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Excitation mechanisms of photoluminescence in double-barrier resonant-tunneling structures

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The excitation mechanisms which lead to photoluminescence (PL) in the quantum wells of double-barrier resonant-tunneling structures are analyzed. It is shown that on an electron-tunneling resonance, in the present structures with wide depletion regions under bias, recombination occurs predominantly between electrons which tunnel into the quantum well and holes which are created in the thick GaAs contacts. These holes drift and diffuse to the barriers where they accumulate, and then tunnel into the well. The importance of photon recycling of photocreated carriers is demonstrated. Finally, the factors which control the variation of PL intensity with applied bias are discussed.

I. INTRODUCTION

Photoluminescence (PL) has been employed recently as a probe of the electronic processes which take place in double-barrier resonant-tunneling structures (DBRTS's).[1-9] It has been shown that key characteristics of DBRTS's, such as charge buildup in the quantum well (QW), and to what degree the resonant-tunneling process is sequential or coherent, can be studied in a direct fashion by optical techniques.[4-6] However, in order to place the analysis of the PL experiments on a firm footing, it is necessary to have a reliable understanding of the PL-excitation (PLE) mechanisms in multilayer DBRTS's.

Such an investigation forms the subject of the present work. The PL signals which provide the most important information on the mechanisms of operation of DBRTS's arise from electron-hole recombination in the QW active regions. It will be shown that in the present structures PL arises predominantly from recombination between electrons which tunnel into the QW on resonance and the low density of minority-carrier holes which are photocreated in the n^+ GaAs regions of the structure and then tunnel into the QW. Furthermore, it is demonstrated that PL emission and reabsorption (usually termed photon recycling) near the GaAs band gap is the dominant PLE mechanism for bias conditions where hole drift is towards the illuminated surface of the structure. In the light of these findings and an analysis of the variation of PL intensity with applied bias, the applicability of different PL techniques for the determination of the space-charge buildup in the QW is discussed. The above conclusions regarding the dominance of hole photocreation in the n^+ GaAs contact regions apply to the present structures, and those studied in Refs. 7 and 8, which have relatively wide spacer layers and depletion regions adjacent to the double-barrier parts of the device. In the structure studied in Refs. 1 and 2, by contrast, direct photocreation in the well plays a much more important role due to the high doping levels in the contacts and the very thin (or no) spacer layers.

The paper is organized as follows. In the next section details of the structures and a brief description of the experimental methods are presented. In Sec. III, PL and PLE spectra under a variety of bias conditions are presented, from which conclusions about the PLE mechanisms as a function of bias are drawn. In Sec. IV the PL-intensity variations as a function of bias are presented and discussed using a simple rate-equation analysis, and finally in Sec. V the main conclusions are summarized.

II. EXPERIMENTAL DETAILS

The experiments reported here were principally carried out on two GaAs-$Ga_{1-x}Al_xAs$ DBRTS's. Structure A is a nominally symmetric DBRTS and contains a 60-Å GaAs QW embedded between 85-Å $Ga_{1-x}Al_xAs$ ($x=0.33$) barriers. Structure B (structure 1 of Ref. 6) is an asymmetric DBRTS consisting of a 58-Å GaAs QW between 83- and 111-Å $Ga_{1-x}Al_xAs$ barriers ($x=0.4$).[10] Full details of the structures are given in Table I. PL was excited with a variety of photon energies ($h\nu_l$) from 1.5

TABLE I. Sample characteristics. Doping levels are given in cm^{-3}.

Composition	Structure *A*	Structure *B*
n GaAs contact	0.25 μm, 1×10^{18} 0.75 μm, 2×10^{17}	0.5 μm, 2×10^{18} 500 Å, 1×10^{17} 500 Å, 1×10^{16}
GaAs	102 Å	33 Å
$\text{Ga}_{1-x}\text{Al}_x\text{As}$	$x=0.33$, 85 Å	$x=0.4$, 83 Å
GaAs	60 Å	58 Å
$\text{Ga}_{1-x}\text{Al}_x\text{As}$	$x=0.33$, 85 Å	$x=0.4$, 83 Å
GaAs	102 Å	33 Å
n GaAs contact	0.5 μm, 2×10^{17} 0.5 μm, 1×10^{18}	500 Å, 1×10^{16} 500 Å, 1×10^{17} 2.0 μm, 2×10^{18}
n^+ GaAs substrate	4×10^{17}	2×10^{18}

eV, below the GaAs band gap in the near infrared, to the violet (2.71 eV), using a series of dye and ion lasers. The excitation intensity was usually $\sim$0.2 W/cm^2 and was sufficiently weak to cause negligible or only very slight perturbation to the current-voltage (*I-V*) characteristics of the device. The structures were processed into 200- or 300-μm-diam mesas, with either annular or circular contacts, permitting optical access to the top surface of the samples, being employed.

