Enhanced current injection from a quantum well to a quantum dash in magnetic field

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Abstract
Resonant tunneling injection is a key ingredient in achieving population inversion in a putative quantum dot cascade laser. In a quantum dot based structure, such resonant current requires a matching of the wavefunction shape in $k$-space between the injector and the quantum dot. We show experimentally that the injection into an excited state of a dash structure can be enhanced tenfold by an in-plane magnetic field that shifts the injector distribution in $k$-space. These experiments, performed on resonant tunneling diode structures, show unambiguously resonant tunneling into an ensemble of InAs dashes grown between two AlInAs barrier layers. They also show that interface roughness scattering can enhance the tunneling current.

Keywords: quantum dots, quantum cascade laser, resonant tunneling diode, low dimensional system, tunneling

1. Introduction

We use quantum dash resonant tunneling diodes (RTDs) to study the injection and outcoupling mechanism in a proposed quantum dot cascade laser (QDCL) structure [1–3] for which various
experimental and theoretical studies exist [4–10]. The QDCL addresses the weaknesses of purely QW based cascade lasers (QCLs) by introducing quantum dots fully quantizing the electronic states into discrete atom-like energy levels. These interrupt the numerous in-plane scattering paths—including optical phonon scattering—in QWs, thereby increasing the upper laser level lifetime. This issue becomes especially prominent for THz-QCLs, which still lack room-temperature operation [11]. Indeed, the reduction of in-plane scattering mechanisms has been shown to dramatically decrease the threshold current of THz-QCLs placed with their growth direction parallel to an applied magnetic field [12]. The latter provides in-plane confinement through the creation of Landau Levels [13]. Furthermore, TE-polarized laser light and surface emission without complicated outcoupling mechanisms would become possible [14].

Transport in RTDs was first demonstrated by Chang et al in 1974 [15]. Since then there has been wide interest in these structures for their potential in electronics and optoelectronics [16]. However, the study of RTDs can also be used for fundamental understanding of transport phenomena at the nanoscale level [17, 18]. This has usually been carried out by studying the tunneling through double barrier RTDs [16]. This type of study is particularly important in the case of 2D- and 3D-confined nanostructures (quantum wires and dots, respectively), where tunneling effects can reveal new phenomena compared to tunneling in one dimensional (1D) confined QWs. Indeed, interesting results on intrinsic properties of quantum dots have been shown using quantum dot-based RTDs [19]. Researchers have focused mainly on self-assembled InAs quantum dots grown on GaAs substrates—a privileged material system for the nucleation of nanoislands under Stranski–Krastanov growth conditions due to the large mismatch between InAs and GaAs [20]. The energy levels of these QDs were already well analyzed by capacitance voltage measurements [21] and photoluminescence spectroscopy [22]. RTD spectroscopy [23] has offered a lot of complementary information, especially when the effect of an in-plane magnetic field was included in the experiments [19, 24–26] as a means of containing the in-plane momentum component of the tunneling electron. In this paper we perform magneto-transport measurements on double-barrier RTDs based on a InAs quantum dashes grown on the InP material system, which, on the other hand, has received less attention in regard to RTD spectroscopy [27, 28].

Here we discuss the transport properties of a double barrier RTD containing elongated quantum dots (called QDashes here) on InP substrate in strong in-plane magnetic fields. These QDashes exhibit TE polarized absorption and emission and are promising for the development of a QDCL with a 3D confined active region [8]. We report a significantly enhanced injection current into the first excited state along the dash width when a magnetic field is applied along the dash elongation. This is explained with an improved k-space overlap of the QW emitter state wavefunction and the dash excited state.

