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At high electric fields, the requirement for light-hole valence-band masses for high-speed p-type digital electronic structures has been well documented.[1] Light-hole masses have been mainly achieved, in layered structures, by the introduction of compressive bi-axial strain in the active quantum layers. This strain is achieved by growing structures with two materials with differing lattice constants, e.g., $In_xGa_{1-x}As$ and GaAs. However, because of interactions between the heavy and light-hole valence-bands, the valence-band masses are nonparabolic. For device applications, the implications that as the carrier density and/or the accelerating electric fields are increased, the band-mass also increases, thereby reducing speed, etc. Thus, in order to be successful, device modeling codes need to take into account band nonparabolicities.

Recently, the conduction- and valence-band energy dispersion curves of modulation doped strained single-quantum-well (SSQW) and lattice-matched single-quantum-well (LMSQW) structures were determined[2-4] by magnetoluminescence measurements. These papers discuss the importance of the energy difference ΔE between the heavy- and light-hole valence-bands in determining the degree of heavy and light-hole mixing. Large ΔE energy differences not only give rise to a small ground-state in-plane light-hole mass, but also reduces the valence-band nonparabolicity.

The energy difference ΔE between the heavy- and light-hole valence bands, due to quantum confinement, in wide ($\approx$ 10 nm) $GaAs/Al_{0.25}Ga_{0.75}As$ LMSQW structures is small and hence the heavy-hole light-hole mixing is large. For these kinds of p-type structures, the in-plane valence-band ground-state is "heavy", e.g., for Fermi energies $E_f > 2$ meV, $m_v \approx 0.35m_0$. However, by reducing the width of the quantum well, the energy difference ΔE can be increased. For example, in $GaAs/Al_{0.25}Ga_{0.75}As$ single quantum wells, the maximum $\Delta E \approx 30$ meV, occurs near a width of 4.5 nm.

In this paper we report the measurement of the conduction and valence-band dispersion curves for n-type SSQW and LMSQW quantum-well structures using magnetoluminescence techniques. The measurements where made in the temperature range of 4 to 76 K and the magnetic field varied between 0 and 6.5 T. The magnetic field direction was parallel to the growth direction, i.e., the Landau orbits are in the plane of the quantum well. With this geometry, all measurements concerning the conduction- and valence-band dispersion curves and masses refer to their *in-plane* values. Data for two representative SSQW and LMSQW structures will be presented and discussed. The SSQW structure (sample BC042: $In_{0.20}Ga_{0.80}As/GaAs$) consisted of a single 80-Å wide quantum well. The heavy and light-hole energy difference ΔE for this structure is about 60 meV and the 2D-carrier concentration and mobility are 5.0×10^{11} cm^{-2} and 2.2×10^4 $cm^2/Vsec$ at 4 K. The LMSQW structure (sample G0260: $GaAs/Al_{0.25}Ga_{0.75}As$) has a 45-Å wide quantum well and as mentioned above, $\Delta E \approx 30$ meV. The 4-K, 2D-carrier concentration and mobility are respectively 6.6×10^{11} $cm^{-2}$and 2.2×10^4 $cm^2/Vsec$. Both structures were grown by molecular beam epitaxy.

For n-type structures, large magnetic fields and low temperatures, only the $n_v = 0$ valence-band Landau level is populated and thus, magnetoluminescence transitions between the conduction-band $n_c = 1, 2, 3, \ldots$ and the valence-band $n_v = 0$ Landau levels are zeroth-order forbidden.[5] At these temperatures (e.g., 4 K), the conduction-band effective mass m_c can be uniquely determined from the n-type samples by analyzing the field dependence of the magnetoluminescence spectra. The interband luminescence transition energy E is given in terms of the bandgap energy E_{gap} and the conduction and valence-band cyclotron energies $\hbar\omega_{c,v} = (2\mu_B H / m_{c,v})$ by

$$E = E_{gap} + (n_c + \tfrac{1}{2})\hbar\omega_c + \tfrac{1}{2}\hbar\omega_v. \qquad (1)$$

For higher temperatures, e.g., 77 K, the $n_v = 0, 1, 2, 3, \ldots$ valence-band Landau-levels are thermally occupied and under these conditions, all transitions are *allowed* and obey the $\Delta n \equiv (n_c - n_v) = 0$ selection rule. For this case, the interband luminescence transition energy E is given by

$$E = E_{gap} + (n + \tfrac{1}{2})(\hbar\omega_c + \hbar\omega_v), \qquad (2)$$

where $n = 0, 1, 2, 3, \ldots$

At low temperatures, the energy difference δE between the $E(n_c+1)$ and $E(n_c)$ magnetoluminescence peaks gives all the necessary information about the conduction band from (1). The measured conduction-band dispersion curves for the SSQW and LMSQW structures are shown in Fig 1. Both dispersion curves are nearly parabolic with $m_c \approx 0.067m_0$ for the SSQW structure and $m_c \approx 0.085m_0$ for the LMSQW sample. The increase to m_c for the LMSQW structure from the bulk value of $m_c \approx 0.067m_0$ to $0.085m_0$ is attributed to the increased bandgap energy by quantum confinement and is in agreement with previous studies.[6,7] The difference in the conduction-band mass m_c between the SSQW and LMSQW samples is simply due to changes to the bandgap energy (compared to their respective bulk values), caused either by quantum confinement and/or strain. These two conduction-band masses have also been verified by cyclotron resonance measurements, on the same samples, with the result that at their respective Fermi energies, $m_c \approx 0.069m_0$ for the SSQW sample and $m_c \approx 0.082m_0$ for the LMSQW structure in good agreement with the aforementioned magnetolumines-