III. RESULTS AND DISCUSSION: PHOTOLUMINESCENCE-EXCITATION MECHANISMS

A typical QW PL spectrum ($T=2$ K) for structure *A*, excited at 1662 meV, is shown in Fig. 1(a) for reverse (negative) applied bias (electron flow to the top contact, Fig. 2(c) band diagram]. The *I-V* characteristics of the structure are presented in Fig. 2(a) and are obtained with a 30-Ω resistor in parallel with the sample to suppress circuit oscillations in the region of the negative-differential-resistance (NDR) features at +0.31 and -0.38 V. The PL spectrum of Fig. 1(a) is obtained with the structure biased at -0.29 V, on resonance for electron tunneling from the emitter contact into the lower quasiconfined electron level in the QW,[11] and out into the collector depletion region beyond the second barrier [Fig. 2(c)]. The PL at 1615.1 meV arises from recombination between electrons in the lower confined level of the conduction-band well and holes in the lowest heavy-hole (HH) level of the valence-band well (E_{1h} recombination). Very strong PL is also observed from the GaAs contact layers, typically 500 times stronger than the QW emission for 1.96 eV excitation, although it should be noted that the PL from the QW is attenuated by a factor of $\sim$5 by reabsorption in the GaAs capping layers.

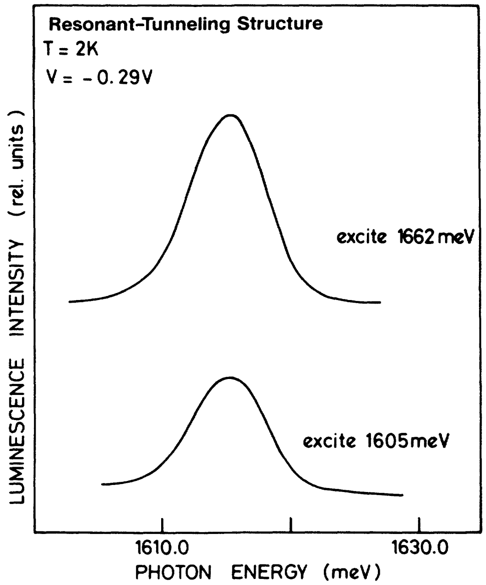

FIG. 1. Photoluminescence spectra for structure *A* taken at 2 K and laser-excitation energies of 1662 and 1605 meV corresponding to down- and up-converted PL processes, respectively.

Important information on the nature of the PLE mechanisms is obtained from the spectrum in Fig. 1(b), where in this case the QW PL at 1615.1 meV is excited at $h\nu_l=1605$ meV, 10.1 meV below the PL energy. This is a clear example of "up-conversion" observed in a PL spectrum.[12] Photons at 1605 meV cannot be absorbed directly in the QW at an significant rate. However, such light is strongly absorbed in the GaAs, with absorption coefficient $\sim 1.6\times10^4$ cm^{-1} at 1600 meV.[13] The observation of strong up-converted PL signals indicates that a significant fraction of the holes which recombine with the tunneling electrons, and hence participate in the QW PL, are photocreated in the GaAs contact regions.

The present structures incorporate either a thick "spacer" layer (30 Å of undoped GaAs followed by 500 Å of 1×10^{16} cm^{-3} GaAs for sample *B*), or a thinner spacer (100 Å for sample *A*) together with an n^+ contact of only moderate doping level ($n=2\times10^{17}$ cm^{-3}, sample *A*). When reverse-biased near the peak of the first resonance, the depletion region adjacent to the collector barrier extends to a depth of about 250 Å in sample *A*, and as much as 900 Å in sample *B*, as calculated from solutions of Poisson's equations for the two structures under the appropriate applied biases. Hole tunneling into the well is expected to be the predominant PLE mechanism[5,6] in such structures (of design similar to that discussed in Refs. 7 and 8). The reason for this is that the hole lifetime in the depletion region is sufficiently long to allow significant accumulation of photoexcited holes in the vicinity of the collector barrier, before tunneling into the well occurs. Direct evidence for this charge accumulation is discussed in Refs. 6 and 7. In the structure studied in Refs. 1 and 2, by contrast, the depletion regions are much shorter due to the high doping levels in the contact ($n = 2\times10^{18}$ cm^{-3}). Hole accumulation at the collector barrier is therefore less probable, and direct photocreation of holes in the QW is expected to play a relatively more important role in the generation of the photoluminescence from the QW. This distinction between the two types of structure, as regards the PLE mechanisms, was discussed by Young *et al.* in Ref. 9.

The importance of holes photocreated in the contact regions is further substantiated by the PLE spectrum shown in Fig. 3(a) for structure *A*, under the same reverse-bias conditions as those employed for Fig. 1. PL is detected at 1614 meV, and the intensity of the PL (I_{PL}) is measured as a function of $h\nu_l$ in the range 1590–1710 meV. A featureless PLE spectrum is observed which extends 25 meV below the detection energy of the PL. Indeed, in separate experiments we have found that the

