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Density-dependent band-gap renormalization of one-component plasma in $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ single quantum wells

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We report the results of a photoluminescence investigation on *n*-type modulation-doped $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ single quantum wells which are intentionally doped in the well center with Be acceptors. Strong collective recombinations of the two-dimensional electron gas with different k states up to the Fermi edge and localized holes bound to ionized acceptors are observed. By using an electron-transfer effect, the density-dependent band-gap renormalization of an electron one-component plasma in a quantum well is quantitatively measured. Experimental results are compared with existing theory.

The investigation of optical properties of the two-dimensional electron gas (2DEG) in modulation-doped quantum wells (MDQW's) has recently attracted great attention.[1-5] An important question from both experimental and theoretical points of view is the dependence of band-gap renormalization (BGR) on carrier concentration in two-dimensional systems.[6-12] Up to now, several methods, namely, line-shape fitting, pump and probe, and gain-absorption crossover measurements, have been used to determine the dependence of BGR on the concentration of the quasi-2D electron-hole two-component plasma. However, only a few experiments have been done to understand the dependence of BGR on the carrier concentration of a 2DEG (one-component plasma). The knowledge of this dependence will provide information on the correlation between electrons and holes in a two-component plasma.[13] Due to the k-selection restriction in the recombination processes it is not possible to study the 2D density of states and relevant ground-state parameters of a 2DEG in a QW *directly* by means of photoluminescence (PL) experiments.

In this paper we present a different method to study the properties of 2DEG in symmetrically (both sides) modulation-doped single-quantum wells (MDSQW's) by conventional PL measurements. In contrast to the case of asymmetrically (one side) modulation-doped SQW,[13] the energy levels in symmetrically modulation-doped SQW are well defined and almost density independent. These features are very important for giving an exact unperturbed band gap. The basic idea of our method relies on a controlled hole-localization mechanism in *n*-type MDSQW's obtained by slightly doping the central region of the well with Be acceptors. The localization of photogenerated holes by ionized Be acceptors lifts the k-selection restriction and makes it possible to obtain the whole energy spectrum of the 2DEG from PL measurements. By taking advantage of an electron-transfer effect, the renormalized band gap and the Fermi energy, which corresponds to the electron sheet concentration, can be simultaneously determined. Our results demonstrate a well reproducible way to study the optical processes involving all the electrons in the 2DEG and its density-dependent BGR.

The samples used in the present study were grown lattice matched on semi-insulating Fe-doped InP substrates by molecular-beam epitaxy (MBE). A five-period (4-nm $Ga_xIn_{1-x}As$)/(4-nm $Al_yIn_{1-y}As$) superlattice and a 250-nm $Al_yIn_{1-y}As$ layer were first grown as buffer layers, and then an *n*-type symmetrically modulation-doped SQW consisting of 20 nm spacer layers and 33-nm Si-doped $Al_yIn_{1-y}As$ barrier layers at each side of the well was deposited. Finally, 20-nm $Al_yIn_{1-y}As$ and 1-nm $Ga_xIn_{1-x}As$ followed as cap layers. In the center of the well a 6.3-nm-wide region was doped with Be acceptors to a level of about 3×10^{16} cm^{-3}. The Be doping level has to be chosen carefully to provide effective hole localization without strong degradation of the 2DEG mobility. The observation of enhanced Pendellösung fringes in the x-ray-diffraction patterns of the investigated samples indicates the excellent structural perfection of the epilayers.[14]

First we concentrate on two $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDSQW samples, having electron sheet concentrations of 1.2×10^{12} cm^{-2} in a 10.5-nm-wide well (sample *a*) and of 1.7×10^{12} cm^{-2} in a 13.0-nm well (sample *b*). The electron sheet concentrations are determined from Shubnikov-de Haas oscillations of magnetoresistance measurements performed at 2.2 K after illumination with a light-emitting diode. The red line (647 nm) of a Kr^+ laser is used as the excitation source for PL experiments. The highest excitation density used in our experiments is adjusted to keep the photogenerated carrier density at least 1 order of magnitude lower than the 2D electron density.

