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Effect of hole-localization mechanisms on photoluminescence spectra of two-dimensional-electron-gas systems

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Optical spectroscopy on a series of *n*-type modulation-doped $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single quantum wells reveals that the Fermi-edge singularity in luminescence occurs only if localization of photogenerated holes leads to positively charged centers. If the hole localization yields electrically neutral centers, no intensity enhancement of the luminescence near the Fermi edge is observed. The different nature of the hole-localization mechanisms consistently explains previous discrepancies in both the low-temperature luminescence and absorption spectra of Si metal-oxide-semiconductor field-effect transistors as well as of modulation-doped $GaAs/Al_xGa_{1-x}As$, $Ga_xIn_{1-x}As/InP$, and $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ quantum wells and heterostructures.

Theoretical and experimental studies of the photoluminescence (PL) and optical absorption in modulation-doped quantum wells (MDQWs) have revealed a strong enhancement in the oscillator strength of the optical transitions involving the electron states near the Fermi edge. That so-called Fermi-edge singularity (FES) results from correlation enhancement due to electron-hole multiple scattering.[1-9] This feature was observed in the optical-absorption spectra of both $GaAs/Al_xGa_{1-x}As$ (Refs. 3 and 4) and $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDQWs.[5,6] However, as for PL experiments, the Fermi-edge singularity was detected only in the spectra of the MDQWs and heterostructures having ternary material (such as $Ga_xIn_{1-x}As$) as active layer[2,8] or of $GaAs/Al_xGa_{1-x}As$ MDQWs with strong well-width fluctuations.[9] In $GaAs/Al_xGa_{1-x}As$ MDQWs of high structural perfection it was not possible to detect the radiative recombination involving the electrons near the Fermi edge due to the lack of appropriate hole-localization mechanisms in the binary GaAs well.[10] The detailed investigations of radiative recombinations of the two-dimensional electron gas (2DEG) both in Si metal-oxide-semiconductor field-effect transistors[11] (MOSFETs) and in $GaAs/Al_xGa_{1-x}As$ MD heterostructures[12] have clearly shown that no such enhancement exists in their PL spectra, although in these cases the localization of photogenerated holes allows electrons near the Fermi edge to recombine radiatively with the photogenerated holes. At a first glance, these two categories of PL results seem to contradict each other, and yet no explanation for this discrepancy has been given.

In this paper, we present a consistent explanation of the existing observations and of experimental results, based on detailed PL and magnetoluminescence investigations on a series of specially designed $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDSQWs with different hole-localization mechanisms. The essential condition for the existence of the FES in the PL spectra is that the localization of the photogenerated holes leads to electrically charged positive centers. If the localization of the photogenerated holes results in electrically neutral centers, no enhancement is induced for the oscillator strength of the recombination of electrons near the Fermi edge. Combined with magnetoluminescence experiments, our results and arguments provide an insight in the nature of the FES and clarify previous contradictory experimental results.

The samples used in the present investigation were grown lattice matched on semi-insulating Fe-doped InP substrates by molecular-beam epitaxy. The layer sequence and doping profile of them are the following: A five periods 40-Å $Ga_xIn_{1-x}As$/40-Å $Al_yIn_{1-y}As$ superlattice (SL) and 2500-Å $Al_yIn_{1-y}As$ are first grown as buffer layers. Then the *n*-type symmetrically modulation-doped SQW, which consists of 200-Å spacer layers and 330-Å Si-doped $Al_yIn_{1-y}As$ barrier layers on each side of the well, is deposited. For sample 1, 2, and 3 the central 63-Å region of the well is doped with Be acceptors at a doping concentration of $\sim 3\times 10^{16}$ cm^{-3}. For sample 4 the well region is not intentionally doped. The well widths of 1, 2, 3, and 4 are 105, 130, 90, and 100 Å, respectively. The 2D electron sheet concentrations in the well for samples 1, 2, 3, and 4 are 1.2×10^{12} cm^{-2}, 1.7×10^{12} cm^{-2}, 2.8×10^{12} cm^{-2}, and 2.3×10^{12} cm^{-2}, respectively, as determined from the Shubnikov-de Haas oscillations of magnetoresistance measurements under illumination. In all samples only one subband is occupied.

