A photoluminescence study of δ -doped GaAs

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Abstract: Samples of GaAs δ -doped with beryllium have been studied with photoluminescence. With a lightly doped sample, (2×10^{16} Be atoms per m^2) a spectral feature is observed which can be interpreted as caused by radiative recombinations between spatially non-confined conduction-band electrons and acceptor-related holes forming a miniband system confined spatially to the δ -doped region. With higher densities of Be, this weak feature disappears. Instead, strong recombination to bulk Be acceptors shows up, indicating that the bulk-density of Be atoms which during growth have diffused away from the δ -layer is so high that such acceptors drain the photoexcited electrons. A narrow, excitonic line situated 0.6 meV above the $n = 1$ free exciton line, lower polariton branch, is seen, but the well-known defect-induced bound excitons in the 1504-1512 meV region are not observed. The results are discussed.

1. Introduction

With a δ -doped semiconductor is normally understood a crystal containing one sheet of foreign atoms, localized within a single monolayer. If the two-dimensional density of these dopant atoms is sufficiently high, a two-dimensional carrier-gas can be formed. Due to diffusion during growth, the spatial distribution of the foreign atoms will in practice be broadened, but as long as their width is shorter than the smallest carrier confinement length, still, a two-dimensional carrier-gas can be created. This has the last few years attracted a great deal of interest as a new field for basic research, see, e.g., refs., 1, 2 and references therein, and in addition, especially n-type δ -doped GaAs is of considerable interest for potential device applications such as a δ -doped GaAs field-effect transistor, refs. 3,4.

A δ -doping carried out with donor dopants will lead to a local, V-shaped bending of the bottom of the conduction band as well as of the top of the valence band, and in the groove of the conduction band, discrete electronic energy levels (a miniband system) will exist. Conversely, with p-type δ -doping, a Λ -shaped cusp will be introduced in the band-gap borderlines, and there will be a miniband system in the valence-band cusp. Degani (ref. 5) has recently carried out a detailed theoretical study of electron energy levels in a silicon (i.e. donor) δ -doped layer in GaAs. He carried out self-consistent calculations based on the local-density approximation for various donor concentrations as well as distributions, to account for the effect of diffusion of the donor atoms along the growth direction. Mainly, he found that the V-shaped groove of the conduction band into the bandgap will contain a series of energy levels, of which the lowest one will be located roughly around 100-150 meV below the bottom of the conduction band. Also, he found that the number of electron energy levels and their position relative to the Fermi energy is sensitive

to all parameters involved, such as donor concentration and spatial distribution. Similar properties are expected for the valence-band cusp in p-type δ -doped GaAs.

In principle, it should be possible with photoluminescence (PL) measurements, to observe radiative recombination between electrons confined to the V-shaped groove of the conduction band and holes in the valence band. However, the latter will spatially be repelled from the region of the δ -doped layer, because the potential confining the electrons is repulsive for the holes. Consequently, the spatial overlap between hole and electron wave functions will be poor, so that the probability for radiative recombination will be low. Attempts have been carried out to observe such radiative recombination but the results have been negative, refs. 1,6. In a trial to study the electronic energy structure of an n-type δ -doped layer, one or more heterojunctions have been introduced, in order to confine the holes to the neighbourhood of the δ -layer (refs. 7-11), and for such heterostructures, strong signals of radiative recombination between two-dimensional electrons and confined holes have been reported (refs. 7-11). However, since the holes are trapped at the heterojunctions, their position in energy is not precisely known.

Correspondingly, for p-type δ -doped GaAs, radiative recombination processes involving conduction-band electrons and holes confined to the cusp in the valence band will spatially be indirect and therefore rare, and until now, such radiative recombination has been seen only when the electrons have been confined with heterojunctions (refs. 11,12). Despite these negative results with samples not containing confining heterojunctions, we decided to grow a few Be δ -doped structures of GaAs without confining heterojunctions and to study them with PL, in the hope to see the spatially indirect radiative recombination processes.

2. Experimental

The samples were produced by molecular beam epitaxy in a VARIAN Modular GEN II growth chamber. First, a layer of 2.5 μm thick, undoped GaAs was grown on a semiinsulating wafer, with a growth rate of 1 μm per hour. Next, the gallium shutter was closed and the surface was stabilized for 10 seconds with unchanged arsenic flux. Then, the δ -doping was carried out with a dopant atom flux of 3×10^{15} atoms per m^2 and per second, whereupon the dopant source was closed, and finally, a top layer of 1 μm thick, undoped GaAs was grown, also at a rate of 1 μm per hour. During all of the growth, the sample temperature was 480 $^\circ\text{C}$, as a compromise to keep diffusion of the dopant atoms as low as possible and at the same time to obtain a sufficiently high crystal quality of the sample.

