Luminescence kinetics of intrinsic excitonic states quantum-mechanically bound near high-quality $(n^{-}-type \text{ GaAs})/(p-type \text{ Al}_x \text{ Ga}_{1-x} \text{ As})$ heterointerfaces

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Recently, an optical emission process, termed the H band, has been observed in GaAs/Al_xGa_{1-x}As heterostructures which has been related to the regions surrounding the heterointerfaces. We show here that the mechanism responsible for this H-band photoluminescence (PL) in our structures is the recombination of quasi-two-dimensional (2D) excitons-and is not due to either the recombination of carriers bound at impurities and/or defects, or the recombination of 2D carriers with 3D free carriers. We have used such PL in high-purity, virtually "interface-free" $GaAs(n^{-})/Al_{0.3}Ga_{0.7}As(p)$ double heterostructures to study H-band decay dynamics, and thus prove that these excitations in our structures are "intrinsic" and arise from quantum-mechanically bound quasi-2D excitons. Time-resolved PL spectra show the emission to be spectrally nonstationary, with lifetimes across the band varying from a few nanoseconds to more than 50 μ s. Further, we find that large interfacial recombination velocities, in inferior samples, may mask the truly intrinsic H-band recombination dynamics. Our accompanying quantum-mechanical numerical modeling of such 2D excitons allows us to interpret and reproduce virtually all of our experimental observations. Indeed, they demonstrate that H-band PL cannot be impurity induced, but instead arises from the recombination of intrinsic excitonic states bound at both heterointerfaces. Hence we find that in thinner structures, these excitonic states may be simultaneously associated with both interfaces, with a critical GaAs thickness at which this "exciton sharing" between heterointerfaces becomes significant of $< 0.5 \,\mu$ m. We also discuss the time evolution of the initially photoexcited 3D bulk excitons as they acquire this subsequent 2D character, through a mechanism at the interfaces analogous to the quantum confined Stark effect in quantum wells. Our combined experimental and theoretical modeling, in these virtually interface-free samples, therefore, provide a direct measure and full quantum-mechanical explanation of the temporal evolution of these intrinsic 2D excitons-from 3D formation to 2D recombination-as undistorted by the deleterious influence of carrier trapping and nonradiative decay (in both the bulk and at interfaces), which may otherwise dominate the usually more-imperfect typical heterostructure. The results presented here are for specific, high-quality, interface-free GaAs/Al_{0.3}Ga_{0.7}As heterostructures; however, these measurement and analysis techniques may also be applicable to other types of structures.

I. INTRODUCTION

Modern epitaxy of structured materials now makes possible detailed, analytical study of the structural and electronic properties of high-electronic-quality, abrupt heterostructure interfaces. $^{1-4}$ Molecular-beam epitaxy (MBE) and organometallic vapor phase epitaxy (OMVPE) are capable of producing truly abrupt heterointerfaces, with interfacial fluctuations of 1-2 monolayers.⁵⁻⁷ Moreover, relative material purity has also drastically improved, as these separate growth techniques have matured and higher-purity sources have become available. As a result, the intrinsic properties of heterointerfaces-e.g., spikes and notches in the energyband edges at the heterointerface-might now be studied spectroscopically, virtually unimpeded by the effects of graded interfaces or consequential residual impurity/ defect concentrations either in the bulk or at the interfaces. We report here detailed results of extensive static and dynamical study of formation and decay of quantum-mechanical excitonic states, bound intrinsically at such high-quality GaAs/Al_xGa_{1-x}As heterointerfaces in double heterostructures.

Recently, optical studies of $GaAs/Al_xGa_{1-x}As$ structures have resulted in the observation of a new and distinct, near-edge phtoluminescence (PL) process.⁸ Referred to as the H band, this PL lies energetically between the edge-bound excitons and the band-to-acceptor (and/or donor-acceptor pair) emissions and has been observed in both n-p and n-n heterostructures. Indeed, such H-band PL has been reported for samples prepared by a variety of techniques, including liquid phase epitaxy (LPE),⁸ MBE,⁹⁻²¹ and OMVPE.²²⁻²⁸ Furthermore, some PL H-band studies conducted in electric^{14, 16, 19} and magnetic^{10, 12, 17, 18} fields have suggested that this recombination may be spatially related to the heterointerface and possibly the electrostatic band bending generally induced there. However, to date, no complete and systematic study of H-band temporal evolution (dynamics) has been reported, especially in heterostructures proven to be electronically optimum. Hence, in our view, a truly adequate and compelling explanation for the excitations responsible for this unique PL-capable of accounting for all of its static and dynamic properties-has not been available.

Previous studies have, for instance, shown (mostly

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through cw PL) relatively complex power and temperature dependences for H-band emission. Yuan et al.⁸ concluded that this new H-band PL must arise from the $GaAs/Al_xGa_{1-x}As$ heterointerface—a supposition supported mostly by chemically removing one of the $Al_x Ga_{1-x} As$ barriers and observing either diminishment or total loss of the H band. Nonetheless, these workers also found accompanying H-band peak energy shifts to be more or less proportional to the logarithm of the excitation-laser power density and that H-band PL intensity seemed to qualitatively diminish with increasing temperature, from 1.8 K to near disappearance above ~ 15 K. Further, electric-field studies^{14,16,19} indicated a tendency for *H*-band PL to shift in energy with applied field. In contrast, magnetic-field studies^{10, 12, 17, 18} found the *H* band to split into several peaks whose magnitudes varied as roughly the cosine of the angle between the field and the growth direction, thus indicating a possible two dimensionality for this excitation and implicating the heterointerfaces with its possible origin. Moreover, the PL also appeared to shift to higher energies with applied magnetic field (by as much as 10 meV at 10 T), but inconclusively the associated diamagnetic shift appeared linear in applied magnetic field in some studies,^{10,12} while appearing nonlinear in field in others.^{17,18} Finally, limited study of H-band temporal decays suggested an increased lifetime with applied magnetic field, ^{17,18} thus making Hband temporal evolution very complex.

Thus, despite many such luminescence and perturbative H-band studies, much controversy still remains concerning the physical origin of this excitation and recombination process. As an example, Alferov et al.¹² have concluded that this PL (found in their MBE structures) was due to the recombination between donor impurities in the narrow-gap material, with unspecified acceptorlike surface states arising from *within* the barrier materials. More recently, others^{13,17,18} have attributed virtually this same PL to yet other unspecified defect-pair recombination, in which one of the defects is located precisely at the $GaAs/Al_xGa_{1-x}As$ interface. Nonetheless, most studies^{8, 10, 14, 19, 20, 27} have yielded the conclusion that the H band may arise from the recombination between a free carrier and a carrier (not necessarily quantum mechanically) confined near heterointerfacial band bending. However, to date, numerous experimental observations still remain incompletely or inadequately explained by any truly definitive physical model or system photoexcitation.