Typical PL spectra obtained from samples *a* and *b* under different excitation intensities at 6 K are shown in Fig. 1. The luminescence line shapes exhibit flat plateaus and abrupt cutoffs at both the renormalized band gaps and the Fermi energies. These features reflect the well-known steplike 2D density of states in the QW. We therefore attribute the observed luminescence to the collective recombination of all electrons with $k=0$ up to the $k=k_F$ (Fermi wave vector) in 2DEG and holes bound to the ionized Be acceptors in the well. A strong support of our assignment comes from magnetoluminescence measurements performed using magnet field up to 10 T.[15] In a magnetic field the flat luminescence band splits into distinct Landau peaks, which clearly reflects the 2DEG origin of the luminescence band. The lifting of the Landau-level selec-

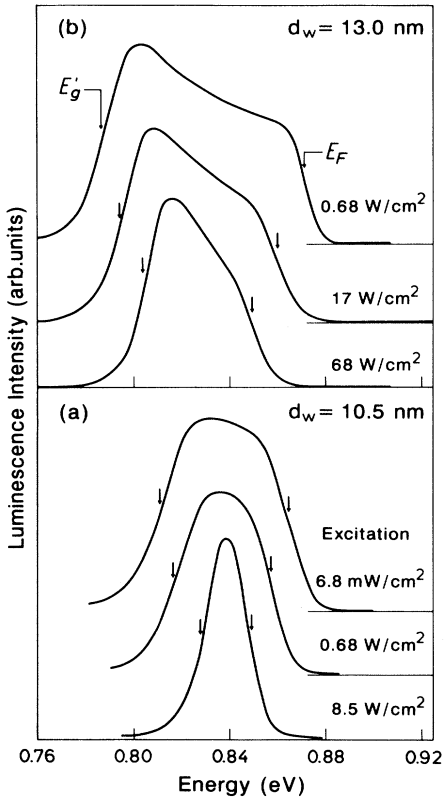

FIG. 1. Excitation-dependent photoluminescence spectra of $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDSQW with a well width of (a) 10.5 nm and with a well width of (b) 13.0 nm at 6 K.

tion rule in magnetoluminescence spectra strongly indicates the localization of the photogenerated holes. Unlike the present case, in conventional MDQW's the line shape of the intrinsic PL spectra is rather sharp,[1-3] because only those electrons near $k=0$ are involved in the optical processes due to k-selection restriction.

With the assumption of k nonconserving transitions and a constant transition matrix element, the luminescence line shape of 2DEG is a rectangular Fermi function near 0 K. This is actually observed in the investigated samples. The PL spectra [Fig. 1(a)] are rectangular bands having some broadening at both the high- and low-energy sides. In Fig. 2 we plot the measured PL energy bandwidths versus the electron concentrations determined directly from Shubnikov-de Haas oscillations of magnetoresistance measurements. The solid line in Fig. 2 gives the Fermi energy (E_F^1) according to the relation $E_F^1=E_F-E_{e1}=n_e h^2/(4\pi m_e^*)$, in which E_{e1}, E_F, n_e, and m_e^* are the first electron-subband level, the Fermi level, the electron sheet concentration, and the electron effective mass, respectively. The m_e^* used in our calculation is $0.053m_0$ determined from our cyclotron resonance measurements.[15] Inspection of Fig. 2 reveals that the experimental results are in good agreement with the calculated curve. This finding provides a way to determine the electron concentration by simply measuring the luminescence energy bandwidth and is the base of our method to measure the density-dependent BGR of an electron one-

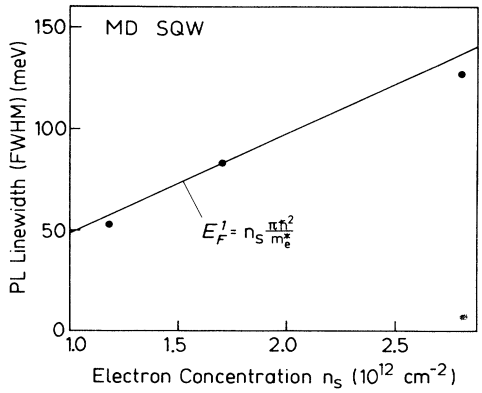

FIG. 2. Measured PL energy bandwidths and 2D electron concentrations for MDSQW's. The solid line gives the value calculated by using the strict 2D density of states.

component plasma. Next we will go back to Fig. 1 and show how the density-dependent BGR in a QW can be experimentally determined.

