Band-edge modifications due to photogenerated carriers in single *p*-type δ-doped GaAs layers

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(Received 7 August 1998; revised manuscript received 5 October 1998)

The photogenerated carrier-induced band-edge modifications of beryllium single δ-doped GaAs layers comprising a two-dimensional hole gas (2DHG) were investigated by means of photoluminescence, selective photoluminescence, and photoluminescence excitation spectroscopies. The results show direct evidence for a photoinduced electron confinement effect, which strongly enhances the radiative-recombination probability between electrons and holes of the 2DHG at low temperatures. [S0163-1829(99)01607-0]

Delta-doped structures have already been extensively investigated as they represent the state of the art in doping profile and became quite important for the microelectronic industry.[1] Although the *n*-type δ-doping structures have received a great deal of attention so far, only recent the *p*-type δ-doping structures became the subject of systematic investigations.[2–4] One remarkable contrast between these two systems is the fact that in photoluminescence (PL) measurements carried out on single isolated δ-doped layers, the expected two-dimensional (2D) emission bands are only observed in *p*-type, but not in *n*-type structures. Moreover, the observed temperature dependence of the PL emission bands associated with the two-dimensional hole gas (2DHG) in *p*-type δ-doped layers exhibits an interesting thermal quenching effect that has attracted interest recently.[4–6]

It has been argued that the thermal quenching ($T \sim 60\,\mathrm{K}$) of the 2DHG-related emission band from *p*-type δ-doped GaAs layers was probably due to the escape of holes from the δ-potential well to the nearby bulk material.[6] However, the rapid thermal quenching ($T \sim 12\,\mathrm{K}$) observed in *p*-type Si layers by Buyanova and co-workers was explained in terms of a shallow electron-potential well induced by photoexcited holes, which are captured by the δ-doping well.[4] According to this model, the quenching of the 2DHG luminescence is due to the thermal activation of confined electrons from the photoinduced-potential well to the continuous states in the host material.

The comparison between the luminescence spectra from *n*- and *p*-type δ-doping GaAs structures was recently performed through rigorous self-consistent band-structure calculations.[5] It was particularly emphasized the role played by the photoinduced electron-confinement effect on the realistic description of the PL spectra from *p*-type δ-doped structures. In the present paper we report on the results obtained by means of PL, selective photoluminescence (SPL), and photoluminescence excitation (PLE) spectroscopies of Be δ-doped GaAs structures. The aim of the paper is to provide direct evidence for such photoinduced effect as proposed by Buyanova and co-workers and confirmed by theory.

A set of three samples was grown by molecular beam epitaxy on a semi-insulating GaAs (001) substrate. The samples comprise a 0.42-μm-thick GaAs buffer layer, a plane of Be atoms, a 0.18-μm-thick undoped GaAs layer, and a 50-A-thick Be-doped GaAs cap layer ($p = 2 \times 10^{18}\,\mathrm{cm}^{-3}$). The growth temperature was 580 °C for the buffer layer and 520 °C for the rest of the structure in order to minimize the dopant diffusion. Both the buffer and the GaAs layers were grown under (2×4) reconstruction to ensure As-stabilized conditions. Thus, a nonintentional residual concentration of *p*-type dopants are present in our samples, estimated to be of the order of $10^{15}\,\mathrm{cm}^{-3}$.[7] The acceptor-sheet concentrations N_s of the δ-doped layers measured by secondary-ions mass spectroscopy were as follows: $N_s = 3.2 \times 10^{12}\,\mathrm{cm}^{-2}$ for sample 1, $N_s = 6.1\times10^{12}\,\mathrm{cm}^{-2}$ for sample 2, and $N_s = 1.3\times10^{13}\,\mathrm{cm}^{-2}$ for sample 3. The optical measurements were performed in an optical helium-bath cryostat with variable-temperature facilities. For standard PL measurements, the samples were excited with the 5145 Å line of an argon-ion laser and the luminescence signal was analyzed by a 0.75 m monochromator providing an energy resolution of about 0.2 meV. The signals were detected by a S1 photomultiplier using standard lock-in techniques. For SPL and PLE measurements the Ar laser was pumping a Ti:sapphire laser whose output wavelength was ranged from 7437 to 8210 Å.

