Optical control of the two-dimensional electron-gas density in single asymmetric quantum wells: Magnetic-field effect

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The effect of a magnetic field on the optical-assisted charge-transfer mechanism in a GaAs/$Ga_{1-x}Al_xAs$ single asymmetric quantum well (SAQW) is investigated. In a 150-Å-thick asymmetric quantum well the maximum photoluminescence blueshift observed at low temperature (2 K) was 10.3 meV at zero field (9.0 meV at 2.53 T). The flat-band condition of the SAQW under zero field is achieved at 0.1 W/cm^2 while 1 W/cm^2 is required to reduce the two-dimensional electron-gas (2DEG) density from 4×10^{11} cm^{-2} down to zero at 2.53 T. The difference in the maximum blueshift is discussed in terms of the field dependence of the 2DEG density, while the difference in the optical excitation required for the saturation condition is explained in terms of inter-Landau-level transition mediated by acoustic phonons. [S0163-1829(99)02327-9]

Single asymmetric GaAs/$Ga_{1-x}Al_xAs$ quantum wells (SAQW's) were first introduced in the past decade and since then they have been used as ideal systems to investigate many of the fundamental aspects concerning the properties of one-component two-dimensional (2D) carrier plasmas.[1] Fundamental aspects, such as many-body effects in two-dimensional one-component carrier plasmas,[2] dimensionality crossover,[3] and Fermi-edge singularity,[4] depend upon the 2D carrier gas density and may represent just a short list of the subjects investigated using SAQW. The typical growth profile used to obtain the *n*-type doped SAQW consists of a short-period superlattice, grown on top of an intrinsic epitaxial buffer layer, followed by the asymmetric quantum well, which is covered with the wide-gap undoped spacer layer and terminated with an intentionally *n*-type doped wide-gap layer. This structure has a 2D electron-gas (2DEG) density in the SAQW, which can be continuously varied from zero up to its maximum value, by applying a bias voltage to the *n*-type doped quantum well in a field effect transistor configuration[5] or simply by illuminating the sample.[6] The mechanism proposed to explain the optical control of the 2DEG density, in zero magnetic fields,[7] has been successfully used to explain the negative photoconductivity in modulation-doped and undoped structures as well.[8] In this work, however, we used magnetophotoluminescence (MPL) measurements to investigate the effect of the magnetic field upon the mechanism of the optical control of the 2DEG density in *n*-type doped GaAs/$Ga_{1-x}Al_xAs$ SAQW. We found that the zero magnetic-field mechanism needs to be extended in two different aspects, to account for the experimental results under nonzero magnetic field. The magnetic-field dependence of the tunneling attempt frequency and the magnetic-field dependence of the 2DEG density at very low optical excitation intensity need both to be taken into account.

The established optical control mechanism used to explain the zero-field experiment requires illumination with photons having energy higher than the band gap of the undoped spacer layer.[7] The attention is focused on the electron-hole pairs photocreated in the spacer layer. In the *n*-type doped structure, the photocreated electron initially moves back to the spatially distant donors while the photocreated hole is drifted into the quantum well by the built-in electric field, there recombining with 2D electrons. Later on, the photocreated electron moves from the donor into the quantum well by tunneling through the spacer layer. At a given optical excitation intensity the steady-state 2DEG density (n_s) is lower than the density (n_s^0) at or near zero excitation. The mathematical description of such a steady-state regime takes into account the rate at which the carriers are photocreated, the electron-hole recombination rate inside the well, and the rate at which the electron tunnels through the spacer layer. In the steady-state regime the electron-hole recombination rate is proportional to the optical excitation intensity, i.e., $n_s h \propto I$, where h is the steady-state hole density. In the steady-state regime the electron-hole recombination rate is also proportional to the rate of tunneling of electrons through the spacer layer, i.e., $n_s h \propto (n_s^0 - n_s)\exp(-D\sqrt{n_s})$, where D is the barrier parameter. Indeed, at the steady-state regime, the relationship between the imposed optical excitation intensity and the structure parameters reads[7]

$$I = C(n_s^0 - n_s)\exp(-D\sqrt{n_s}), \tag{1}$$

where C is related to the tunneling attempt frequency. The exponential term in Eq. (1) comes from the calculation of the carrier tunneling current through a triangular barrier with a height proportional to n_s, while the difference $(n_s^0 - n_s)$ represents the out-of-equilibrium carrier density. As far as the experimental results are concerned, a blueshift $(-\Delta E_r)$ in the photoluminescence (PL) spectra as a function of the optical excitation intensity has been usually taken as the signature of the optical control mechanism.[7] Here, the blueshift $(E_r - E_r^0)$ means the difference of the PL peak energy at near-zero optical excitation intensity (E_r^0) and the PL peak energy at a given optical excitation energy (E_r). It has been assumed that both band bending and band-gap renormalization are responsible for the observed blueshift. The contribution to the blueshift due to the band bending goes linearly with the steady-state 2DEG density while the band-gap renormalization depends strongly upon the carrier plasma density according to $(n_s)^\alpha$. The exponent α is related to the

