Optical spectroscopy of a double-barrier resonant-tunneling structure containing a narrow-gap, strained-layer, quantum-well region

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(Received 20 November 1991)

Photoluminescence excitation (PLE) and photoluminescence (PL) spectroscopies are employed to study the charge buildup (n_s^e) in the quantum well of a symmetric GaAs-$Al_xGa_{1-x}As$-$In_yGa_{1-y}As$-$Al_xGa_{1-x}As$-GaAs ($x=0.33$, $y=0.09$) double-barrier resonant-tunneling structure. The use of a narrower-gap indium-containing quantum-well region allows PLE to be employed without the spectroscopic interference from the n^+-type GaAs contact regions which occurs in conventional double-barrier structures. The structures are shown to be on resonance at zero applied bias ($V=0$), with electron densities in the well at $V=0$ of $\sim 10^{11}$ cm^{-2} due to the charge transfer required to establish equilibrium. The form of the I-V characteristics at the first resonance close to $V=0$ is explained on the basis of tunneling from electron states in the three-dimensional contacts into the two-dimensional quantum-well level. The contribution of extrinsic processes to the PL spectra is discussed.

I. INTRODUCTION

In the present paper, photoluminescence excitation (PLE) and photoluminescence (PL) spectroscopies are employed to study the space-charge buildup in the quantum-well (QW) active region of a strained-layer GaAs-$Al_xGa_{1-x}As$-$In_yGa_{1-y}As$-$Al_xGa_{1-x}As$-GaAs ($x=0.33$, $y=0.09$) double-barrier resonant-tunneling structure (DBRTS). The use of the narrower-gap In-containing QW region allows the charge buildup to be investigated with only minimal spectroscopic perturbation from the thick n^+-type GaAs contact layers, which occurs for more conventional DBRTS's with GaAs QW regions. The strained-layer DBRTS's are also shown to have additional interesting characteristics from the point of view of their electrical transport and tunneling properties. In particular, such structures are found to be on resonance at zero applied bias (V), with significant charge buildup occurring in the QW to establish equilibrium at $V=0$.

Young *et al.*[1] reported photoluminescence from a DBRTS and deduced the electron charge buildup (n_s^e) in the QW on resonance from a study of the variation of PL intensity (I_{PL}) with bias. However, these deductions were questioned on the basis that the n_s^e determination was not quantitative.[2] In addition, it has been pointed out that I_{PL} was only expected to be proportional to electron density at low n_s and that I_{PL} is also controlled by the variation of the hole density in the well with applied bias.[3] PL line-shape analysis and magneto-PL studies have been shown to be reliable techniques for the determination of charge buildup on resonance for n_s^e values $\gtrsim 1.0\times10^{11}$ cm^{-2}.[4] However, one difficulty with low-temperature PL spectroscopy is that it can be affected by extrinsic processes. Indeed, the highest-resolution PL spectra from DBRTS's have shown evidence for partially resolved structure, due at least in part to recombination at defect-related centers.[4]

PL excitation spectroscopy does not suffer from this drawback. In PLE optical-absorption processes in the structure are investigated by study of the variation of the PL intensity as a function of the excitation laser energy. PLE is sensitive to the total density of states of the system and is not biased toward localized states which are favored by carrier thermalization in PL. PLE has been shown to be a precise method for study of high-carrier-density effects in modulation-doped quantum wells.[5,6]

However, as discussed in Refs. 3 and 7 for conventional GaAs-$Ga_{1-x}Al_xAs$ DBRTS's with $\gtrsim 100$-Å undoped spacer regions and contact doping $\lesssim 5\times10^{17}$ cm^{-3}, the dominant hole photocreation which leads to QW PL arises in the n^+type contacts. As a result, the PLE spectra contain only very weak or no features related to QW absorption; instead, they are determined by excitation processes in GaAs.[3,7] These difficulties are avoided in the present work since the holes are photocreated predominantly *in* the narrower-gap QW and the PLE spectra are dominated by QW-related absorption features. Yoshimura, Schulman, and Sakaki have recently published a PLE study of a GaAs-$Ga_{1-x}Al_xAs$ DBRTS.[8] They were able to study the variation of n_s^e with V by using a structure with relatively high doping close to the barriers (5×10^{17} cm^{-3}) and 100-Å spacer layers.[8] The high doping close to the barriers prevents significant hole accumulation at the collector barrier and to the suppression of the contribution of holes photocreated in the contacts to the QW PL.[3,7]

One additional optical method to determine $n_s^e(V)$ in DBRTS's will be mentioned before closing the introduction. Bar-Joseph *et al.* have shown that differential absorption spectroscopy[9] is a sensitive technique for studying space-charge buildup in QW's. However, one draw-

back of the method is that it is only applicable to structures grown on transparent substrates such as $In_yGa_{1-y}As$-$Al_zIn_{1-z}As$ DBRTS's on InP and not to GaAs-$Ga_{1-x}Al_xAs$ structures grown on GaAs substrates.

