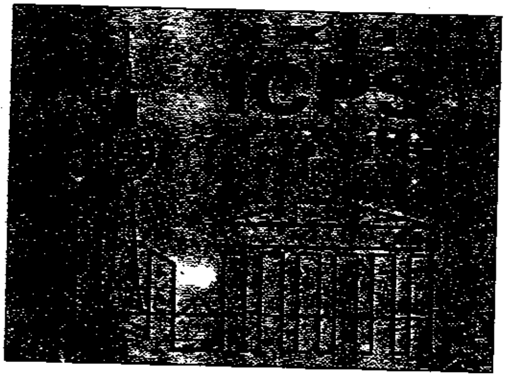
FFLER
RMANN

23rd
International
Conference
on

THE PHYSICS OF SEMICONDUCTORS

Volume 3



Berlin, Germany
July 21 – 26, 1996

Editors

MATTHIAS SCHEFFLER
ROLAND ZIMMERMANN

23rd International Conference on
THE PHYSICS OF

. 3

DYNAMICS OF OPTICAL SINGULARITIES IN A TWO-DIMENSIONAL ELECTRON GAS

S. ZIMMERMANN[†], L. VIÑA[†], H. SCHWEIZER[‡], F. SCHOLZ[‡], S. HAACKE[§] and B. DEVEAUD[§]

[†]*Depto. de Física de Materiales C-IV, Universidad Autónoma, Cantoblanco. E-28049 Madrid, Spain*
[‡]*Physikalisches Institut der Universität Stuttgart, Pfaffenwaldring 57, D-70550 Stuttgart, Germany*
[§]*Swiss Federal Institute of Technology. EPFL/IMO. CH-1015 Lausanne. Switzerland*

ABSTRACT

We have established the coexistence of localized and free holes in modulation-doped InGaAs/InP quantum wells, which show Fermi-edge singularities in the cw photoluminescence and excitation spectra. Time-resolved PL spectra at 5 K and low excitation densities reveal a long-lived peak at the low-energy side of the spectrum, which vanishes rising the temperature at ~30 K or increasing the excitation density. The simultaneous presence of free and localized holes explains the lineshapes observed in cw measurements and the presence of Fermi-edge singularities.

The presence of free carriers in a semiconductor quantum well (QW) modifies its optical properties. A strong enhancement in the oscillator strength of optical transitions in the vicinity of the Fermi edge has been reported both in absorption and emission of modulation doped QWs.[1-3] This enhancement, known as Fermi-edge sigularity (FES), results in n-type samples from many-body interactions between a photoexcited hole and the sea of electrons in the QWs.[4] Photocreated holes in semiconductors are free to move in the valence band and therefore its recoil reduces the FES. Furthermore, to observe the FES in emission, non-k conserving transitions have to contribute to the photoluminescence (PL) spectrum.[1] Localization of the holes, e.g. by random alloy fluctuations, allows efficient recombination of electrons up to their Fermi energy and enhances the electron-hole interaction due to the fact that the hole becomes a practically infinite effective mass.

The temporal evolution of FES has been studied by time-resolved photoluminescence (TRPL) spectroscopy in a two-dimensional hole gas in GaAs QWs.[5] In this work, we present a study of the temperature and excitation-density dependence of the TRPL spectra in n-type modulation doped QWs, which show FES in the cw PL and excitation (PLE) spectra. Our results confirm the coexistence of localized and free valence-band holes in these samples. We have investigated three different single $In_{0.53}Ga_{0.47}As$/InP QWs, with carrier concentrations ranging from 6×10^{11} cm^{-2} to 1.4×10^{12} cm^{-2}. The lineshapes of the cw PL and PLE spectra and their temperature dependence indicate the existence of Fermi-edge singularities. TRPL spectra were obtained using an up-conversion spectrometer (5 ps resolution), with the samples mounted in a cold finger cryostat. Pulses from a Styryl 8 dye laser, synchronously pumped by a mode-locked Nd:YAG laser, were used to excite the samples. We will concentrate here in the sample with the lowest density.

