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Indirect optical transitions from carriers trapped on the delta doping and on the parabolic quantum well

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Abstract

In this work, doped AlGaAs/GaAs parabolic quantum wells (PQW) with different well widths (from 1000 Å up to 3000 Å) were investigated by means of photoluminescence (PL) measurements. In order to achieve the 2DEG inside the PQW Si delta doping is placed at both side of the well. We have observed that the thickness of this space layer plays a major rule on the characteristics of the 2DEG. It has to be thicker enough to prevent any diffusions of Si to the well and thin enough to allow electrons migration inside the well. From PL measurement, we have observed beside the intra well transitions, indirect transitions involving still trapped electron on the delta doping and holes inside the PQW. For the thinness sample, we have measured a well defined PL peak at low energy side of the GaAs bulk emission. With the increasing of the well thickness this peak intensity decreases and for the thickest sample it almost disappears. Our theoretical calculation indicated that carriers (electron and holes) are more placed at the center of the PQW. In this way, when the well thickness increases the distance between electrons on the delta doping and holes on the well also increases, it decreases the probability of occurrence of these indirect optical transitions.

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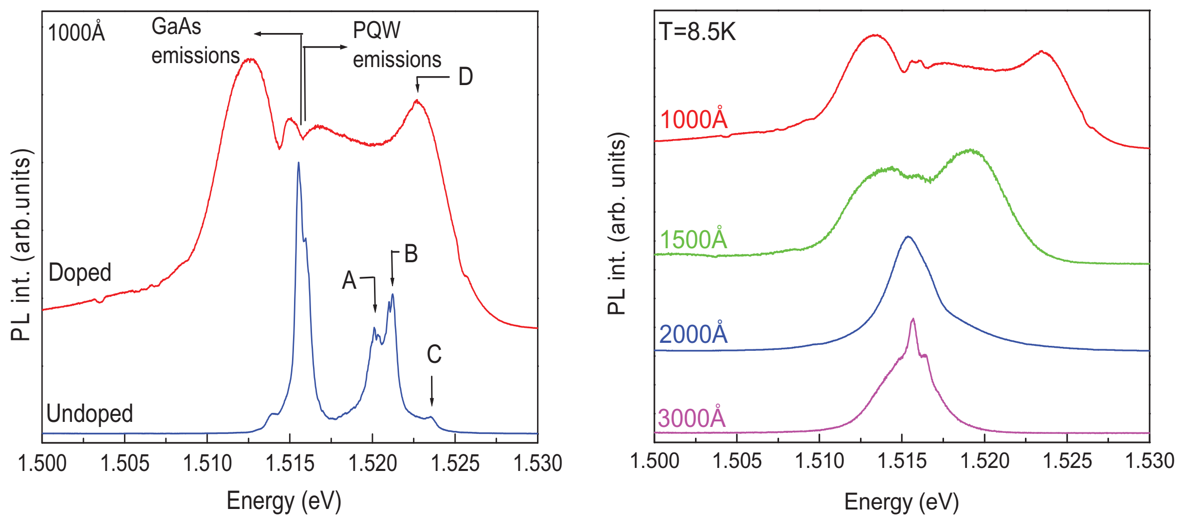
1. Introduction

Recent advances in the semiconductor growth techniques have offered the opportunity to fabricate structures with potential profiles of almost any shape. Closely perfect parabolic effective potential profiles have been grown by this technique. In these structures it is possible to form an almost homogeneous bi dimensional electron gas (2DEG). In this way PQW is a very suitable to study the electron-electron interaction on semiconductor system and variety of collective phenomenon such spin-density wave Wigner crystallization and many body effects on the optical and magnetic measurements [1, 2].