The paper is organized in the following way. In Sec. II details of the DBRTS's and the experimental techniques are described. In Sec. III A the zero-bias charge distribution and current-voltage characteristics are discussed. Then, in Secs. III B and III C, the PL and PLE results are presented, together with an analysis of the variation of charge density in the well with bias. In Sec. III D the variation of PL intensity with bias is discussed briefly, and finally in Sec. IV the main conclusions of the paper are summarized.

II. EXPERIMENTAL DETAILS

The experiments were carried out on a symmetric GaAs-$Al_{0.33}Ga_{0.67}As$-$In_{0.09}Ga_{0.91}As$-$Al_{0.33}Ga_{0.67}As$-GaAs DBRTS grown by molecular-beam epitaxy at 530 °C.[10] The structure is very similar to a standard GaAs-$Al_xGa_{1-x}As$ DBRTS except that the usual GaAs QW region between the $Al_xGa_{1-x}As$ barriers has been replaced by the narrow-gap $In_{0.09}Ga_{0.91}As$ strained layer. The details of the structure are given in Table I. Here 10-Å GaAs layers are included between the $Al_xGa_{1-x}As$ barriers and the $In_yGa_{1-y}As$ QW to minimize roughening effects at the alloy to alloy interfaces.[11] The width of the pseudomorphic $In_yGa_{1-y}As$ layer of 75 Å is well below the critical thickness for strain relief of >200 Å at $x=0.09$.[12] The material was processed into 100–400-μm-diam mesas with an annular top contact to permit optical access. Results for a 200-μm-diam mesa are reported here.

PL was excited at ≈ 5 K using $\simeq 0.1$–0.5 W/cm^2 from a Styryl-9 dye laser (1.44–1.54 eV) or a He-Ne laser (1.96 eV). The PL was dispersed by a 0.85-m double-grating spectrometer with typical resolution of approximately 3 Å and detected with a cooled GaAs photomultiplier.

TABLE I. Composition of alloy layers, doping of GaAs regions, and layer thicknesses. All alloy regions are nominally undoped.

Material	Composition, doping	Thickness
GaAs n-type contact	1×10^{18} cm^{-3}	9000 Å
GaAs n type	2×10^{17} cm^{-3}	1000 Å
GaAs	undoped	100 Å
$Al_xGa_{1-x}As$	$x=0.33$	85 Å
GaAs	undoped	10 Å
$In_yGa_{1-y}As$	$y=0.09$	75 Å
GaAs	undoped	10 Å
$Al_xGa_{1-x}As$	$x=0.33$	85 Å
GaAs	undoped	100 Å
GaAS n type	2×10^{17} cm^{-3}	1000 Å
GaAs n-type contact	1×10^{18} cm^{-3}	9000 Å
GaAs n-type substrate	1×10^{18} cm^{-3}	

III. RESULTS AND DISCUSSION

A. Zero-bias charge distribution and current-voltage characteristics

The equilibrium-band diagram of the DBRTS, for zero applied bias, is shown in Fig. 1. It was calculated using a self-consistent solution of Poisson's and Schrödinger's equations, employing a finite-difference method and treating the electron-electron interactions in the Hartree approximation. Both electron and heavy-hole dispersions are assumed to be parabolic, with effective masses $0.07m_0$ and $0.35m_0$, respectively. The alloy compositions and layer widths used in the calculations were those given by the nominal growth parameters. The calculations show that there are two quasiconfined electron levels (E_1 and E_2) in the well.

In order to establish equilibrium at $V=0$, electrons must flow from the doped GaAs contact regions (band

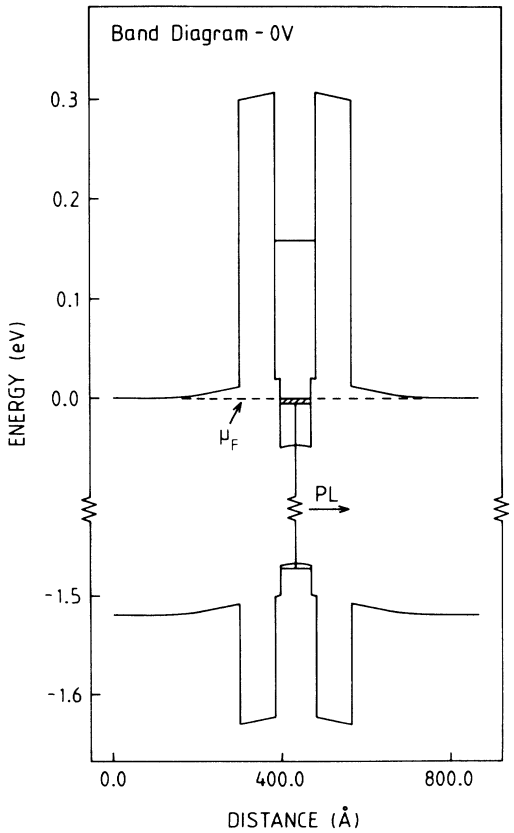

FIG. 1. Zero-bias band diagram of strained-layer double-barrier resonant-tunneling structure, obtained from self-consistent Hartree calculations. The band bending arises from charge transfer of 1×10^{11} cm^{-2} into the quantum well from the doped contact regions to establish equilibrium. The zero of energy is defined as the bottom of the conduction band in the GaAs contacts far from the double-barrier region. The dashed line shows the position of the electron Fermi level μ_F.