The PL spectra of samples 1, 2, and 3 at low temperature are plotted in Fig. 1. Low optical excitation densities of 100 mW/cm^2 are used for the measurements in order to avoid heating of the electrons as well as the variation of their concentration. Under such excitation conditions only 2.5×10^{8} cm^{-2} nonequilibrium holes are generated, which are much less than the density of the existing 2DEG. In all spectra the luminescence intensity increases rapidly on the low-energy side. Then, the luminescence intensity remains almost unchanged as the detection energy goes up until a sharp Fermi cut-off occurs. This behavior simply reflects the constant 2D density of states. Both sides of the steplike PL spectra, different from the shape of the Fermi function at low temperature, are broadened. This broadening results from alloy fluctuations and an increase of electron temperature of the high concentration 2DEG. The energy bandwidth of the luminescence spectra is a linear function of the corresponding electron sheet concentration. Temperature dependent PL measurements

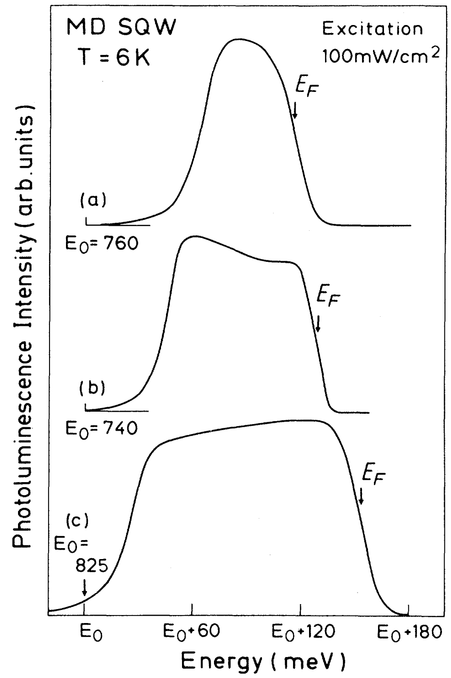

FIG. 1. Photoluminescence spectra of $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDSQWs with Be doping in the central region of the well. The electron sheet concentrations and the energy bandwidths of the PL spectra for samples *a*, *b*, and *c* are 1.2×10^{12} cm^{-2}, 1.7×10^{12} cm^{-2}, and 2.8×10^{12} cm^{-2} and 52.2, 85.0, and 129 meV, respectively.

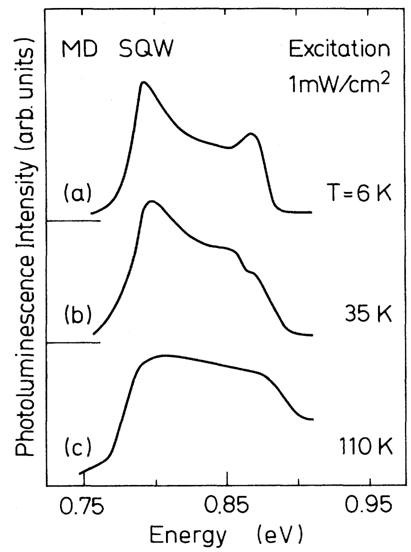

FIG. 2. Temperature-dependent photoluminescence spectra of the 100-Å $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDSQWs without Be doping in the central region of the well (sample 4). The full width at half maximum is 96 meV, much smaller than the energy separation (148 meV) of the first and second electron energy levels.

of sample 1 reveal that the localized photogenerated nonequilibrium holes are totally thermalized above 180 K.[13] These findings and also our magnetoluminescence results[13] clearly indicate that the radiative recombinations involve all electrons with different *k* from zero up to the Fermi edge with photogenerated holes bound to ionized Be acceptors which are incorporated intentionally in the central region of the well. It is obvious to detect the absence of any intensity enhancement near the Fermi edges simply by comparing the spectra of Fig. 1 with those of Fig. 2 as well as those in Ref. 2. The slight increase in intensity of the PL plateau versus the detection energy of spectrum *c* is not universal. Other samples with identical structure and similar electron concentration show the opposite behavior.