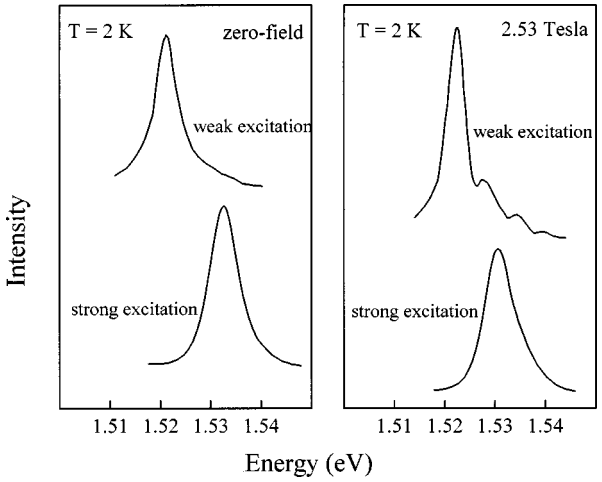

FIG. 1. Typical low-temperature (2 K) photoluminescence spectra taken under low and strong optical excitation intensity at (a) zero field and at (b) 2.53 T. We focus our attention only on the recombination line coming from the SAQW.

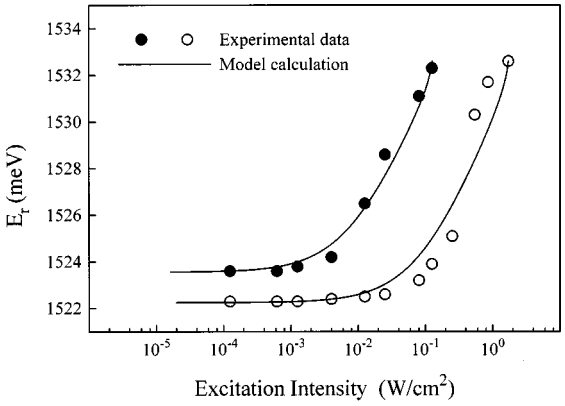

FIG. 2. The SAQW recombination energy versus the excitation intensity at 2.53 T (full circles) and at zero field (open circles). Circles are experimental data while full lines represent the best fitting according to the model discussed in this work.

dimensionality of the system, being $\alpha=\frac{1}{2}$ for 3D carrier plasmas[9] and $\alpha=\frac{1}{3}$ for 2D carrier plasmas.[10] In our case we assume that only the first electron subband is populated, thus leading to the one-third-power dependence for the band-gap renormalization. The 2DEG density dependence of the PL blueshift is given by

$$-\Delta E_r = An_s + B\sqrt[3]{n_s}, \tag{2}$$

where A and B are, respectively, the band bending and band-gap renormalization coefficients. Taking ΔE_r in units of meV and the carrier density in units of $10^{11}\,\mathrm{cm}^{-2}$ the band bending coefficient has been calculated to be on the order of 1 meV cm^2.[11] The band-gap renormalization coefficient (B), on the other hand, can be obtained from the experimental data.

