Photoluminescence characterization of single heterojunction quantum well structures

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A photoluminescence emission band at 830 nm has been detected in single heterojunction quantum well structures (modulation-doped structures) in the range of 250–400 K. This emission band is observed neither in heterojunction structures without a two-dimensional electron gas (2DEG), nor in n^+ AlGaAs and GaAs. The intensity of the emission band increases as the mobility of the samples with 2DEG and shows excitonic behavior in its variation with incident laser excitation intensity. This photoluminescence emission was observed in samples grown by both molecular beam epitaxy and by organometallic vapor phase epitaxy. This effect may be useful as a rough identification of high quality, modulation-doped heterostructures.

Heterostructures based on various materials are currently widely investigated because of carrier confinement in thin quantum wells[1] and carrier mobility enhancement in a two-dimensional electron gas (2DEG).[2] These properties make heterostructures suitable for applications in optoelectronics, high-speed digital, and high-frequency microwave circuits.

Two-dimensional electron gas quantum well heterostructures have been widely investigated using magnetoresistive measurements[3] and field-effect transistor (FET) devices.[4] Both techniques require elaborate sample preparation. Photoluminescence (PL) characterization, on the other hand, requires little or no sample preparation. Although double heterojunction quantum wells have been extensively characterized using photoluminescence,[5,6] very little has been reported on the photoluminescence characterization of single heterojunction quantum wells (so-called modulation-doped structures).

We report here a study of single heterojunction quantum wells using photoluminescence spectroscopy. Specifically, an emission band centered at approximately 830 nm (1.493 eV) has been observed in the photoluminescence spectra of modulation-doped heterostructures grown by both organometallic vapor phase epitaxy (OMVPE) and molecular beam epitaxy (MBE). This photoluminescence emission appears in the temperature range between 250 and 400 K and increases in intensity with increasing 2DEG mobility of the heterostructure. The emission is found to be excitonic in nature and is explained in terms of confined particle recombination at the heterostructure.

The heterostructures used in this investigation were grown by both OMVPE and MBE. The OMVPE layers were grown at atmospheric pressure using trimethylgallium, trimethylaluminum, and arsine at 650 °C. The structures typically consisted of 5000 Å of nominally undoped GaAs followed by 200 Å of undoped AlGaAs with Al composition of 30% and 400–800 Å of Te-doped n^+ AlGaAs with an electron concentration of $1–3\times10^{18}$ cm^{-3}. Some samples had a four-period superlattice layer of 100 Å GaAs and AlGaAs grown before the undoped GaAs layer. Other samples also had a 200 Å cap layer of n^+ GaAs. The MBE growth conditions have been described elsewhere.[7] The MBE samples had a 1 μm undoped GaAs layer, 50 Å undoped AlGaAs, 350 Å of n^+ AlGaAs and 200 Å cap layer of n^+ GaAs doped with Si to an atomic concentration of 5×10^{18} cm^{-3}. The superlattice layer has five periods consisting of 80 Å GaAs and 120 Å AlGaAs. 1 μm gate-length modulation-doped field-effect transistors (MODFET's) made from some of these samples (with 200 Å undoped AlGaAs space layer, 200 Å n^+ GaAs cap layer, and 400 Å n^+ AlGaAs layer) had transconductances of 170 mS/mm at 300 K and 270 mS/mm at 77 K for the OMVPE grown material while devices fabricated from the MBE material had transconductances of 205 mS/mn at 300 K and 420 mS/mm at 77 K.

The photoluminescence measurements were taken in a closed cycle refrigerator over a temperature range of 8–400 K. The excitation source was a Lexel 85.5 argon-ion laser with operating wavelength at 514.5 nm and power densities ranging from 0.10 to 17 W/cm^2. The photoluminescence radiation was dispersed with a SPEX 1870C 1/2 m spectrometer and detected using a Hamamatsu R980 photomultiplier.