2. Samples

The samples studied here were grown by molecular beam epitaxy. The reference sample, EV1737, contains a 4.5 nm InGaAs QW between two 10 nm AlInAs barriers. The QDash sample, EV1742, contains 6 ML of InAs QDashes between the same type of barriers. The QDash formation in Stranski–Krastanov growth mode occurred after ~3 ML and the wetting layer is ~0.9 nm thick (see figure 1 (inset)). Both structures are sandwiched between two 30 nm
not intentionally doped spacer layers of InGaAs. For the contacts, a $n = 10^{18}$ cm$^{-3}$ silicon doped InGaAs layer is used. All layers, except for the InAs quantum dashes, are lattice-matched on InP, namely Al$_{0.48}$In$_{0.52}$As and In$_{0.53}$Ga$_{0.47}$As. The top contact additionally consists of a gold layer on top. Both etched mesa are $210 \times 210 \mu$m$^2$ in size.

3. Results and discussion

As discussed in [8], the quantum dashes have an extension of approximately $14 \pm 5$ nm along [110], $71 \pm 37$ nm along [1–10] and $2.4 \pm 0.5$ nm along the growth direction [001] measured with TEM (figure 1 (inset)) and SEM [8]. Experimentally observed by a relatively narrow intersublevel absorption [8], the samples exhibit a good effective size homogeneity in their width. The aspect ratio is such that the relatively large size inhomogeneity in the length is not affecting the transition we are observing, which is controlled by the width of the dash. From now on, we will refer to the crystallographic directions above as $x, y, z$ respectively and electronic excitations in the dashes are noted as $|ln_x, n_y, n_z\rangle$. The spin degree of freedom is ignored. In optical transmission, a clear absorption line is observable at 89 meV with a corresponding dipole moment of $\langle x \rangle = 1.7$ nm [8]. With the aid of a 3D-Schrödinger solver, the latter was assigned to an excitation from the ground state $|1, 1, 1\rangle$ to the first excited state along the width $|2, 1, 1\rangle$ [8].

Figure 1 shows a 1D Schrödinger–Poisson simulation of the QW reference sample. For the QDash sample the situation looks qualitatively similar, if the conduction band is plotted in a profile through the height of the quantum dash. At zero bias, two depletion layers appear in the spacer layers beyond the AlInAs barriers due to the carriers in the QW (not shown). Under bias, those form a triangular well (see figure 1), into which spatially extended electrons can thermalize and whose energy can be tuned by the applied voltage. Any tunneling process across the first AlInAs barrier is only allowed, if an empty final state with matching energy and...
momentum exists. Since the triangular well electrons have a relatively well defined energy (defined by the voltage, with just a few tens meV uncertainty, see figure 1) and momentum distribution peaked at \( \vec{k} = 0 \), this system is well suited to probe the electronic states between the barriers of our samples.

3.1. Current–voltage characteristic

The current–voltage (\( I-V \)) characteristic of the QW sample at 4 K is shown in figure 2(a) (red curve). Two clear resonances for each bias direction appear at around \(-0.43/+0.50 \) V and \(-1.55/+1.8 \) V for zero \( B \)-field. Those are assigned to resonant tunneling through the ground state \(|1\rangle\) and first excited state \(|2\rangle\) of the QW. An energy separation of 254 meV between the two QW states is obtained from the 1D Schrödinger solver. Dividing this energy by the measured voltage separation, we obtain an estimation for the electrostatic lever arm factor \( \alpha_A = e (\partial V_A/\partial V) \approx 210 \) meV/V (definitions in figure 1).

For the QDash sample, a first resonance appears at \(-0.83/+0.65 \) V (red curve in figures 2(b) and (c)). The resonance current is around four times lower at positive bias, because the tunneling distance is effectively 0.9 nm longer here (due to the wetting layer). Due to the absence of lower resonances (experimentally tested down to current densities of \( 10^{-6} \) A cm\(^{-2} \)), the resonance is assigned to the tunneling from the 2DEG in the triangular well to the QDash ground state. This is confirmed by absorption measurements, which give a quantum dash ground state to continuum energy separation of 370 meV, compared to a more than 500 meV conduction band offset between AlInAs barrier and InGaAs spacer (where the triangular well is). Further confirmation is obtained from the transport measurements in \( B \)-field discussed below.