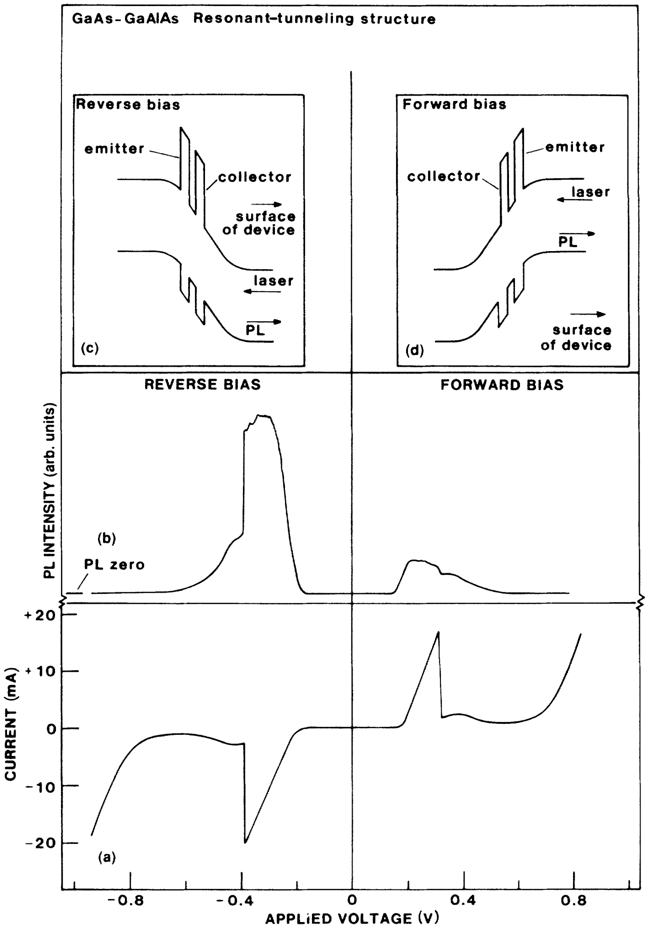

FIG. 2. (a) *I-V* characteristics for structure *A* (300-μm mesa) under illumination conditions employed for (b). (b) PL intensity as a function of bias at 1614 meV with detection bandwidth ±1.5 meV, excited at $h\nu_l = 1700$ meV. The form of the variation is very similar to that of the integrated PL intensity since the PL peak shifts by only 2 meV from -0.2 to -0.5 V, and the linewidth is only a weak function of bias. The weak decreases in I_{PL} from the saturation points to the cutoffs of the resonances (-0.34 to -0.40 V, $+0.24$ to $+0.30$ V) are accurate representations of the variation of the integrated PL intensity with bias. Point-by-point measurements of the integrated PL intensities in this region reproduce the variations shown in the figure very well. (c) Schematic band diagram for reverse applied bias. The directions of electron and hole flow are indicated. (d) Same as (c), but forward bias.

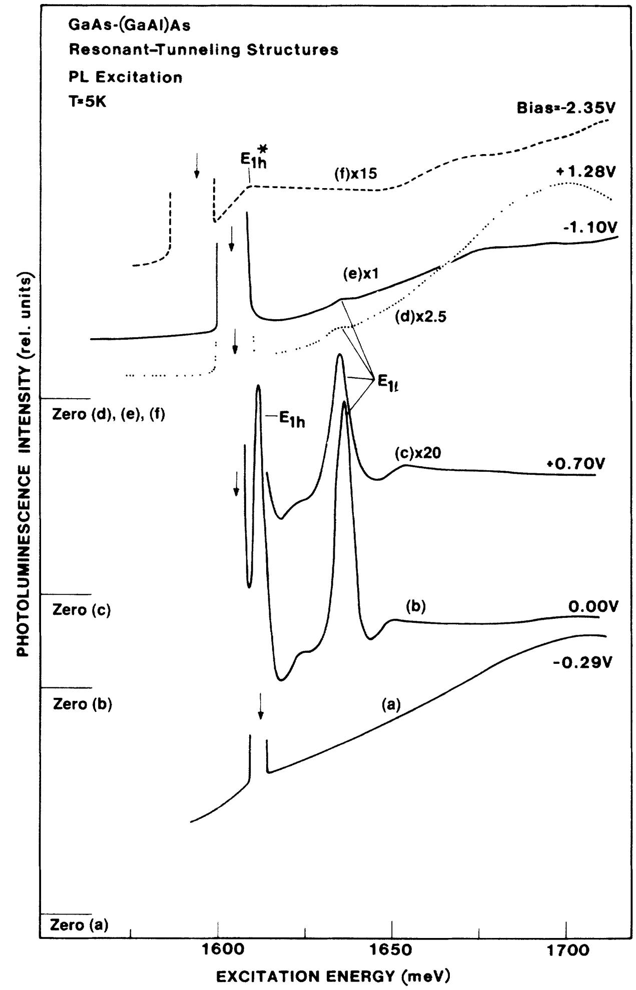

FIG. 3. PL-excitation spectra (a) for structure *A* at -0.29 V, and (b)–(e) for structure *B* at 0, $+0.7$, $+1.28$, -1.1 and -2.35 V. Dominant QW excitation features are observed at 0 and $+0.7$ V [(b) and (c)] since under these conditions electron (and hole at 0 V) tunneling into the well is negligible. The PL detection energies, indicated by downward-pointing arrows, for the various spectra are 1614, 1606.6, 1604.3, 1604.6, and 1595 meV for (a), (b), and (d)–(f), respectively.