In contrast, here we show that the *H*-band emission, in our structures, is not impurity induced, but instead results from an *intrinsic* two-dimensional (2D) excitonic emission. As will be shown, this becomes apparent through detailed dynamical behavior found by time resolving the *H*-band PL in a series of otherwise identical, virtually interface-free GaAs/Al_{0.3}Ga_{0.7}As double heterostructures, in which the GaAs-layer thickness is made the single and most important structurally varied sample parameter. We then offer an analytical and numerically solved, fully quantum-mechanical model for the *H*-band excitation and simulation of its subsequent temporal evolution and definitively show that observed decays in our structures may only be explained by the combined effect of *both* double heterointerfaces. Our calculations thus explain virtually all of our experimentally observed static and dynamic properties of low-temperature H-band emission.

II. EXPERIMENTAL METHODS

Samples used were OMVPE-prepared GaAs/ Al_{0.3}Ga_{0.7}As double heterostructures, with GaAs thicknesses ranging from 0.1 to 2.0 μ m. Al_{0.3}Ga_{0.7}As layers were 0.5 μ m thick in all samples and were unintentionally *p*-type (carbon) doped at ~3×10¹⁶ cm⁻³, whereas GaAs layers were nominally undoped *n* type at ~1×10¹⁵ cm⁻³. All heterostructures were prepared at 750° C, at V/III ratios of 40, with undoped (*n*-type) 0.5- μ m-thick GaAs buffer layers, on semi-insulating substrates. To help promote interfacial abruptness, all samples were prepared with growth interruptions at each heterointerface.

Photoluminescence experiments were performed in a variable-temperature optical cryostat, allowing detailed studies versus temperatures between 1.8 and 50 K. Samples were mounted strain-free with rubber cement to the sample probe, with the temperature monitored by a Sidiode mounted (in the same fashion) to the probe backside. Luminescence was excited by a synchronously pumped, cavity-dumped DCM (4-dicyanomethylene-2methyl-6-p-dimethylaminostyryl-4H-pyran) dye laser, with pulse width of 1.0 ps and tunable from 6400 to 7000 Å. The luminescence was collected and then dispersed by a 0.85-m double-grating spectrometer and detected by a chilled RCA C31034A photomultiplier. Time decays were collected using the time-correlated single-photoncounting technique;²⁹ care was taken to ensure that photon pileup did not occur, by keeping detection rates at least two orders of magnitude below the laser repetition rate; the total system time resolution was better than 0.5 ns. Photoexcited carrier densities for all kinetics studies were $\sim 10^{15} - 10^{16} \text{ cm}^{-3}$.

III. EXPERIMENTAL RESULTS

Because our study may relate to the GaAs/ $Al_xGa_{1-x}As$ heterointerfaces, a careful characterization of these interfaces is of ultimate importance. Without such thorough study of the interface and bulk properties, one may never be certain that observed processes are not related to-if not totally originating from-poor interfacial and/or bulk properties. We have thus thoroughly characterized all samples by measuring the absolute in-terface quality, 3^{0-33} as quantified by the interface recombination velocity S, representing the nonradiative decay of carriers at each heterointerface. Such generally nonradiative and uncontrollable decay may drastically alter PL efficiencies and lifetimes, and is usually calculated from PL efficiency and/or lifetime measurements.³⁰⁻³⁵ We have therefore calculated S from room-temperature lifetime measurements of all samples, finding $S \leq 40$ cm/s (Refs. 30-33)—among the lowest reported (by detailed GaAs-thickness dependences) for any GaAs/

Al_xGa_{1-x}As structure,³⁵ to date—with roomtemperature band-to-band recombination lifetimes of over 2.5 μ s.³⁰⁻³³ Such high-quality interfaces should therefore allow carriers to reside near them, for long times, without decaying nonradiatively; we may thus be assured that ensuing dynamics found are not adversely affected (or distorted) by the interface. In addition, our long observed lifetimes indicate that bulk nonradiative recombination in our samples may be neglected as well.

A low-temperature (1.8 K) PL spectrum of a 0.3-µmthick GaAs-layer double heterostructure is shown in Fig. 1. All samples, regardless of GaAs thickness, show the same general features-luminescence with prominent free-exciton emission peaking at 1.51515 eV (8180.8 Å), $^{30-33}$ with weaker emission peaking near 1.490 and 1.492 eV attributable to donor-acceptor pair (DAP) and band-to-carbon acceptor (BA_C) recombination. The unusually high sample quality is confirmed by the prominence of free-excitonic emission, in preference to the usually intense shallow-impurity-bound excitons found in even the purist epitaxial GaAs;³⁶⁻³⁹ indeed, in our samples, such excitonic PL associated with both residual donors and acceptors is found to be weaker in the PL spectra, just below the free exciton (Fig. 1). We attribute the strength of the free-exciton emission to the high quality of the heterointerfaces rather than to the purity of the epilayers alone. The broader PL feature located between these edge excitons and the band to acceptor was identified by Yuan et al.⁸ and termed the H band. It is important to recognize that this emission lies energetically between all the known shallow band-edge excitons⁴⁰ and the shallowest band-to-acceptor luminescence (from carbon).⁴¹ Thus one may conclude the H band may not be attributed solely to the recombination of carriers at impurities within the GaAs layer itself.

Also shown in Fig. 1 is the PL excitation (PLE) spectra, detected at the peak of the *H*-band emission. Clearly, the dominant PLE peak exactly coincides with the freeexciton PL. This is indicative of the importance of free excitons to a full understanding of *H*-band kinetics (i.e., formation). Also evident in the PLE spectra is the band-to-band absorption which subsequently leads to *H*-band emission. This same feature is evident in the free-exciton PLE (detector set at free-exciton emission energy 8180.8 Å). Thus the band-to-band absorption may lead to *H*-band emission through the intermediate formation of free excitons.

Figure 2 shows 1.8-K PL spectra for a representative set of such samples, with varying GaAs-layer thicknesses. All spectra show the same general features, namely, freeexciton PL, edge-bound exciton PL, and relatively strong *H*-band PL; these spectral features are reproducible in all samples. Thus the high quality of these structures, as evidenced by the uncommon free-exciton emission, is consistently uniform. Moreover, upon chemical removal of the top $Al_{0.3}Ga_{0.7}As$ layer,³⁰⁻³² we find *H*-band PL absent and free-exciton emission replaced by the wellknown double-humped structure,⁴² with a dip at the free-excitonic resonance (1.515 15 eV), which is generally associated with exciton-polariton⁴³ and dead-layer effects,⁴⁴⁻⁴⁶ a result most probably linked to the high interfacial quality experienced by both the free excitons and the *H*-band excitations.

