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Excitons in strained (Ga,In)Sb/GaSb quantum wells

N. Bertru, O. Brandt, R. Klann, A. Mazuelas, W. Ulrici, and K. H. Ploog
Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5–7, D-10117 Berlin, Germany

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We examine the nature of the lowest-energy optical transition in high-quality (Ga,In)Sb/GaSb quantum wells. Despite the weak electron-hole interaction existing in this system, we observe a distinct exciton resonance in absorption. From the analysis of this resonance, we determine the binding energy and the oscillator strength of the quantum-confined exciton. The coincidence of the photoluminescence peak with the absorption resonance demonstrates that the dominant radiative channel is excitonic. Finally, we show that the thermal quenching of luminescence is related to the thermionic emission of excitons out of the well. [S0163-1829(97)06707-6]

Semiconductor heterostructures based on narrow-gap materials have been the subject of increasing interest in recent years.[1] These efforts are motivated by the possibility to extend optical studies to the mid-infrared region, and to eventually achieve cw lasing in this spectral range. Most studies have been performed on (Ga,In)As/InP and (Ga,In)(As,Sb)/GaSb heterostructures[2,3] for which high-quality samples have become available. An alternative materials system for this spectral range is (Ga,In)Sb/GaSb (Refs. 4 and 5) the band gap of which ranges from 0.81 eV (GaSb) to 0.15 eV (InSb). Despite its potential, little knowledge has been acquired about the physical properties of this materials system. The main reason for this fact is the lack of high-quality samples as illustrated by the dominance of impurity-related emission in the photoluminescence spectra of (Ga,In)Sb/GaSb strained quantum wells (QW's).[6,7]

Here, we present a detailed spectroscopic study of the optical properties of high-quality (Ga,In)Sb/GaSb QW's. We show that the optical response is dominated by free excitons in both absorption and emission. From the analysis of the absorption spectrum, we determine both the binding energy and the oscillator strength of the quantum-confined heavy-hole exciton.

We concentrate in our study on a sample consisting of five (Ga,In)Sb QW's separated by GaSb barrier layers. The sample is grown by conventional solid source molecular-beam epitaxy (MBE) on GaSb(001) substrate. Monomeric Sb, generated by thermal cracking of Sb_4 at 900 °C, is used as the Sb source. During growth, the substrate temperature is set to 400 °C and the V:III flux ratio is maintained at 1.8. Further details about the substrate preparation and the optimization of growth have been described elsewhere.[8] For the absorption measurements, we use a Fourier transform spectrometer with a resolution of 1.0 cm^{-1}. Photoluminescence (PL) spectra are recorded using a HeNe laser ($\lambda = 632.8$ nm) and a Kr laser ($\lambda = 647.1$ nm) for high excitation density measurements. The luminescence signal is detected with a liquid-nitrogen-cooled InSb detector.

Before discussing the optical properties, we present in Fig. 1 the symmetrical (004) and asymmetrical (115) x-ray diffraction rocking curves (XRC's) of the investigated sample. The pronounced splitting of the substrate and buffer layer peaks is due to the unintentional incorporation of 0.5% As into the buffer layer. In addition to these peaks, the XRC profiles exhibit satellite peaks up to the eighth order. This observation provides evidence for the high overall structural quality and the smooth internal interfaces of the heterostructure. The simulated XRC profiles are obtained assuming a thickness of 37 and 320 Å for the (Ga,In)Sb and GaSb layers, respectively, and an In content of 20%. The perfect fit achieved with these parameters for both symmetrical and asymmetrical patterns demonstrates that the mismatch between the strained $Ga_{0.8}In_{0.2}Sb$ QW and the GaSb barrier layers is accommodated entirely by elastic tetragonal distortion.

Figure 2 displays the absorption spectrum of this sample as recorded at 10 K. A clear excitonic resonance is observed at 736 meV, i.e., 75 meV lower than the GaSb band gap. We attribute this feature to the generation of heavy-hole excitons confined within the QW. In addition to the excitonic resonance, a steplike continuum characteristic of a two-dimensional (2D) density of states is observed. The absence of the light-hole exciton resonance indicates that the light-hole states are not confined in the QW, in analogy with the situation discussed for the (Ga,In)As/GaAs QW.[9]

For a pure 2D system, the absorption can be described based on expressions derived by Shinada and Sugano.[10] In

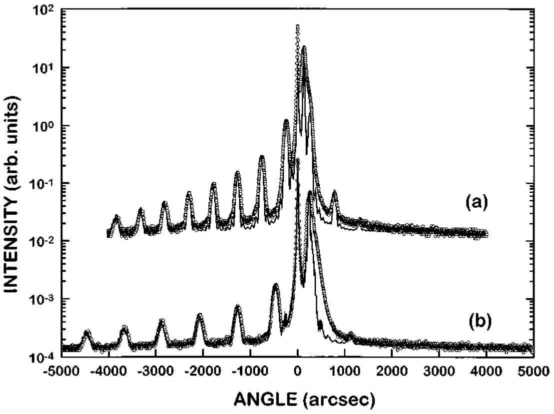

FIG. 1. Experimental (open circles) and simulated (solid line) x-ray diffraction patterns of the sample under investigation recorded in the vicinity of (a) the symmetrical (004) reflection and (b) the asymmetrical (115) reflection, respectively.

