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Electronic states and optical transitions in modulation-doped n-type $Ga_xIn_{1-x}As/Al_xIn_{1-x}As$ multiple quantum wells

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We report the results of a detailed spectroscopic investigation of the optical properties of modulation-doped $Ga_xIn_{1-x}As/Al_xIn_{1-x}As$ multiple quantum wells. The emission processes are dominated by the radiative recombination between the free carriers and the photogenerated holes occurring at $\mathbf{k}=0$. The absorption edge is blue shifted to the Fermi level of the electron plasma owing to exclusion-principle effects. A simple model for the calculation of the emission line shape reveals information on the energy parameters of the optical transitions. Finally, we provide direct evidence for absorption enhancement at energies close to the Burstein-Moss edge, disappearing around 50 K, which is ascribed to many-body interactions in the two-dimensional electron plasma.

INTRODUCTION

Modulation-doped quantum wells (MDQW) are a unique system for use in studying the optical properties of two-dimensional (2D) electron plasmas in semiconductors. The possibility of achieving a confined dense Fermi gas in a stationary condition in the quantum well allows one to investigate the free-electron optical transitions even under conditions of very low excitation intensities. In addition, MDQW-based electronic devices have considerable technological importance owing to the high electron mobility achieved through the spatial separation of the dopant atoms and the mobile electrons confined, respectively, in the barrier and in the quantum well. The study of modulation-doped quantum wells and heterostructures has, therefore, a twofold interest: first, to directly investigate the electronic properties and optical transitions in the one-component plasma in semiconductors and, second, to test new technologically important heterostructures with improved materials characteristics for device applications. Several experimental results have already been reported on the optical and electronic properties of $GaAs/Al_xGa_{1-x}As$ MDQW's.[1-3] Conversely, the $Ga_xIn_{1-x}As/Al_xIn_{1-x}As$ MDQW's have been much less investigated[4] owing to the difficulties in the fabrication of quantum wells of good quality having abrupt interface characteristics.[5]

This paper is addressed to the optical investigation of the electronic transitions in $Ga_xIn_{1-x}As/Al_xIn_{1-x}As$ MDQW's, emitting in the technologically important near-infrared region. Absorption, photoluminescence, and photoluminescence excitation measurements at different sample temperatures have been performed in order to probe the optical response of the multiple quantum wells confining a dense electron plasma. From our data we deduce that the effect of the screening of the Coulomb interaction in the dense Fermi gas results in the disappearance of the excitonic features from the emission spectra. The luminescence properties are governed by the free-electron recombination at $\mathbf{k}=0$, while the many-body interaction leads to an enhancement of the absorption close to the Fermi edge.

EXPERIMENT

The investigated samples are high-quality modulation-doped n-type $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ multiple quantum wells grown by molecular-beam epitaxy (MBE) on InP substrates. The samples consist of 50 $Ga_xIn_{1-x}As$ wells sandwiched between 24-nm $Al_xIn_{1-x}As$ barriers, whose central 6-nm region was doped with Si. Two samples of different well widths have been investigated: sample (a) with 3.4 nm well width and sample (b) with 8.2 nm well width. In both samples the electron density, determined by means of Hall effect and magnetotransport measurements, was $n_s=4\times10^{11}$ cm^{-2}. Undoped $In_xGa_{1-x}As/In_xAl_{1-x}As$ heterostructures with identical well widths have also been grown as reference samples. It is worth noting that the narrowing of the well width becomes an important test for the actual interface quality of the multiple quantum well structure, especially in the $Ga_xIn_{1-x}As/Al_xIn_{1-x}As$ system.[5]

Photoluminescence (PL) measurements have been performed with the samples kept at temperatures ranging from 3.5 to 300 K by using a Kr^+ laser operating either with the blue (476 nm) or with the red (617 nm) line. The luminescence was dispersed and analyzed by a 1-m single monochromator, equipped with a cooled Ge infrared detector, and a lock-in detection system. The absorption and photoluminescence excitation (PLE) measurements have been carried out with the same detection system, but by using a 150-W halogen lamp as source, which was dispersed by a double monochromator in the infrared spectral range.