gap $E_g \approx 1.515$ eV) into the narrower-gap $In_yGa_{1-y}As$ QW [strained band gap $E_g = 1.419$ eV for $x = 0.09$ (Ref. 13)]. The GaAs-$I_yGa_{1-y}As$ band offsets were assumed to be distributed in the ratio 70:30 (Ref. 14) between the conduction and valence bands, with a resulting conduction-band offset of 67 meV. The quantum confinement energy of the E_1 level is calculated to be 42 meV, relative to the bottom of the $In_yGa_{1-y}As$ quantum well. Since the E_1 level is below the GaAs conduction-band edge, electrons pass from the contacts into the well until the Fermi level (μ_F) is equalized throughout the structure [15]. The occurrence of this charge transfer is seen very clearly from the band bending in Fig. 1. A value for E_F in the QW of 3.7 meV, corresponding to $n_s = 1.1 \times 10^{11}$ cm^{-2}, is obtained from the calculations at $V = 0$. This result contrasts very strongly with that for a conventional GaAs-$Al_xGa_{1-x}As$ DBRTS where $n_s = 0$ at $V = 0$, since in this case the quantum confined level in the QW is at a higher energy than the Fermi level in the contacts at zero applied bias.

As a result of the equalization of the Fermi levels in the contacts and the well in the strained-layer DBRTS, the structures are expected to be on resonance at $V = 0$.[10] When a small bias is applied, electrons will tunnel from the three-dimensional (3D) states in the emitter contact (Fermi energy of 18 meV, corresponding to a doping level of 2×10^{17} cm^{-3}) into the two-dimensional (2D) states in the QW. Such 3D-2D tunneling has been discussed by Luryi.[16] In a conventional GaAs-$Ga_{1-x}Al_xAs$ DBRTS, the onset of tunneling, with conservation of energy and lateral momentum, arises when the confined 2D state in the well is biased to be at the same energy as the Fermi level in the contacts. The peak of the resonance, with maximum current flow, corresponds to the applied bias where the 2D level in the well is resonant with the bottom of the conduction band in the emitter. For higher biases resonant tunneling with conservation of energy and momentum is no longer possible. For the present strained-layer DBRTS, the 2D QW level is below E_F in the contacts at $V = 0$, and so the structure is on resonance at $V = 0$, as stated earlier. The above picture of 3D-2D tunneling is expected to apply well in the region of the first resonance, since it occurs at very low bias (< 20 mV; see below). As the bias is increased further, electron accumulation at the emitter barrier will occur and the tunneling will have increasingly 2D-2D character.

The experimental I-V characteristics, measured at 4 K, for the device under 0.5 W/cm^2 illumination are shown in Fig. 2(a). They are found to be in good agreement with the above expectations. Two resonances are observed in the I-V characteristics with peaks at $+0.012$ V (-0.015 V) and $+0.8$ V (-0.8 V), corresponding to tunneling into the E_1 and E_2 levels in the QW, respectively. Positive bias refers to the top of the device biased positively with respect to the substrate such that electrons flow toward the top contact, which is exposed to laser light. The low-bias region (-0.15 to $+0.15$ V) is shown on an expanded scale in the inset to Fig. 2. As predicted, the structures are on resonance at $V = 0$ with no defined onset and a finite slope to the I-V characteristic being observed around $V = 0$. Beyond the peaks of the first resonances, features due to LO-phonon-assisted inelastic tunneling[17] are observed at ± 0.045 and ± 0.07 V, labeled LO_1 and LO_2 in Fig. 2(a).