Figure 1(a) shows the room-temperature photoluminescence spectrum of a typical high-mobility modulation-doped structure grown in our OMVPE reactor. The structure of this sample is as described above, except that there is no n^+ GaAs cap layer and the n^+ AlGaAs layer is 800 Å. The spectrum for an MBE grown sample with a structure exactly as described above is shown in Fig. 1(b). The spectrum shows an emission band at 696 nm (1.781 eV) which is due to the 800 Å n^+ AlGaAs layer and an emission band at 830 nm (1.493 eV). The MBE sample does not show the high-energy emission band because of a lower AlGaAs layer thickness and possibly because of a lower luminescence effi-

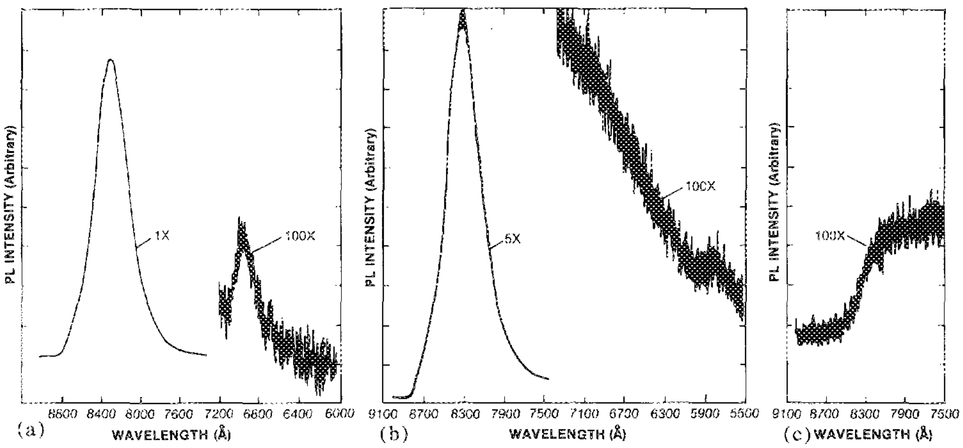

FIG. 1. Photoluminescence spectra at 300 K of (a) OMVPE grown heterostructure with a 2DEG, (b) MBE grown heterostructure with a 2DEG, and (c) OMVPE grown heterostructure with no 2DEG. Laser excitation intensity is 5 W/cm^2.

ciency of the MBE material. In addition to observing the 830 nm emission from simple AlGaAs/GaAs heterostructures as described above, it was also observed from structures incorporating the four-period superlattice as well as from those structures having the N^+ GaAs cap layer. The half-width of the 830 nm emission is 60 meV. It is obscured by the GaAs band-edge luminescence below 200 K but dominates the spectrum between 250 and 400 K. The intensity of the emission band decreases with temperature and the peak shifts to higher energies as the temperature increases. In contrast, the spectrum of a similar OMVPE grown sample with low mobilities [Fig. 1(c)] does not show any emission band in the range of 750–850 nm. The 830 nm emission peak was not observed after the heterojunction layer was removed by chemical etching from a sample similar to that of Fig. 1(a). In this case, the photoluminescence spectrum was identical to Fig. 1(c).

In addition, no photoluminescence emission as shown in Figs. 1(a) and 1(b) was observed in 1 μm n^+ AlGaAs, thick undoped GaAs layers or thin (1000 Å) n^+ GaAs doped to the same electron concentration as the sample of Fig. 1(a). These samples were grown epitaxially on GaAs in the same reactor. Only a 1 μm n^+ GaAs layer ($n \sim 10^{18}$ cm^{-3}) showed a broader emission band with the peak between 800 and 840 nm, but with PL intensity lower by one to two orders of magnitude.

Figure 2 shows the variation with temperature of the Hall mobility for the samples of Figs. 1(a) and 1(c). The mobility of the sample showing the 830 nm emission band increases monotonically down to 15 K, indicating that there is a 2DEG in this sample.[2] The mobility of the sample showing no emission band, on the other hand, peaks at about 60 K. Thus, this sample does not have a 2DEG in the heterostructure.[2] The Hall mobilities of various modulation-doped samples were measured at 77 K. A general trend of increasing PL intensity with the 2DEG mobility was found. The sample with the lowest 77 K mobility of 6000 cm^2/V s also had the lowest PL intensity. This PL intensity increased gradually by an order of magnitude for samples with a mobility of 30 000 cm^2/V s. For samples with mobility higher than 30 000 cm^2/V s (i.e., 45 000–90 000), the PL intensities increase sharply by as much as two orders of magnitude. There is enough scatter in the data that no more than a trend can be deduced.