The excitation power densities in the PL and PLE measurements were ranging between 10^{-4} and 10^{-1} W cm^{-2}.

RESULTS AND DISCUSSION

In Figs. 1(a) and 1(b) we show the absorption spectra recorded at 4 K in samples (a) and (b), respectively. These curves are compared with the absorption spectrum (dashed line) measured under the same conditions in the undoped $Ga_xIn_{1-x}As/Al_xIn_{1-x}As$ quantum wells (QW's) having the same well widths. In the case of the

MDQW, the absorption curves exhibit flat structures and relatively sharp edges, around 1205 and 1375 nm for samples (a) and (b), respectively. The PL spectra peak around 1254 nm for sample (a) and around 1443 nm for sample (b). By comparing these spectra with the absorption spectra of the undoped QW's, one can see that neither the absorption peaks nor the luminescence band of the MDQW's lie at the energy position of the excitonic transitions measured in the corresponding undoped sample (the peaks labeled E_{1hh} in the absorption spectra of the undoped QW's are related to the $n=1$ heavy- and light-hole exciton transitions[6]). In particular, the absorption edge in the MDQW's is blue shifted with respect to the fundamental excitonic transition in the undoped QW, while the luminescence is displaced towards the low energies. In addition, we observe a shift of about 40 meV between the absorption and the luminescence peaks in the MDQW's spectra. This value is much larger than the Stokes shift measured under identical conditions in the corresponding undoped QW's (between 10 and 15 meV).

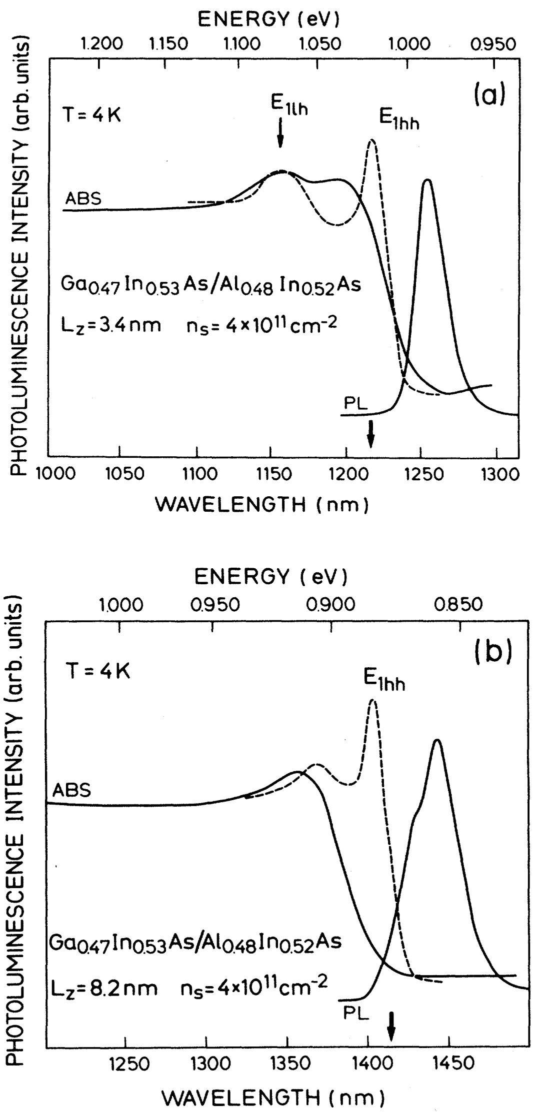

FIG. 1. (a) Absorption (ABS curve) and photoluminescence (PL curve) recorded at 4 K from sample (a). The dashed line represents the absorption spectrum measured in the undoped QW having the same well width. (b) The same as panel (a) but for sample (b).