When the photoexcitation density is increased, the spectra in Fig. 1(a) clearly show a progressive narrowing of the linewidth. A similar effect has been observed in asymmetrically modulation-doped SQW's or heterojunctions.[13,16,17] At first glance this finding is hard to understand. Actually, it results from an electron-transfer effect. From the energy-band diagram of Fig. 3 we see that the photogenerated electron-hole pairs in the barrier layers are separated by the strong electric field. Due to the thick spacer layers (20 nm) and very-high-energy barriers at the well interfaces (380 meV) the photogenerated electrons are driven away from the well, while the corresponding holes are driven into the well. These holes recombine with the electrons in the well thus causing the reduction of the 2DEG concentration, namely, the narrowing of the linewidth.

When the electron concentration decreases as a result of the increase of photoexcitation density [shown in Fig. 1(a)], the renormalized band gap (E_g') shifts to higher energy. This energy shift simply reflects the reduction of the electron-electron exchange and correlation interactions.

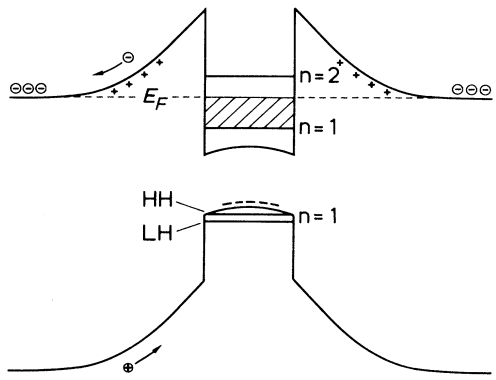

FIG. 3. Schematic energy diagram of the investigated MDSQW samples.

The same measurements applied to sample *b* [Fig. 1(b)] reveal the identical effect. The electron concentration in the well can be reduced from 1.7×10^{12} cm^{-2} to 9×10^{11} cm^{-2} when the excitation density is increased from 0.68 W/cm^2 to 68 W/cm^2.

Monitoring the renormalized band gap E_g' as a function of the electron concentration determined by the PL bandwidth, we easily obtain the density-dependent BGR. The band gap (E_0) of bulk $Ga_xIn_{1-x}As$ lattice matched to InP:Fe substrate is 0.804 eV,[18] which agrees well with the data obtained from our bulk $Ga_xIn_{1-x}As$ samples. The electron (E_{e1}) and heavy-hole (E_{h1}) energy levels for the first subbands in the well are calculated by using a simple finite quantum-well model.[19] The binding energy of holes by the ionized Be acceptors in 2DEG (E_{Be}) is determined to be 12 meV from the temperature-dependent PL measurements.[15] Taking all these contributions into account, the unperturbed band gap of the SQW, $E_g=E_0+E_{e1}+E_{h1}-E_{Be}$, is determined to be 0.829 eV for sample *a* and 0.814 eV for sample *b*. For simplicity, the band bending in the well has not been considered because it has only a minor influence on the electron energy level in thin QW's.[5]

In Fig. 4 the BGR, i.e., $\Delta E=E_g'-E_g$, is plotted as a function of the electron concentration. The error in the experimental data results from the slight composition fluctuation of $Ga_xIn_{1-x}As$. The solid curves in Fig. 4 are the theoretical calculations of the electron-density dependence of BGR with different hole- and electron-density ratios (n_h/n_e) for the strict 2D case after Ref. 12. The finite well width of a real QW structure (a quasi-2D case) partially restores the validity of the *strict* 2DEG assumption used in the theoretical calculation, and reduces the absolute value of the BGR. It has been demonstrated that if