QW PL can be excited efficiently down to 1500 meV in the region of the band-tail absorption of the GaAs contact layers, with a pronounced drop in the PL intensity being found at photon energies less than the effective band edge of the n^+ contact material at 1518 meV. No QW excitation features are observed in Fig. 3(a). Transitions from the lowest light-hole subband to the lowest electron level would be expected at 1648 meV, but no features are discernible in the PLE spectrum. This demonstrates very clearly that when biased on the tunneling resonance (in reverse bias), which ensures a high electron density in the well ($\sim 10^{11}$ cm^{-2}; see Sec. IV), the PL arises from recombination between the electrons and holes photocreated in the 1-μm-thick GaAs contact regions. These photocreated holes drift and diffuse to the collector barrier (for electrons), tunnel into the QW at a density n_s^h of 10^7-10^8 cm^{-2} (see Sec. IV for discussion) under the illumination conditions employed, and recombine with the higher density of electrons in the well. Photon up-conversion by up to 115 meV arises since the electrons and the holes gain energy relative to their respective band edges as they tunnel through the high-field regions across the emitter and collector barriers.

When biased on an electron-tunneling resonance, direct photoexcitation in the QW, in the present structures, makes a negligible contribution to the observed PL, as discussed above. However, away from resonance, QW excitation would be expected to be more prominent since, then, the electron density in the well, due to tunneling, is very low in typical structures with relatively thin collector barriers ($\lesssim 85$ Å).[14] The hole-tunneling rate from the n^+ GaAs contact into the well is expected to be much less sensitive to resonant conditions as a function of bias, since hole tunneling into the several (up to five) quasiconfined heavy- and light-hole levels[15] can occur in the wells under study. At all but very low bias voltages, the holes generated in the n^+ GaAs, although at least partially thermalized, will have a range of kinetic energies when they arrive at the collector barrier [see Fig. 2(c)]. This allows hole tunneling, in principle at all biases studied, particularly when broadening of the hole levels in the well and impurity or defect and phonon-assisted tunneling processes are also taken into account.[15] This statement is supported by the interpretation of the PLE experiments at different biases, and the integrated PL-intensity variations with bias (Sec. IV), where no specific features due to resonant hole tunneling are observed. To summarize the main point in this paragraph, since the hole-tunneling rate is a relatively insensitive function of bias, the form of the PLE spectrum is determined by the electron density in the well, which by contrast, in general, is a strong function of applied voltage. When biased on an electron resonance, the PLE will be dominated by photocreation in the GaAs, since both the hole and electron populations in the well are supplied by tunneling from the contacts. However, away from an electron resonance, n_s^e in the well is low,[14] and significant PL can only arise by direct photocreation of electrons in the QW. Under these circumstances, the QW features will dominate the PLE spectrum. These statements are supported by the experimental results which will now be presented.

The variation of the PLE mechanisms with applied bias is examined in detail in Figs. 3(b)–3(f), for structure *B*. The presence of the thick 111-Å $Ga_{1-x}Al_xAs$ barrier in this structure leads to enhanced charge buildup in the well, when the 111-Å barrier is on the collector side of the structure in reverse bias. The structure contains two well-confined electron levels due to the larger Al composition ($x=0.4$) in the barrier compared to structure *A*. Electron charge densities of 2.2×10^{11} and 3.2×10^{11} cm^{-2} at the two resonances, at -0.7 and -2.44 V, have been deduced from magneto-PL and magnetocapacitance studies.[4,6,10] In forward bias, on the other hand, where the 83-Å barrier is on the collector side, very little charge buildup ($<2\times10^{10}$ cm^{-2}, an upper limit deduced from the sensitivity of the capacitance measurements[10]) occurs on the resonances at 0.3 and 1.3 V. By contrast, in reverse bias, even between the two resonances, n_s^e is $\gtrsim 5\times10^{10}$ cm^{-2} due to tunneling by elastic (impurity or defect) or inelastic (LO-phonon) processes and the enhanced charge storage due to the presence of the thick 111-Å collector barrier. Indeed, for the present purposes, as far as charge buildup is concerned, structure *B* can be considered to be "on resonance" in reverse bias from the onset of the first resonance at -0.3 V to the cutoff of the second resonance at -2.44 V. Further details of the PL and *I-V* characteristics for this structure (*B*) are given in Refs. 4 and 6. Peaks in the *I-V* characteristics of structure *A* in Fig. 2(a), arising from LO-phonon-assisted inelastic tunneling of the type referred to above, can be seen at -0.43 and $+0.38$ V.