The described features are related to the specific recombination processes involving the 2D electron plasma in the quantum well. Optical transitions in MDQW's involve electrons from the Fermi sea and photoexcited holes. In order to fulfill the **k**-conservation rule, the photoemission processes should involve electrons and holes with the same momentum (i.e., vertical transitions). Since in low-intensity photoluminescence experiments the photogenerated low-density hole gas rapidly thermalizes at the top of the valence band ($\mathbf{k}=0$), the **k** conservation for optical transitions in MDQW can only be achieved if recombination processes occur at $\mathbf{k}=0$. The **k** selection rule breaks down in the presence of interface defects or impurities which localize the holes. This localization results in a momentum spread of holes which can then recombine with electrons having larger **k** vectors. In other words, these holes can recombine with high-energy electrons having **k** vectors ranging between $\mathbf{k}=0$ and $\mathbf{k}=k_F$ [where $k_F=(2\pi n_s)^{1/2}$ is the **k** vector at the Fermi energy]. It is therefore expected that the hole localization due to interface roughness or defects will result in an asymmetric broadening on the high-energy side of the luminescence by involving higher-momentum (and higher-energy) electrons in the Fermi sea (see, e.g., Ref. 14).

As far as the absorption is concerned, only the states above the Fermi level are available for the transitions since the dense electron population in the well fills all the states from the bottom of the first conduction subband up to the Fermi level $F_e=\hbar^2 k_F^2/2m$. In the present experiment the electron density provided by the modulation doping in the barrier is $n_s=4\times 10^{11}$ cm^{-2}, giving a Fermi level of about 23 meV (we use the effective masses reported in Ref. 6). It is therefore expected that absorption processes can only involve electrons of energy higher than the Fermi level, while emission processes occur at the subband energy corresponding to electronic transitions at $\mathbf{k}=0$.

The observed spectra depicted in Fig. 1 clearly exhibit the discussed features. The absorption edge of the MDQW is blue shifted by about 40 meV with respect to the luminescence emission. This shift well accounts for the Burstein-Moss shift $E=(1+m_e/m_h)F_e$ expected for the 23-meV band filling of the actual Fermi level.[7] Conversely, the luminescence provides information on the recombination among the lowest-energy carriers in the 2D plasma and the holes. Particularly, the absolute energy position of the luminescence line does not correspond to the optical transition between the first electronic and heavy-hole subband in the undoped well, since the actual band-gap energy is renormalized by the exchange and correlation interaction in the one-component plasma.

Nevertheless, the observed luminescence does not exhibit any high-energy broadening close to the Fermi edge which would be due to nonvertical transitions. This feature can be considered as a proof of the excellent quality of the investigated MDQW, in which defect-related localization centers seem to be negligible.

Furthermore, as shown in the comparison of Figs. 1(a) and 1(b), neither the luminescence nor the absorption peaks observed in the spectra of the MDQW's can be ascribed to excitonic transitions. In fact, the observed energy positions of these spectral features do not correspond to the excitonic transition energies calculated [arrows in Fig. 1 (Ref. 8)] and measured in the identical undoped quantum wells (dashed lines in Fig. 1).

In addition, any excitonic contribution to the optical transitions in semiconductor quantum wells containing a degenerate electron population can be excluded on the basis of a recent calculation by Kleinman.[9] In this reference it has been shown that at electronic densities resulting in Fermi energies larger than the exciton binding energy, the free exciton relaxes into plane-wave states for the electron and the hole, from which radiation occurs at the renormalized energy gap.