The samples were studied thoroughly with PL from 10 to 300 Kelvin. As excitation source was used an argon-ion laser (488 nm), and the PL spectra were recorded with a one-meter scanning spectrometer (McPherson model 2051) with an instrumental resolution better than 0.1 nm.

3. Results and discussion

First, we shall discuss possible observations of recombination radiation related to the δ -doping, which might be expected to show up at an energy approximately 100-150 meV below the band-gap region, cf. the introduction, and then, we shall discuss radiation observed in the near-bandgap region.

With a sample fairly lightly doped (2×10^{16} Be atoms per m^2), a weak band was observed at 880.0 nm, see fig. 1, lower curve. The corresponding transition energy, 1.409 eV, is 0.110 eV below the band gap energy of bulk GaAs. Consequently, it agrees well with the energy estimated for radiative recombination between a conduction-band electron and a δ -doping related hole in the first miniband of the Λ -cusp of the valence band, cf. the introduction. Corresponding studies of several other samples of GaAs, either bulk-doped with Be or undoped, and grown on the same machine, showed absolutely no structure in this wavelength region. Furthermore, such a transition has not been reported in refs. 13,14, which concern PL studies of GaAs bulk doped with Be, from lightly to heavily doped. Consequently, it is possible to identify the transition at 880.0 nm as resulting from radiative recombination of conductionband electrons and holes in the lowest miniband of the Λ -shaped cusp.

Figure 1.
PL spectra of two GaAs samples δ -doped with Be as indicated in the figure. Note that the signals are on a logarithmic scale.

Figure 2.
The near-bandgap-region PL spectrum of a GaAs sample δ -doped with Be (2×10^{16} atoms per m^2).

Another transition, at 850.6 nm (fig. 1, lower curve) may correspondingly be caused by radiative recombination of conduction-band electrons and holes in the second miniband in the cusp, because it corresponds to a transition energy of 1.457 eV, which is 0.062 eV below the band-gap energy of GaAs.

However, it may also be a phonon replica of the strong peak at 830.0 nm, which is a (e, A_{As}^0) transition, where the acceptor can be carbon or beryllium, which has diffused from the δ -layer during growth.

With a sample more heavily doped with Be (8×10^{16} atoms per m^2), the band at 880 nm could barely be seen (fig. 1, upper curve). Also, essentially nothing was seen at 850.6 nm. However, a very intense and broad feature was seen with a maximum at 830.5 nm (fig. 1, upper curve). This corresponds to well-established band-to-acceptor transitions (e, A^0) , where the acceptor can be beryllium as well as carbon, since they have almost identical binding energies (refs. 13,14). Thus, we can conclude that in this more heavily doped sample, so many Be atoms have during growth diffused from the δ -doped region that at least a part of the sample acts as lightly bulk doped with Be. In such a region, the (e, A^0) transitions will be spatially direct and will therefore drain the photo-excited electrons away from the Λ -shaped cusp, and in this way, the δ -doped transitions at around 880 nm will be strongly suppressed, remembering that these are spatially indirect, cf. the introduction. Thus, the absence of the band at 880 nm with the more heavily doped sample is not in contradiction with the observation and identification made for the lightly doped sample, but may merely indicate the difficulty of observing the δ -doping related recombination, as described in the introduction.

In the near band-gap region (i.e. slightly below 820 nm), we observed naturally excitonic transitions. With the lightly-doped sample, these lines were very narrow, see fig. 2, whereas with a more heavily-doped sample, the structures could not be resolved so well. For the sake of completeness, we mention that the spectrograms shown in fig. 1 were recorded with more open slits than used in fig. 2. Thus, the resolution seen in fig. 1 is instrumental, whereas the resolution in fig. 2 is set by the sample. Most of the excitonic transitions could easily be identified as well-established, see, e.g. ref. 15, the identifications are given in fig. 2. However, between the $n = 1$ state of the free exciton, lower polariton branch, (which is the strongest peak in fig. 2), and the $n = 2$ state of the free exciton, a fairly intense line showed up, separated only by 0.0006 eV from the $n = 1$ transition. This might be the $n = 1$ free exciton, upper polariton branch (ref. 15). However, if so, then the energy separation between the lower and the upper polariton branches we observe is larger than that given in ref. 15. In addition, with dozens of other GaAs samples grown with the same machine, we observe only the lower polariton branch, in agreement with spectrograms shown in ref. 15 and elsewhere. Therefore, the line seen 0.0006 eV above the $n = 1$, lower polariton branch, is not safely identified as the upper polariton branch, but might be related to the δ -doping.

At the end, we mention that we failed to observe the so-called Künzel-Ploog complex at wavelengths slightly above 820 nm, cf. fig. 2. This may indicate a high sample quality.

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