PHYSICAL REVIEW B VOLUME 43, NUMBER 14 15 MAY 1991-I

Fermi-edge singularity and band-filling effects in the luminescence spectrum of Be-δ-doped GaAs

J. Wagner
Fraunhofer-Institut für Angewandte Festkörperphysik, Tullastrasse 72, D-7800 Freiburg, Federal Republic of Germany

A. Ruiz* and K. Ploog
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-7000 Stuttgart 80, Federal Republic of Germany
(Received 3 December 1990)

Photoluminescence studies of the quasi-two-dimensional hole gas (2DHG) at a single Be-δ-doped layer in GaAs reveal Fermi-edge enhancement and photoinduced band filling in the low-temperature emission spectra. Strong radiative recombination is observed of the 2DHG with the photocreated electrons confined by GaAs/$Al_xGa_{1-x}As$ heterointerfaces placed at both sides of the doping spike. For optical excitation with a sufficiently large penetration depth to generate electrons on both sides of the doping spike, a filling of the valence subbands with photocreated holes is found for excitation power densities exceeding a certain threshold. Excitation with light generating electrons only at the near-surface side of the doping spike does not lead to such band filling, but yields luminescence spectra which show a strong enhancement in intensity at the Fermi edge. The observation of a Fermi-edge singularity is indicative for non-k-conserving recombination of electrons weakly localized at the topmost heterointerface.

An isolated doping spike of, e.g., Si or Be in GaAs forms a quasi-two-dimensional electronic system.[1] The electrons or holes are confined in a space-charge-induced potential well leading to a two-dimensional electron gas (2DEG) or hole gas (2DHG) where usually several subbands are occupied.[1,2] So far most of the studies have been carried out on n-type planar (δ-) doped GaAs layers[1,2] or on δ-doped GaAs n-i-p-i structures.[1] Only recently have single Be doping spikes in GaAs also been investigated in more detail.[3] A variety of optical techniques, such as Raman[4,5] and infrared absorption spectroscopy,[6] have been applied to the study of Si(n-type)-δ-doped GaAs layers. Photoluminiscence spectroscopy, which has been used successfully to investigate the 2DEG in modulation-doped heterojunctions,[7–10] has found so far only little use for studying single δ-doping spikes. This is due to the repulsive interaction between the photogenerated holes (electrons) and the electrostatic potential confining the 2DEG (2DHG) which results in a too small overlap between electron and hole wave functions to produce a detectable luminescence signal.[11] Recently, single Si-δ-doping spikes have been placed sufficiently close to the GaAs surface or a GaAs/$Al_xGa_{1-x}As$ heterointerface to localize the photocreated holes and consequently to enhance the wave-function overlap.[12] In such structures, radiative recombination of the 2DEG has indeed been observed.

Fermi-edge singularities have been observed in the photoluminescence spectrum of n-type modulation-doped heterojunctions[10] and quantum wells.[13–15] This enhancement of the luminescence intensity at the Fermi edge, the so-called Fermi-edge singularity, is a consequence of many-body interactions between electrons and holes.[14,16] To observe such a Fermi-edge enhancement in n-type modulation-doped systems, non-k-conserving transitions have to contribute to the luminescence spectrum.[10,13] This can be realized, e.g., by a localization of the photocreated holes, which allows efficient recombination of electrons up to the electron Fermi energy.[10,13]

As discussed above, Fermi-edge singularities have been observed in the photoluminescence spectra of n-type modulation-doped structures,[10,13–15] where the electrons forming the 2DEG and the ionized donors are spatially separated. In the present study we show that a Fermi-edge singularity can also be observed in p-type doped $Al_xGa_{1-x}As$/GaAs/$Al_xGa_{1-x}As$ double heterostructures with a Be doping spike placed at the center of the GaAs layer. In this structure, the hole wave functions have significant overlap with the ionized acceptors.

