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RECOMBINATION AND SHAKE-UP IN DOPED QUANTUM WELLS

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Résumé.—Le mélange de polarisation observé dans le spectre de la luminescence des puîts quantiques de type n est expliqué à travers les processus à plusieurs électrons impliqués dans l'émission de la lumière.

Abstract.—Polarization mixing observed in the luminescence spectra from n-doped quantum wells is explained by the many-electron processes involved in light emission.

1. Introduction

Sooryakumar et al. [1] have measured the emission spectra from an n-doped GaAs-AlGaAs quantum well in two different polarizations. The emitted light is wave-guided along the interface planes of the quantum well (the y-axis) and its intensity is measured in the polarization normal to the interfaces (the z-axis) and in the polarization parallel to the interfaces (the x-axis). Unexpected by the single-particle transition theory, the intensity \( I_z \) has the same threshold as \( I_x \). We proposed that the polarization mixing at the threshold is due to additional many-electron processes analogous to the shake-up in soft X-ray emission in a metal. We constructed a phenomenological model including both the recombination and the shake-up processes which not only explains the spectra in both polarizations but also their stress dependence. [2]

In this paper, we examine in more detail the many-body processes which the model is supposed to simulate and comment on other works on the same or related topics of optical transitions in the presence of an electron plasma.

2. Simple Recombination

In luminescence emission spectrum, the initial state of the system is prepared by low intensity laser excitation which generates a low density of holes which relax to a quasi-equilibrium near the top of the valence band. The simple recombination process consists in the de-excitation of an electron from the existing Fermi sea to a hole in the valence band emitting a photon. The zone-center states of the valence subbands of the quantum well can be characterized by the \( z \)-component of the angular momentum \( m_J \) [3]: \( m_J = \pm 3/2 \) for the heavy holes and \( m_J = \pm 1/2 \) for the light holes. A selection rule for the recombination emission may be regarded as the conservation of angular momentum if the photon with polarization \( z \) is taken to have \( m_J = 0 \).
and one with polarization $x$ to have $m_J = \pm 1$. Since the top heavy-hole subband lies above the top light-hole subband, we expect the intensity $I_\alpha$ to start at the conduction subband to the top heavy-hole subband threshold $E_{ck}$ and the intensity $I_\sigma$ to become strong at the higher energy conduction to light-hole subband threshold $E_{ct}$ since the transition from the spin 1/2 conduction electron to the heavy hole does not emit photons with zero angular momentum according to the above selection rule.

On the contrary, the observed $I_\sigma$ spectrum starts at the same threshold as the $I_\alpha$ spectrum. It cannot be explained by the gradual rise of the calculated single-particle $I_\sigma$ spectrum due to the $m_J$ mixing in the heavy-hole subband.

3. Many-Electron Effects

The phenomenological formula for the emission intensity in the $\alpha$ polarization is given by

$$I_\alpha(\omega) = \sum_{jk} [M_\alpha(jk) + \lambda(M_\alpha(j'k'))_{j'}] e^{-E_{jk}/kT} \delta(E_{ck} - E_{jk} - \hbar\omega).$$  

(1)

$M_\alpha(jk)$ is the single-electron transition probability from the conduction state $ck$ to the valence band state $jk$ with momentum $k$ at polarization $\alpha$. Two terms which account for the many-electron effects will now be examined in detail.

The exponential factor in (1), in the non-interacting approximation, would be the thermal distribution of the initial hole state with $\Gamma$ being the hole temperature. To fit the high energy side of the of $I_\alpha$ spectrum, $\Gamma$ is about 20K [2]. Although the hole temperature could be higher than the lattice temperature which is kept at 2K, such high hole temperature is unreasonable. Previous fit [4] of the emission spectrum gave a hole temperature of about 6K by using a parabolic hole band with the hole mass of $0.45m_0$. The higher value of $\Gamma$ comes from a broader calculated heavy-hole subband, which is also reasonable in view of the fact that the relevant mass is the transverse mass of 0.11$m_0$. The justification for such a large $\Gamma$ is then not the initial hole temperature but the broadening of initial hole spectral density due to self-energy effects by the same processes (Fig. 1a) as the shake-up to be described presently.