In Fig. 3(b), a PLE spectrum (structure *B*) is shown at zero bias. Very-well-defined heavy- and light-hole QW exciton features are observed (similar observations were reported in Ref. 9 at $V=0$). This is expected at $V=0$ since tunneling of carriers from the contact layers will not occur, and PL from the QW can only arise by direct photoexcitation of the QW. A similar high-quality QW PLE spectrum is observed for structure *A* at $V=0$. At $V=+0.7$ V in Fig. 3(c) for structure *B*, the QW excitation features are again dominant, since in forward bias, between resonances, electron tunneling through the thick (111-Å) emitter barrier is highly improbable. Thus, PL is only detectable with significant intensity if the QW is excited directly.

However, when the bias is increased to the second tunneling resonance at $+1.28$ V [Fig. 3(d)], substantial electron tunneling into the well from the emitter can occur, and the QW E_{1l} transition is only a minor feature in the excitation spectrum. E_{1h} cannot be studied easily since it occurs very close to the PL detection energy. The situation is very similar at -1.1 V, between the two tunneling resonances in reverse bias. As discussed earlier, even between the resonances in reverse bias, $n_s^e \sim 5\times10^{10}$ cm^{-2}, and so E_{1l} is again only a minor feature in the PLE spectrum in Fig. 3(e), the holes being supplied mainly from the n^+ GaAs contact. Finally, in Fig. 3(f) the PLE spectrum at -2.35 V, on the second reverse-bias resonance where $n_s^e \approx 3\times10^{11}$ cm^{-2}, is shown. At such high carrier density, the excitonic features in the PLE spectrum are expected to be broadened and reduced in intensity by the effects of phase-space screening and associated manybody interactions.[16,17] A broad E_{1h} feature (labelled E^*_{1h}) is indeed observed in Fig. 3(f). Since the PL spectrum has a 12-meV linewidth at this bias due to the high n^e_s value, the PL detection can be moved to sufficiently lower energy to allow E_{1h} detection. QW excitation features are visible at -2.35 V since at high biases beyond ~ -1.0 V the hole-collection rate in the QW begins to decrease markedly. As discussed in Ref. 6, for $|V|>1$ V for this structure (B), holes which tunnel through the first "collector" barrier [see Fig. 2(c)] have sufficient energy to pass straight over the top of the second barrier, thus leading to a decrease in n^h_s in the well at higher biases. This is the principal reason for the factor-of-15 decrease in PL intensity between -1.1 and -2.35 V [compare gains of Figs. 3(e) and 3(f)]. Therefore, under high-bias conditions, direct hole photocreation in the QW is expected to play a larger role, accounting for the reasonably prominent E_{1h} feature in Fig. 3(f).

We turn now to a comparison of the PLE processes for reverse and forward biases. Since, except under special circumstances at high bias, most of the holes which participate in the QW PL originate in the n^+ GaAs contacts, there is an inherent asymmetry between the two bias directions. This is easily seen by inspection of Figs. 2(c) and 2(d). For reverse bias the holes photocreated by the laser light in the 1-μm-thick top contact drift and diffuse to the collector barrier and then tunnel into the QW [Fig. 2(c)]. For forward bias, holes photocreated in the top contact cannot make any direct contribution to the PL since they drift away from the QW in the electric field, and diffusion to the GaAs below the QW is prevented by the $Al_xGa_{1-x}As$ barrier. Thus the holes which contribute to QW PL in forward bias can only be created in the lower GaAs n^+ contact or in the QW itself. PLE spectra for forward bias for structure A on resonance show only a very weak E_{1l} feature (at 1648 meV) of 4% of the intensity of a featureless background which has very similar form to that of Fig. 3(a), showing that excitation in the GaAs makes the major contribution to the QW PL in forward bias also.

However, consideration of the absorption coefficients of the laser photons used for excitation, and also of the ratio of PL intensities observed for reverse and forward applied biases, shows that the holes which contribute to the PL in forward bias cannot, in general, be generated directly by the laser in the lower GaAs contact. The variation of PL intensity ($I_{\rm PL}$) from the QW with applied bias is shown in Fig. 2(b), for 1700 meV excitation. A ratio of maximum PL intensities ($r_{\rm PL}$) of 5.3 between reverse and forward biases is observed. We have found a very similar ratio in two other symmetric DBRTS's. There is very little change in $r_{\rm PL}$ with increasing excitation energy, a value of 9 being found at $h\nu_l=2510$ meV.[18] Furthermore, we find that the absolute PL intensities are almost independent of $h\nu_l$ from 1700 to 2540 meV.

The absorption coefficients (α) at 1700 and 2540 meV are 1.7×10^4 and 9×10^4 cm^{-1}, corresponding, respectively, to 75% and 99.99% of the laser light being absorbed in the top 1-μm GaAs contact. Hence, a very strong dependence on $h\nu_l$ of the ratio $r_{\rm PL}$ is predicted if the holes are created directly in the 1-μm-thick GaAs contacts above and below the QW for the two respective bias directions. For example, a value for $r_{\rm PL}$ of 7×10^4 at $h\nu_l=2540$ meV would be expected in this model, in very marked disagreement with experiment. Implicit in this estimate for $r_{\rm PL}$ is the assumption that all photocreated holes (above and below the QW) have an equal chance of reaching the collector barrier—that is, that the minority-carrier hole-diffusion length (l_D) is $\gtrsim 1$ μm. In the opposite extreme, the assumption of a rather short hole-diffusion length of $\sim$2000 Å, in the heavily doped contact layers, can account qualitatively for the observed values of $r_{\rm PL}$ between $h\nu_l\sim1700$ and 2540 meV. However, this model must be rejected immediately since it predicts a very strongly decreasing PL intensity with increasing $h\nu_l$ from 1700 to 2540 meV, again totally contrary to the experimental findings. Thus, regardless of diffusion length, *direct* excitation of holes in the n^+ GaAs contact layers cannot give rise to significant PL in the forward-bias direction for $h\nu_l \gtrsim 2000$ meV, since the absorption coefficient is too large to allow any significant direct excitation of holes beyond the barriers.