A second weaker resonance appears at \(-1.05 \) V (see figures 2(b), (c)). The corresponding resonance at positive bias appears only under certain \( B \)-fields at around +0.93 V, for reasons discussed later. The voltage separation to the ground state resonance is around 0.25 V. Assuming \( \alpha_B \approx \alpha_A \), the state causing the second resonance is 53 meV above the ground state. We will discuss later that this is an underestimation since the resonance is produced by emitter electrons with large in-plane momenta and thus a higher energy. The corrected energy matches relatively well with the absorption line found at 89 meV due to the state \(|2\rangle, 1, 1\rangle\) [8]. These numbers are comparatively close together compared to the other possible dash excitations along the length (\( \sim 5 \) meV) and height (\( >300 \) meV). Note that the two resonances observed stem in fact from a series of close lying states \(|1, n, 1\rangle\) and \(|2, n, 1\rangle\) with \( n = 1, 2, 3... \) separated only by a few meV. In the following two sections, the \( B \)-field dependence of the \( I-V \) characteristic is discussed.

3.2. Anisotropic transport in magnetic field

The \( I-V \) characteristic has been measured for different magnetic fields between \(-12 \) and \(+12 \) T. For the reference sample, seven \( IV \) curves at positive \( B \)-fields along the \( x \)-direction ([110]) are plotted in figure 2(a). Due to sample symmetries, the in-plane rotation of the \( B \)-field by 90° (not shown) and the change of its sign (see figure 2(a)) have virtually no effect on the \( I-V \) characteristics.

The in-plane magnetic field mainly affects the 2DEG and the tunneling process. First, the subband energies of the 2DEG experience a relatively weak diamagnetic energy shift, proportional to \( B^2 \), in the order of a few meV at 12 T [29]. Second, the Lorentz force semi-
Figure 2. IV-characteristics at different in-plane $B$-fields: (a) QW reference sample with $B \parallel x$ ([110]). The curves at $B \neq 0$ are offset by a factor 0.5 from each other for clarity. (b) QDash sample with $B \parallel x$ (offset factor 0.8) and (c) QDash sample with $B \parallel y$ (offset factor 0.8). The insets in (b)–(d) sketch the dash, $B$-field, current and acquired electron momentum (see equation (1)) direction for each measurement. (d) False color representation of the current based on the same measurement as in (c). Additionally, current maxima are marked with black triangles, minima with orange ones, respectively. For symmetry, we mark the local extrema of the absolute current values. Conductance maxima are shown in green and minima in blue.
classically causes the tunneling electrons to acquire an in-plane momentum of

\[
k_{\perp B}(B) = eB\Delta s/\hbar,
\]

where \(\Delta s = \langle \psi_{L} | z | \psi_{R} \rangle | - \langle \psi_{L} | z | \psi_{R} \rangle | \) is the effective tunneling distance between the centroids of the emitter and collector states. For the QDash sample, the momentum acquisition is around \(k_{\perp B}/B = 0.20 \times 10^{8} \text{m}^{-1}\text{T}^{-1}\), assuming \(\Delta s = 13 \pm 1.5 \text{nm}\). Since the QW has a parabolic in-plane dispersion, an additional bias is required at a finite \(B\)-field to reach the maximum overlap between the emitter states and the mostly empty QW states [30]. The combination of both effects leads to a quadratic increase of the peak bias voltage, which is clearly observable for the reference sample (see black curve in figure 2(a)).

The Lorentz force further strongly influences the onset and offset bias voltages of each resonance [31]. The onset and offset voltages correspond to the beginning and the end of a significant overlap between the triangular well and the square well dispersion. If both emitter and collector have a parabolic in-plane dispersion, the onset bias voltage as a function of the \(B\)-field takes the shape of two parabolas with minima at some \(\pm B_{\text{min}} \neq 0\), while the offset and valley voltages increase parabolically (dashed yellow line in 2a) [31]. Here, \(B_{\text{min}} \approx 6 \text{T}\) for the both samples, which corresponds to a 2DEG Fermi wavevector \(k_{F} = (1.2 \pm 0.2) \times 10^{8} \text{m}^{-1}\).