The sample used for the present study was grown by molecular-beam epitaxy on undoped semi-insulating (100) GaAs substrates at a growth temperature of 610 °C. After a GaAs/AlAs superlattice buffer, a 20-nm-thick $Al_{0.33}Ga_{0.67}As$ barrier was grown, followed by a 60-nm-wide GaAs layer where a Be doping spike with an intended dopant density of 8×10^{12} cm^{-2} was placed in the center of this layer. On top of the GaAs layer another 10-nm-thick $Al_{0.33}Ga_{0.67}As$ barrier was grown capped by 1 nm of GaAs. The actual width of the doping spike measured by secondary-ion mass spectroscopy (SIMS) was found to be less than 10 nm. There is an inherent asymmetry in the sample structure due to Fermi-level pinning at the surface and the inequivalence of the two heterointerfaces.[17] A schematic energy-band diagram of the present sample structure is shown in Fig. 1. The photoluminescence spectra were excited with different lines of a Kr-ion laser. The samples were cooled by He exchange gas in a continuous-flow variable-temperature He cryostat. The emitted light was dispersed in a double monochromator and detected by a cooled intrinsic Ge diode. Photoluminescence excitation (PLE) spectroscopy was performed using the tunable output of a Ti:sapphire laser.

The two GaAs/$Al_xGa_{1-x}As$ barriers were placed near the doping spike to ensure a sufficient confinement of the

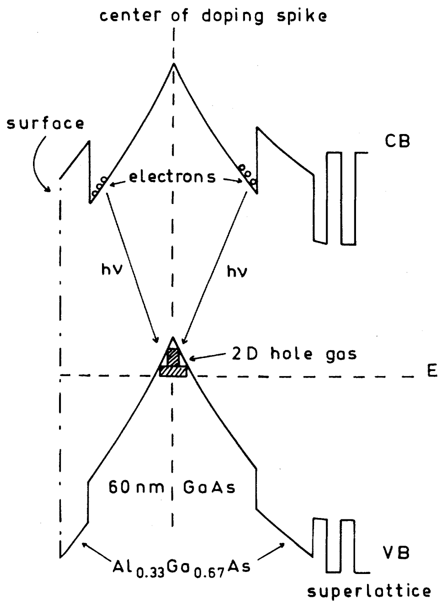

FIG. 1. Schematic energy-band diagram of the δ-doped $Al_{0.33}Ga_{0.67}As$/GaAs:Be/$Al_{0.33}Ga_{0.67}As$ heterostructure used in the present study.

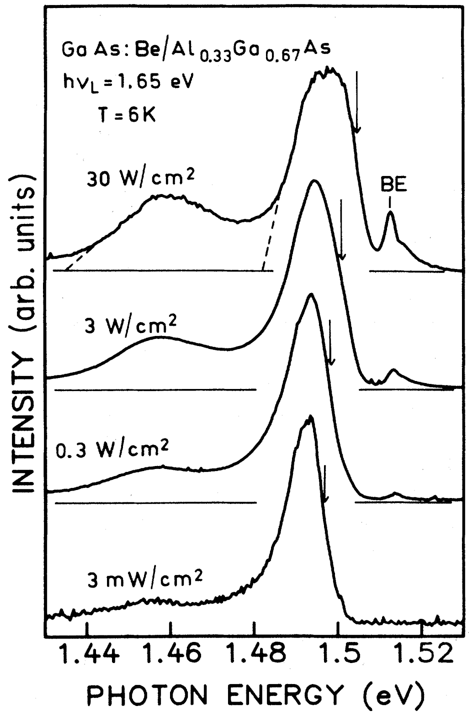

FIG. 2. Excitation-intensity-dependent photoluminescence spectra excited at 1.65 eV. The arrows at the high-energy side of the most intense luminescence band mark the photon energy at which the emission intensity is 50% of its peak value.

photocreated electrons to enhance radiative recombination of the 2DHG present in the δ-doped GaAs layer. Strong photoluminescence from the 2DHG is observed as shown in Fig. 2, which displays a sequence of excitation intensity-dependent luminescence spectra. The spectra were excited at 1.65 eV, i.e., below the band gap of the $Al_{0.33}Ga_{0.67}As$ barriers, and recorded with the sample cooled to 6 K. The two dominant peaks in the photoluminescence spectrum at 1.460 and 1.496 eV arise from radiative recombination of holes in the 2DHG. The PLE spectrum of the 2DHG emission was found to reflect the intrinsic absorption spectrum of the 60-nm-wide GaAs layer. Relatively weak bound exciton (BE) emission from the undoped GaAs buffer layer is resolved at 1.513 eV for excitation intensities $\gtrsim 0.3$ W/cm^2.