We find in all of our heterostructure samples that Hband intensity also decreases dramatically with increasing temperature.²⁵ H-band PL is, in fact, fully quenched



FIG. 1. Low-temperature (1.8 K) time-integrated PL spectrum of a typical 0.3- μ m-thick GaAs-layer double heterostructure. Free excitons (F,X) dominate. PL-excitation spectrum at 1.8 K are also shown for detection of H-band emission at the peak of the H-band emission (dashed line).



FIG. 2. Low-temperature (1.8 K) time-integrated PL spectra for 2.0, 1.0, 0.3, and 0.2- μ m GaAs-layer thicknesses. The bottom spectrum is for a 2.0- μ m-thick sample, with the top Al_{0.3}Ga_{0.7}As layer chemically removed.

and undetectable from the background at just ≥ 14 K. The impurity-induced transitions, i.e., (DAP), (BA_C) , (D^0, X) , etc., are, however, still present in the spectra above 14 K and do not decrease in intensity with increasing temperature nearly as drastically as the H band. As further documentation of this rapid quenching, we have measured the spectrally integrated H-band intensity versus temperature. An activation energy for this emission process may then be extracted (through least-squares fitting with an Arrhenius function), with the best fit to our data yielding ~ 0.75 meV; similarly, all other samples yield activation energies $\leq 1 \text{ meV.}^{25}$ This unusually small activation energy compared to shallow edge excitons (e.g., $\sim 5 \text{ meV}$ for a donor-bound exciton⁴⁰), together with the unique energetic H-band peak position, argue against the H-band PL process being associated with the extrinsic recombination of carriers trapped at residual impurities/defects either in the GaAs or precisely at the $GaAs/Al_{0.3}Ga_{0.7}As$ heterointerfaces.

Yuan et al.⁸ have shown that the H-band peak position after cw excitation may also be power dependent, moving to higher energies as the logarithm of the excitation power density in their LPE structures; this we have also verified in all of our OMVPE heterostructure samples as further proof of H-band observation and identification. This static H-band behavior may be understood as being due to the changes in interfacial bandbending resulting from the addition of free photocarriers (and/or excitons), as will be shown in detail later. We also find that *H*-band PL is absent upon chemical removal of the top $Al_{0.3}Ga_{0.7}As$ layer,²²⁻²⁶ as in Fig. 2, thus again showing qualitative verification of *H*-band identity, parallel to those of Yuan et al.⁸ Having thus confirmed *H*-band activity in all of our heterostructures, we proceeded to the previously sparsely studied, 19-21,28 dynamical time-evolution characteristic of the H-band recombination process.²²⁻²⁶

Because the *H*-band peak energy critically depends upon a variety of experimental conditions and because very little may be inferred from cw PL about such possible dynamics of the *H*-band, detailed time-resolved PL measurements were performed, aimed at understanding the emission kinetics.²²⁻²⁶ We have performed such time-resolved PL measurements in all of our samples.²⁴ These data immediately demonstrate that the *H* band is not stationary in time, but, in fact, moves toward decreasing emission energies, as time goes by, with a total (cumulative) shift being ≥ 25 meV.²⁴

Such *H*-band time evolution may be further quantified by measuring the detailed intensity versus time (time decay) at discrete energies throughout the emission spectrum. Hence Figs. 3(a) and 3(b) show such decay kinetics at various emission energies for 2.0- and 0.2- μ m samples, respectively, with all decays being *highly nonexponential*,²²⁻²⁶ but readily fit to a bimolecular decay of the form³⁰⁻³⁵

$$I(t) = \frac{Ae^{-t/\tau}}{1 + C[1 - e^{-t/\tau}]}$$
 (1)

Such an implied PL intensity time dependence results from the solution of the differential equation $^{30-35}$

$$\frac{dp(t)}{dt} = -\alpha p^2 , \qquad (2)$$

where

$$\alpha p_0 = \frac{1}{\tau} . \tag{3}$$

Implicit in these equations are the conditions n = p, where n(p) is the total electron (hole) densities (photoin-



FIG. 3. Photoluminescence-decay kinetics at 1.8 K, versus emission energy for (a) 2.0- μ m and (b) 0.2- μ m structures. Fits (solid lines) were obtained using Eq. (1).

jected, plus built in) and n_0 (p_0) is the built-in electron (hole) density. Least-squares fits to the data, using Eq. (1), lead to well-defined and eminently comparable decay lifetimes (representative of the asymptotic exponential decay); these long nonexponential decays (with systematic trends versus emission energy) are typical of all of our heterostructure samples.

By measuring our derived lifetime (τ) versus emission energy and versus GaAs thickness, the direct influence of this active GaAs layer on H-band dynamics may be straightforwardly deduced. (Such lifetimes were only measured at energies either well above the band-toacceptor luminescence or well below the edge-excitonic luminescence, so as to minimize the influence of two spectrally overlapping processes in the decays.) Figure 4 shows these lifetimes, as deduced from nonlinear-leastsquares fits to Eq. (1) versus emission energy, for all double heterostructures studied. (Note that the thinnest structure-300 Å-just begins to show the effects of quantum confinement and the concomitant blueshift in emission energy.) Quite generally, we find lifetimes increase exponentially with decreasing emission energy,²²⁻²⁶ with results for thicker structures (e.g., 0.5, 1.0, and 2.0 μ m) being virtually identical at all emission energies and with lifetimes ranging from several nanoseconds to more than 50 μ s. As the GaAs-layer thickness decreases below $\sim 0.5 \ \mu m$, however, significant systematic differences rapidly become evident, appearing only on the low-energy side of each H-emission band. We thus find the significant result that H-band lifetimes appear to saturate at different values for different GaAs thicknesses, with the onset of saturation occurring at higher energies for thinner GaAs layers.²²⁻²⁶ The fact that different structures (with similar purities and virtually identical interfaces—as determined by the interface recombination velocity) have differing emission dynamics further sup-



FIG. 4. Measured time-decay lifetimes at different energies across the H band. Data for all structures were taken under identical conditions and the lifetimes obtained using Eq. (1) are those shown in Fig. 5.

ports the notion that *H*-band emission may indeed be of intrinsic origin and hence not impurity induced. Further, we find experimentally that structurally identical, but electronically and optically inferior samples, with *larger* interfacial recombination velocities, yield drastically *shorter* nonexponential *H*-band kinetics and corresponding lifetimes while showing virtually identical *H*-band PL, Fig. 5; hence their behavior versus time may not be trusted to be truly indicative of an intrinsic decay process, but instead would presumably reflect the irrelevant (and unwanted) dynamics of the unidentified competing extrinsic nonradiative recombination associated with an electronically (and possibly atomically) inferior interface.