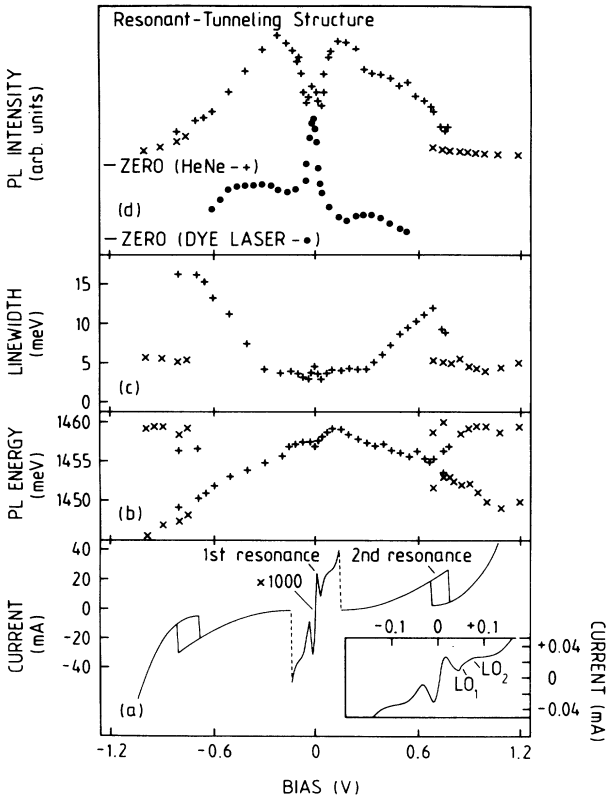

FIG. 2. Summary of PL data relative to I-V characteristic of DBRTS's: (a) current, (b) PL peak position, (c) PL linewidth, (d) PL intensity excited at 1.47 eV, (●) PL intensity excited at 1.96 eV (+, ×) as a function of applied bias. The symbol × in (b)–(d) signifies the off-resonance low-current state at the second resonance. The inset shows an expanded version of the I-V characteristics of (a), in the 0 to ± 0.15 V region. The linewidth data show that there is charge in the well at zero bias which is reduced as bias is applied, but rises as the second resonance is approached.

Beyond the phonon satellites, the current rises fairly rapidly to the second resonances at ± 0.8 V, which correspond to tunneling into the second quasiconfined electron level. These resonances show bistability, manifested as hysteresis loops in the I-V characteristics.

B. Photoluminescence spectra

A representative selection of PL spectra from the QW active region, as a function of applied bias, is shown in Figs. 3(a)–3(g) (left-hand side of figure). The spectra, excited at 1.96 eV with the He-Ne laser and taken at a temperature of 4 K, result from recombination between electrons in the lowest electron QW state and photocreated minority-carrier holes in the highest heavy-hole state (E_{1hh} recombination). The figure shows spectra for (a) zero bias; (b) $+0.012$ V, the voltage at which there is

maximum current due to tunneling into the first confined level; (c) +0.036 V, the position of the valley current at the first resonance; (d) +0.1 V; (e) +0.3 V; (f) +0.45 V; and (g) high- and (h) low-current states for +0.7 V. PL peak position, width (full width half maximum), and integrated intensity (1.96 eV laser excitation) are shown in Figs. 2(b)–2(d). Similar measurements were taken with the dye laser, whose photon energy was set at 1.47 eV, above the effective energy gap of the QW (1.463 eV), but below the band gap of the GaAs contacts (1.51 eV). In this case the electron-hole pairs are produced directly in the quantum well, rather than predominantly in the contact as in the case with the He-Ne laser at 1.96 eV. The width and peak position results are very similar to those produced by the He-Ne laser and are not shown. However, the integrated intensity as a function of bias does show significant differences, as shown in Fig. 2(d) and discussed in Sec. III D. The QW PL spectra of Fig. 3 are superimposed on the sloping background from recombination in the GaAs contacts to higher energy.

The photon energy of the QW PL peak at $V=0$ is 1457 meV. This energy is in good agreement with the value of

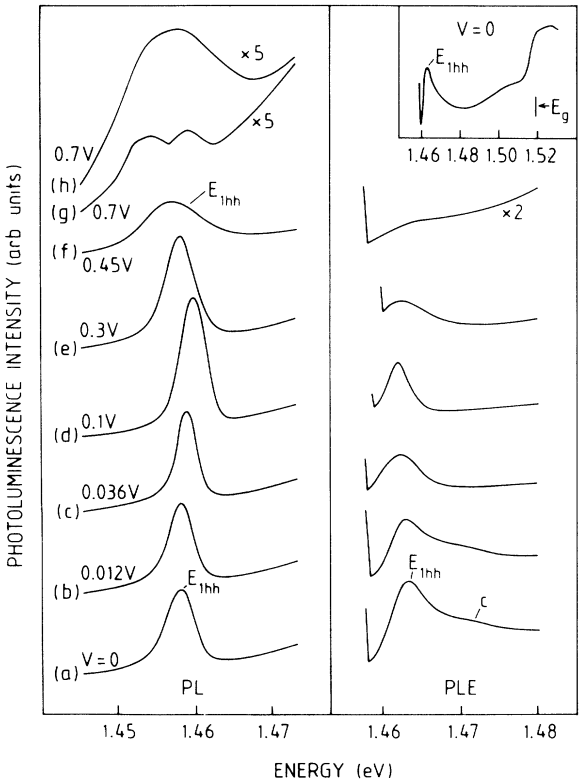

FIG. 3. PL (left-hand side) and PLE (right-hand side) spectra as a function of applied bias at (a) $V=0$; (b) +0.012 V, the peak of the first resonance; (c) +0.036 V, the bias of the valley current at the first resonance; (d) +0.1 V; (e) 0.3 V; (f) 0.45 V; and (g), (h) 0.7 V off and on second resonance states. The inset shows a PLE spectrum over a wider energy range from 1.46 to 1.53 eV above the GaAs band gap of ~1.515 eV, labeled E_g in the inset. The main PL and PLE features arise from E_{1hh} quantum-well transitions. The weak feature labeled c arises from transitions into E_{1hh} continuum states.