From the above, it appears that there is a correlation between the observation of the 830 nm emission band and the existence of a 2DEG or a high quality quantum well at the heterojunction. At the same time, the intensity of the PL emission correlates with the mobility of the modulation-doped samples. Since this emission band was not observed in undoped GaAs, thin n^+ GaAs, and n^+ AlGaAs samples, we conclude that it originates from the 2DEG quantum well existing at the heterojunction. This can be explained as being due to the recombination of excitons confined to the 2DEG quantum well. Alternately, it may be due to band-to-band recombination of electron-hole pairs in the vicinity of the quantum well. That the luminescence is excitonic in nature is suggested by Fig. 3. This shows that the variation of the photoluminescence intensity with laser excitation is superlinear for the luminescence from the modulaton-doped sam-

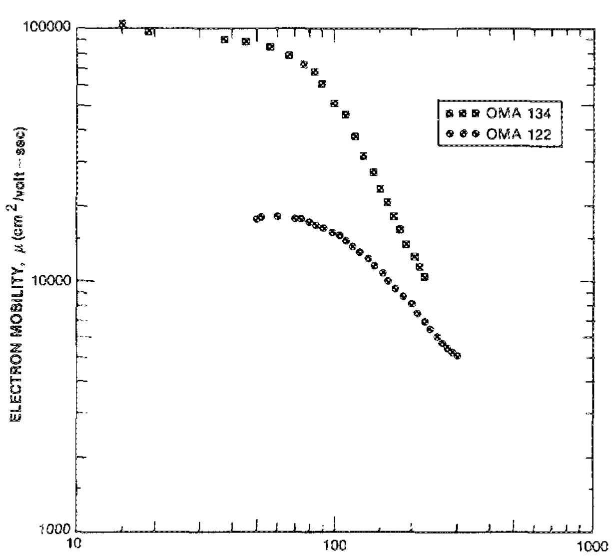

FIG. 2. Temperature variation of the Hall mobility of the samples of Figs. 1(a) and 1(c).

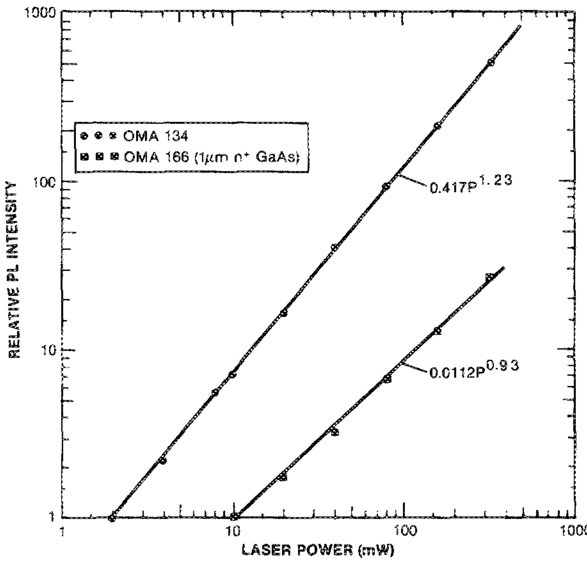

FIG. 3. Variation of photoluminescence intensity with incident laser power density for AlGaAs/GaAs heterostructure and for n^+ GaAs.

ples. On the other hand, for an n^+ GaAs sample for which band-to-band recombination predominates, the luminescence intensity variation is sublinear. Quantum well photoluminescence due to excitonic recombination has been shown to have a superlinear variation with laser excitation.[6] Rectangular quantum wells grown in our laboratory have been found to also have a superlinear variation at 300 K with an exponent of 1.5.