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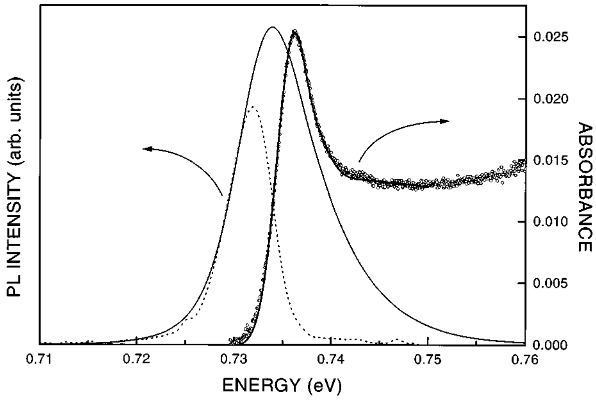

FIG. 2. Experimental (open circles) and theoretical (solid line) absorption spectrum and PL spectra taken with excitation densities of 0.25 (dashed line) and 250 W/cm^2 (solid line) of the sample under investigation.

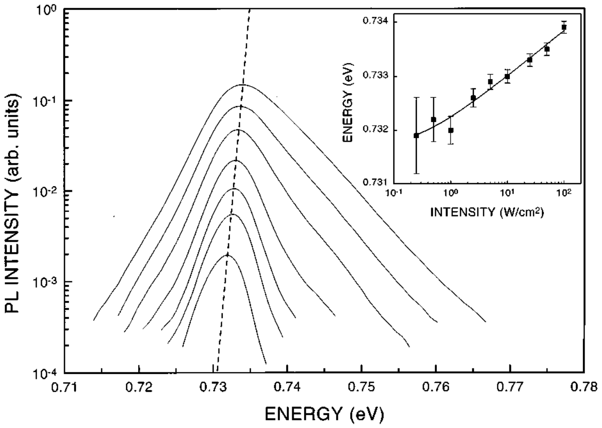

FIG. 3. Logarithmic plot of PL spectra recorded at excitation densities between 0.25 and 250 W/cm^2. The inset shows the shift of the PL peak energy with excitation density and a logarithmic fit to these data.

order to get quantitative information on the quantum-confined exciton, we fit the experimental absorption spectrum to these theoretical expressions. As evidenced by the data of Fig. 2, an excellent agreement is obtained when using an exciton binding energy of 2.5 meV. To go further, we note that the area of the absorption resonance is directly proportional to the oscillator strength f of the heavy-hole exciton.[11] The oscillator strength of the 1S heavy-hole exciton is thus determined to be 13×10^{-5} Å^{-2}.

Both the exciton binding energy and the oscillator strength are considerably smaller than commonly measured and calculated for QW in other materials systems[12–15] (for a comparison, see Table I). To demonstrate the consistency of our results, we independently derive the exciton binding energy E_X from the oscillator strength f:

$$E_X=\frac{\pi\hbar^2}{16\mu}\frac{E_G}{E_P}f, \tag{1}$$

where μ is the reduced mass of the exciton, E_P is the Kane matrix element, and E_G is the energy gap. Although Eq. (1) is valid for infinite barriers only and cannot be used for an absolute determination of the binding energy, it allows for a comparative statement using values derived for other materials systems (see Table I). This procedure results in a value of 2.5±0.5 meV for the exciton binding energy and thus agrees well with that derived from the fit of the absorption spectrum. Furthermore, we note that the exciton binding energy of bulk $Ga_{0.8}In_{0.2}Sb$ is estimated to be about 1 meV.[16] The twofold increase of the binding energy in the 37 Å $Ga_{0.8}In_{0.2}Sb$/GaSb QW is comparable to the increase in binding energy found for the (Ga,In)As/GaAs QW of similar thickness and In content (see Table I).