IV. THEORETICAL-MODEL RESULTS

The electronic structure of heterojunctions has been the subject of much attention since the early $1960s.^{47-52}$ Much work focused on electrostatic bending of the conduction and valence bands at the heterointerfaces, which results from differences in properties of the two materials composing the heterojunction—including electron affinities, dielectric constants, band gaps, doping type,



FIG. 5. (a) 1.8-K photoluminescence spectra of two comparable 0.5- μ m double heterostructures. (b) Measured time-decay lifetimes at different energies across the H band for the same 0.5- μ m double heterostructures. Surface recombination velocities S were determined for both samples from 300-K band-toband recombination lifetime measurements.

and doping densities. It has generally been recognized that this band bending may confine carriers next to the interface in the notch formed by such band bending.⁵³ The species of such carriers which may become quantum-mechanically confined (electron or hole) depends on the type of heterojunction (i.e., *n-n* or *p-n*, respectively), while the confined carrier is two dimensional and is restricted in movement to directions parallel to the interface. Much work has been done on the two-dimensional electron gas which may form in these electrostatic potential notches,⁵³ especially in relation to high-electron-mobility-transistor or HEMT structures.

Yuan et al.⁸ have postulated that the H-band emission, in their n-n double heterostructures arises from the recombination of a 2D confined electron with a 3D free hole. Such recombination might then occur by tunneling in the tails of the high-field regions of the GaAs layers; however, such mechanisms cannot explain all experimental H-band observations (i.e., temperature dependence, etc.). Alternatively, emission from such states might also be interpreted as the recombination of a quasi-2D exciton; indeed Balslev⁵⁴ adopted such a view as a means of including a possible existing electron-hole Coulomb interaction (within the scheme proposed by Yuan *et al.*⁸). In this picture, the photoexcited free carriers and highly mobile 3D excitons, which form in < 1 ns,⁵⁵ must diffuse (or be field driven) to the GaAs high-field interfacial regions; the exciton energy then decreases, due to the quadratic Stark shift⁵⁶ and the field-induced polarization of the exciton perpendicular to the interface. Thus the photoexcited excitons might become attracted for a variety of reasons to the heterointerface and steadily evolve into quasi-2D excitons-with the H-band emission then being the result of radiative recombination of these 2D, intrinsically bound excitons. Hence this H-band PL may be thought of as resulting from an intrinsic quantum confined Stark effect, 57-59 wherein the field results from the heterojunction, and the quantum confinement is due to the sharp electrostatic potential profile at the heterointerfaces.53

Such regions adjoining the heterointerfaces are the high-field regions of the heterostructure, with a peak field sufficiently great to possibly ionize any free excitons which might gravitate toward those interfaces. It therefore might be questioned whether these quasi-2D excitons may be allowed to exist, as the field required to ionize bulk free excitons in GaAs is only 4.5 kV/cm.⁵⁹ (It will be shown below that these quasi-2D excitons may indeed exist in these structures, albeit in the high-field tail.) In connection with this, Köhler *et al.*⁵⁹ have found that 2D excitons in quantum wells may survive in electrostatic fields of up to 100 kV/cm, largely as a result of the quantum confinement accompanying the reduction in dimensionality from 3D to 2D.

Thus, here the first step in modeling *H*-band emission along these lines is to determine the electronic bands of the entire structure. Figure 6 shows such a selfconsistent solution of Poisson's equation, obtained numerically, for the 0.5- μ m structure. (Our structures form *p*-*n* heterojunctions; therefore the discussion throughout the rest of this paper will be restricted to this case, unless

FIG. 6. Results of our model numerical calculation for the static limit. Conduction- and valence-band potentials for the GaAs layer were obtained from self-consistent solution of Poisson's equation; carrier-envelope wave functions were obtained from solutions of Schrödinger's equation, as described in the text.
$$E_T$$
 is the transition energy referenced to the band edge and E_B is the exciton binding energy. (Note that the energy scales are correct, with the energy gap between conduction and valence bands having, for convenient illustration, been reduced.)

otherwise explicitly noted.) In modeling this band structure, and hence the *H*-band emission, it is thus imperative to include *both* heterointerfaces, thus causing the GaAs-layer thickness to become an important, if not critical, parameter.²²⁻²⁶

Laser photoexcitation, generic to all of these PL Hband experiments, generates additional free carriers which may alter the resultant band structure. In this context, photoexcited holes will diffuse and drift to the high-field region near the interface, thereby altering (selfconsistently) the electrostatic fields determining the entire heterostructure band structure. Since these photoexcited carriers must decay both radiatively and perhaps nonradiatively, the total carrier density, and hence the band structure, must change drastically with time, especially near the heterointerface. In view of this, any realistic physical model must consist of self-consistent timedependent simultaneous solutions of (i) Poisson's equation, (ii) the Boltzmann equation, governing carrier transport and decay, (iii) Schrödinger's equation, and (iv) the electron-hole Coulomb interaction. Such a complete model is indeed most complex and thus beyond the scope of this work. Nonetheless, we find a more calculationally simplistic (but still realistic) physical model may be adopted, and readily solved, in which we parametrize the time evolution (dynamics) of the entire heterostructure while neglecting the details of the actual carrier transport. In this spirit, the band structure of Fig. 6 was approximated by fitting it to an expression of the form

$$\varphi_v(z) = F_i d_i a_B e^{-(|z|/d_i a_B)} \tag{4}$$

and



$$\varphi_c(z) = \varphi_v(z) + E_g , \qquad (5)$$

where i=1,2 correspond to the GaAs and Al_{0.3}Ga_{0.7}As layers, respectively. Here also, F_i represents the maximum field at the heterointerface in each layer, d_i^{eq} becomes a characteristic screening length parameter, as measured in units of the simpler, 3D exciton Bohr radius (a_B) , and z is the growth direction.