The figures 2(b) and (c) show the results for the QDash sample with the \(B\)-field applied along \(x\) (width of dashes) and \(y\) (dash elongation), respectively. In the first case, one can clearly see that the peak and valley voltages follow the same quadratic trend already observed in the reference sample. The onset voltage trend is less clear, but also shows two minima at positive bias at around \(\pm 4 \text{T}\). We explain these findings with the fact that the quantum dashes of 71 nm length (along \(y\)) have many unresolved close lying excited states along \(y\). Along \(k_{y}\), this almost recovers the parabolic dispersion seen before in the QW sample, which lets one expect a similar transport behaviour.

In the \(B\)-field along \(y\) (see figure 2(c)), the ground state resonance voltage (black) is almost unaffected by the \(B\)-field and the valley bias voltage (yellow) reduces for increasing \(B\)-fields. Here the dash width confinement gives a clear deviation from the parabolic dispersion and consequently a significantly different transport behaviour as the one found in the reference sample and also in the QDash sample for \(B\)-fields along \(x\).

### 3.3. Magneto-assisted tunneling to \(|2, 1, 1\rangle\) state

Unlike photoluminescence, magneto-transport clearly reveals the existence and nature of the \(|2, 1, 1\rangle\) state. The resonance is observed at about \(-1.05 \text{V}\) and \(+0.93 \text{V}\) (extrapolated from the resonance appearing above \(4 \text{T}\) in figures 2(c), (d)) for zero \(B\)-field and shows a rich pattern of features with in-plane \(B\)-field applied as shown in figures 2(b)–(d). For fields along \(y\) (dash elongation, see figures 2(c), (d)), the current shoulder shifts to higher bias voltages (more clear at negative bias) and becomes stronger. At zero \(B\)-field, the resonance is weak at negative bias and completely absent at positive bias. For \(\vec{B}\) along \(x\) (dash width, see figure 2(b)), the state \(|2, 1, 1\rangle\) only reveals its existence with a weak current shoulder at negative bias (see figure 2(b)), which is turned off at around \(4 \text{T}\). No resonance at all appears at positive bias.

Because electrons tunneling in the presence of an in-plane \(B\)-field acquire a momentum, the magneto-tunneling spectroscopy enables to probe the square of the \(k\)-space wavefunction of bound electronic states [19, 24–26]. A confined electronic state has a more extended \(k\)-space wavefunction in the \(k_{x} - k_{y}\) plane, than a spatially extended electron in a 2DEG. The triangular
well electron distribution can crudely be approximated with \( \psi_k (\vec{k} - \vec{k}_{LB} (B)) \approx \delta (\vec{k} - \vec{k}_{LB} (B)) \), where \( \vec{k}_{LB} (B) \) is the acquired in-plane momentum after tunneling through the injection barrier (see equation (1)). The tunneling matrix element \( M \) is proportional to the overlap integral of the emitter and collector wavefunction in \( k \)-space [32]. With the above approximation, \( M \) becomes directly proportional to the value of the confined electron wavefunction at \( \vec{k}_{LB} (B) \). In our case, the tunneling current at the \( l_2, 1, 1 \) resonance is [19]

\[
I = \text{const} \cdot |M|^2 \propto \left| \psi_{|2,1,1\rangle} (\vec{k}_{LB}) \right|^2.
\] (2)

The accuracy of this probability density measurement is mainly limited by the fact that the wavefunction itself is perturbed by the \( B \)-field as well [26]. Quantitatively, this is not completely negligible in our case, since the magnetic length \( l_B = (\hbar / eB)^{1/2} \) is 8 nm at 12 T and thus shorter than the QDash width. Nevertheless, the qualitative shape of the wavefunction remains unaffected.