1458 meV obtained from the calculations employed for Fig. 1, for an indium composition of 0.09 after allowance for an excitonic binding energy of 10 meV,[18] and is, therefore, in good agreement with that expected from the growth parameters.

The variation of the PL linewidth (full width half maximum) with bias, summarized in Fig. 2(c), will now be discussed. There is a local maximum in width (4.5 meV) at zero bias. As the bias is increased, the width decreases until a minimum value of 3.1 meV at ±0.036 V is reached, the bias corresponding to the onset of LO-phonon-assisted tunneling at the first resonance. The linewidth subsequently increases to ~4.2 meV at ~±0.1 V and then remains approximately constant up to ±0.3 V. Beyond ±0.35 V, at the onset of the strong increase of current due to tunneling into the second resonant level, the linewidth increases strongly up to ~±0.8 V, the peak of the second resonance, beyond which it falls abruptly.

The variation of PL linewidth with bias arises principally from changes of electron density in the well with bias.[4] Electrons recombine from filled states, in the range from the bottom of the lower bound state to the Fermi energy, with the photocreated holes. Thus, as discussed in Ref. 4, the variation in PL linewidth will reflect changes of the Fermi energy and hence the electron density in the well with bias. At zero bias there are already electrons in the well, giving the peak in width shown. At low voltages an increase in bias results in a decrease of n_s^e in the well and hence a decrease in width, to the minimum at ±0.036 V.

This initial decrease of n_s^e with V is expected since the quasi-Fermi level on the collector side is lowered relative to the QW when bias is applied, and hence charge will flow out of the well. This decrease in n_s^e outweighs the potential increase in n_s^e as a result of tunneling from the emitter, which from comparison with a GaAs-$Al_xGa_{1-x}As$ structure of similar barrier widths (discussed in Ref. 4) is expected to be $<3\times10^{10}$ cm^{-2} at the first resonance. An increase of tunnel current with bias to the peak of the resonance is nevertheless expected. With increase of bias more electrons can tunnel from the three-dimensional contact into the QW, until the cutoff of the resonance corresponding to alignment of the bottom of the conduction band with the QW confined state is reached[16] (see discussion in Sec. III A).

The decrease of linewidth from 0 to ±0.036 V can be used to estimate n_s in the well at $V=0$. The linewidth at $V=0$ will be given by a convolution of a Fermi function with the inhomogeneously broadened off-resonance line shape taken as the minimum width of 3.1 meV at ±0.036 V.[4] From such a line-shape analysis, E_F at $V=0$ is deduced to be 3.9 meV, corresponding to $n_s^e=1.1\times10^{11}$ cm^{-2}, in satisfactory agreement with the value obtained from the self-consistent calculations and with that value obtained from the self-consistent calculations and with that obtained from the more precise PLE measurements discussed later (Sec. III C). The accuracy ($\sim\pm0.4\times10^{11}$ cm^{-2}) of the n_s^e determination from analysis of the PL linewidth is limited by the closeness of the $V=0$ linewidth to the minimum off-resonance value.

The strong increase of linewidth beyond ± 0.35 V up to ± 0.8 V is due principally to charge buildup in the well on the second tunneling resonances. However, inspection of Fig. 3(g) ($+0.7$ V) and the PL peak positions beyond $\sim \pm 0.7$ V [Fig. 2(b)] shows that the PL spectra in the off-resonant state exhibit a double-peaked structure in these bias ranges. The occurrence of such additional structure inhibits detailed quantitative conclusions being reached as to the magnitude of the variation of $n_s^e(V)$ on the second resonance, from analysis of Fig. 2(c). Similar double-peaked PL spectra were reported by Skolnick *et al.* for a GaAs-$Ga_{1-x}Al_xAs$ DBRTS (Ref. 4), and attributed to the contribution from defect-related PL processes. In that case, however, the free-carrier broadening at high bias was a factor of 3–5 times greater than the energy splitting of the double-peaked structure, thus allowing clear conclusions on the variation of n_s^e with V to be reached over the whole bias range. In the present DBRTS, the linewidth in the high-current state in Fig. 3(g) is close to the splitting in the low-current state where the free-carrier broadening is removed. However, the narrowing which occurs between the on- and off-resonance states of Figs. 3(g) and 3(h) clearly demonstrates the occurrence of charge buildup at the second resonance. Inspection of Fig. 2(b) shows that the high-energy PL peak shows a strong shift of peak position of ~ 8 meV at ± 1 V expected from the quantum confined Stark effect. The lower-energy peak, probably defect related, shows a much smaller shift with bias. However, its intensity is bias dependent, and thus it is certainly also a QW-related feature.