From the above discussion we deduce that the observed luminescence in $Ga_xIn_{1-x}As/Al_xIn_{1-x}As$ MDQW's is mainly due to free-electron recombination around $\mathbf{k}=0$. In addition, owing to the effects of the exclusion principle on the states below the Fermi level, absorption transitions occur at energies higher than the luminescence line, with a Burstein-Moss energy shift which is a function of the actual Fermi level of the 2D electron gas. Moreover, many-body effects in the dense one-component plasma leads to the disappearance of the excitonic features in the absorption spectra. The peak observed close to the Burstein-Moss edge in the absorption spectra of both samples (a) and (b) can be related to the electron interactions in the 2D plasma and will be discussed in the following.

It is worth noting that, according to the calculated electronlike dispersion of the light-hole valence band in the $In_xGa_{1-x}As$,[10] the structure labeled 1lh in the absorption spectrum of Fig. 1(a) can be ascribed to the resonance at the intersubband transition involving the first conduction and light-hole subbands.[6] No such structure can be resolved in the absorption spectrum of the 8-nm-well-width MDQW where the splitting of the heavy-hole and light-hole subbands is much smaller than in sample (a). In this case the broadening of the absorption peaks due to the high carrier density in the well can mask the fine structure of the spectral features.

The temperature dependence of the luminescence observed from samples (a) and (b) is displayed in Figs. 2(a) and 2(b), respectively. Sample (a) shows a sharp free-carrier emission peak having a very symmetrical shape and about 17-meV full width at half maximum (FWHM). The emission still persists at room temperature although it is weakened by about 2 orders of magnitude with respect to the low-temperature luminescence. The sharp high-energy tail of the luminescence indicates a low carrier temperature and the absence of any hole localization. Similar results have been obtained in sample (b) although the free-carrier luminescence is slightly affected by extrinsic emission. Particularly at low temperature the electron-hole recombination is convoluted with a shallow-impurity emission disappearing around 40 K. Above this temperature the free-carrier luminescence recovers the line shape already observed in sample (a) but with a low-energy emission band probably due to acceptor levels in the $Ga_xIn_{1-x}As$ well. The luminescence efficiency of this sample decreases more rapidly with temperature as compared to the sample (a), and only a very weak emission is observed above 200 K.

A more quantitative analysis of the luminescence line shape provides further information on the optical transitions in the investigated MDQW's. The spectral intensity of emission $I(\hbar\omega)$ has been calculated on the basis of a simple statistical model which takes into account $\mathbf{k}$ conservation in the optical transitions and constant matrix element.