2. Results and discussion

All the samples here investigated were grown in a Gen II Molecular Beam Epitaxy system on top of epi-ready semi-insulating GaAs (001) substrates. The structure of the PQW is the follow: first, an 1-mm-thick GaAs buffer was grown followed by with a 20x $(AlAs)_5(GaAs)_{10}$ superlattice in order to improve the crystal purity and quality. Then a 500 Å-thick AlGaAs layer was grown with the Al content varying linearly from 0% to 31% using the digital alloy technique, after which it was grown an 1000-Å-thick $Al_{0.31}Ga_{0.69}As$ layer. Then, an AlxGa1-xAs parabolic quantum well was grown with the Al content varying from x=0 in the center of the parabola to x =0.20 at the edges of the parabola. The parabolic well were surrounded by $Al_{0.31}Ga_{0.69}As$ barriers containing two Si spikes symmetrically located at 200Å from the borders of well. The Si concentration was 1 x 10^{12} cm^{-2} for the sample with 3000 Å wide parabolic well and 5 x 10^{12} cm^{-2} for the remaining ones. Inside the well, the parabolic potential profile was achieved by the digital-alloy technique using a 20-Å-period superlattice in which the respective thickness of GaAs and AlAs were varied accordingly. Finally, it was grown a cap layer consisting of a 400-Å $Al_{0.31}Ga_{0.69}As$ followed by a 100-Å thick GaAs layer. Photoluminescence measurements were performed in a closed circuit optical crystal operating with helium from 8.5 K to 300 K. The samples were excited with the 5145 Å line of an argon laser with spot diameter size of 300 μm. The signal was analyzed by a monochromator and detected by a cooled charge coupled device.



(a) (b)

Figure-1. Low temperature photoluminescence measurements of (a) doped and undoped PQW with well thickness of 1000Å and (b) doped parabolic quantum well with different well thickness.

Fig.1.a shows the low temperature (8.5K) PL measurements for the doped and undoped samples. Considerable difference can be seen between these two spectra. For the undoped sample, we can see that the PL spectrum consists of two peaks with slight shoulders at high and low energy side. Based on our PL measurements as a function of

temperature and excitation power (not showed here) we ascribe the major peak at 1.515 eV and full width at half maximum (FWHM) of nearly 3 meV to the GaAs free exciton, and its shoulder at high energy side to a neutral donor to bound exciton. The peak at 1.516eV is associated to GaAs band-to-band recombination. Beside these GaAs related emissions, three other ones are also present, named A, B and C. The last ones are related to emission associated to electron and photo-created heavy and light holes inside the parabolic quantum well. As already analyzed at Ref.3 the peak A at 1.5205 eV is associated to the fundamental e1-hh1 (first electron level to first heavy hole one); the peak B is associated to e1-lh1 (first electron level to first light hole one) and the peak C to e1-lh3 (first electron to third light hole one). These assumptions were based on theoretical calculation and parity selection rules. A huge difference can be noticed on the PL spectrum of doped sample. It is very large (~14 meV) and is formed by different transitions. We can observe a peak at 1.513 eV followed by two fine structures at the bulk GaAs spectral energy range and a large band with an enhancement on the PL intensity at 1.523 eV. The peak at 1.513 eV (lower than the GaAs band gap) is more probably associated with the doped delta layer (extrinsic emission) and will be discussed later in detail. The two fine structures around 1.515 eV can result due to the free and bond exciton in the GaAs layer. The large structure is ascribed the to the transitions involving the filled states at conduction band on the PQW from the fundamental up to the Fermi level (FL) with photo-generated holes at fundamental levels . This low temperature luminescence is only possible to be observed if *k* conservation does not restrict the participation of all the electrons of the Fermi gas in the recombination process. This condition is ensured because the holes are strongly localized in real space and have sufficient spread of k vector to enable electrons up to $k = k_f$ to recombine without significant restriction of *k* conservation. In the present case the holes in the AlGaAs parabolic wells are localized, probably due to alloy fluctuation of the digital alloy [4].

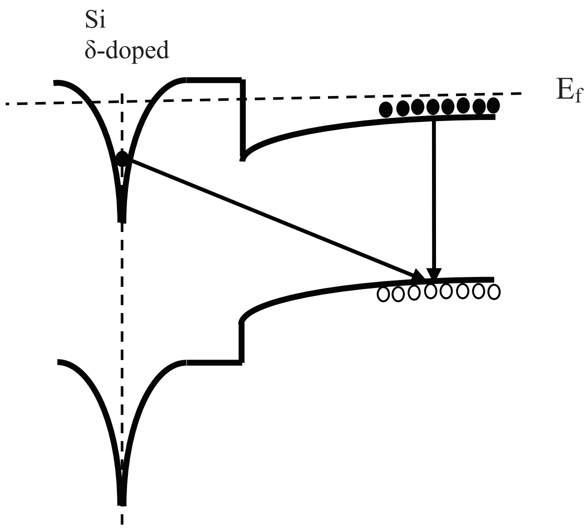


Figure 2. Schematic diagrams of n-type delta doped PQW.