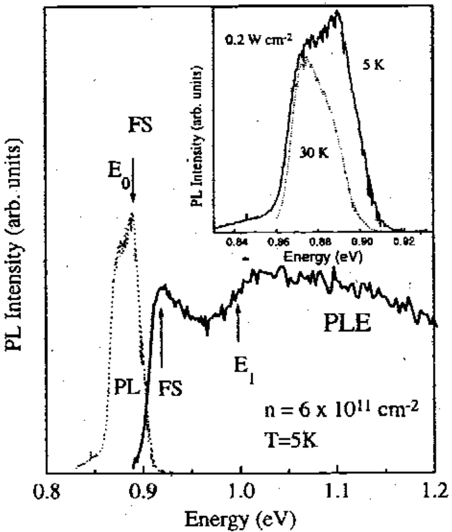


Fig. 1. Excitation spectra of a n-modulation doped $In_{0.53}Ga_{0.47}As$/InP QW at 5 K. The arrows depict the FES and second subband (E_1). The dotted line shows the PL from the first subband (E_0) with the down-arrow pointing to the FES. The inset compares the PL at two temperatures.

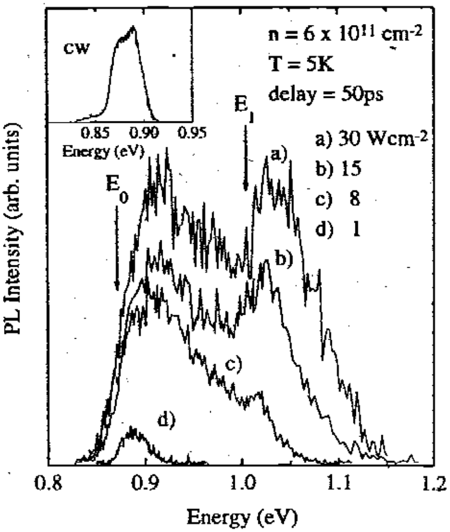


Fig. 2. TRPL spectra, corresponding to the sample of Fig. 1, taken 50 ps after excitation at 1.68 eV, for different excitation densities. The beginning of the PL from the first (E_0) and second (E_1) subbands are marked by arrows. Inset: cw PL for comparison

The cw PL (dotted line) and excitation (solid line) spectra of a sample with an electron density $n = 6x10^{11}$ cm^{-2} is shown in Fig. 1. The shift between the PL and PLE arises from the phase-space filling by the electrons, which blocks the absorption underneath the Fermi energy in the conduction band. The Fermi-edge singularities (FS in the spectra) are clearly observed as peaks at the high energy side of the PL and at the beginning of the pseudo-absorption spectrum. Transitions to the second electron subband (E_1) can be recognized at an energy of ~1 eV. The strong temperature dependence of the peak labeled FS in the PL is documented in the inset of the figure: rising the temperature from 5 K to 30 K the peak vanishes. This dependence confirms the assignment of this structure to a Fermi-edge singularity.[4]

Figure 2 shows low temperature TRPL spectra taken 50 ps after excitation at power densities ranging from 30 W cm^{-2} to 1W cm^{-2}. The excitation energy was 1.68 eV, above the InP band gap. The low energy peak (E_0) corresponds to recombination of free holes with electrons in the Fermi sea of the first subband. The small blue shift of this peak with increasing power density denotes the displacement towards higher energies of the product of the density of states and the subband occupation with increasing band filling.

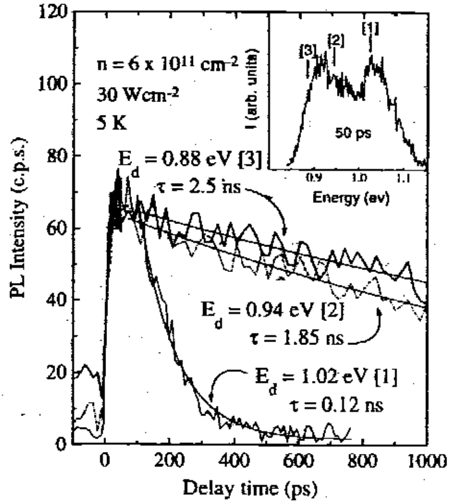


Fig. 3. Time evolution of the PL for an excitation power density of 30 Wcm^{-2} at three different detection energies. The lines show the best fit to an exponential decay. The inset shows the TRPL spectrum at 50 ps and 30 Wcm^{-2}.

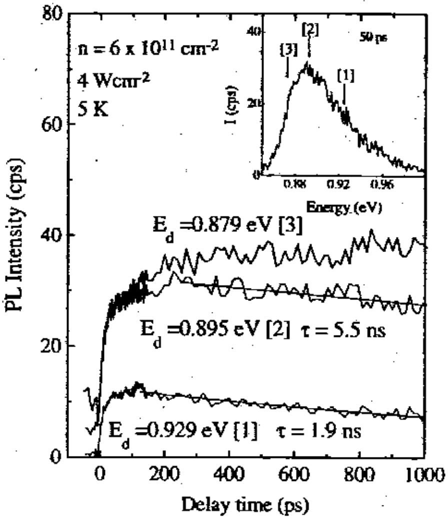


Fig. 4. Time evolution of the PL for an excitation power density of 4 Wcm^{-2} at three different detection energies. The lines show the best fit to an exponential decay. The inset shows the TRPL spectrum at 50 ps and 4 Wcm^{-2}.