The emitter and collector wavefunctions are sketched in the insets of figure 3(a). The \( B \)-field along \( x \) (dash width) probes the squared Fourier transformation of the \( |2, 1, 1\rangle \) wavefunction along the \( y \)-axis, thus \( \left| \psi_{|2,1,1\rangle} (0, k_{LB}, 0) \right|^2 \). The state is first order excited along \( x \) (dash width) and thus has an odd parity wavefunction with an approximately zero contribution at \( k_x = 0 \) (see figure 2(b) at about \(-1.05 \) V (weak) and \(+0.93 \) V (resonance completely absent)). Note, that the odd parity already results from a (locally) symmetric dash potential along \( x \), which is still well fulfilled for large size inhomogeneity samples. For \( B \)-fields along \( y \), two strong peaks at non-zero \( k_x \) are expected (see right sketch in figures 3(a) and 2(c), (d) for the measurement result). This also explains the increase of the resonance bias with \( B \)-field (see figure 2(d), especially at negative bias): at zero \( B \)-field, the resonance current is mainly caused by high energy emitter electrons with \( k_x \approx k_F \), which best match the tunneling selection rule. Transport exclusively supported by electrons with \( k = k_F \) was also reported in a similar system by Beckel et al [33]. At \( \pm 12 \) T, the resonance current is mainly supported by emitter electrons at the minimum of the dispersion parabola, which requires a higher bias to reach the alignment to the dash state. The weak resonance at \(-1.05 \) V and zero \( B \)-field probably arises from scattering at the rough AlInAs barrier grown on top of the QDash layer. This is confirmed by the absence of the resonance at \(+0.93 \) V, where the injection barrier is virtually flat. Thus, in the case of odd parity in-plane wavefunctions, scattering helps to produce a well-defined resonance current.

The relative change of the \( l_2, 1, 1 \) resonance current as function of \( k_{LB} = k_x \) is plotted in figure 3(a) and overlapped with the result of our 3D-Schrödinger simulation [8]. The wavefunction peak is found at \((2.4 \pm 0.3) \times 10^8 \) m\(^{-1}\) in the measurement (error from tunneling length uncertainty \( \Delta s = 13 \pm 1.5 \) nm) and at \((2.1 \pm 0.5) \times 10^8 \) m\(^{-1}\) in the simulation (error from measured dash width inhomogeneity \( \Delta D = 14 \pm 5 \) nm). This is around a factor of two larger than the measured half width of the 2DEG emitter \( k_F = (1.2 \pm 0.2) \times 10^8 \) m\(^{-1}\).

Figure 3(a) shows that the tunneling current into the \( l_2, 1, 1 \) state at negative bias increases around tenfold with the aid of the magnetic field. At positive bias, the increase is even larger, since there is no scattering assisted resonance at zero \( B \)-field. Unlike the typical magneto-tunneling spectroscopy studies on just a few or single quantum dots, which only show currents in the order of mA cm\(^{-2}\) [19] (and references therein), we observe ensemble averaged resonances in the A cm\(^{-2}\) range (see figure 3(b)). Despite the large size inhomogeneity of the dashes [8], the \( l_2, 1, 1 \) resonance is still well observable due to a lack of other dash excitations.
in that energy range. Further, the results are reproducible in other samples from the same wafer, showing that not just a few individual dots are probed.

4. Conclusion

In conclusion, we presented a magneto-transport study of quantum dash RTDs, with dashes identical to those previously used in a quantum dash cascade laser structure [8]. We showed, that the in-plane momentum space overlap factor of the injector and the upper laser state wavefunction can dominate the amount of injection current to fulfil the inversion condition. The resonant injection can otherwise become negligible—despite the presence of a real space wavefunction overlap, energetically matched emitter and collector states and a large dash size.
inhomogeneity. An in-plane magnetic field is able to provide the right in-plane momentum to maximize the $k$-space overlap. Another possibility might be an engineered scattering assisted injection, since scattering allows to transform some of the momentum along the growth direction into in-plane momentum to fulfil the tunneling selection rule. This could explain the lack of lasing action in [8] and should be taken into account when designing QDCLs.

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