This admittedly non- (explicitly) time-dependent approach provides a physical and realistic starting point for numerical calculation and essentially corresponds to the case of no photoexcitation, or the long-time limit $(t \rightarrow \infty)$. In the opposite extreme (i.e., creation of a large number of electron-hole pairs in the GaAs layer), these additional carriers are available to screen the heterointerface electrostatic field, thereby reducing the heterointerface band bending; thus, as $t \rightarrow 0$, the conduction and valence bands of the GaAs layer should approach a flatbanded condition. Such dynamics (and their intermediate cases) may thus be modeled by parametrizing d_1 , the screening length, in the GaAs layer as a virtual (relative) time parameter following pulsed photoexcitation. Since the actual photoexcitation was performed energetically below the Al_{0.3}Ga_{0.7}As band gap (thereby only generating additional carriers in the GaAs layer), as a first approximation, its band structure may be considered constant. Thus, as $d_1 \rightarrow 0$ corresponds to short times after the delta-function photoexcitation pulse, likewise, $d_1 \rightarrow d_1^{eq}$ time simulates the decay of the photoexcited carriers in the long-time limit.

The envelope function for the quasi-2D exciton [subject to the potentials of Eqs. (4) and (5)] may then be determined by numerically solving Schrödinger's equation, with the appropriate Hamiltonian. Assuming that the total solution may be factored into separable electron and hole solutions, the total Hamiltonian thus becomes⁵⁴

$$\mathcal{H} = \mathcal{H}_e + \mathcal{H}_h , \qquad (6)$$

where the corresponding wave function must be a product of electron and hole envelope wave functions

$$\Psi = \sqrt{2/\pi} a_{\perp}^{-1} \Phi_{e}(z_{e}) \Phi_{h}(z_{h}) e^{-[(|\mathbf{r}_{\perp}|/a_{\perp}) + i\mathbf{K}_{\perp} \cdot \mathbf{R}_{\perp}]}, \quad (7)$$

where \mathbf{r}_{\perp} and \mathbf{R}_{\perp} are the relative and center-of-mass exciton coordinates, respectively, projected onto the x-y plane (plane of the interface). Correspondingly, \mathbf{K}_{\perp} is the wave vector of the resultant quasi-2D exciton, a_{\perp} is its Bohr radius, and Φ_e and Φ_h are the separate electron and hole envelope wave functions (assumed to be normalized). The wave function of the confined particle, the hole, may then be readily found from

$$\mathcal{H}_h \Phi_h(z_h) = E_h \Phi_h(z_h) , \qquad (8)$$

where

$$\mathcal{H}_{h} = -\frac{\hbar^{2}}{2m_{h}} \frac{\partial^{2}}{\partial z_{h}^{2}} - \varphi_{v}(z_{h})$$
⁽⁹⁾

and Eqs. (8) and (9) may be straightforwardly solved numerically for $\Phi_h(z_h)$ and E_h . In this view, the mean position for the hole along the direction perpendicular to the

heterointerface may then be defined as

$$\overline{z}_h = \int z [\Phi_h(z_h)]^2 dz \quad . \tag{10}$$

The corresponding quantum-mechanical solution for the free particle, the electron, is found from

$$\mathcal{H}_e \Phi_e(z_e) = E_e \Phi_e(z_e) \tag{11}$$

and

$$\mathcal{H}_e = -\frac{\hbar^2}{2m_e} \frac{\partial^2}{\partial z_e^2} - V_{\text{eff}}(z_e) , \qquad (12)$$

where

$$V_{\text{eff}}(z_e) = -\varphi_c(z_e) - \frac{e^2}{4\pi\varepsilon_0} \frac{2}{\pi a_\perp^2} \int_0^\infty \frac{e^{(-2r_\perp/a_\perp)} 2\pi r_\perp dr_\perp}{\sqrt{[r_\perp^2 + (z_e - \overline{z}_h)^2]}},$$
(13)

accounts for the static Coulomb interaction between electrons and holes. Direct influences of the sharply changing (and time-dependent) electric fields at the heterointerfaces are thus included in the calculation solely through the band bending described by $\phi_c(z_e)$ and $\phi_v(z_h)$. (In contrast to the *p-n-p* structures studied in our experiments, corresponding *n-n-n* or *n-p-n* structures may be solved by reversing the role of electrons and holes in the above model.)

For both particles, the ground-state envelope wave functions are the final bound-state solutions sought and a_{\perp} may then be systematically varied to minimize the total energy; because these are one-dimensional attractive potentials, there must therefore be at least one bound state for both the electron and hole. By comparing these resultant bound-state energies with kT, we may then subsequently determine whether or not excitons may form. Since all of our time-decay measurements were performed at 1.8 K, where $kT \sim 0.15$ meV, we may assume the electron and hole excited states may therefore be safely neglected. (In this context, we find that the energy spacing of the first excited state of the hole confined in the heterointerface potential notch is $\sim 3 \text{ meV}$ for $d_1 \rightarrow d_1^{eq}$, and the corresponding spacing for the electron is ~ 0.6 meV.) Perhaps significantly (or fortuitously) our experiments show no evidence of such excited states in the PL spectra; indeed, for the calculation, these additional states only become important for $d_1 \rightarrow 0$ and/or for samples with wide GaAs layers. We have also made the simplification that the Coulomb potential energy between electrons and holes, which is responsible for binding them together to form the quasi-2D exciton, is much smaller than the hole confinement energy in the heterointerface notch—this then limits the validity of our model to the parameter space of $d_1 \ge 1$.

Figures 7(a) and 7(b) show our calculated results for screening lengths d_1 from 0.5 to 12 and 0.5 to 9, respectively. Figure 7(a), with $d_1 = d_1^{eq} \approx 12$, corresponds to the case of no photoexcitation—or equivalently $t \rightarrow \infty$ —in which the conduction- and valence-band potentials were taken from the self-consistent solutions of Poisson's equation in Fig. 6. The time-dependent H-band dynamics are



FIG. 7. (a) Model calculation results for a structure with a $0.5-\mu$ m GaAs-layer thickness. Only the GaAs band structure is shown (solid). Dotted lines and hatched areas represent hole-envelope wave functions, while dashed lines and shaded areas represent electron-envelope wave functions. E_B is the 2D exciton binding energy, E_e and E_h are the electron and hole confinement energies, respectively, d is the screening parameter, and f is the electron-hole wave-function overlap integral. (Note that the energy scales are correct, with the energy gap between conduction and valence bands having, for convenient illustration, been reduced). (b) Model calculation results for a structure with a $0.2-\mu$ m GaAs-layer thickness. Only the GaAs band structure is shown (solid). Dotted lines and hatched areas represent hole-envelope wave functions, while dashed lines and shaded areas represent electron-envelope wave functions. E_B is the 2D exciton binding energy, E_e and E_h are the electron and hole confinement energies, respectively, d is the screening parameter, and f is the electron-hole wave-function and valence bands have areas represent electron-envelope wave functions. E_B is the 2D exciton binding energy, E_e and E_h are the electron and hole confinement energies, respectively, d is the screening parameter, and f is the electron-hole wave-function overlap integral. (Note that the energy scales are correct, with the energy-gap between conduction and valence bands having, for convenient illustration, been reduced).