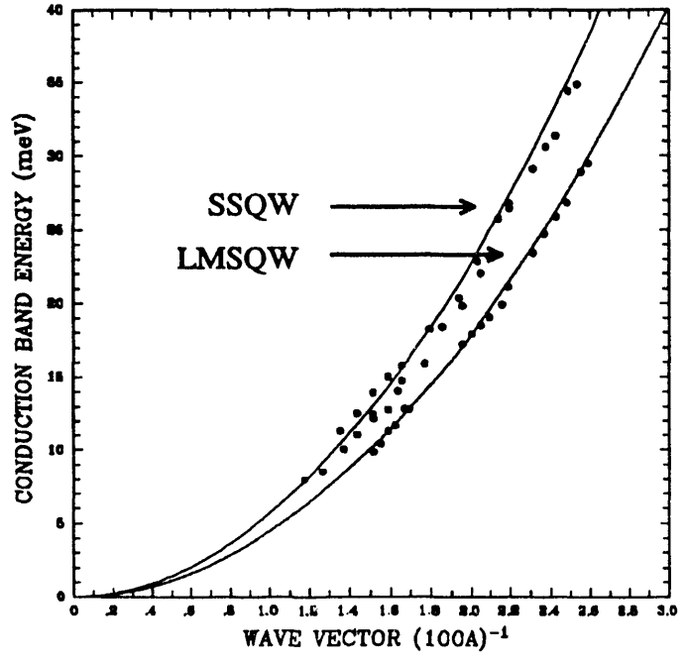

Figure 1. Conduction-band dispersion curves for the SSQW and LMSQW. The solid lines drawn represent parabolic conduction band masses of $m_c \approx 0.067m_0$ for the SSQW sample and $m_c \approx 0.085m_0$ for the LMSQW structure.

cence data. With a knowledge of the conduction-band dispersion curve, the magnetic field dependent valence-band energy can now be derived from high temperature (76 K) data using (2). Figure 2 shows the valence-band dispersion curves for the SSQW and the LMSQW samples as determined by our measurements. The method and justification used for relating the wavevector k to the magnetic field H has been fully discussed by Lyo and Jones.[8] The upper dispersion curve in Fig. 2 is the expected parabolic zone-center mass dispersion curve with $m_v \approx 0.09m_0$. The dispersion curves drawn through the two sets of data are based upon a plane-wave $k \cdot p$ calculation presented by Lyo and Jones.[9] The maximum value of the wavevector of about 3% of the Brillouin zone is determined by the Fermi energy of the conduction bands. From Fig. 2, it is evident that the valence bands are nonparabolic. For the range of data shown in the figure, the valence-band mass for the SSQW structure varies between $0.11m_0$ and $0.22m_0$ However, for the LMSQW structure, at small wavevectors, $m_v \approx 0.15m_0$ and for larger wavevectors, e.g., $E_v \approx 10$ meV, $m_v \approx 0.35m_0$. Also, it is apparent in Fig. 2 that the valence-band dispersion curve for SSQW structure is more parabolic compared to the LMSQW structure's dispersion curve. As previously mentioned, the energy separation ΔE, between the heavy- and light-hole bands is about 60 meV for the SSQW structure and about 30 meV for the LMSQW structure. Magnetoluminescence data[2,3] for other structures, with differing values for ΔE, confirm that as ΔE is increased, the valence bands become more parabolic and the masses become lighter. A maximum value for ΔE of about 75 meV was achieved in a 80-Å wide $In_{0.25}Ga_{0.75}As$/GaAs SSQW.

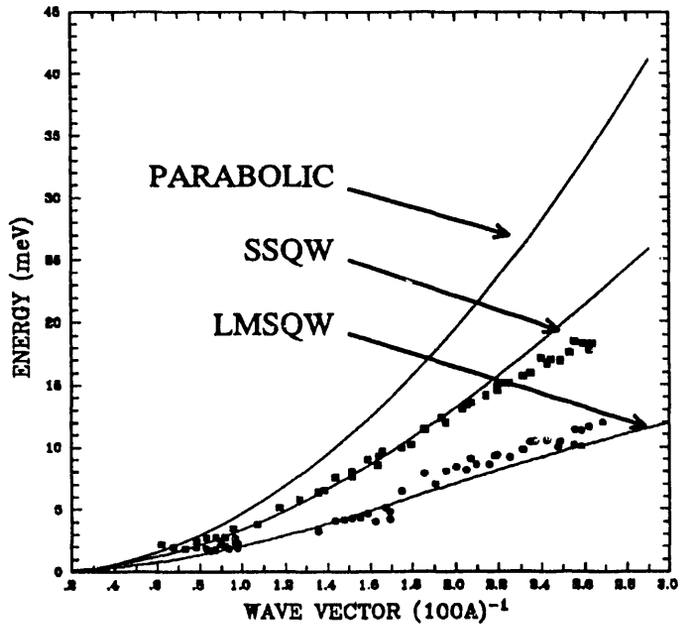

Figure 2. Valence-band dispersion curves for the SSQW BC042 and the LMSQW G0260. The solid line labeled *parabolic* represents the dispersion expected for a mass of $0.09m_0$. The solid curves drawn through the data points result from $k \cdot p$ calculations

Thus in conclusion, using magnetoluminescence techniques, we have shown that the conduction bands are very nearly parabolic while the valence bands are nonparabolic. Furthermore, the ground-state in-plane valence-band masses for a InGaAs/GaAs SSQW and LMSQW GaAs/AlGaAs 4.5 nm are light. The valence-band mass m_v is energy dependent and varies between 0.15 and 0.3 for nominal Fermi energies. The agreement with $k \cdot p$ calculations[9] is good. Thus, with these conduction- and valence-band dispersion curves, it should now be possible to incorporate this kind of data into device modeling codes and hence, take into account nonparabolic effects.

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