Next, we turn to the analysis of the emission properties of the (Ga,In)Sb/GaSb QW. The PL spectra recorded at low (dashed line) and high (solid line) excitation density are shown in Fig. 2 together with the absorption spectrum. At low-excitation power, the PL line has a width of 4 meV (to the best of our knowledge, the narrowest ever observed for this system) and peaks at an energy 5 meV lower than the exciton resonance in absorption. When increasing the excitation density, the PL line shifts to the blue and asymmetrically broadens at the high-energy side. This evolution is shown in more detail in Fig. 3. It can be seen that the PL line develops from a narrow Gaussian to a broad band with exponential leading and trailing edges. The inset of Fig. 3 shows the corresponding shift of the PL peak energy, which is well described by a logarithmic fit. These observations are consistent with an initial saturation of localized states, which dominate emission at low excitation power, and a subsequent phase-space filling at higher excitation power. Throughout the excitation range used here, the luminescence of these $Ga_{0.8}In_{0.2}Sb$ QW's is thus excitonic in nature.

Figure 4 shows the PL spectra recorded at various temperatures. The line shape of the PL band changes from a

TABLE I. Parameters characterizing the exciton resonance in absorbance for the sample studied in this work and for QW of similar width in other materials systems for which quantitative data are available (see Refs. 12–14). Compiled are the band gap E_G, the maximum absorption probability $p_{\max}$, the oscillator strength f, the integrated absorbance S, the exciton binding energy E_X, and the exciton Bohr radius a_B.

	$In_{0.2}Ga_{0.8}Sb$/GaSb	$In_{0.53}Ga_{0.47}As$/InP	$In_{0.13}Ga_{0.87}As$/GaAs	GaAs/$Al_{0.25}Ga_{0.75}As$
E_G (eV)	0.736	0.85	1.45	1.65
$p_{\max}$	4.38×10^{-3}			
f (Å^{-2})	13×10^{-5}			80×10^{-5}
S (meV)	0.018	0.11		0.16
E_X (meV)	2.5±0.5	6.6	8–9	11.5
a_b (Å)	300	145		95

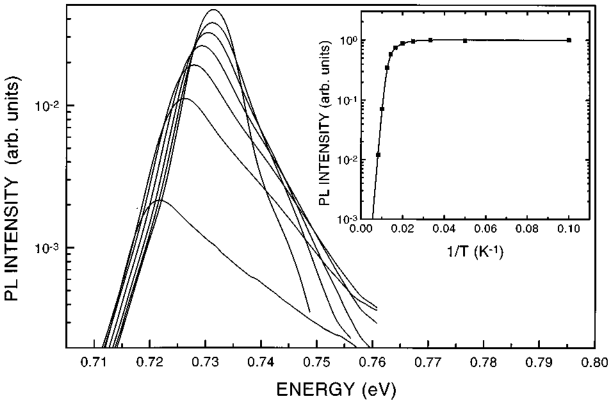

FIG. 4. Logarithmic plot of PL spectra recorded at temperatures between 5 and 110 K. The inset shows the evolution of the (spectrally integrated) PL intensity with temperature and an exponential fit, yielding an activation energy of 80 meV.

narrow Gaussian at low (5–40 K) temperatures to a highly asymmetrical band with pronounced broadening at the high-energy side at higher temperatures (>50 K). We interpret this finding as being due to the increasing participation of band-to-band recombination at higher temperatures. A more quantitative statement would require a detailed line-shape analysis of the PL band including excitonic and band-to-band contributions. Simultaneously, the PL intensity drops drastically at temperatures above 50 K. The inset of Fig. 4 shows the evolution of the PL intensity vs temperature in more detail. The slope of this curve corresponds to an activation energy of 80 meV, which is close to the total confinement energy within the $Ga_{0.8}In_{0.2}Sb$ QW. This coincidence of activation and confinement energy is also found for (Ga,In)Sb QW with different (lower) In content. We thus conclude that the PL quenching results from the thermionic emission of free excitons out of the QW, in analogy with observations on a shallow QW in the (In,Ga)As/GaAs and InAs/InP systems in which nonradiative recombination within the well was found to be absent.[17,18]

In summary, we have studied the optical properties of GaInSb/GaSb QW grown by MBE. In absorption, a distinct excitonic resonance was observed, allowing the quantitative determination of the binding energy and the oscillator strength of the quantum-confined exciton. Furthermore, we have shown that the radiative decay of free excitons is the dominant recombination channel in these high-quality (Ga,In)Sb/GaSb quantum wells.

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[1] See, e.g., *Proceeding of the 7th Conference on Narrow Band-Gap Semiconductors,* edited by J. L. Reno (Institute of Physics, Bristol, 1993).

[2] See, e.g., *Properties of InGaAs,* edited by P. Bhattacharya (INSPEC, London, 1993).

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