The second term in the square bracket of (1) is an average of the one-electron conduction to valence band transitions over the Fermi sea, approximating the shake-up processes. The factor $\lambda$ is an adjustable parameter measuring the strength of the electron-hole interaction.

The lowest order shake-up processes are given by the Feynman diagrams Fig. 1c, d, e, g. Fig. 1b describes the process in Fig. 1c and its exchange counterpart 1d. The shake-up takes place in two steps: (1) A hole initially at state $k$ of the valence subband excites an electron-hole pair $k_1$ and $k_2$ from the conduction subband Fermi sea through the screened Coulomb interaction. The hole itself recoils to state $k'$ in the same or a different valence subband. (2) A conduction electron at state $k'$ drops into the $k'$ hole, emitting a photon. Thus, even if the initial hole state $k$ is at the top of the valence subband and, hence a pure $\pm 3/2$ state, the intermediate state $k'$ provides polarization mixing for the light emission. The hole, besides shaking up an electron-hole pair from the Fermi sea can also excite a plasmon.

Fig. 1e represents the initial-state interaction or the exciton effect. Fig. 1f explains the process of a hole exciting an electron-hole pair in the conduction band Fermi sea and then combines with the conduction electron to form an exciton which de-excites emitting a photon. Such processes yield no strong polarization mixing. For example, if $k = 0$, the exciton contains
a sum of electron-hole pairs at \( k' \) outside the Fermi radius and, thus, has the same symmetry as the initial-hole state and cannot mix other angular momentum components.

Fig. 1g has the same vertex structure as 1e but the difference is in the retarded screened Coulomb interaction. The process has an intermediate state like that in Fig. 1b rather than Fig. 1f.

These diagrams are complicated to evaluate and the problem is compounded by the uncertainty of the importance of the higher order diagrams. The simple average in (1) simulates the effect of the recoil due to shake-up. With \( \lambda \) chosen to reproduce the ratio of the strength of \( I_s \) to \( I_\tau \) near the threshold, the spectra are well accounted for. The validity of the model is further confirmed by its ability to account for the stress dependence for both polarizations with no further adjustable parameters. [2]

4. MND Singularities and Excitons

In the X-ray case, the localized core-hole can excite a large number of electron-hole pairs near the Fermi surface and give rise to the MND singularity [5]. By analogy, manifestations of the singularity has been suggested in the GaAs quantum well [6]. The MND singularity ceases to exist when the hole to electron mass ratio is not very large [7]. This is the case in the GaAs quantum well where the relevant mass for the heavy-hole subband is the transverse mass of 0.11 \( m_0 \). Or, in terms of the band energies at the Fermi wave vector, for the sample in Ref.[2], the electron band has 30 meV and the top hole band 8.3 meV. The \( I_s \) spectrum has more strength in the lower energy threshold than near the Fermi level. A contrary observation was recently found in the InGaAs quantum well [8] where the peak at the Fermi level is interpreted as the MND singularity due to the transition from a hole localized by the strong potential fluctuations in the alloy quantum well.

Chang and Sanders [9] claimed erroneously to have calculated the shake-up processes proposed by us. The initial state which they took consists of a exciton of conduction electron above the Fermi level and the valence band hole plus a hole in the conduction band such that the total momentum of the state is zero. Their initial state is very different from ours of a single hole but is more akin to the intermediate state in Fig. 1b. Their initial state is assumed to be in thermal equilibrium whereas the intermediate state in the shake-up comes from the excitation of a hole. Their low estimate of 5K for the temperature of the initial state is the direct result of the over-estimate of the hole mass of 0.35\( m_0 \) as discussed above. By taking the unscreened Coulomb interaction and only the ladder diagrams in the exciton, they have overestimated the bound exciton effect [7]. Such exciton, if existed, would have been seen near the threshold of the excitation spectrum in the GaAs quantum well. Their computed \( I_s \) peaks at the higher end of the spectrum and has little strength at the lower threshold, contrary to experiment.

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Fig. 1 Many-electron processes in luminescence. The broken line denotes the hole in valence band, the line conduction electron, and the wavy line the photon or screened interaction. (a) The hole self-energy. (b)-(g) See text.

References