therefore modeled here by parametrizing d_1 such that increasing time after pulsed excitation corresponds to increasing d_1 . In this connection, there are several important points to note in the figures. (i) For small d_1 (short times) the band bending is indeed quite small and the photoexcited electrons and holes appear uniformly distributed throughout the GaAs layer; this situation corresponds to bulk excitation, with accompanying fast diffusion of carriers throughout the GaAs layer yielding an effectively (instantaneous) homogeneous carrier distribution. (ii) As d_1 increases (increasing time) the band bending at the heterointerfaces increases, thus forming heterointerfacial potential notches which rapidly confine the mobile holes. (iii) The additional Coulomb interaction between electrons and holes causes the distribution of electrons to follow that of the holes-thereby moving the photoexcited electrons also toward the heterointerfaces early on. (iv) As d_1 increases further, the conduction band bending, resulting from the high field at the heterointerface, next forces the electrons back toward the

center of the GaAs layers—and away from the holes, which become increasingly quantum confined near the heterointerface. (v) Finally, the electrons and holes reach their maximum separation, corresponding to one-half of the total GaAs-layer thickness, a long-time result occurring for $d_1 < d_1^{\text{eq}}$. The relatively striking differences between results in Figs. (7a) and 7(b) should be especially noted here, namely, that the carriers appear to reach their maximum separation both for smaller values of d_1 and for thinner GaAs layers. These analytical results therefore display at least the qualitative time-evolutional dependences of H-band dynamics abundantly clear in our experiment versus GaAs thickness.

Importantly for direct comparison with data, the *H*band-emission transition energy and quasi-2D exciton binding energy may also be readily calculated from the approach in Fig. 7, with results shown in Fig. 8 (the transition energy is measured from the optical band gap, at the measurement temperature). Here the transition energy is equal to the total valence-band bending minus the



FIG. 8. PL transition energy (E_T) and binding energy of the quasi-2D exciton (E_B) as obtained from model calculation, with transition energies being referenced to the optical band gap (1.5194 eV). (a) Results for 0.5- μ m structure and (b) results for 0.2- μ m structure. *d* is the screening parameter.

sum of electron and hole confinement energies, E_e and E_h in Figs. 7(a) and 7(b), respectively. E_B is calculated from solutions for the ground-state energy with and without the Coulomb potential in Eq. (13). Our model calculation thus predicts the *H*-emission energy to decrease linearly with increasing d_1 (or simulated time). It also predicts that the maximum PL energy shift for the 5000-Å structure will be ~25 meV and for the 2000-Å structure about 20 meV. Further, we find the quasi-2D exciton binding



energy E_B^{3D} to continuously vary with d_1 (or time) and to always be less than the experimental 3D exciton binding energy $E_B^{3D} = 4.2 \text{ meV}.^{42,56}$ For small d_1 , however, E_B^{2D} approaches E_B^{3D} ; as it should, but as d_1 increases, E_B^{2D} decreases asymptotically to ~0.45 meV. Results for the 2000-Å-layer thickness are similar, although here E_B^{2D} saturates near 1.0 meV instead.

With the envelope wave functions for both electrons and holes properly deduced, the relative *H*-band transition lifetime may then be readily calculated. Since the oscillator strength of the transition f is directly related to this spatial electron-hole wave-function overlap [which composes the exciton, Eq. (7)]—thus implicitly including exciton effects—as

$$f = |\langle \Psi_h | \Psi_e \rangle|^2 f_0 , \qquad (14)$$

and the lifetime of the transition is related to the oscillator strength as

$$\tau^{-1} \propto f , \qquad (15)$$

then the relative change in oscillator strength, and hence lifetime, may be straightforwardly deduced. (Here f_0 represents the transition oscillator strength when the envelope wave functions of the carriers are perfectly overlapped as bulk 3D excitons.) Figure 9 shows the calculated results for the 2000-Å structure, compared directly against the corresponding experimental results of Fig. 4, with agreement being quite good. The theoretical band structures for four different transition energies [taken from Figs. 7(a) and 7(b)] are also shown in relation to the relative oscillator strength calculated. Thus our simple (time-simulated) physical model appears to accurately and quantitatively predict the saturation behavior found experimentally in our thin structures; correspondingly, the calculation for a thicker structure does not result in saturation, again in agreement with our experiments.

An important result also coming directly from our calculation shows that our observed lifetime saturation, occurring at higher energies for thinner structures, must arise from the finite size of the GaAs layer—or,

> FIG. 9. Comparison of results between the model calculation and experimental results for a double heterostructure with a 0.2- μ m GaAslayer thickness. Solid symbols represent the model calculation, while open symbols represent experiment. The theoretical band structures for several transition energies are shown in surrounding figures.

equivalently, to the effects of the companion heterointerface. Thus the quantum-confined electrons and holes reach their maximum separation, equal to half of the GaAs-layer thickness, at progressively smaller values of d_1 —thus higher energies—as the GaAs-layer thickness decreases. This result is therefore equivalent to the 2D excitons being effectively shared by both heterointerfaces, hence causing the spatial wave-function overlap to become approximately constant, hence yielding our observed lifetime saturation.²²⁻²⁶ Further, the calculation shows that the transition is indirect in real space (recombination of quasi-2D excitons with a continuous distribution of radii), which explains our observed long, nonexponential *H*-band time decays.

Yuan et al.⁸ have reported that the H band has a recombination lifetime of ~ 1.3 ns. Nonetheless, their actual decay kinetics were measured at only a single emission energy (1.5079 eV, 8220 Å)-a result considerably shorter than we find (Fig. 4). Also, Zhao et al.¹⁴ report H-band lifetimes in a GaAs/Al, Ga1-, As double heterostructure (with a 500-Å GaAs-layer thickness) in which observed lifetimes increase with decreasing emission energy-but again lifetimes at any given energy are significantly shorter than those reported here (by a factor of 500 at the lowest emission energies). Further, these authors¹⁴ also reported exponential intensity decays for Hband emission, a result which is difficult to reconcile with models based on the recombination of a quasi-2D exciton with a continuous distribution of radii or on a 2D carrier recombining with a free 3D carrier. An additional significant fact to note is that, in our experience, samples of poorer interfacial quality (as determined by the inter-face recombination velocity) $^{30-33}$ yield shorter lifetimes than those we quote in Fig. 4, as demonstrated in Fig. 5, while neither of these previous studies^{8,14} included any form of interface characterization. The results of these two previous studies, therefore, may have been adversely affected (or inadvertently dominated) by nonradiative interfacial recombination. Further, the saturation in lifetime we find and explain as being associated with a small (or finite) GaAs-layer thickness proves additionally that these earlier studies, basically confined to narrow structures, must not have been reflecting true H-band intrinsic dynamics.