Figure 1 shows the PL spectrum of each sample. They were measured with an above-band-gap excitation energy (2.4 eV), an excitation power density of 7 W/cm^2, and recorded with the samples cooled at 2 K. In the near-band-gap region, all spectra show a weak free-exciton (FE) emission at 1.515 eV, and a weak bound-exciton emission at 1.513 eV, both originating from the GaAs host material. The PL spec-

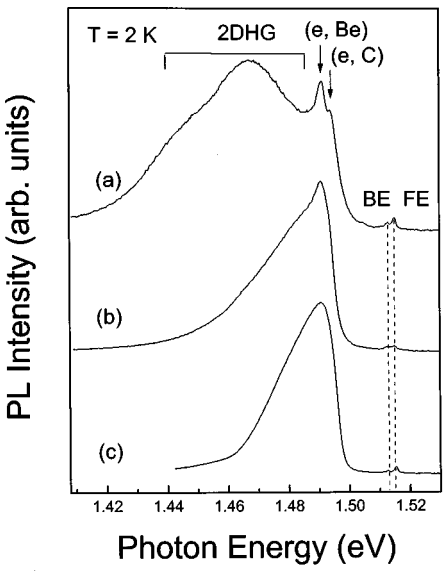

FIG. 1. Normalized PL spectra of Be-δ-doped GaAs layers with different Be concentrations: (a) 1.3×10^{13} cm^{-2}; (b) 6.1×10^{12} cm^{-2}; (c) 3.2×10^{12} cm^{-2}.

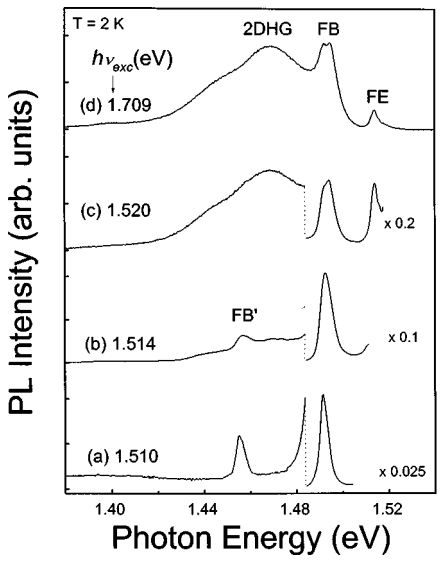

FIG. 2. SPL spectra of sample 3.

trum of the most doped sample exhibits well-resolved free-to-bound (FB) transitions at 1.492 and 1.494 eV, probably involving Be (e,Be) and C (e,C) acceptors, respectively.[8] In addition, broad PL bands (denoted as 2DHG bands) are observed at lower energy. The width of this 2DHG band increases with increasing doping as predicted by the calculations.[6] The spectral position and shape of these observed broad bands, which we ascribe to the radiative recombination of photocreated electrons with holes of the 2DHG, are very similar to those already reported for δ-doping spikes located at 0.02 μm (Ref. 9) and 0.5 μm (Ref. 6) from the GaAs/air interface. From now on, only experimental results related to sample 3 will be discussed, as they are richer in details and show the same general trends as for the other two samples.

As reported previously,[6] we observed that the intensity of the 2DHG band decreases with increasing temperatures and is no longer distinguishable from the background signal at temperatures higher than 60 K. When the sample temperature is raised from 2 to 60 K, the intensity of the FE emission decreases by a factor of 3, meanwhile the intensity of the 2DHG bands decreases by two orders of magnitude. Recent self-consistent calculations[5] showed that the model that ascribes the 2DHG band to the radiative-recombination processes between photoexcited electrons in extended states and confined holes from the 2DHG does not account for this quenching effect. Thus, even if one takes into account an overall reduction of the radiative-recombination processes, once nonradiative transitions are more pronounced at higher temperatures the quenching of the 2DHG peak would not be expected. The explanation for this effect requires the capture of the minority carriers by a photoinduced well.

Experimental support for the confinement of optically excited electrons in single p-type δ-doped structures is provided by SPL experiments. The results of such measurements are shown in Fig. 2. All the spectra were recorded at the same temperature (2 K) and excitation density ($P_{\rm exc}=7$ W/cm^2). The most important feature of Fig. 2 is the abrupt change in the luminescence spectra when the energy of the excitation radiation is larger or smaller than the fundamental gap of the host material. For the highest excitation energy (1.709 eV), the SPL spectrum shows a pronounced 2DHG emission band, simultaneously with the excitonic and FB emissions originating from the GaAs host material. When the excitation energy is lowered down to 1.520 eV, the 2DHG emission band remains almost unchanged (shape and intensity) while the intensity of the FB peak increases, as a consequence of the larger penetration of the exciting radiation into the GaAs bulk region. The PL spectra obtained with an excitation energy lower than the GaAs band gap (for instance, 1.510 eV) are completely dominated by the recombination between a free electron and a hole bound to a neutral acceptor (FB) and by its phonon replica (FB$'$). In this case, the 2DHG is no longer observed, as the electrons are excited from negatively ionized acceptors or excited acceptor states to the conduction band, i.e., free-electrons and holes bound to acceptors are photogenerated. Therefore, the repulsive potential of the conduction band, induced by the δ-doped layer, prevents that photocreated electrons recombine with holes of the 2DHG and we do not observe the 2DHG band (only bulk-GaAs-related emissions are observed).