Figure 4 shows that the energy of the emission band increases with temperature. This is contrary to the variation of band-edge luminescence for which a decrease of the luminescence peak energy with temperature is observed. Hence, the photoluminescence neither originates from a "hidden" $Al_{0.06}Ga_{0.94}As$ layer near the heterojunction nor from the superlattice layers in some of the structures. A decrease of

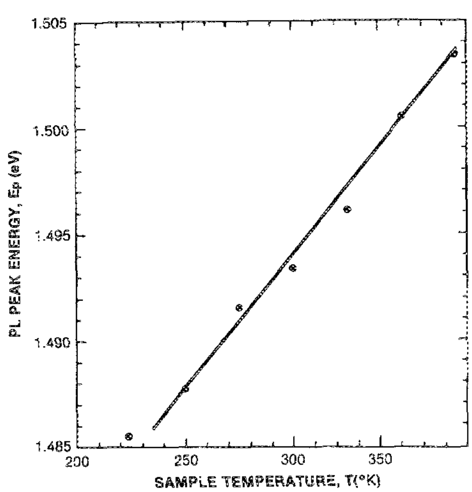

FIG. 4. Variation of the peak energy of the 830 nm emission band with temperature. Laser excitation intensity ~ 5 W/cm^2.

emission peak energy is expected from these sources. The observed energy shift with temperature can be explained in terms of band filling due to an increase in Fermi level (relative to the quantized levels) as more electrons are transferred into the 2DEG from the AlGaAs at high temperatures. The energy of the Fermi level relative to the ground state in the 2DEG is given by[8]

$$E_F = KT \ln[\exp(h^2 N_s/mKT) - 1] + E_0, \qquad (1)$$

where E_0 is the ground state in the 2DEG, N_s is the electron concentration in the 2DEG in m^{-2}, T is the temperature in K, m is the electronic mass, K is the Boltzmann constant, and h Planck's constant. The data of Fig. 4 can be fit to a linear equation of the form

$$E_p = 1.198 \times 10^{-4}\, T + 1.458, \qquad (2)$$

where E_p is the peak energy of the luminescence band in electron volts. Substitution of the constants and $N_s = 1.18 \times 10^{12}$ cm^{-2} into the first term of Eq. (1) yields a slope equal to that of Eq. (2). This indicates that electron concentration changes of the order observed in the 2DEG structures are capable of changing the Fermi level such that the emission peak changes as in Fig. 4. Assuming that $E_0 = 1.458$ eV by comparing Eqs. (1) and (2), then the energy of the ground state (referenced to the bottom of the conduction band) can be deduced to be 0.036 eV. This value is comparable to that previously reported for AlGaAs/GaAs[7] heterostructures.

A near-room-temperature photoluminescence emission band at 830 nm has been observed in AlGaAs/GaAs modulation-doped heterostructures. The emission band was observed only in heterostructures with a 2DEG quantum well and was explained in terms of excitonic recombination at the single heterojunction quantum well. This effect was observed in both MBE and OMVPE grown materials. The luminescence intensity increased with the mobility of the 2DEG and appeared to be indicative of the quality of the 2DEG quantum well. This luminescence peak may therefore be useful as a preliminary identifier of AlGaAs/GaAs heterostructures with device quality 2DEG channels.

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[1]R. Dingle, W. Wiegmann, and C. H. Henry, Phys. Rev. Lett. **33**, 827 (1974).

[2]S. Hiyamizu, J. Saito, K. Nambu, and T. Ishitawa, Jpn. J. Appl. Phys. **22**, L609 (1983).

[3]L. L. Chang, H. Esaki, C. A. Chang, and L. Esaki, Phys. Rev. Lett. **38**, 1489 (1977).

[4]K. Lee, M. S. Shur, T. J. Drummond, and H. Morkoç, IEEE Trans. Electron Devices **ED-30**, 207 (1983).

[5]P. M. Frijlink and J. Maluenda, Jpn. J. Appl. Phys. **21**, L574 (1982).

[6]F. Y. Juang, Y. Nashimoto, and P. Bhattacharya, J. Appl. Phys. **58**, 1986 (1986).

[7]S. Dhar, W. P. Hong, P. K. Bhattacharya, Y. Nashimoto, and F. Y. Juang, IEEE Trans. Electron Devices **ED-33**, 698 (1986).

[8]C. Hamaguchi, K. Miyatsuji, and H. Hihara, Jpn. J. Appl. Phys. **23**, L132 (1984).