Highly anisotropic optical properties of single quantum well waveguides

J. S. Weiner, D. S. Chemla, and D. A. B. Miller
AT&T Bell Laboratories, Holmdel, New Jersey 07733
H. A. Haus
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
A. C. Gossard and W. Wiegmann
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
C. A. Burrus
Crawford Hill Laboratory, AT&T Bell Laboratories, Holmdel, New Jersey 07733

(Received 20 May 1985; accepted for publication 22 July 1985)

The first measurements of the linear and nonlinear anisotropic absorption of light propagating along the plane of a single quantum well are reported and discussed in terms of the structure of the valence band in ultrathin semiconductor layers. Nonlinear optical effects are compared to those of multiple layer structures and to recent theory.

An interesting property of quantum well structures is that, due to the two-dimensional confinement, excitonic effects are greatly enhanced compared to those of bulk material. As a result of this enhancement excitonic absorption has been observed at room temperature in GaAs multiple quantum well structures (MQWS)[1] and more recently in InGaAs/InAlAs MQWS.[2] Room-temperature excitonic resonances in GaAs MQWS's have already been used for high-speed modulators,[3] optical switches,[4] and mode locking of diode lasers.[5] An additional effect due to the reduced dimensionality is that the band-to-band transitions are predicted to be anisotropic for light propagating parallel to the plane of

0003-6951/85/190664-04$01.00

the layers.[6] In particular, the heavy-hole absorption should disappear or at least be significantly reduced for light polarization perpendicular to the layers. This has been proposed as an explanation for the polarization-dependent gain exhibited by quantum well lasers.[7,8] Sooryakumar *et al.*[9] have observed anisotropic photoluminescence from modulation-doped superlattices. So far, however, absorption measurements have only been made at normal incidence[1] in which this polarization is not accessible.

In this letter we present the first measurements of linear and nonlinear quantum well absorption for light propagating along the plane of the layers. In this geometry the optical electric field can be either parallel or perpendicular to the layers. We use a novel structure consisting of a single quantum well (SQW) inside a "leaky" waveguide. We observe the expected strong anisotropy in the excitonic absorption. We have also studied, for the first time in this geometry, the excitonic optical nonlinearities. For light polarized parallel to the layers our results agree well with those obtained using MQWS's with light propagating perpendicular to the layers.[10] We also report the first observation of saturation of the light hole (lh) absorption in the perpendicular polarization configuration for which the heavy hole (hh) exciton is absent. Our results represent the first demonstration that the optoelectronic applications of excitonic effects in quantum well structures can be implemented in integrated optics, with an additional degree of freedom provided by the strong linear and nonlinear dichroism.

The selection rules for absorption depend intimately on the quantum well band structure. The quantum size effect has the symmetry of a uniaxial perturbation, which splits the heavy hole and light hole valence bands at the zone center.[11] These symmetry considerations predict that the lh and hh bands have pure $|3/2, \pm 1/2\rangle$ and $|3/2, \pm 3/2\rangle$ character respectively near $k = 0$. The oscillator strengths of the hh and lh band-to-band transitions are predicted to be 3/4 and 1/4 respectively for electric field vector $\hat{e}$ parallel to the plane and 0 and 1 respectively for $\hat{e}$ perpendicular to the plane.[6] These assignments have been qualitatively verified by spin polarization measurements.[12,13]

The design of the waveguide samples is critical to the success of the experiment. In order that the absorption length be reasonably long, we used a single quantum well (SQW) centered in the waveguide. The attenuation of the light propagating in the waveguide depends upon the amplitude of the optical electric field at the center of the guide. The lowest order guided mode has its maximum amplitude at the center of the guide and will be strongly absorbed; however, any higher order modes and radiation modes of the guide which are excited can have relatively weak field intensities at the quantum well and will therefore be only weakly absorbed. It is important that the waveguide design is such that these modes are stripped off before they reach the detector.

The waveguide structure consists of 1.95 μm of GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice (SL) grown by molecular beam epitaxy on a GaAs substrate. The thicknesses of the GaAs and $Al_{0.3}Ga_{0.7}As$ layers are 39 and 52 Å, respectively. A single 107-Å-thick layer of GaAs is centered in the SL to form a single quantum well. The refractive indices of the SL and substrate were computed using the procedure of Ref. 14 to be $N_{SL} = 3.54$ and $N_s = 3.63$ respectively, where we have neglected the birefringence due to the thinness of the layers, which is legitimate far from the gap of the SL. The principle of the light guiding is as follows. Since $N_{SL} > 1$, the light rays propagating at grazing incidence in the SL undergo total internal reflection at the waveguide/air interface. At the SL/substrate interface the refractive index discontinuity $N_{SL} - N_s$ is negative, so the light rays only experience partial internal reflection, but, if the sample is short enough then guiding can occur. The SL layer therefore behaves as a "leaky" waveguide.[15–17]

The advantages of the leaky waveguide structure are simplicity and ease of control over the lossiness of each mode. According to Ref. 17 the loss of a leaky waveguide is

$$\alpha_s = s^2\lambda^2/2l^3 N_{SL}(N_s^2 - N_{SL}^2)^{1/2}, \tag{1}$$

where $s = 1,2,3,...$ is the mode number, l the thickness of the superlattice layer, λ the light wavelength, and N_{SL} and N_s are the refractive indices of the SL layer and substrate, respectively.