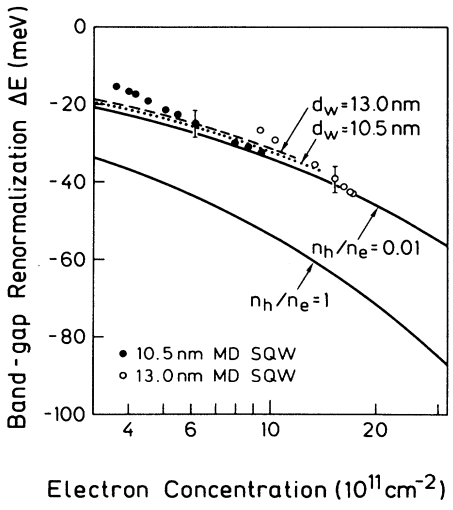

FIG. 4. Band-gap renormalization (ΔE) as a function of the 2D electron concentration. The ● and ○ represent the data of sample *a* with 10.5-nm well width and of sample *b* with 13.0-nm well width, respectively. The dotted and dashed lines correspond to the corrected quasi-2D density dependence of BGR for the 10.5 nm and 13.0 nm wells, respectively.

the density dependence of BGR is expressed in terms of quasi-2D rydberg (excitonic binding energy) and the quasi-2D interparticle distance r_s^* (excitonic Bohr radius), one can obtain one-parameter universality.[12] Therefore, we assume that the calculated curve (the solid line in Fig. 4) for a strict 2D electron one-component plasma is identical to that for a quasi-2D one, when the energy and length units for the ordinate and abscissa are expressed in terms of rydbergs and Bohr radii, respectively. The quasi-2D Bohr radius a_B^* is defined to be $e^2/[8\pi\varepsilon_0\varepsilon_r E(L_z)]$, where $E(L_z)$ denotes the excitonic binding energy for a QW with finite width L_z. By using the 2D rydberg of 10.8 meV and quasi-2D rydbergs of 7 meV and 6.5 meV for 10.5-nm and 13.0-nm $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ QW's, respectively, we plot the corrected quasi-2D density-dependent BGR in Fig. 4. The well width dependence of the BGR is obvious. The larger the well width, the smaller the absolute reduction of the band gap. From Fig. 4 one can see that the measured data are in agreement with the calculated curves within experimental error. At the low-concentration range, $4\text{-}6\times10^{11}$ cm^{-2}, the measured BGR of electron one-component plasma is around half of the calculated BGR of a two-component plasma ($n_h/n_e=1$), while at higher concentrations the measured BGR becomes larger than half of that of two-component plasma. This finding implies that at high concentration the electron-electron exchange and correlation interactions become stronger. It is important to point out that even in this case for which few holes are present, the valence band is still renormalized.[20] Therefore, we cannot simply attribute the measured BGR of the one-component plasma only to the contribution of electrons.

Due to the advantage of our method, namely, the ability to determine the band gap and the electron concentration simultaneously in a single sample, the tendency of the density-dependent BGR is accurately determined. Careful inspection of Fig. 4 reveals that when the 2DEG concentration increases, the measured BGR has a larger slope than the theory predicted. This discrepancy in slope can be understood qualitatively in terms of electron-phonon interaction. The cited calculation for a strict 2D case was done within the ε_0 approximation,[21] which would become less appropriate with increasing carrier density since the Fermi energies become comparable to the LO-phonon energy.[12,21] In our samples the Fermi energies (53 and 75 meV for samples *a* and *b*, respectively) are larger than the LO-phonon energy (32 meV) of $Ga_xIn_{1-x}As$.[22] The interaction between electrons and phonons is thus expected to be rather strong.[12] As a result, the measured density-dependent tendency should be stronger than the calculated one.

In conclusion, collective recombinations of 2DEG and localized holes bound to ionized Be acceptors have been observed in *n*-type MDSQW's. By changing the optical excitation density the electron density in the well can be tuned over a wide range. Taking advantage of this effect, we have measured quantitatively the electron-density dependence of BGR in single-quantum wells. The absolute value of the BGR of a one-component plasma is around half of the calculated one of a two-component

electron-hole plasma at the concentration of $4-6\times10^{11}$ cm^{-2}. At higher concentration it becomes larger than half of the calculated one of two-component plasma. The discrepancies in slope between the measured data and the theoretical curves have been qualitatively discussed. The dependence of BGR on well width has also been observed: The wider the well, the smaller the absolute BGR.

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