C. Photoluminescence excitation spectra

PLE spectra obtained for detection energies close to the peak of the QW PL are presented in the right-hand part of Figs. 3(a)–3(f). The pronounced peak at the PLE onset corresponds to electron-1–heavy-hole-1 (E_{1hh}) transitions. At the relatively low n_s values expected for $V \lesssim 0.2$ V, the E_{1hh} transitions will have properties at low temperature which are predominantly excitonic in character.[6,19] The weak feature at $V=0$ in Fig. 3(a) (right-hand side) labeled *c*, 9 meV above the E_{1hh} peak, is identified as transitions into $E1$-HH1 continuum states. This energy is close to the excitonic binding energy of 10 meV expected in a 80-Å-wide $In_yGa_{1-y}As$-$Al_xGa_{1-x}As$ QW.[18] The PLE spectrum at $V=0$ over a wider energy range (1.46–1.53 eV) is shown in the inset to Fig. 3. The E_{1hh} features of Fig. 3(a) are again visible, together with excitation transitions into the n^+-type GaAs regions above ~ 1.51 eV.

The results of the PLE measurements as a function of bias are summarized in Figs. 4(b) and 4(c), together with *I-V* [Fig. 4(a)] and PL width [Fig. 4(d), same data as Fig. 2(c)] for comparison. The energy separation of the PLE-PL peak positions (the Stokes shift) (Ref. 18) is plotted in Fig. 4(b) and the width of the PLE E_{1hh} transitions (full width half maximum) in Fig. 4(c).

The variation of the PLE-PL Stokes shift with applied bias is a direct measure of the variation of E_F and hence n_s^e in the QW as a function of bias. The optical-absorption transitions which give rise to the PLE spectra can only occur into empty states above the electron Fermi energy. They will occur at an energy threshold of $E_g+(1+m_e/m_h)E_F$, and hence study of this Moss-Burstein shift permits the determination of $E_F(V)$ and hence $n_s^e(V)$. The holes created in this photoexcitation

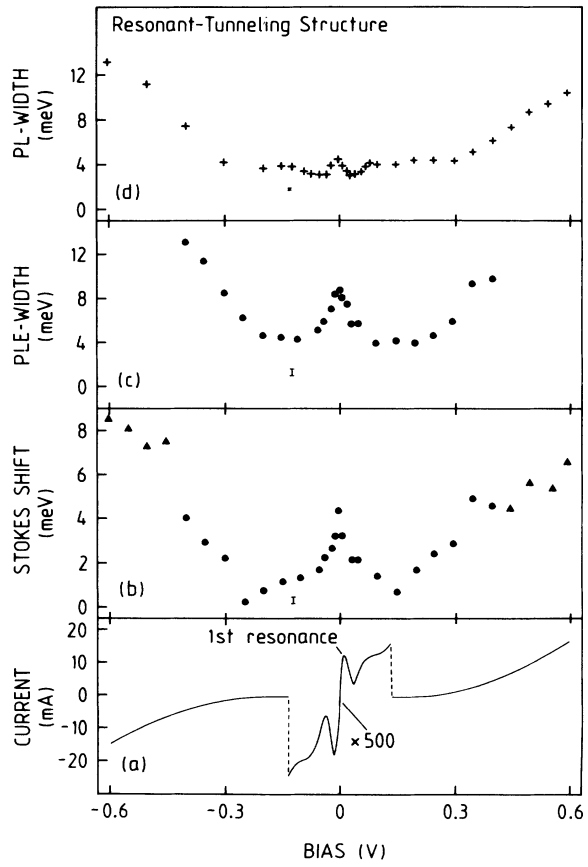

FIG. 4. Summary of PLE data relative to the *I-V* characteristic of DBRTS's: (a) current; (b) Stokes shift, the energy separation between PL and PLE peak positions; (c) linewidth of E_{1hh} PLE transitions; and (d) linewidth of E_{1hh} PL transitions as a function of applied bias. The results (●, ▲) for the Stokes shift and PLE linewidth in (b) and (c) are obtained using dye laser excitation, whereas the PL linewidth results in (d) are obtained using 1.96 eV He-Ne excitation [same data as Fig. 2(d)]. The Stokes (Moss-Burstein) shift (Δ) is directly related to the Fermi energy in the well by $\Delta=(1+m_e/m_h)E_F$. Like the linewidth there is a maximum at 0 V which is reduced as bias is applied as a result of the charge moving out of the well. Δ increases again as the second resonance is approached. The errors for most of the points in (b)–(d) are indicated by vertical bars on the respective figures. The measurements, represented by triangles in (b), are subject to larger errors (± 1.5 meV) due to the weakness of the dye laser excited PL above $\sim \pm 0.5$ V. The results of (b) and (c) are controlled by the variation of charge density in the well with bias, whereas PL linewidth results for $|V| > 0.036$ V may also be influenced by contributions from extrinsic recombination processes. PLE width results are not plotted in (c) beyond ± 0.45 V because of the difficulty in obtaining reliable width measurements of the weak PLE spectra against the broad monotonic background at high bias [see Fig. 2(f)].

process recombine with the higher density of electrons already present in the well and give rise to the observed PL. This determination of $n_s^e(V)$, which does not involve any line-shape fitting procedure, is a more direct and reliable method than study of the PL linewidth. As mentioned briefly in Sec. II B, the PL spectra can be perturbed by contributions from defect-related processes, particularly at $n_s \lesssim 10^{11}$ cm^{-2} where the free-carrier broadening is of the same order as the contributions from these other extrinsic mechanisms.