The GaAs/$Ga_{0.65}Al_{0.35}As$ SAQW sample ($W1413$) used in this work presents a 150-Å GaAs asymmetric quantum well that is followed by a 300-Å $Ga_{0.65}Al_{0.35}As$ undoped spacer layer. The structure has a $4.0\times10^{11}\,\mathrm{cm}^{-2}$ 2DEG density at low temperatures and mobility higher than $10^5\,\mathrm{cm}^2/\mathrm{V\,s}$. The sample was cooled at 2 K in an optical superconducting magnet and optically excited above the band gap of the undoped $Ga_{0.65}Al_{0.35}As$, using the 5145-Å argon-ion laser line. The luminescence spectra were recorded as a function of optical excitation intensity (I) using a double monochromator and standard photocounting techniques. The magnetic field was applied parallel to the sample growth direction. Figure 1(a) shows typical low-temperature spectra at zero field, while Fig. 1(b) shows typical low-temperature spectra at 2.53 T. Figures 1(a) and 1(b) show photoluminescence data at zero field and at 2.53 T, respectively. The spectra represent intrinsic E_1-HH_1 band-to-band recombination involving the photogenerated holes and electrons of the 2DEG. Figure 1(a) shows that the PL recombination energy shifts from 1522.3 meV at an optical intensity of about $10^{-4}\,\mathrm{W/cm}^2$ towards saturation at 1532.6 meV, around 1 W/cm^2. Figure 1(b), however, shows that the recombination energy shifts from 1523.6 meV at an optical intensity of about $10^{-4}\,\mathrm{W/cm}^2$ towards saturation at 1532.6 meV, around 0.1 W/cm^2. In Fig. 2 open circles show the optical excitation intensity dependence of the E_1-HH_1 peak energy at zero field while full circles show the optical excitation intensity dependence of the E_1-HH_1 peak energy at 2.53 T. Despite the qualitative similarity observed in the optical intensity dependence of the energy upshift at zero field and at nonzero field there are two quantitative differences. The magnetic field (i) causes the energy upshift saturation to occur at lower optical intensity, here reduced by one order of magnitude, and (ii) reduces the total energy upshift, here around 10%.

Though MPL experiments have been used to study modulation-doped semiconductor heterostructures[12] and semiconductor heterojunctions,[13] the optical control mechanism of the 2DEG density under the action of a nonzero external magnetic field has not been explained. The similarity of the optical excitation intensity dependence of the photoluminescence blueshift in the absence and in the presence of the magnetic field (see Fig. 2) indicates that the optical control mechanism, involving electron-hole photogeneration at the spacer layer, holds in both cases. Under the action of an external magnetic field (H) the 2D-carrier motion becomes Landau quantized. The in-plane quantum confinement of the 2DEG, introduced by the application of a magnetic field parallel to the growth direction, however, alters the effective electron tunneling rate from the un-ionized donors back into the quantum well, while the potential barrier is expected not to be modified. At this point we claim that under the action of a magnetic field a first additional condition has to be imposed, namely, electrons need to find an empty Landau state inside the quantum well in order for the tunneling process be effective. The basic reason for the additional condition lies on the effect of the magnetic field over the 2D density of states (DOS), which switches from a flat profile at zero field to a discrete profile, such as a sequence of Gaussian-shaped distributions, at nonzero magnetic field. As far as the DOS is concerned, the tunneling electron will always find a state to be inside the quantum well at zero field. On the other hand, under the action of a magnetic field, the tunneling electron may hit the quantum well with an energy lying in between two adjacent peaks of the DOS profile, thus having little chance to be effectively transferred into the quantum well, except for the case of an assisted transition to the first available Landau level. The first avail-

able electron state inside the quantum well lies just above the Fermi level, to where the electron will attempt to tunnel. To reach the first empty Landau state in the quantum well a phonon-assisted tunneling process is assumed to occur. We claim that the electron tunnels to an intermediate state lying in between $|N,N_L\rangle$ and $|N,N_L+1\rangle$ and from there to the next empty Landau level $|N,N_L+1\rangle$, where $N=1,2,3,...$ represent electron subbands and $N_L=0,1,2,...$ are Landau quantum numbers. The electron transition rate (W) from the intermediate state, described in terms of adjacent Landau states, is readily calculated at low temperatures, for magnetic fields parallel to the heterostructure growth axis.[14] We claim that only inter-Landau transitions mediated by acoustic phonons are assumed to take place in our case. Roughly speaking, under the action of a magnetic field the total electron transition rate is proportional to the phonon occupancy, where the phonon energy matches the inter-Landau-level spacing ($\hbar\omega_c=e\hbar H/m^*$), i.e., $W(H)\propto\hbar\omega_c/[\exp(\hbar\omega_c/KT)-1]$. Therefore, the electron tunneling attempt frequency [see Eq. (1)] has to be corrected by the total transition rate $W(H)$, which has to approach unity as the external field tends to zero. In other words, $W(H)\rightarrow 1$ as $H\rightarrow 0$, as long as $W_{\rm norm}(H)=(\hbar\omega_c/KT)/[\exp(\hbar\omega_c/KT)-1]$. The temperature in $W_{\rm norm}(H)$ is related to the phonon bath temperature and we call it the average lattice temperature ($T_{\rm latt}$). We then rewrite the expression for $W_{\rm norm}(H)$ as

$$W_{\rm norm}(H)=\frac{\hbar\omega_c/KT_{\rm latt}}{\exp(\hbar\omega_c/KT_{\rm latt})-1}. \tag{3}$$

The optical control mechanism of the 2DEG density in SAQW, including the effect of the applied field, now reads

$$I=C(n_s^0-n_s)W_{\rm norm}(H)\exp(-D\sqrt{n_s}). \tag{4}$$

The MPL blueshift experiments are indeed described by combining Eqs. (2) and (4).