V. DISCUSSION

Because of the obvious complexity of the *H*-band dynamics reported both here, and in the literature, it is difficult to make any universal conclusions concerning the exact physical mechanism responsible for his emission in all structures. It may therefore be possible that different heterostructures may yield nearly identical emission, but as a result of entirely different physical mechanisms. This may, in fact, be part of the observed structural dependences reported thus far: In particular, heavily doped structures, or single heterostructures, may yield *H*-band emission through the model originally proposed by Yuan *et al.*⁸ (2D carrier recombining with a free 3D carrier), and excitonic effects, as we emphasize here, may not be present due to the electrostatic screening accompanying heavy doping. Indeed, we find that for wide structures, $E_B^{2D} \rightarrow kT$, thus thermally ionizing free excitons into free carriers. In addition, there are certain reports of slightly different *H*-band behavior from that originally reported by Yuan *et al.*⁸ An example is Zhao *et al.*,⁹ who show the *H* band to persist to temperatures ≥ 30 K, in their heavily doped, single-sided heterostructures; this may be further proof of the above-noted issues. In any case, we find from our current perspective that nearly all reported results refute the *H*-band emission as arising from impurities or defects.

The experimental results presented here regarding the H band, and the excellent agreement between these data and our calculation, prove conclusively this emission in our structures to be of intrinsic origin and not impurity induced. The dominance of free excitons in both the PL and PLE spectra shows the high quality of the heterointerfaces and is circumstantial proof of the importance of excitonic effects in any emission process at low temperatures. Taken together, all of our results can only lead to a quantum-mechanical 2D-excitonic description for the H band, in our samples.

Thus, in summary, we may put forth as fact the following experimental observations for our samples: $^{22-26}$ (i) H-band emission weakens with increasing temperature and is not detectable in any PL above 15 K, whereas the PL bands associated with both donors and acceptors, (D^0, X) , (DAP), (BA_C) , etc., persist to higher temperatures. (ii) Time-resolved PL spectra reveal H-band emission to be spectrally dynamic. (iii) Lifetime measured at various emission energies show that the precise physical structure of the double heterostructures (in particular, the GaAs-layer thickness) drastically influences emission dynamics. (iv) Extrapolation of these lifetimes to higher energies is in good agreement with the expected 1.8-K GaAs band edge of 1.5194 eV (Refs. 42 and 56) and its corresponding excitonic lifetime of ≤ 1 ns.⁶⁰ As for our model calculations, the following may also be observed:²²⁻²⁶ (i) *H*-band activation energies are indeed quite small (≤ 1 meV). (ii) Transition energies extend to 25 meV below the band gap and are dependent on sample structure. (iii) Oscillator strengths increase for decreasing emission energies, with saturation evident in thin structures. Thus we may again emphasize that our combined experiment and theory are all entirely consistent with this emission as being intrinsic, and not impurity induced.22-26

The temperature dependence of the *H*-band PL and the derived activation energy²⁵ are in good agreement with the binding energy of our quasi-2D exciton, as calculated from our physical model. E_B^{2D} , as calculated from the model, and shown in Fig. 8, is a smoothly varying function of d_1 —and hence time, with early times (or small d_1) leading to almost insignificantly small band bending at the heterointerface. Next, with carrier decay the screening of the heterointerface field is reduced and the potential notch in the valence band at the heterointerface begins to form. Holes quantum confined in this notch then electrostatically attract electrons twoard the interfaces through the Coulomb interaction and the resulting quantum confined exciton acquires two-dimensional char-

acter, with a binding energy approaching 4 meV—the bulk free-exciton binding energy. As time (or d_1) increases still further, the separation between carriers [as calculated from the mean position of the electrons and holes as in Eq. (10)] begins to increase, until it reaches maximum separation equal to precisely half the GaAs-layer width. Thus, as the exciton evolves from a 3D entity into a quasi-2D quantum-mechanically interfacially bound exciton, the wave function changes from spherical to ellipsoidal, with a concomitant increasing of the effective radius of the quasi-2D exciton. The binding energy, E_B^{2D} , decreases as a result of the inverse relation between the binding energy of the exciton and its radius, as displayed in Fig. 8, and indeed saturates at ≤ 1.0 meV, resulting from the saturation in carrier separation.

An additional fact to be noted is that H-band emission occurs at energies just below the band gap and extends down 25 meV (Refs. 22-26) below the GaAs band gap (1.5194 eV).^{42,56} Our model predicts, to first order, the same maximum-energy shift of the PL (Fig. 8) and a direct proportionality between the transition energy and the screening length d_1 . This PL transition energy is determined virtually entirely by the hole-confinement energy and is almost insignificantly affected by the excitonic binding energy (≤ 1.0 meV). Our calculation also predicts maximum PL energy shifts to be dependent on the GaAs-layer thickness; hence thinner structures should have a smaller maximum-energy shift. However, since the experimentally determined H-band position at the maximum energy shift lies close to the band-to-acceptor PL, such subtle differences are beyond our ability to spectroscopically resolve.

The energy at which saturation in the lifetime occurs (as discussed in relation to Fig. 4) is also predicted by our model. This energy may be deduced by finding the screening length at which the carriers reach their maximum separation and by then recalculating the transition energy for this screening length. As a case in point, for the double heterostructure with a $0.5-\mu m$ GaAs-layer thickness, the carriers should reach a maximum separation for $d_1 \approx 8$. The corresponding calculated transition energy is then $E_T \approx 20$ meV (1.499 eV), which is in surprisingly good agreement with the data of Fig. 4. For thicker structures the corresponding emission energies at which saturation occurs are even lower, whereas for thinner structures the carriers reach maximum separation for smaller values of d_1 , and thus higher energies. This is again confirmed in the data in Fig. 4, which clearly show that the lifetime saturation for the 0.1- μ m double heterostructure occurs at a higher emission energy than for the corresponding $0.2 - \mu m$ structure, just as theoretically expected.

Further, we find from calculation that without excitonic electron-hole Coulomb interaction, the relative change in lifetime which may be predicted over the *H*-emission band is entirely insufficient to account for our data. For example, in our *p*-*n*-*p* structures the electron wave function would, at all simulated times (all d_1), be centered in the *n*-type GaAs layer. The electron wave function therefore never becomes attracted toward the heterointerface and the holes residing there. This nonphysical situation would necessarily result in exceedingly long radiative lifetimes (fully spatially indirect free carriers), a finding inconsistent with our observations.