Now we would like to discuss the broad band at low energy side of GaAs emission with energy of 1.513 eV. In Fig. 1.b we show low temperature PL results for PQW with different well thickness from 1000 Å to 3000 Å. In all samples the GaAs related emission is present at 1.516 eV. We can observe that as the well thickness increases both the emissions at low and high energy side of the GaAs one increase. Although the behaviour of these emissions seems similar, they have complete different origins. As above mentioned, the high energy emission is related to recombination processes of electrons from the two dimension electron gas at the parabolic quantum well and, as we will see, the low energy emission is an extrinsic emission associate to the doped delta layer present in our doped. It is possible to observe in fig.1.b that this emission almost disappear as the well thickness increases. For these samples it is possible to observe just a slight broadening at the low energy side of the GaAs emission.

Measurements of PL as a function of temperature and photoexcitation intensity show that this emission has a typical extrinsic behaviour, it means it disappears at high temperatures and saturates with increasing of laser power excitation intensity. The energy of this peak suggests that it can be interpreted as arising from the recombination of photogenerated holes inside the parabolic quantum well and electrons trapped at the Si-delta doping. One important aspect to reinforce this hypothesis is that on undoped samples (fig.1.a) do not show any emission peak or low energy broadening around the energy of 1.513eV. In order to better understand this emission, on figure 2 we show band diagram representative of our doped samples. The PQW emission consists of vertical transitions inside the well. In real space electrons and hole are located at the same space (vertical arrow at fig.2). Beside the PQW one other potential can confine carriers. The ionized δ-doped Si form a deep V shape potential which attracts electron. We have performed theoretical calculation for our structure and it has revealed that carrier inside the PQW located mostly at the centre of the well, for both electrons and photogenerated holes. In this way, transitions between electrons inside the δ-doped Si V shape potential and photocreated holes are indirect transitions (see fig.2).

The recombination probability is strongly dependent on the overlap of electron and hole wave functions. Normally, indirect transitions are forbidden due to the lack of wave function overlap. However, wave function spread into the barrier, principally that one for electron in the δ-doped Si potential. This provides the observation of this kind of transition. Our calculation showed us that this probability is definitely different of zero. Based on this information, we ascribe the emission at 1.513 eV to indirect transitions between electrons on de δ-doped potential with holes inside the PQW. This emission disappears as the thickness of well increases due to the fact that the above sited wave function overlap decreases, decreasing the transition probability, as a consequence separation of electron inside the δ-doped from the holes inside the well. Remember that, by our calculation, holes are majority located at the centre of the well. So, increasing the well thickness holes are more and more far away from the δ-doped region. Finally, to explain the behavior of the luminescence in function of the temperature and laser power excitation we have to said that: when the temperature of the sample increases, electrons trapped at the δ-doped gain energy to escape from this region, decreasing then, the PL emission as observed. The saturation of PL intensity with increase of the power excitation is related to the fact that the number of carrier trapped at δ-doped potential, differently from the carrier inside the well, are limited which cause the PL intensity saturation.

3. Conclusion

Photoluminescence measurements at different temperatures and laser power intensity have been performed to investigate the optical response of wide parabolic quantum wells with different well widths (1000 Å and 3000 Å). For undoped samples, the fundamental and also excited transitions of the PQWs were observed. For the thinner sample, we have observed that the optical transitions obeyed the parity rule and we have detected beside the e1-hh1 fundamental transition, the e1-lh1 and the e1-hl3 excited ones. For the doped sample, we have observed the many body effect known as Fermi Edge Singularity and also, one emission below the GaAs emission. This emission is a PQW thickness dependent. The origin of this particular emission comes from indirect (in real space) transition between electrons trapped silicon delta doping at and holes inside the PQW. Measurements as function of both temperature and laser power incident, corroborate our assumption.

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