$ is the cyclotron energy, $n$ is the Landau level index and $d$ is the period of the superlattice. The complete quantisation of the electronic motion greatly limits the range of scattering processes which can produce transitions between the localised Wannier–Stark states. For example, an elastic or quasi-elastic process in which an electron hops from one quantum well to another by transferring potential energy along $F$ into in-plane kinetic energy is, in general, forbidden in a quantising magnetic field by energy conservation. However, a quasi-elastic hopping transition in which an electron changes Landau level index by $\Delta n$ whilst traversing $Dp$ periods of the superlattice is possible when the potential $V_a$ across one period of the superlattice is given by $\Delta peV_\alpha = \Delta n\hbar \omega_c \pm \hbar \omega_A$, where $\hbar \omega_A \approx \hbar \nu_A \Delta k$ is the energy of an acoustic phonon emitted (+) or absorbed (−) in the transition and $\Delta k \approx (eB/h)^2$. Purely elastic processes are also possible owing to interface roughness or impurity scattering. Another mechanism by which an electron can make a hopping transition involves coupling to longitudinal optic (LO) phonons. This coupling allows an electron to hop from the $n$th Landau level of the $p$th quantum well to a state an energy $\hbar \nu_{LO}$ above the $n$th Landau level of the $(p + \Delta p)$th quantum well, where $\hbar \nu_{LO}$ is the energy of an LO phonon in GaAs and $l$ is an integer. In this case the condition for a resonant transition is $\Delta peV_\alpha = \hbar \nu_{LO}$, although multiphonon ($l > 1$) processes are higher order and thus less likely. The peak at 0.4 V at low magnetic fields is attributed to the process in which a electron hops to a next nearest neighbour

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Fig. 1. Current–voltage characteristics in magnetic fields applied parallel to the growth axis in pulsed fields up to 37 T at approximately 1.5 T intervals. Characteristics are displaced vertically for clarity.
(Δp = 2) quantum well and emits a single LO phonon. With increasing magnetic field the strength of this transition decreases rapidly owing to the q-dependence of the matrix element. In high magnetic fields, the in-plane change in wavevector, Δq// ≈ (eB/h)² and thus the matrix element [6] varies as 1/B.

Processes in which an electron both changes Landau level index and couples to an LO phonon whilst hopping between wells are also possible. The process (Δn, Δp, l) ∈ (0, 2, 1) is shown schematically in Fig. 2 for the case εLO < hωc for a transition from the |n, l⟩ = |0, 0⟩ state of the pth well to the polaronic |n, l⟩ = |0, 1⟩ state of the (p + 2)th well. The subsequent relaxation of the electron from the polaronic state to the |0, 0⟩ state of the destination well by emission of an LO phonon is also shown.

In Fig. 3 are plotted the values of V_u as a function of applied magnetic field for some of the possible hopping transitions (Δn, Δp, l) for l = 0, 1. A transition (0, Δp1, 1) will intersect the transition (Δn, Δp2, 0) when hωc/εLO = (Δp2/Δp1)(1/Δn). When this occurs for Δp1 = Δp2, there will be ad-mixing between the |n, l⟩ = |n, 1⟩ and |n, l⟩ = |n + Δn, l⟩ transitions.

Fig. 2. Schematic diagram illustrating a transition (Δn, Δp, l) = (0, 2, 1) from a |n, l⟩ = |0, 0⟩ state to a |n, l⟩ = |0, 1⟩ state, in which an electron hops across two periods of the superlattice without changing Landau index, for the case hωc > εLO. The electron can then relax to the |n, l⟩ = |0, 0⟩ state of the destination well by emission of a single LO phonon, as is also shown.

Fig. 3. Plot as a function of magnetic field of the voltage across a single period of the superlattice, V_u, at which hopping transitions (Δn, Δp, l) can occur for Δn = 0, 1, Δp = 1, 2 and l = 0, 1, where Δn is the change in Landau level index and l indicates coupling to an LO phonon whilst traversing Δp periods of the superlattice. The thick line shows schematically the effect of the magneto-polaron interaction for the (1, 2, 0) and (0, 2, 1) transitions.
0) states in the destination well. This magneto-polaron effect will produce an anti-crossing, as shown by the thick lines in Fig. 3 for the (1, 2, 0) and (0, 2, 1) transitions. For the device considered here, hopping through these two states at the point where they anti-cross is expected to occur when $V = 0.39$ V and $B = 21$ T [7]. This can be compared with the feature with the behaviour of the lowest voltage feature marked with an arrow in Fig. 1. A similar effect has previously been observed in the tunnel current of a single quantum well [8]. Note that there cannot be polaronic pinning for $\Delta p_1 \neq \Delta p_2$ because the overlap between the $|n, 1\rangle$ state in the $p + \Delta p_1$ well and $|n + \Delta n, 0\rangle$ state in the $p + \Delta p_2$ well is too small.

The features at higher voltages cannot be accounted for so simply, but may be associated with polaron effects involving LO modes of the AlAs barrier or hopping at higher values of $\Delta p$ and $\Delta n$ and possibly also multiphonon features, which have been observed in the $I(V)$ characteristics of resonant tunnelling devices [8].

In conclusion, hopping mechanisms in a GaAs/AlAs superlattice under high magnetic fields parallel to the growth axis have been studied. Evidence of polaronic pinning was observed, with strong anti-crossing between transitions involving a change of Landau level index and transitions involving the coupling to LO phonons.

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References

[7] The very small collector depletion layer ($< 26$ Å) in the structure results in the applied bias $V$ being directly proportional to $V_u$.