For incident radiation with above-band-gap energy, electrons from both the acceptor impurity states and from the continuous states of the GaAs valence band can be excited into the conduction band. Thus, in these experimental conditions, holes bound to acceptors (as for the previous case) and free holes are simultaneously photogenerated. Since the δ-doping well is attractive for the photogenerated free holes, part of the free holes are now captured by the δ-doping well while part of them might be trapped by the background ionized acceptors. The capture of the free holes by the δ-doping potential well gives rise to an additional internal electric field attracting the free electrons in the direction of the δ-doped region. The attracted electrons cannot approach indefinitely the δ-doped region, as they are also repelled by the negatively charged δ plane. The result of the electrostatic repulsion caused by the negatively ionized dopant sheet and the attractive potential created by the excess of holes of the 2DHG is the formation of a confining potential well for the

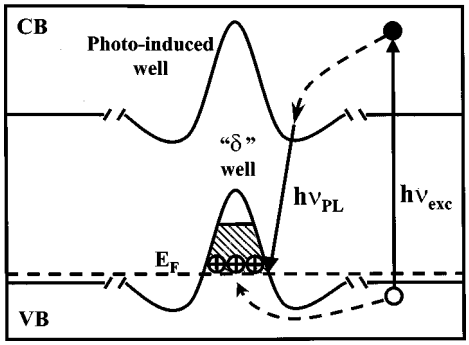

FIG. 3. Schematic band-edge diagram for a single *p*-type δ-doped GaAs layer illuminated by a radiation with an energy larger than the band gap. The empty and full circles represent the photogenerated holes and electrons, respectively. The symbol $\otimes$ represents the free holes captured by the δ-potential well. E_F denotes the Fermi level position.

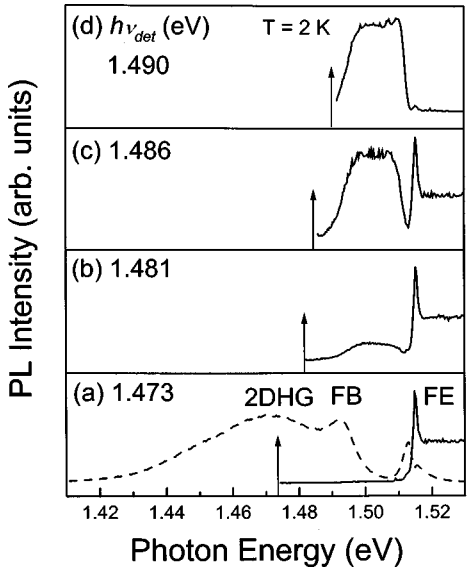

FIG. 4. PLE spectra obtained with different detection energies from sample 3. In each spectrum, the vertical arrow indicates the position of the detection energy. The dashed curve presented at the bottom represents the PL spectrum of sample 3 obtained with above-band-gap excitation energy.

electrons aside the doping spike (see the schematic representation in Fig. 3). The close proximity of this photoinduced potential well with respect to the δ-potential well assures a high probability of radiative recombination between photogenerated electrons and holes of the 2DHG. In this way, two efficient channels of recombination are available for the minority-carrier recombination: the channel associated to the 2DHG (which results in the 2DHG band) and the channel associated with the background impurities (leading to the FB emissions).

This photoinduced well will not be formed if the electrons excited into the conduction band come from acceptor levels (generally due to carbon contamination) as in this case the holes are not mobile and will not be captured by the δ well. Thus, for optical excitation with below-band-gap energy, no photoinduced potential well is created. This explains the absence of the 2DHG bands under such experimental conditions in *p*-type δ-doped GaAs layers.

Our interpretation of the SPL measurements is reinforced by PLE measurements. The PLE spectra obtained when the detection position of the spectrometer is set within the energy range of the 2DHG emission band only reflect the intrinsic absorption edge of the GaAs layers [Fig. 4(a)]. However, when the signal is detected in resonance with the FB emissions [Figs. 4(b)–4(d)], a pronounced feature can be observed below the GaAs fundamental edge. It is worth noting that the intensity of the PLE signal above the FE resonance is almost constant for all the detection energies used in our measurements, while the intensity of the feature located below the GaAs band edge increases when the detection energy approaches the maximum of the FB emissions.