As far as the explanation of the nonzero magnetic-field experiments are concerned the second aspect to be taken into account is related to the maximum blueshift value, as described by Eq. (2). The maximum blueshift obtained from the experiments is related to the 2DEG density at near-zero optical excitation intensity (n_s^0), being very much close to the value obtained by replacing the 2DEG density obtained from transport measurements into Eq. (2). The 2DEG density at near-zero optical excitation intensity (n_s^0), however, depends upon the applied magnetic field. To calculate the magnetic-field dependence of n_s^0 in a SAQW a variational approach was used to solve self-consistently the coupled Schrödinger and Poisson equations, including Hartree and exchange-correlation potentials, in the effective-mass approximation. At this point we observe that the energy levels $E_N^{(N_L)}(H)$ and $HH_N^{(N_L)}(H)$ depend upon H not only explicitly, through the usual Landau ladders, but also implicitly through the magnetic-field dependence of the confinement energies $E_N(H)$ and $HH_N(H)$. The magnetic-field dependence of the confinement energy (E_N,HH_N) arises from the fact that eigenvalues, carrier concentration, and Fermi energy are all H dependent. The coupled $n_s(H)$ and $E_N(H)$ variation is expected to be small at low fields. However, the coupled $n_s(H)$ and $E_N(H)$ variation becomes larger near the magnetic quantum limit ($N_L=0$).[15]

Assuming that the Fermi level lies in the N_Lth Landau level ($N=1$), i.e., $|E_F-E_1^{(N_L)}(H)|\leqslant\sigma$, where $\sigma=\hbar\omega_c/4\sqrt{H}$ is the half-width of the Landau level due to impurity scattering, the magnetic-field dependence of the 2DEG density reads[16]

$$n_s(H)=\frac{n_C}{\sqrt{2\pi}}\left[2(N_L+1)\int_0^1\exp(-x^2/2)dx-\int_Q^1\exp(-x^2/2)dx\right], \tag{5}$$

where

$$Q=4\sqrt{H}\left[\frac{E_F-E_1(H)}{\hbar\omega_c}-\left(N_L+\frac{1}{2}\right)\right],$$

$n_C=eH/\pi\hbar a_B^2$ is the degeneracy factor, and N_L an integer determined by

$$\frac{E_FE_1(H)-\sigma}{\hbar\omega_c}\leqslant N_L+\frac{1}{2}\leqslant\frac{E_F-E_1(H)+\sigma}{\hbar\omega_c}.$$

The fundamental interband transition (E_1-$HH_\cdot$) splits into several lines, which move rapidly to higher energies. As the intensity of the applied magnetic field increases the higher Landau levels are progressively depopulated while the density of states is increased. In particular, the magnetic-field dependence of the 2DEG density is determined by the localized and delocalized density of states. We found that the broadening of the Landau levels also plays a central role in the magnetic-field dependence of the 2DEG density.[16] As a consequence of the applied magnetic field the 2DEG density presents an oscillatory behavior as shown in Fig. 3. At 4.51 T, for instance, the 2DEG density starts to rise. The 2DEG density goes linearly with the applied magnetic from 4.51 T up to 4.59 T, being proportional to $6n_C$. In this range the Fermi energy is located above $E_1^{(5)}(H)$. At 4.59 T $E_1^{(5)}(H)$ is just populated to the peak. A further increase in H beyond 4.59 T results in depopulation of the $N_L=5$ Landau level, which dominates over the increase in density of state as a function of H. Consequently, the carrier concentration decreases. This persists up to 5.60 T when $E_1^{(5)}(H)$ is completely depopulated. The rise that follows is similar to the earlier one except for the Fermi energy, which is now above $E_1^{(4)}(H)$. Indeed, near the magnetic quantum limit ($H=19.0\,\mathrm{T}$) changes on the 2D electron density become larger.[16]