Concurrently, the onset of the peak red shifts as a consequence of band gap renormalization. The second peak, E_1, assigned to recombination of electrons from the second subband, shows also a small blue shift with increasing power density. The behavior of the PL between 0.93 eV and 1 eV indicates that the carrier temperature increases with power. Only for power densities below 5 W cm^{-2} the spectral range of the PL becomes comparable to that of the cw spectrum (inset). However, even at the lowest power used in our experiments, the carrier temperature is still too high to allow a direct observation of the FES in time-resolved measurements. The reduction of the FES at high densities of photoexcited carriers and/or high temperatures has been also observed in cw measurements.[6]

The time evolution of the PL at three different detection energies is shown in Fig. 3 for a power density of 30 W cm^{-2}. The inset depicts the corresponding TRPL spectrum at 50 ps (the arrows mark the detection energies). Their rise-times are of the order of 10-20 ps. The second subband presents a fast decay with a time constant of 120 ps, comparable to that of the barrier PL (not shown). The decay time grows considerably for the first-subband to 1.85 ns and 2.5 ns, detecting at 0.94 eV and 0.88 eV, respectively. Lowering the excitation density to 4 W cm^{-2} the contribution from the second subband disappears (see Fig. 4). The high-energy side of the first-subband PL shows a rise time of ~150 ps, and a new peak appears in the low-energy side of the spectrum with rise- and decay times

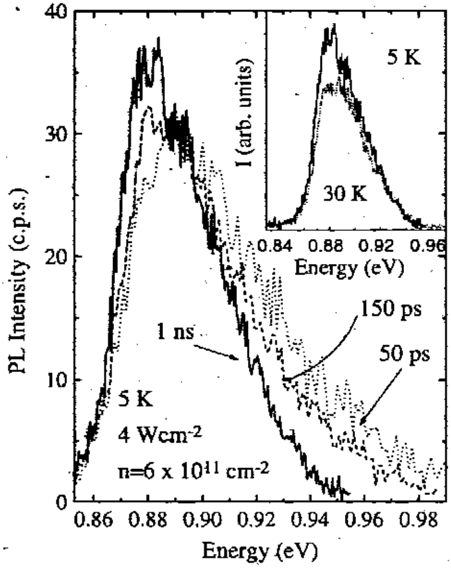


Fig. 5. TRPL spectra at different time delays for low power excitation. The inset shows the temperature dependence of the spectra at 1 ns.

of ~1 ns and ~6 ns, respectively. The long decay time indicates a contribution from localized holes, which have a large lifetime due to their small wavefunction overlap with free electrons. Similar results are obtained for excitation below the band gap of InP. This new peak is clearly seen at long times (1 ns) in Fig. 5, which compiles TRPL spectra of the first subband at different times. The high temperature of the carriers at short times hinders its observation. An additional proof of the localization of the holes is obtained from the temperature dependence of the TRPL spectra shown in the inset of Fig. 5. Rising the temperature from 5 K to 30 K the holes are freed and the low energy peak in the PL disappears.

In summary, we have studied the dynamics of the optical singularities in the emission spectra of a two-dimensional gas of electrons by time-resolved photoluminescence spectroscopy.The temperature and excitation-density dependence of the time-resolved spectra establish the coexistence of localized and free valence-band holes in samples which present Fermi-edge singularities in the cw spectra.

Acknowledgments

This work was partially supported by the Spanish CICyT Grant No. MAT94-0982 and by the "European HC Mobility" Program ULTRAFAST CHRX-CT93-0133.

References

1. 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).
2. W. Chen, M. Fritze, W. Walecki, A.V. Nurmikko, D. Ackley, J.M. Hong and L.L. Chang, *Phys. Rev. B* **45**, 8464 (1992).
3. T. Mélin and F. Laruelle, *Phys. Rev. Lett.* **76**, 4219 (1996).
4. S. Schmitt-Rink, C. Ell and H. Haug, *Phys Rev. B.* **33**, 1183 (1986).
5. D. Richards, J. Wagner, H. Schneider, G. Hendorfer, M. Maier, A. Fischer and K. Ploog, *Phys. Rev. B.* **47**, 9629 (1993).
6. H. Kalt, K. Leo, R. Cingolani and K. Ploog, *Phys. Rev. B*, **40**, 12017 (1989).