As expected from the earlier discussions of the expected variation of n_s^e with bias and from the results of the PL measurements, the Stokes shift Δ [Fig. 4(b)] exhibits a local maximum at $V=0$ ($\Delta=4.5$ meV). As V is increased, Δ is found to decrease through the first resonances, has a minimum value at $\sim\pm0.15$ V, and then increases again at the second resonances to ~ 8 meV at $\sim\pm0.5$ V, beyond which the dye-laser-excited QW PL is too weak for reliable PLE to be carried out. In the absence of free carriers, a finite Stokes shift is expected due to carrier thermalization in PL to lower-energy tail states. The minimum observed value of 0.5 ± 0.5 meV at ±0.15 V. All variations in the Stokes shift in excess of this minimum value can be attributed to free-electron band filling.[20]

Thus, at $V=0$, the free-carrier-related contribution to the Stokes shift is 4.0 meV. E_F is thus found to be 2.7 meV (using $m_e=0.07m_0$, $m_h=0.15m_0$)[21] and $n_s^e(V=0)=8\times10^{10}$ cm^{-2}, in good agreement with the results from the PL line-shape analysis ($E_F\sim3.9$ meV) and the predictions of the self-consistent calculations ($E_F=3.7$ meV).[22]

In contrast to the PL line shape, $\Delta(V)$ continues to decrease up to $\sim\pm0.15$ V, whereas the PL linewidth has a minima at ±0.04 V. The PL linewidth increases to a plateau in the regions of the LO-phonon-assisted inelastic tunneling peaks (±0.07 V), before increasing in a similar fashion to the PL beyond the onsets of the second resonances ($V>0.25$ V).

The reliability of the variation of the Stokes shift as a measure of $n_s^e(V)$ in the $\pm(0.04-0.15$ V) regions, as opposed to the PL linewidth, is given strong support by the variation of the PLE linewidth with bias. Although the E_{1hh} transitions in PLE are predominantly excitonic in character, the interaction with free carriers in the QW is nevertheless significant. As discussed, for example, in Refs. 6 and 21, for $n_s \gtrsim 3\times10^{10}$ cm^{-2}, the E_{1hh} transitions are in fact many-body "Mahan" excitons, with the character of a Fermi-energy edge singularity. At low temperature ($T<4$ K) and $n_s \lesssim 10^{11}$ cm^{-2} as in the present experiments, the change of excitonic oscillator strength due to phase space and exchange screening effects is expected to be small.[6] However, significant broadening of the E_{1hh} transitions is expected because of the presence of free carriers, as observed, for example, in the PLE spectra of $In_yGa_{1-y}As$-InP (Ref. 6) and $Al_xGa_{1-x}As$-$In_yGa_{1-y}As$-GaAs (Ref. 23) QW's for $n_s\sim5\times10^{10}$ cm^{-2}.[7] This broadening arises because of the contribution of indirect absorption processes at finite E_F and because of lifetime broadening in the final state of the transitions.[6,21]

The main point for the present work is that the PLE E_{1hh} linewidth provides a sensitive qualitative measure of the presence of free carriers in the QW and of the variation of $n_s^e(V)$ with bias. The method is not quantitative since both a reliable theoretical treatment and detailed experimental calibrations are lacking.

The form of the observed variation of the PLE E_{1hh} linewidth in Fig. 4(c) is in very good agreement with that found for the Stokes shift in Fig. 4(b). In particular, the PLE width exhibits a clear minimum in the 0.12–0.2-V region, in agreement with Fig. 4(b), but in contrast to the PL width in Fig. 4(d). Thus, on the basis of the results of Figs. 4(b) and 4(c), we conclude that $n_s^e(V)$ decreases from its expected local maximum value of 8×10^{10} cm^{-2} at $V=0$, to close to zero ($\lesssim2\times10^{10}$ cm^{-2}) at $\pm0.12-0.2$ V before increasing to 1.7×10^{11} cm^{-2} at ±0.5 V [$E_F=5.5$ meV deduced from Fig. 4(b)], as charge builds up in the QW on the second resonance.