Instead, we propose that the QW PL in forward bias is excited by a process of photon recycling by photons of energy close to the GaAs band gap. Photon recycling has been shown to play a major role in the excitation of buried layers beyond the absorption length of the excitation beam in materials of high quantum efficiency.[19,20]

As mentioned earlier, very strong PL from the GaAs contact layers is observed with main peaks at 1493 and 1518 meV, and a high-energy tail extending up to 1540 meV. The near-band-edge emission that comprises a large fraction of the GaAs PL has $\alpha\sim10^4$ cm^{-1}, and since it is emitted isotropically it will be reabsorbed in part deeper within the structure. This leads to electron-hole-pair creation at depths within the sample 1–2 μm beyond the primary generation volume, even when l_D is less than 1000 Å. Such processes are probable for materials of high quantum efficiency such as high-quality n^+ GaAs, and of high refractive index, where only $\sim$2% of the PL (in GaAs) can leave the sample within the critical angle on the first reflection from the surface.[19,20]

In order to determine whether such photon recycling is sufficiently important to account for the hole generation which leads to the QW PL in forward bias, a test structure was grown, shown in the inset of Fig. 4. It consists of (from the top) a 1-μm n^+ GaAs layer, a $Ga_{1-x}Al_xAs$ ($x=0.4$) barrier to prevent carrier diffusion out of the 1-μm n^+ layer, and a 1-μm-thick, undoped GaAs layer all grown on a semi-insulating GaAs substrate of low radiative efficiency.

The important distinction between this structure and a DBRTS is that the PL spectra from the GaAs layers above and below the barrier layer are easily distinguished, which helps very greatly in determining the excitation mechanism of PL from the buried GaAs. For $h\nu_l$ of 2540 meV ($\alpha=9\times10^4$ cm^{-1}) nearly all the laser light will be absorbed in the first 2000 Å of the n^+ top layer. The PL spectrum of the structure excited at 2540

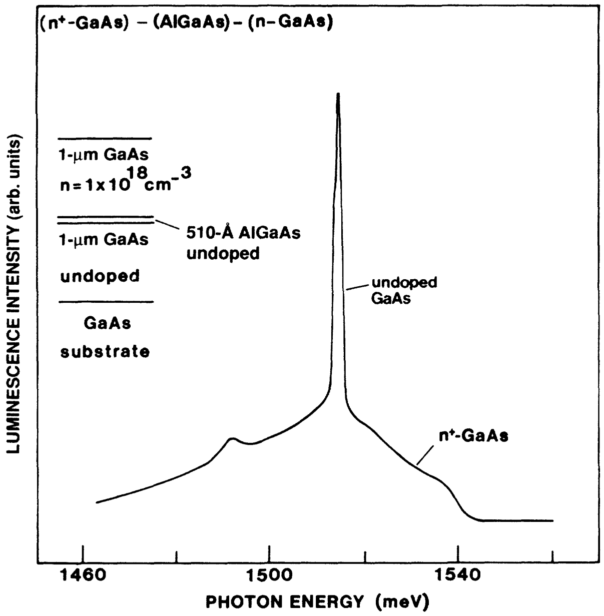

FIG. 4. PL spectrum for n^+ GaAs, $\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$, and an undoped GaAs test structure, shown schematically in the inset, grown on semi-insulating GaAs substrate. The broad band extending from 1460 to 1540 meV arises from the n^+ GaAs, whereas the sharp peak at 1510 meV is due to emission from the undoped GaAs. The observation of strong PL from the undoped GaAs, with ~10% of the intensity of that from the n^+-type GaAs, provides clear evidence for the occurrence of photon recycling.

meV is shown in Fig. 4. It is seen that the signal from the undoped GaAs has ~10% of the intensity of that from the n^+ GaAs, in the spectral range from 1500 meV to higher energy. Since direct photoexcitation of the undoped layer does not occur and the $\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$ barrier prevents carrier diffusion out of the n^+ GaAs, it is concluded that the PL from the undoped GaAs must arise from reabsorption of PL from the n^+ GaAs–that is, by photon recycling.

This result demonstrates the importance of photon recycling in a structure very similar to a DBRTS. Furthermore, the ratio of the undoped to n^+ GaAs signals is reasonably close to that observed between reverse and forward biases for the PL from the QW in the symmetric resonant tunneling structure (A). Thus we conclude with a high degree of confidence that emission and reabsorption of photons near the GaAs band gap leads to the generation of holes in the lower GaAs n^+ contact in DBRTS's, and hence to the observed QW PL signals in forward bias, other possible mechanisms having been excluded earlier.