For a direct comparison, we now turn to the luminescence results obtained from the $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDSQW (sample 4), having no intentional acceptor doping in the central region of the $Ga_xIn_{1-x}As$ well. Its temperature dependent PL spectra of Fig. 2 obtained under identical optical excitation density show that at 6 K (spectrum *a*) a peak with a sharp low-energy tail appears at the low energy side of the spectrum. When the detecting energy goes up, the PL intensity decreases slowly. Before reaching the low-temperature Fermi cut-off, a strong enhancement in the intensity occurs. When the sample temperature increases, this enhancement splits into two features (spectrum *b*). It smears out at 35 K and disappears when the sample is heated to 110 K. We attribute these features to the weak localization of photogenerated nonequilibrium holes by the inherent alloy disorder and by well-width fluctuations of the $Ga_xIn_{1-x}As$ well. This kind of weak localization of nonequilibrium holes only partly relaxes the *k*-selection rule and allows them to recombine with electrons at all occupied *k* states up to the Fermi edge. Different from the case of Fig. 1, here the oscillator strength is obviously *k* dependent. The temperature behavior shows that the intensity enhancement depends strongly on the sharpness of the Fermi edge. Actually, the intensity enhancement near the Fermi edge at low-temperature resembles the expected characteristics of FES, which results from the strong correlation and multiple scattering of electrons near the Fermi edge by the localized holes.[1,2] It is also worth noting that luminescence involving the second electron subband does not exist in our case because the observed spectral linewidth of 96 meV is much smaller than the separation (148 meV) of the first and second electron levels.

In Fig. 3 we show the excitation-density dependence of the luminescence of sample 4. When the optical excitation density is low (<0.5 W/cm^2), the shape of the PL spectrum *a* is almost independent of the excitation density. When the excitation density increases to 5.5 W/cm^2, the enhancement at the Fermi-edge decreases (spectrum *b*) due to the increase of photogenerated nonequilibrium holes and eventually disappears under an optical excitation density larger than 55 W/cm^2 (spectrum *c*), corresponding to a density of 3×10^{11} cm^{-2} nonequilibrium holes. This finding agrees with the behavior of the FES in absorption spectra of $GaAs/Al_xGa_{1-x}As$ MDQWs under different excitation densities,[7] hence supporting our previous assignment.

From the described experimental results we can directly

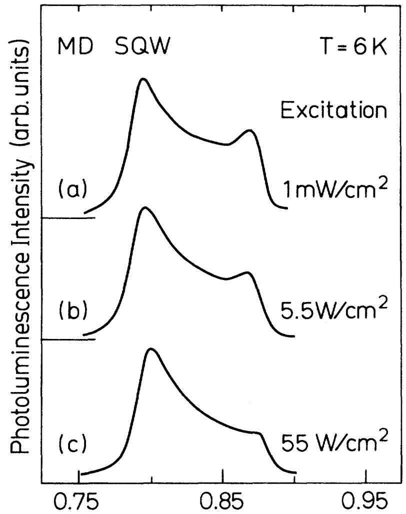

FIG. 3. Excitation-density dependence of photoluminescence spectra of MDSQW without Be doping in the center region of the well. At the excitation density of 55 W/cm^2 (spectrum c) the photogenerated nonequilibrium hole concentration is about 3×10^{11} cm^{-2}.