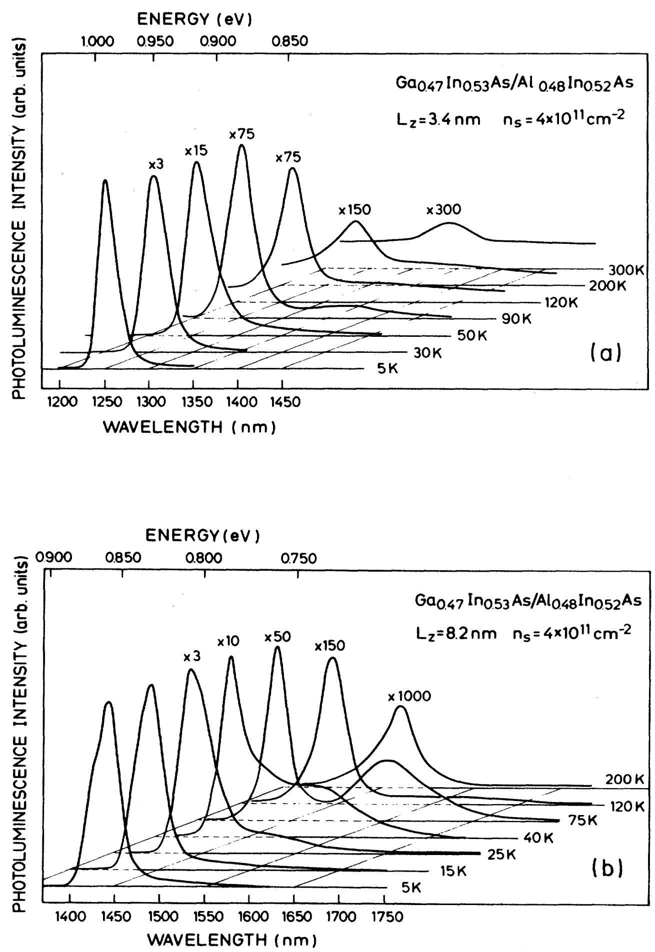

FIG. 2. (a) Temperature dependence of the luminescence from sample (a). The spectra are multiplied by constant factors to be compared. (b) The same as panel (a) but for sample (b).

$$I(\hbar\omega)\sim\frac{1}{\{1+\exp[-(\hbar\omega-E_g')/\Gamma]\}}\times\frac{\exp\left[-\dfrac{m_e}{m_e+m_h}(\hbar\omega-E_g')/kT_e\right]}{\left[\exp\left[\dfrac{m_h}{m_e+m_h}(\hbar\omega-E_g'-F_e)/kT_e\right]+1\right]}\,. \tag{1}$$

In Eq. (1) E_g' is the renormalized gap and kT_e is the thermal energy. The thermalized hole population is accounted for by the Boltzmann distribution function, while the Fermi distribution function accounts for the one-component electron plasma. The 2D steplike density of states has been approximated by the first term of Eq. (1) which represents a step function phenomenologically broadened by the Γ parameter.

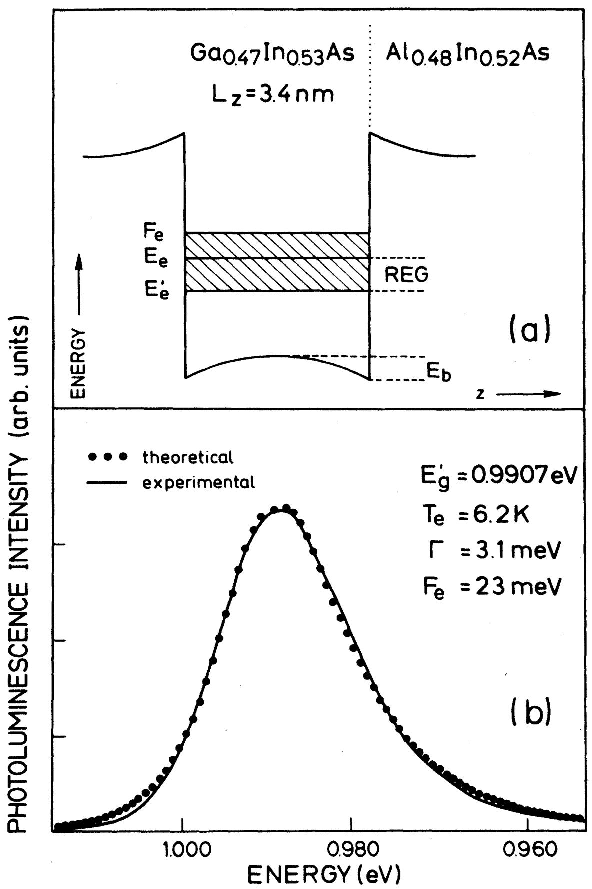

FIG. 3. (a) Scheme of the conduction-band structure in a MDQW. E_e is the unperturbed quantized subband, while E_e' is the renormalized subband (REG is the reduction of the energy gap). F_e is the Fermi level of the 2D electron gas. E_b is the band bending due to the electrostatic field at the interface. The numerical values of the above parameters are discussed in the text. (b) Experimental photoluminescence curve of sample (a) at 5 K (solid line) and theoretical emission line shape (dots) calculated by means of Eq. (1). The best fit parameters are discussed in the text.