The ratio (r_{PL}) of the reverse-bias to forward-bias PL intensities is found to be very sensitive to temperature above 40 K, increasing by a factor of 4 from 40 to 100 K. This initially puzzling result is, in fact, expected within the photon-recycling model and indeed provides further support for the above arguments. The GaAs band-edge PL, which gives rise to the necessary hole creation below the barriers in forward bias, decreases in intensity by a factor of 0.7 over the same temperature range. The contribution of four successive emission-absorption cycles, a not unreasonable number,[19,20] each quenched by 0.7, would account for the required fourfold decrease in the number of holes available for recombination in forward bias.

IV. VARIATION OF PHOTOLUMINESCENCE INTENSITY WITH BIAS

In this section a brief discussion will be given of the principal factors which control the variation of I_{PL} with bias in DBRTS's. Of particular interest is the correlation that can be expected between the variations of I_{PL} and tunnel current (I) through the device as a function of bias. Attention will be focused principally on the results presented in Figs. 2(a) and 2(b) for the nominally symmetric structure A.

The observed PL will be, in general, a function of both n_s^e and n_s^h in the QW (Ref. 1) (n_s^e and n_s^h refer specifically to sheet carrier densities in the QW). At the *peak* of the resonances in structure A, we obtain values of n_s^e of 1×10^{11} cm^{-2} from the peak sharpening observed in magneto-PL measurements, due to the removal of free-carrier broadening effects in magnetic field. It is more difficult to obtain a reliable value for n_s^h, but an upper limit for the hole density in the entire structure of 10^9 cm^{-2} is obtained from the laser flux of 0.2 W/cm^2, and a minority-carrier lifetime of 10^{-9} s for the n^+ GaAs measured in our structures from the decay time of the n^+ GaAs PL.[21] The PL from the GaAs is ~500 times stronger than that from the QW. If allowance is made for the factor-of-5 attenuation of the QW PL by the GaAs, an approximate value for n_s^h of 10^7 cm^{-2} is obtained (with an upper limit of 10^8 cm^{-2}), very much less than n_s^e under resonance conditions.

On the assumption of bimolecular electron-hole recombination, which should be a reasonable approximation at $n_s^e \sim 10^{11}$ cm^{-2} when excitonic effects are relatively weak, the decay rate for the minority-carrier holes can be written as

$$\tau^{-1} = A + Bn_s^e \ . \tag{1}$$

Bn_s^e ($=\tau_R^{-1}$) is the radiative decay rate. Here, A is a nonradiative term which includes any process which competes with radiative recombination, particularly in the present case, hole tunneling out of the well. For excitonic recombination, which will occur at lower n_s^e, the treatment is similar to the above, except that the Bn_s^e term is replaced by an exciton-formation rate (proportional to n_s^e) which competes with nonradiative processes. The quantum efficiency is given by

$$\eta = \tau/\tau_R = Bn_s^e/(A + Bn_s^e) \ . \tag{2}$$

$I_{\mathrm{PL}}=\alpha g_s^h \eta$, where α is a constant of proportionality and g_s^h is the areal generation rate of holes in the QW, proportional to the laser-excitation intensity at a given bias. The minority-carrier hole density $n_s^h=g_s^h\tau$, and is also proportional to excitation intensity under the weak-excitation conditions employed where the lifetime τ is almost independent of excitation intensity.[22]

When $A \gg Bn_s^e$, the nonradiative limit, η is proportional to n_s^e, and I_{PL} is proportional to both n_s^e and g_s^h. However, as n_s^e increases within a resonance, the probability for radiative recombination increases and, when $Bn_s^e \gg A$, the radiative limit is reached, $\eta \rightarrow 1$, and I_{PL} depends only on g_s^h (proportional to excitation intensity). The dependence of I_{PL} on n_s^e in the above two limits was pointed out by Young *et al.* in Ref. 1. In both the above limits and in the absence of direct excitation of electrons in the well, the dependence of I_{PL} on hole-generation rate, g_s^h, and hence on excitation intensity, is expected to be linear. This is in agreement with the observed behavior at nonzero bias under the low-excitation conditions employed in the present work.