The disagreement of the PLE variations of Figs. 4(b) and 4(c) with the PL linewidth [Fig. 4(d)] in the ±0.04 to ±0.2 V region, where the PL linewidth exhibits an increased value beyond the minimum at ±0.04 V, most probably arises from a small contribution of extrinsic processes to the PL spectra in this region. This is particularly likely in view of the double-peaked structure observed in PL at high bias (off resonance) where the rapidly moving excitonic peak is sufficiently separated in energy from the lower-energy extrinsic peak to reveal the presence of an additional contribution to the PL. At lower bias the two peaks will be sufficiently close in energy that the individual contributions cannot be resolved. Thus care must be exercised in attributing small variations (~1 meV) in the PL linewidth with bias to variations in $n_s^e(V)$, as pointed out in Ref. 4, without additional information from, for example, magneto-optical spectroscopy or PLE studies, as in the present work.

D. Variation of quantum-well photoluminescence intensity with bias

The variation of PL intensity with bias for 1.96 and 1.47 eV excitation in Fig. 2(d) can be understood qualitatively from the above analysis of the variation of n_s^e in the well, together with consideration of the variation of photocreated hole density (n_s^h) with V. For the 1.47 eV dye laser excitation [Fig. 2(e)], the photoinjected holes, which act as a probe of the majority-carrier electron population, are created directly in the QW region. When bias is applied both electrons and holes are swept out of the well. I_{PL} is expected to be proportional to both n_s^e and n_s^h (Ref. 3) and so decreases strongly with V, as observed in Fig. 2(d), to a minimum value at $\sim\pm0.15$ V, close to the bias of the minimum value of $n_s^e(V)$ deduced from the PLE. An increase in I_{PL} is observed at the onset of the second resonances ($\sim\pm0.35$ V) as $n_s^e(V)$ increases again; this increase is opposed by the decreasing $n_s^h(V)$, which dominates for $V>0.5$ V, with the QW PL being unobservable beyond ±0.6 V. For 1.96 eV excitation, the minority-carrier holes are also created in the contact regions, from

where they drift and diffuse to the collector barrier for $V>0$, accumulate, and then tunnel into the QW. Thus, in this case, I_{PL} is controlled also by the collection rate of holes into the QW, from the contacts, as a function of V. The initial decrease of I_{PL} with V up to ± 0.036 V is consistent with the initial decrease of n_s^e with V discussed above. As the bias is increased further, n_s^h is expected to increase initially, as hole collection from the contacts increases, accounting for the increase in I_{PL} from ± 0.036 to $\sim \pm 0.15$ V in the region where n_s^e is a relatively slowly varying function of bias. For higher biases ($V \gtrsim 0.24$ V), n_s^h will decrease also as the holes which tunnel from the collector gain sufficient energy in the applied field that they are able to pass directly over the emitter barrier without capture by the QW region (see Ref. 4 for further discussion).

IV. CONCLUSIONS

Electrical and optical investigations of a double-barrier resonant-tunneling structure containing a narrower-gap, indium-containing, strained-layer, quantum-well region have been reported. The use of the narrow-gap quantum well has been shown to lead to a major change in the I-V characteristics compared with conventional GaAs-$Al_xGa_{1-x}As$ DBRTS's. In contrast to a conventional structure, the strained-layer DBRTS was found to be on resonance at zero applied bias. This behavior has been shown to arise from the narrower gap of the $In_yGa_{1-y}As$ QW region, relative to that of the GaAs contact regions. This leads to charge transfer from the doped n^+-type contacts into the $In_{0.09}Ga_{0.91}As$ QW in order to establish a constant Fermi level in the system at $V=0$. The form of the I-V characteristics at the first resonance has been explained on the basis of tunneling from the 3D contact into the 2D QW level.

The use of the narrower-gap QW region allows PL and hence PLE spectroscopy to be performed under conditions where significant hole photocreation, leading to QW PL, takes place in the QW active region. This contrasts again with the situation for GaAs-$Al_xGa_{1-x}As$ structures where the dominant hole photocreation arises in the thick GaAs contacts, since in this case the QW transition energy is at a higher energy than that of the band gap of n^+-type GaAs.

As a result of the narrow QW band gap, both PL *and* PLE spectroscopies could be employed to study the variation of the charge density in the QW with applied bias. Values of n_s^e of $\sim 1\times 10^{11}$ cm^{-2} at $V=0$ were deduced from the optical measurements, in good agreement with values of n_s^e obtained from self-consistent solution of Poisson's and Schrödinger's equations. When bias was applied at the first resonance close to $V=0$, n_s^e was found to decrease as charge flowed out of the well as the quasi-Fermi level in the collector contact was lowered below the confined level in the QW. At the second tunneling resonance, n_s^e was found to increase once again because of charge buildup during the tunneling process, in a manner very similar to that observed for conventional GaAs-$Al_xGa_{1-x}As$ structures.

Finally, the contribution of extrinsic processes to the PL has been deduced from the observation of a double-peaked structure in the spectra at high bias. Disagreement between the form of the variation of the PL linewidth in the 0.04–0.2 V region and that of the Stokes shift and PLE linewidth has been suggested to arise from an extrinsic contribution to the PL linewidth.

ACKNOWLEDGMENTS

We thank P. E. Simmonds for most helpful comments on the manuscript and D. J. Mowbray and D. M. Whittaker for very informative discussions.

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