In Fig. 3(a) scheme of the energetics of the 2D plasma in the conduction band of the MDQW is depicted. As previously discussed, the 2D electron plasm leads to an energy band filling up to the Fermi level. The presence of a dense electronic population results in the shrinkage of the gap which is taken into account in our simple model by red shifting the subband energy. The band bending calculated in our sample is of the order of 10 meV and does not affect the actual energy position of the subbands in the quantum well.[11] The model takes into account only **k** conserving electronic transitions occurring between the lower edge of the conduction subband and the top of the valence subband, as discussed at the beginning of this section. Fitting parameters in the calculations are the reduction of the energy gap (REG), which is accounted for by the shifted subband energy E_e', the electron effective temperature T_e, and the phenomenological broadening parameter Γ.

In Fig. 3(b) we show the result of a least-squares fit carried out on the photoluminescence spectrum of sample (a) obtained at 5 K by means of Eq. (1). The calculation reproduces the experimental spectrum with the best fit parameters reported on the figure. The transition energy is renormalized by about 20 meV at $n_s=4\times10^{11}$ cm^{-2}, comparable to other results obtained in different MDQW heterostructures.[1,3,4] The electron temperature is found to be very close to the lattice temperature, supporting the interpretation of optical transitions involving thermalized holes and $\mathbf{k}=0$ electrons without any excess energy due to optical photogeneration (at least at the low excitation rate employed in the experiments). Finally, the broadening parameter is found to be 3.1 meV, which is a very reasonable broadening for the deviation of the density of states from the ideal steplike behavior. Our simple model cannot give accurate information on the plasma Fermi level since the sensitivity to this parameter is partly masked by the presence of the kT_e and Γ terms which, respectively, broaden the high- and low-energy sides of the calculated spectra. However, the line shape of Fig. 3(b) has been obtained by using the Fermi energy of 23 meV as discussed previously.

Once the nature of the electronic transitions has been established, we briefly discuss the peak observed at low temperatures at the edge of the PLE and of the absorption spectra. In Fig. 4 we show the photoluminescence excitation spectra of sample (a) recorded in the temperature range 5–53 K. The most interesting feature is the existence of a peak close to the Burstein-Moss edge which rapidly disappears by increasing the temperature. Such a structure cannot be related, as already discussed, to excitonic absorption processes. It is therefore connected to some absorption enhancement due to the 2D electron plasma. The shape and the temperature dependence of the observed peak are very similar to the Fermi-edge singularity (FES) already observed in GaAs/Al$_x$Ga$_{1-x}$As MDQW's.[12,13] It is worth noting that such absorption enhancement is a characteristic feature of the many-body interaction in the dense electron gas interacting with the photogenerated hole. In fact, it is the direct manifestation of the enhanced electron-hole multiple scattering in-

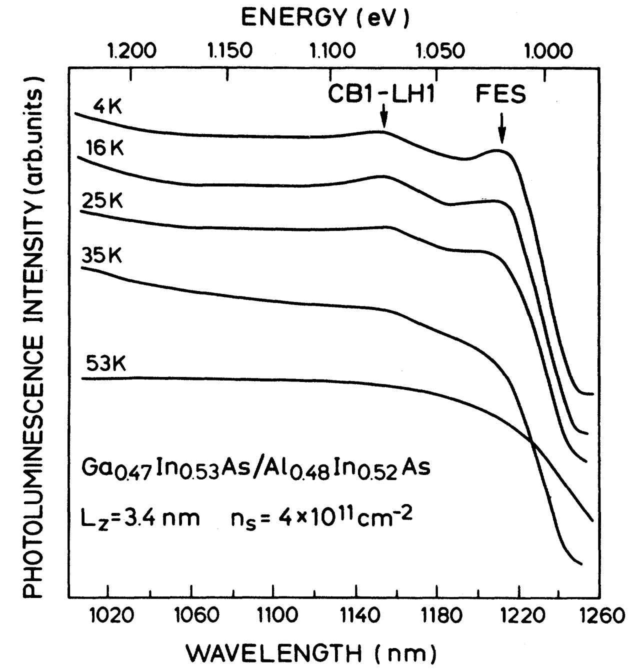

FIG. 4. PLE spectra of sample (a) at different temperatures. The spectra have been multiplied by constant factors to be compared.