The emission peaks at 1.460 and 1.496 eV are assigned to recombination involving two different hole subbands. The possibility of the former peak being a phonon replica of the latter peak involving the emission of a longitudinal-optical phonon can be ruled out because in this case the relative intensities are expected to be constant. However, the contrary is observed with the relative intensity of the 1.460-eV emission increasing with increasing power density. Taking just the difference in peak energy, an energy spacing between the two subbands involved of 36 meV is obtained. Taking the intersection of the extrapolated slope of the low-energy edge of each peak with the base line as a measure for the subband energies, as indicated in the topmost spectrum of Fig. 2, a spacing of 46 meV is derived.

Unfortunately, a detailed study of the valence subbands formed in *p*-type δ-doped GaAs has yet to be reported. To get a rough estimate of the expected subband spacings, we have calculated the energy levels of heavy and light holes in the space-charge-induced V-shaped potential well,[18] neglecting any effects of screening by the holes which would have to be included self-consistently. The appropriate heavy- and light-hole masses for bulk GaAs were taken from Ref. 19. The resulting spacings between the first heavy- and light-hole subband and the first and second heavy-hole subband are 60.8 and 112.7 meV, respectively. These values represent an upper limit with the actual spacing being reduced by screening effects.[2] Keeping this in mind, one may assign the 1.460- and 1.496-eV emission peaks to recombination from the first heavy-hole and the first light-hole subband, respectively. This assignment is consistent with the emission from the light-hole subband being stronger than that from the heavy-hole subband, even though fewer electrons occupy the higher-lying subband. This is due to the more extended light-hole wave function leading to an enhanced overlap with the photocreated electrons. The present identification of the observed emission peaks gets further support from the comparison with photoluminescence spectra of δ-doped GaAs *n-i-p-i* structures which show recombination from the first heavy-hole and first light-hole subbands as the two emission lines lowest in energy.[18,20]

For excitation intensities exceeding ≈ 0.3 W/cm^2, the emission spectrum of the 2DHG changes in two ways. First, the relative intensity of the recombination involving holes in the first heavy-hole subband (1.460-eV peak) increases. Second, the high-energy edge of the emission from the first light-hole subband centered at 1.496 eV shifts to higher energies with increasing excitation intensity. The change in the relative intensity can be explained by an increase in the concentration of photocreated electrons and holes for higher excitation intensities leading to an enhanced overlap between electron and hole wave functions. The energy shift of the high-energy cutoff, which represents the Fermi edge in the hole distribution, indicates a filling of the doping-induced potential well with photogenerated holes. This shift amounts to 7.2 meV for the highest excitation intensity used. On the other hand, the low-energy edge of the 1.496-eV line and the peak of the 1.460-eV recombination band remain fixed in energy within $\approx 1-2$ meV for all excitation intensities. This shows that under photoexcitation with the present excitation intensities, band-filling effects are dominant and the actual shape of the potential well, which determines the subband energies, remains essentially unchanged.

Figure 3 shows a similar sequence of excitation intensity-dependent luminescence spectra as displayed in Fig. 2, but for excitation at 3.00 eV, which is strongly absorbed both in the $Al_{0.33}Ga_{0.67}As$ and GaAs layers. The penetration depth $1/\alpha$, where α denotes the absorption coefficient, amount to 20 nm for GaAs.[21] Therefore electrons are mainly photoexcited in the region between the doping spike and the sample surface and get trapped close to the topmost heterointerface. In contrast to the photoluminescence spectra excited at 1.65 eV (Fig. 2), the width of the emission peaks, as well as their relative intensities, are independent of the excitation intensity. At the high-energy side of the 1.496-eV luminescence band, a distinct peak is clearly seen, which indicates a strong enhancement of the recombination of holes close to the Fermi edge.[10,13–16] The assignment of this peak to a Fermi-edge singularity gets further support from temperature-dependent photoluminescence spectra shown in Fig. 4. As expected,[10,13,15] the Fermi-edge enhancement weakens with increasing sample temperature and is no longer resolved in the present sample for temperatures exceeding 20 K because of the increasing thermal broadening of the Fermi edge and decreasing electron-hole coupling. This is the first observation of a Fermi-edge singularity in the luminescence spectrum of a 2DHG and in a sample structure where the holes have significant overlap with the ionized acceptors. All the previous reports deal with n-type modulation-doped heterojunctions[10] and quantum wells.[13–15]