It is well known that PLE spectra reflect both the variation of the absorption coefficient with the energy of the excitation light, as well as the carrier-capture efficiency into the radiative states. Therefore, we can attribute the observed strong feature to different radiative-recombination paths of carriers, as the absorption coefficient changes very smoothly in this energy range. The absence of any feature below the GaAs band edge when the detection is resonant with the 2DHG emission [Fig. 4(a)] indicates that the electrons originating from the acceptor level do not recombine with the holes of the 2DHG. As already discussed, photocreated holes from the acceptor levels are immobile, and thus cannot be captured by the δ-doping well. Therefore, the confining potential for the electrons is not created and they are swept away by the repelling potential and captured by the acceptor impurities as shown in Fig. 2(a). On the other hand, the observed PLE signal above the GaAs band edge of Fig. 4(a) indicates that when free holes are created, the main radiative-recombination path is through the 2DHG. In this case, free holes are captured by the δ well and induce the formation of the photoinduced electron well in the conduction band, increasing drastically the wave-function overlap of electron-hole pairs. When the PLE measurements are carried out in the same conditions, but the detection is realized in resonance with the FB emissions [Figs. 4(b)–4(d)], a strong feature appears below the GaAs band gap and is related to the impurities-assisted radiative recombinations, as expected.

PL measurements as a function of temperature for different photoexcitation densities (7 and 7×10^2 W/cm^2) provided another experimental support for the existence of the photoinduced potential. Our results (not shown here) showed that the PL intensity of the 2DHG band decreases earlier when the excitation-power density is lower. At higher values, we expect an increase of the concentration of photocreated electrons and holes. Consequently, the depth of the δ-potential well decreases (due to the screening of the ionized acceptors of the δ-doped region by the excess of holes captured by the δ well) while the depth of the photoinduced potential increases (due to the increasing number of electrons accumulating near the δ-doped layer). A deeper photoinduced confining potential for the electrons in the conduction band is associated to a higher barrier in the valence band for the holes of the 2DHG (see Fig. 3). In this way, the thermal activation energies of confined electrons and holes of the 2DHG will be larger when the excitation-power density increases consistent with our results.

The results reported here lead to an explanation for the

absence of any luminescence signal associated to the 2DEG in *n*-type single δ-doped layers. Self-consistent calculations[3,5] have shown that the Fermi level in *n*-type δ-doped layers is always located close to the GaAs continuum states, differently from the Fermi level in *p*-type δ-doped GaAs layers that is always located inside the δ-potential well. In this way, the capture process of photogenerated minority carriers in *n*-type δ-doped layers is not efficient and the depth of the photoinduced hole well in the valence band is very small (if it does exist). A photoinduced potential well with these characteristics does not strongly confine the photocreated holes and is responsible for the weak magnitude of the overlap integral between the wave function of holes and electrons of the 2DEG, justifying the absence of any PL signal of the 2DEG in *n*-type single δ-doped GaAs layers.

In conclusion, our data show direct evidence for a photoinduced potential-well formation in an isolated *p*-type δ-doped GaAs structure. The absence of such effect in *n*-type δ-doped GaAs would explain the lack of luminescence signal related to the confined electrons in these systems.

[1] E. F. Schubert, in *Epitaxial Microstructures*, edited by A. C. Gossard, Semiconductors and Semimetals Vol. 40 (Academic, New York, 1994), p. 1.

[2] R. Enderlein, G. M. Sipahi, L. M. R. Scolfaro, J. R. Leite, and I. F. L. Diaz, Mater. Sci. Eng., B **35**, 396 (1994).

[3] G. M. Sipahi, R. Enderlein, L. M. R. Scolfaro, and J. R. Leite, Phys. Rev. B **53**, 9930 (1996).

[4] I. A. Buyanova, W. M. Chen, A. Henry, W.-X. Ni, G. V. Hansson, and B. Monemar, Phys. Rev. B **53**, 9587 (1996).

[5] G. M. Sipahi, R. Enderlein, L. M. R. Scolfaro, J. R. Leite, E. C. F. da Silva, and A. Levine, Phys. Rev. B **57**, 9168 (1998).

[6] A. M. Gilinsky, K. S. Zhuravlev, D. I. Lubyshev, V. P. Migal, V. V. Preobrashenskii, and B. R. Semiagin, Superlattices Microstruct. **10**, 399 (1991).

[7] Estimated from Hall measurements on molecular beam epitaxy grown bulk GaAs.

[8] D. J. Ashen, P. J. Dean, D. T. J. Hurle, J. B. Mullin, A. M. White, and P. D. Greene, J. Phys. Chem. Solids **36**, 1041 (1975).

[9] D. Richards, J. Wagner, H. Schneider, G. Hendorfer, M. Maier, A. Fischer, and K. Ploog, Phys. Rev. B **47**, 9629 (1993).