The correlation between I_{PL} and tunnel current (I) at the onsets of the resonances at ±0.2 V in Figs. 2(a) and 2(b) arises because of the increases of n_s^e with V as charge begins to build up in the QW. Magnetocapacitance and magneto-PL measurements on the present structures show clearly that n_s^e increases linearly with bias on a tunneling resonance.[6,10] However, the linear dependence of I_{PL} on bias, expected in the nonradiative regime $A \gg Bn_s^e$, holds only through about the first 20% of the resonances in Fig. 2(a), up to $n_s^e \sim 2\times10^{10}$ cm^{-2}. For higher bias, I_{PL} quickly saturates [Fig. 2(a)] and even shows a small subsequent decrease towards the cutoff of the resonance. The saturation of I_{PL} with V very probably arises since the radiative limit, $Bn_s^e \gg A$, where I_{PL} is independent of n_s^e, has now been reached. It is difficult to make a reliable quantitative prediction of the n_s^e value for which $Bn_s^e \approx A$ should be attained. However, taking the values $B=2.3\times10^{-3}$ cm^{2}s^{-1} [in two-dimensional units for a 90-Å QW measured at 15 K (Ref. 23)] and $n_s^e=2\times10^{10}$ cm^{-2} at $Bn_s^e \approx A$, where saturation occurs from the present experiments, a nonradiative decay rate A of 4.6×10^7 s^{-1} ($\tau_{\mathrm{NR}}=22$ nsec) is predicted,[24] a not unreasonable value[25] possibly limited by hole tunneling out of the well. Although this estimate is rough, it does make the point that it is likely that I_{PL} will saturate as a function of V through a tunneling resonance for high-quality samples with relatively thick barriers where significant charge buildup occurs.[26] The forms of the I_{PL}-versus-V variations in Fig. 2(b) for both bias directions are found to be independent of excitation intensity in the range corresponding to hole densities of $\sim 5\times10^6$ to 10^8 cm^{-2}. This shows that the saturation behavior in Fig. 2(b) is not related to the number of photocreated holes, as expected in the above model in the regime where $n_s^h \ll n_s^e$.

In the radiative limit, I_{PL} is controlled by the variation of g_s^h with bias. The decrease of I_{PL} with bias from the saturation points to the cutoffs of the resonances may arise from a decrease of the hole-collection rate in the QW with bias. As discussed earlier for structure B, with increasing bias, an increasing fraction of the holes tunneling through the collector barrier will have sufficient energy to pass directly over the top of the emitter barrier, thus leading to a decrease of n_s^h in the QW (expected to begin at 0.3–0.4 V for structure A; see Refs. 5 and 6). At the negative differential resistance (NDR) features at −0.38 and +0.31 V, electron charge is ejected from the wells and an abrupt decrease of I_{PL} is observed, as the structures return to the nonradiative regime.

The features due to LO-phonon-assisted inelastic tunneling at −0.43 and 0.38 V are more prominent in I_{PL} versus V [Fig. 2(b)] than in I versus V [Fig. 2(a)], relative to the respective peak heights of I_{PL} and I at the peaks of the resonances, as also observed in Ref. 8. This is expected since, if I_{PL} has saturated at the peaks of the resonance (radiative regime, independent of n_s^e), at the LO-phonon satellites the structure will be closer to the nonradiative regime, and hence very sensitive to relatively small values of n_s^e which build up in the well. Indeed, the relatively greater prominence of the LO-phonon features in I_{PL} versus V than in I versus V provides further evidence that I_{PL} does saturate as n_s^e builds up through the resonance. The strong increase of I beyond ±0.7 V is due to nonresonant tunneling through the whole structure, with which no significant charge buildup is associated. Since I_{PL} is only sensitive to variations in resonant current (at low n_s^e), it does not give rise to any feature in I_{PL} versus V.

The independence of I_{PL} on n_s^e in the radiative limit is shown very clearly for structure B in reverse bias. In this case n_s^e is greater than 5×10^{10} cm^{-2} from −0.5 to −2.4 V. As a result, the only correlation between I_{PL} and I is observed at the onset of the first resonance at −0.4 V, the rest of the rather smooth I_{PL} variation with bias (shown in Refs. 4 and 6), peaking at −1.0 V between the resonances, being controlled by the variation of n_s^h with V. The smooth variation of I_{PL} versus V for this structure, and the absence of any features in I_{PL} versus V for structure A other than those at the electron-tunneling resonances, provide support for the interpretation that hole tunneling into the QW is a relatively insensitive function of bias. In particular, as proposed in Sec. III, it can be concluded that n_s^h does not exhibit any sharp resonances with voltage, at least in the bias ranges of principal interest.

It is clear from the above considerations for both structures A and B that some care should be used in interpreting the variations of I_{PL} solely in terms of the variation of n_s^e with bias.[27] A close correlation is expected only at low n_s^e values. Furthermore, a direct comparison of intensities between reverse and forward bias is very likely to be misleading since the PLE process is inherently asymmetric in structures with wide depletion regions under bias. However, if a correlation between I_{PL} and I at the onset of a resonance is observed, this is a very clear indication of the occurrence of charge buildup in the well. A more reliable method for the determination of the magnitude of charge buildup (for $n_s^e \gtrsim 10^{11}$ cm^{-2}) is provided by study of the PL linewidth and magneto-PL investigations.[4,6]

V. CONCLUSIONS

In conclusion, a study of PLE mechanisms and the factors which control the variation of PL intensity with bias in DBRTS's has been presented. In the present structures, with relatively wide spacer layers and depletion regions, it has been demonstrated that hole generation in the GaAs contacts and photon recycling play major roles in the excitation of PL in the QW regions. Furthermore, it has been shown that I_{PL} is only a sensitive function of resonant-tunneling current at low values of electron charge density in the well.

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