In order to observe such a Fermi-edge enhancement in the luminescence spectrum of a 2DHG, non-k-conserving transitions must become possible via, e.g., the participation of weakly localized electrons.[10,13] For the luminescence spectra from the present sample excited with 3.00-eV photons, the inherent roughness of the topmost $GaAs/Al_{0.33}Ga_{0.67}As$ heterointerface leads to a sufficient localization of the photocreated electrons being pushed towards that interface by the repulsive potential of the doping spike. Further, the electrons photogenerated only at the near-surface side of the Be-δ-doping spike cause an additional asymmetry of the confining potentials due to screening effects. This may lead to a modification of the electron-hole wave-function overlap favoring the observation of a Fermi-edge singularity in the luminescence spectrum. In contrast, for excitation at 1.65 eV, electrons are photogenerated at both sides of the doping spike at about equal concentrations because of the much larger penetra-

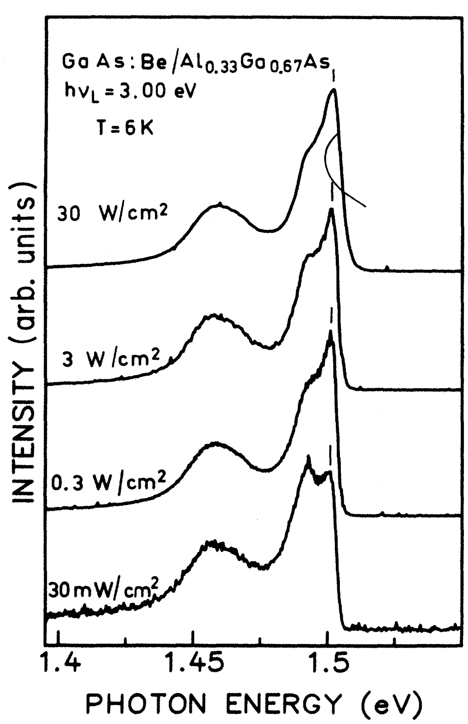

FIG. 3. Excitation-intensity-dependent photoluminescence spectra excited at 3.00 eV. The vertical lines mark the enhancement in luminescence intensity at the Fermi edge.

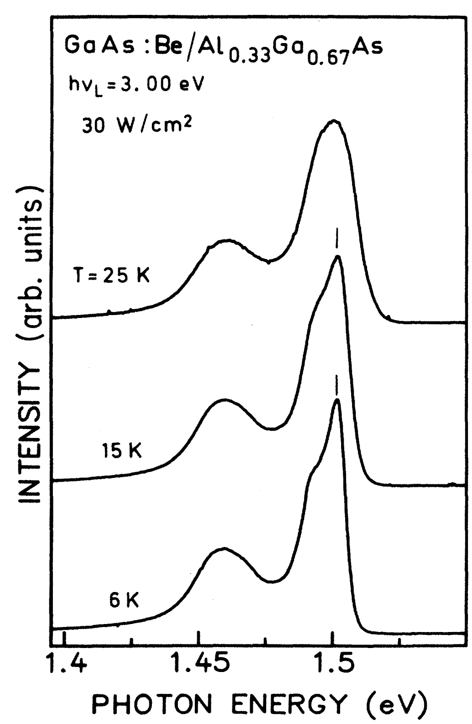

FIG. 4. Temperature-dependent photoluminescence spectra excited at 3.00 eV. The vertical lines mark the enhancement in luminescence intensity at the Fermi edge.

tion depth of the light.[21] Therefore the resulting potential is expected to be more symmetric than in the previous case and electrons localized at both interfaces contribute to the luminescence spectrum. This difference in the actual potential shape as a consequence of different penetration depths of the exciting light may explain the absence of any detectable Fermi-edge enhancement in the luminescence spectra recorded with 1.65-eV excitation. The presence of a sufficient density of photocreated electrons at the topmost heterointerface as a prerequisite for the observation of a Fermi-edge singularity in the present sample may also explain the decreasing strength of this singularity for 3.00-eV excitation at extremely low power densities (see lowest spectrum in Fig. 3).