Given our above intrinsic excitonic description of Hband processes, further details of dynamics may be elaborated and speculated upon. For example, extrapolation of measured lifetimes to higher energies (as shown in Fig. 4 and discussed above) directly signify the physical origins of the H band, in that H-emission energies nearest the band gap (and at earliest times) result from conduction- and valence-band potentials which must be flat, due to the electrostatic screening from the large number of photoexcited carriers. Hence, following pulsed excitation, carrier evolution eventually contributing to *H* emission would have to be envisioned as follows: First, electron-hole pairs photoexcited within the GaAs layers generates free carriers, which in turn may quickly condense into bulk 3D excitons. Next, these excitons and free carriers may diffuse and drift towards the high-field regions of the material-both heterointerfaces-where the very presence of such large numbers of excitons and free carriers would reduce the interfacial band bending. However, as these very excitons migrate toward the interfaces, the field they experience there may become sufficient to reionize them into free carriers. Hence large numbers of free electrons and holes drawn to the heterointerfaces further add to (or prolong) the flat banding. Next, these carriers would be expected to radiatively recombine, near the band-gap energy, with a lifetime determined by the high electron-hole gas density. Then, as the carrier concentrations diminish due to recombination, band bending at the heterointerfaces becomes increasingly restored, which would then serve to quantum confine the holes in the heterointerface potential and ultimately form the quasi-2D excitons. At this point the field at the interface, and the subsequent band bending, may be considered sufficiently reduced that these quasi-2D excitons may appear 3D-like, but nonetheless weakly confined; this explains why our quasi-2D exciton binding energy approaches that of a 3D exciton for small d_1 . (However, for $d_1 \approx 0$, an exciton picture breaks down and is inappropriate near the heterointerfaces.) Finally, at longest times these quasi-2D excitons would be expected to continue to recombine, all the while increasing (restoring) the band bending, and with these excitons become increasingly more oriented perpendicular to the interface (polarized), and with their PL energy becoming increasingly smaller until the remaining photoexcited carriers had all decayed. In wide structures (>0.5 μ m) and at long times, the charge separation is sufficient to field ionize the excitons yielding spatially separated, uncorrelated electrons and holes localized at the center and edges of the structure, respectively. (We should note here that our small calculated binding energies of these quasi-2D excitons directly includes these electric-field changes, through their influence upon the conduction- and valence-band potentials.) Thus these arguments suggest that quantum confinement, together with the finite GaAs-layer thickness, would actually eventually prevent the 2D excitons bound at the interfaces from being ionized by the still relatively strong heterointerfacial fields.

As for the steadily and dramatically increasing H-band exciton lifetimes as emission energy decreases (Figs. 4 and 9), this arises naturally in our picture as being due to the steadily increasing (as time goes on) field-induced charge separation and the corresponding decrease in electronhole overlap. Thus the field is intrinsic to the heterojunction region of the structure, with the band bending resulting from this field causing a time- and energy-dependent redshift; at the same time, this band bending also serves to partially confine the exciton, thus imparting to it 2D character. We might thus refer to the mechanism responsible for H band as an intrinsic quantum confined Stark effect.^{57-59,61} Here, unlike in traditional quantumwell experiments under applied electric field, no externally applied field is necessary-the heterojunction instead provides it all. Similar types of behavior (PL redshift and increasing lifetimes with increasing field) in quantum-well systems with applied fields have indeed been observed and adequately explained by such mechanisms.^{59,61}

VI. CONCLUSIONS

Previous theoretical work⁵⁴ relating to the H band has only considered the effect of a *single* heterointerface on a quasi-2D exciton. The complex dynamics of quasi-2D excitonic motion, evolution, and recombination have not therefore been considered in detail previously. As noted above, the importance of the companion interface in double heterostructures cannot be neglected, or even underestimated, in exciton recombination kinetics. Therefore, a complete study of the dynamics of H-band PL, as unencumbered by complicating effects, can only be done in wide structures. This conclusion is in contrast to some earlier work on near-quantum-well size structures.¹⁹⁻²¹ Further, the interfaces must be of demonstrably high quality, as quantified by, for example, interface recombination velocity studies, as at least one species of carrier may reside at the interface for long periods of time-as long as tens of microseconds. We have made measurements of the recombination dynamics and modeled the carrier dynamics responsible for the H-band PL in ideal high-purity structures. Our simple theoretical model shows that the Coulomb interaction between electrons and holes (forming excitons) is essential to adequately describe our observed H-band decay dynamics versus emission energy. Our combined results thus explain the detailed dynamics of excitons quantum confined at a single $GaAs/Al_xGa_{1-x}As$ heterointerface and prove that these dynamics may be readily understood with a simple quantum confined 2D-excitonic description.

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FIG. 6. Results of our model numerical calculation for the static limit. Conduction- and valence-band potentials for the GaAs layer were obtained from self-consistent solution of Poisson's equation; carrier-envelope wave functions were obtained from solutions of Schrödinger's equation, as described in the text. E_T is the transition energy referenced to the band edge and E_B is the exciton binding energy. (Note that the energy scales are correct, with the energy gap between conduction and valence bands having, for convenient illustration, been reduced.)



FIG. 7. (a) Model calculation results for a structure with a 0.5- μ m GaAs-layer thickness. Only the GaAs band structure is shown (solid). Dotted lines and hatched areas represent hole-envelope wave functions, while dashed lines and shaded areas represent electron-envelope wave functions. E_B is the 2D exciton binding energy, E_e and E_h are the electron and hole confinement energies, respectively, d is the screening parameter, and f is the electron-hole wave-function overlap integral. (Note that the energy scales are correct, with the energy gap between conduction and valence bands having, for convenient illustration, been reduced). (b) Model calculation results for a structure with a 0.2- μ m GaAs-layer thickness. Only the GaAs band structure is shown (solid). Dotted lines and hatched areas represent hole-envelope wave functions, while dashed lines and shaded areas represent electron-envelope wave functions. E_B is the 2D exciton binding energy, E_e and E_h are the electron and hole confinement energies, respectively, d is the screening parameter, and f is the electron-model areas represent electron-envelope wave functions. E_B is the 2D exciton binding energy, E_e and E_h are the electron and hole confinement energies, respectively, d is the screening parameter, and f is the electron-hole wave-function overlap integral. (Note that the energy scales are correct, with the energy-gap between conduction and valence bands having, for convenient illustration, been reduced).