relate the difference in the PL spectra to the different localization mechanisms in the MDSQWs. Previous experimental results have shown that the FES exists only in the PL spectra of MDSQW in which the photogenerated holes are localized by alloy disorder[2] and/or by well-width fluctuation.[9] In contrast, no such enhancement is observed in the PL intensity of those 2DEG systems where the photogenerated holes are bound to ionized acceptors.[11,12] This finding provides direct evidence for the different nature of the localization mechanism. In the MDSQWs doped with Be acceptors in the central region of the well, after being photogenerated the holes relax to the top of the valence band and are bound to the ionized Be acceptors. These localization centers, the ionized acceptor and hole pairs, are electrically neutral. But in the case of other localization mechanisms, such as alloy disorder,[2] well-width fluctuation,[9] or interface roughness,[8] the localization of the holes results in positively charged centers. These centers are spatially located in the 2DEG region and hence attract the electrons around them through Coulomb interaction. However, it is difficult for an electron with a k state far below the Fermi edge just to move towards the positively charged center to screen it, because the electron cannot be scattered to other electron states below the Fermi edge at low temperature due to the exclusion principle. As a result, only the electrons near the Fermi edge have a larger probability to be scattered to other empty k states above the Fermi edge, or in other words, to be attracted by the hole and to move to it. In fact, due to the strong electron-electron correlation at low temperature, the scattering is multiple electron-hole scattering and results in the enhancement of the oscillator strength near the Fermi edge. As for the neutral localization center, they do not exert any Coulomb interaction on the electrons. Therefore, the radiative recombination probabilities for all electrons with localized holes are almost the same without any preference for those electrons near the Fermi edge, resulting in the absence of any enhancement in the intensity of the luminescence spectra.

Our experimental results show exactly the expected behavior, and the given arguments can consistently explain previous experimental results of the optical properties of 2DEG systems.

In $GaAs/Al_xGa_{1-x}As$ MDQWs the FES can be observed in the PL spectra only when strong well-width fluctuations are present.[9] The FES has been observed more clearly in the PL spectra of both $Ga_xIn_{1-x}As/InP$ MDSQWs (Ref. 2) and $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MD heterostructures[8] where alloy disorder and interface roughness localize the photogenerated holes. It is obvious that here the localization center is positively charged. In contrast, in another category of sample configurations, such as Si MOSFETs (Ref. 11) and MD $GaAs/Al_xGa_{1-x}As$ heterostructures,[12] the photogenerated holes are bound to ionized acceptors, resulting in electrically neutral centers. As a consequence, no FES has been observed in the PL spectra of these structures.

However, referring to the absorption spectra of both $GaAs/Al_xGa_{1-x}As$ and $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDQWs, the optical process is different from that of the PL. In this case, the incident photons excite electron and hole pairs instantaneously. The positively charged hole attracts the electrons in the Fermi sea through Coulomb interaction. Due to the strong correlation of electrons at low temperature, multiple scattering of the electrons near the Fermi edge occurs following the above discussion. These processes do not require any localization mechanisms. Therefore, irrespective of the nature of the localization mechanisms, for both $GaAs/Al_xGa_{1-x}As$ and $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDQWs the intensity enhancement in the absorption spectra near the Fermi edge has been observed.[3-7]

As a confirmation of our arguments given above, magnetoluminescence experiments have been carried out on samples 1, 2, and 3.[13] In a magnetic field normal to the layers the luminescence band splits into Landau levels. If charged centers exist, their long-range Coulomb potential can be screened by free electrons. Upon the change of filling of the highest Landau level the strength of screening varies. As a result the line width of the Landau level oscillates via the filling factor.[11] Strikingly, the magnetoluminescence spectra of the MDSQWs doped with Be in the center of the well do not show any such oscillation of the linewidth of the Landau-level luminescence with the magnetic field up to 19 T. This finding demonstrates that no charged long-range-scattering centers exist under illumination. Hence, the localization centers consisting of photogenerated holes and ionized acceptors in the well do not provide extra charge and do thus not induce any electrical screening effect through Coulomb interaction. The dominant scattering mechanism here is the short-range scatterings of alloy and interface roughness. These scattering centers are also electrically neutral. These magnetoluminescence results support our previous arguments on the different localization mechanisms in MDSQWs.

In summary we draw the following conclusions. First, the luminescence of MD heterostructures and QWs involving electrons near the Fermi edge can be observed only when some localization mechanism exists which localizes the photogenerated nonequilibrium holes and lifts the k-selection restriction. Second, different hole-localization mechanisms play a very important role to determine the actual line shape of the PL spectra. The FES in the PL spectra can be observed only when the localization of the photogenerated nonequilibrium holes creates electrically charged positive centers. Third, the ionized acceptors are very efficient to bind holes. After becoming electrically neutral, no screening effect will be induced. Fourth, due to the different optical processes the FES can be observed in the optical absorption spectra of both $GaAs/Al_xGa_{1-x}As$ and $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ MDQWs regardless of the localization mechanisms.

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