In conclusion, we have shown that intense photoluminescence can be observed from the 2DHG at a single Be-δ-doped layer in GaAs. A confinement of the photocreated holes is achieved by GaAs/$Al_xGa_{1-x}As$ heterointerfaces placed near the doping spike. Depending on the penetration depth of the light used to excite the luminescence, band-filling effects and Fermi-edge enhancement are observed in the recombination spectrum. The Fermi-edge singularity is seen in the emission spectrum of a 2DHG and in a sample structure with a significant overlap of the hole wave functions with the ionized acceptors.

We would like to thank M. Ramsteiner, H. Schneider, and P. Koidl for many stimulating discussions; M. Maier and T. Fuchs for careful SIMS analysis of the samples; and H. S. Rupprecht for continuous support of the work at the Fraunhofer-Institut. Part of the work at the Max-Planck-Institut was sponsored by the Bundesministerium für Forschung und Technologie (Bonn, Federal Republic of Germany).

*Permanent address: Centro Nacional de Microelectronica, Serrano 144, E-28006 Madrid, Spain.

[1]For a recent review, see K. Ploog, M. Hauser, and A. Fischer, Appl. Phys. A **45**, 233 (1988).

[2]F. Koch and A. Zrenner, Mater. Sci. Eng. B **1**, 221 (1989), and references cited therein.

[3]E. F. Schubert, J. M. Kuo, R. F. Kopf, H. S. Luftman, L. C. Hopkins, and N. J. Sauer, J. Appl. Phys. **67**, 1696 (1990).

[4]G. Abstreiter, R. Merlin, and A. Pinczuk, IEEE J. Quantum Electron. **QE-22**, 1771 (1986).

[5]J. Wagner, M. Ramsteiner, D. Richards, G. Fasol, and K. Ploog, Appl. Phys. Lett. **58**, 143 (1991).

[6]N. Schwarz, F. Müller, G. Tempel, F. Koch, and G. Weimann, Semicond. Sci. Technol. **4**, 571 (1989).

[7]C. H. Yang, S. A. Lyon, and C. W. Tu, Appl. Phys. Lett. **53**, 258 (1988).

[8]I. V. Kukushkin, K. von Klitzing, and K. Ploog, Phys. Rev. B **37**, 8509 (1988).

[9]I. V. Kukushkin, K. von Klitzing, K. Ploog, and V. B. Timofeev, Phys. Rev. B **40**, 7788 (1989).

[10]Yong-Hang Zhang, De-Sheng Jiang, R. Cingolani, and K. Ploog, Appl. Phys. Lett. **56**, 2195 (1990).

[11]C. H. Perry, K. S. Lee, W. Zhou, J. M. Worlock, A. Zrenner, F. Koch, and K. Ploog, Surf. Sci. **196**, 677 (1988).

[12]J. Wagner, A. Fischer, and K. Ploog, Phys. Rev. B **42**, 7280 (1990).

[13]M. S. Skolnick, J. M. Rorison, K. J. Nash, D. J. Mowbray, P. R. Tapster, S. J. Bass, and A. D. Pitt, Phys. Rev. Lett. **58**, 2130 (1987).

[14]G. Livescu, D. A. B. Miller, D. S. Chemla, M. Ramaswamy, T. Y. Chang, N. Sauer, A. C. Gossard, and J. H. English, IEEE J. Quantum Electron. **QE-24** 1677 (1988).

[15]J. S. Lee, Y. Iwasa, and N. Miura, Semicond. Sci. Technol. **2**, 675 (1987).

[16]S. Schmitt-Rink, C. Ell, and H. Haug, Phys. Rev. B **33**, 1183 (1986).

[17]See, e.g., R. Köhrbrück, S. Munnix, D. Bimberg, D. E. Mars, and J. N. Miller, Appl. Phys. Lett. **57**, 1025 (1990), and references cited therein.

[18]E. F. Schubert, T. D. Harris, J. E. Cunningham, and W. Jan, Phys. Rev. B **39**, 11011 (1989).

[19]J. S. Blakemore, J. Appl. Phys. **53**, R123 (1982).

[20]B. Ullrich, C. Zhang, and K. von Klitzing, Appl. Phys. Lett. **54**, 1133 (1989).

[21]M. Cardona and G. Harbeke, J. Appl. Phys. **34**, 813 (1962).