We first emphasize the experimental data at zero field. Equations (1) and (2) were used to fit the zero-field experimental data, represented by open circles in Fig. 2. Coefficients $A-D$ associated with Eqs. (1) and (2) were fitted assuming energy and 2DEG density in units of meV and $10^{11}\,\mathrm{cm}^{-2}$, respectively. The value for the 2DEG density at zero field and very low optical intensity was set at $n_s^0=4.0$, according to previous transport measurement characterization. The solid line going through the open circles in Fig. 2 represent the best fitting with $A=1.0$, $B=4.0$, $C=0.43$, and $D=1.2$. On the other hand, Eqs. (2) and (4) were coupled

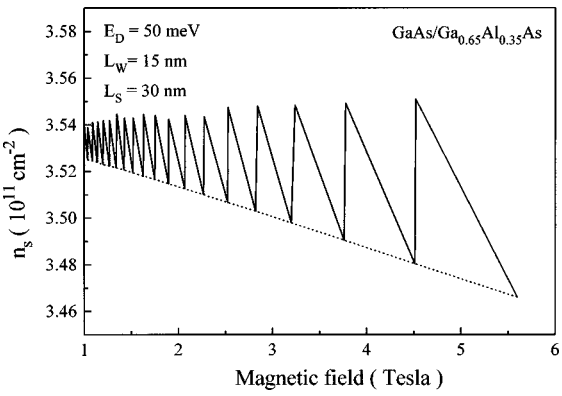

FIG. 3. Magnetic-field dependence of the 2DEG density. The structure parameters correspond to the SAQW of $GaAs/Ga_{1-x}Al_xAs$ used in our experiment.

together to fit the optical intensity dependence of the MPL energy upshift at 2.53 T. Parameters A and C were fixed at their zero-field fitted values ($A=1.0$ and $C=0.43$), once it has been assumed that they are not modified by the application of a magnetic field. Though we have assumed the field independence of the parameter D, it was included in our fitting procedure in order to test the validity of our statement. The solid line going through the full circles in Fig. 2 represent the best fitting of the 2.53-T data with $n_s^0=3.6$, $B=3.6$, $D=1.2$, and $T_{\mathrm{latt}}=13.2$ K. As expected, no change on the fitted value for D at $H=0$ and $H=2.53$ T was observed, suggesting that the geometry of the barrier is essentially the same in both cases. The band-gap renormalization term ($B\sqrt[3]{n_s}$) is slightly reduced ($\sim$1 meV) due to the applied magnetic field, as indicated by the reduction of the B parameter from 4.0 at zero field down to 3.6 at 2.53 T. The n_s^0 value, however, changes from 4.0 at zero field down to 3.6 at 2.53 T. Such a reduction in n_s^0 is in excellent agreement with our calculation, as indicated in Fig. 3. At zero field we found from our calculation $n_s^0=4.15$, while at 2.53 T we found $n_s^0=3.56$, in units of $10^{11}\,\mathrm{cm}^{-2}$ (see Fig. 3). Indeed, the effect of the magnetic field on the optical depletion mechanism would be investigated through the analysis of the field (H) dependence of the blueshift ($-\Delta E_r$), under a fixed optical excitation intensity (I). At intermediate optical excitation intensities an almost linear dependence of the blueshift versus magnetic field has been reported in the literature.[12,13] At fixed excitation intensity such a behavior is described by coupling together Eqs. (2) and (4), through the parametric variable (n_s).

In summary, we investigated the zero and nonzero field band-to-band recombination energy upshift, in an n-type doped $GaAs\text{-}Ga_{1-x}Al_xAs$ SAQW, as a function of the optical excitation intensity. The zero-field model proposed by Chaves *et al.*[7] was extended to account for the nonzero field experiments. The effect of the magnetic field on the 2DEG density was used to explain the reduction of the maximum energy upshift on the order of 10% at 2.53 T. Electron-phonon interaction was assumed to explain the reduction of the optical excitation intensity required to obtain the maximum energy upshift. At 2.53 T the optical excitation intensity required to reduce the 2DEG density, from $4\times10^{11}\,\mathrm{cm}^{-2}$ down to zero, is one order of magnitude lower ($\sim$0.1 W/cm^2) as compared to the zero-field condition ($\sim$1 W/cm^2). The nonzero field model proposed here includes the lattice temperature as a parameter to be fitted from the experimental data. In our case we found the lattice temperature on the order of 13.2 K. Indeed, in the range of our experiment we found that the barrier parameter (D) is field independent, while the dark 2DEG density (n_s^0) and the band-gap renormalization coefficient (B) have both been reduced by about 10%.

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