volving electrons at the Fermi energy. The increase in the absorption at the Burstein-Moss edge is due to an increase of the multiple-scattering processes only for those electrons close to the Fermi level which can be scattered into empty states, while electrons below F_e are prevented from undergoing scattering processes owing to the exclusion principle. In other words, the electron sea undergoes a charge redistribution towards the photogenerated holes resulting in a screening of the Coulomb interaction and in the increase of the electron correlation which leads to the absorption enhancement.[11] When increasing the temperature, the electrons gain energy and their Fermi distribution spreads. As a consequence, the strength of the correlation effect is reduced dramatically, leading to the disappearance of the FES feature in the PLE spectra above 50 K. A similar temperature kinetics has been observed for the FES in the absorption spectra of $GaAs/Al_xGa_{1-x}As$ MDQW's[12,13] and in luminescence for the $Ga_xIn_{1-x}As/InP$ MDQW's.[14]

In samples where hole localization due to alloy fluctuations or interface defects plays an important role, such a Fermi singularity can be observed even in the luminescence spectra, in accordance with the breakdown of the **k**-conservation rule which then allows nonvertical transitions between electrons at the Fermi energy and thermalized holes. In this case the emission line shape can be calculated by using a many-body calculation which quantitatively evaluates the electron correlation factor of the 2D gas.[11,14]

Nevertheless, the FES structure is an intrinsic property of MDQW heterostructures containing a degenerate electron gas, and therefore manifests itself in the changes of the absorption edge which does not follow the expected statistical shape. The observation of this spectral feature in the PLE spectra of the $Ga_xIn_{1-x}As/Al_xIn_{1-x}As$ MDQW is a further proof of the high quality of the investigated heterostructures, while the observation of the same effect in luminescence can be related to the participation of extrinsic localization effects assisting the optical transitions at the Fermi level.

CONCLUSIONS

In conclusion, we have reported the results of a detailed spectroscopic investigation of the optical properties of *n*-type modulation-doped $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ quantum wells. It is established that the radiative-recombination processes are dominated by the free-carrier emission in the temperature range 4–300 K. Particularly, the luminescence can be ascribed to optical transitions at $\mathbf{k}=0$ wave vector, mainly involving electrons at the renormalized subband edge and photogenerated holes. No luminescence involving electrons at the Fermi edge has been observed, indicating the excellent quality of the interfaces in the investigated MDQW, in fact hole localization due to alloy fluctuations does not affect the optical properties. A phenomenological line-shape model calculation allows us to deduce the main energetic parameters of the 2D electron plasma, giving a band-gap renormalization of about 20 meV and an electron temperature close to the lattice temperature. Finally, an absorption enhancement has been observed at the Burstein-Moss edge in the PLE spectra, which shows a strong temperature dependence. This feature is ascribed to the increased electron correlation in the 2D plasma close to the Fermi energy, similar to that already observed in modulation-doped $GaAs/Al_xGa_{1-x}As$ multiple-quantum-well heterostructures.

ACKNOWLEDGMENTS

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using the relation $m_h = \gamma_1 + \gamma_2$ given by M. Altarelli, in *Heterojunctions and Semiconductor Superlattices,* edited by G. Allan, G. Bastard, N. Boccara, M. Lannoo, and M. Voos (Springer-Verlag, Berlin, 1986), p. 35. The γ_1 and γ_2 factors are the Luttinger parameters of the $Ga_xIn_{1-x}As$, taken from K. Alavi, R. L. Aggarwal, and S. H. Groves, Phys. Rev. B **21**, 1311 (1980).

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