For our sample we calculate that $\alpha_1 = 170\ \text{cm}^{-1}$ and $\alpha_2 = 680\ \text{cm}^{-1}$. From the filling factor of the SQW and the absorption lengths previously measured at normal incidence[1] we estimate that the peak excitonic absorption should be $\alpha_x = 200\ \text{cm}^{-1}$, so the total loss of the lowest order mode, $\alpha_1 + \alpha_x$, is always less than half the loss of the second order mode, α_2. As a result, any light coupled into higher order modes of the waveguide is always more strongly attenuated than that in the lowest order mode.

Light from a tunable Styryl-9 (LDS 821) dye laser was spatially filtered, focused by 6.5 mm focal length lenses to $\sim 1.5\ \mu$m beam radius, and directly coupled into and out of the cleaved sample faces.

The solid and broken lines in Fig. 1 represent the absorption for $\hat{e} \parallel$ plane and $e \perp$ plane, respectively. There is a clear shift in the absorption edge between the two polarizations, which corresponds to the difference between the hh and lh exciton energies. For $\hat{e} \parallel$ plane both the hh and lh exci-

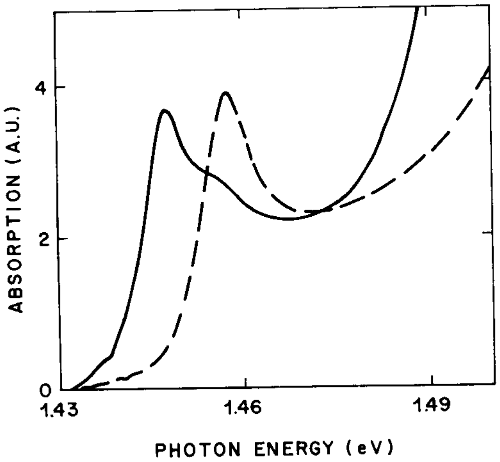

FIG. 1. Room-temperature absorption spectra of a 191-μm-long single quantum well waveguide. The solid and broken curves are for incident polarization parallel and perpendicular respectively to the plane of the layers. The heavy and light hole exciton peaks lie at energies of 1.447 and 1.457 eV, respectively.

tons are present and the spectrum reproduces all the features observed in the usual geometry. For $\hat{e}\perp$ plane only the lh exciton is observed with increased oscillator strength. The absorption coefficient at the exciton peaks is approximately 200 cm^{-1}, which agrees with the estimate cited earlier. The strong increase in absorption at the high-energy side of the spectra is due to the absorption edge of the superlattice which comprises the waveguide. This too shifts with the change in incident polarization.

We have used a semi-empirical line shape model in order to determine the relative oscillator strengths of the excitons in both polarizations.[10] We will denote the oscillator strengths of the hh and lh excitons for $\hat{e}\|$plane and $\hat{e}\perp$plane as hh$_\parallel$, lh$_\parallel$ and hh$_\perp$ and lh$_\perp$ respectively. In Table I the measured ratios of oscillator strengths are compared to those predicted by symmetry. The two sets follow the same qualitative trends, although with some quantitative discrepancies. For example, lh$_\parallel$/lh$_\perp$ and lh$_\parallel$/hh$_\parallel$ are significantly larger than predicted and hh$_\perp$/hh$_\parallel$ is nonzero. These ratios set an upper limit of 30% to the valence-band mixing in the exciton wave function.

Describing the quantum well valence band within the effective mass approximation and accounting for the band discontinuities does predict some mixing of the hh and lh valence bands away from the zone center. Also, the bound state wave function is comprised of a linear combination of single particle states over an area of the two-dimensional Brillouin zone of the order of 1/(exciton area). We find, therefore, that the experimental results are consistent with those obtained by integration of the valence to conduction-band transitions over that part of the Brillouin zone. Let us note that current understanding of the absorption line shape at the lh exciton is poor, so the discrepancies involving the lh oscillator strength may not be significant. Several band structure calculations for quantum well structures have indicated that the effective mass of the $n = 1$ lh subband is infinite or even negative, depending on the composition and well width.[18,19] This would lead to a peak in the joint density of states and hence an increased lh exciton oscillator strength, but there is no evidence of this in our spectra.

We also studied the intensity dependence of the absorption spectra for both polarizations. At high intensities the excitonic absorption saturates. For excitation long compared to the exciton ionization time, the dominant mechanisms are due to free carriers.[10] Previous studies of screening were performed with MQWS's and at normal incidence. In this case carriers in adjacent wells may contribute to the saturation process. Our measurements of a single quantum well represent the first study of absorption saturation in which the carriers are confined in a single layer. The comparison with previous studies provides a means to evaluate the relative importance of interactions within a layer and between adjacent layers in MQWS optical nonlinearities.

TABLE I. Ratios of the oscillator strengths of the exciton peaks for the two incident light polarizations. The theoretical values are based on symmetry arguments and do not include band mixing.

	$\frac{hh_\perp}{hh_\parallel}$	$\frac{lh_\parallel}{lh_\perp}$	$\frac{lh_\parallel}{hh_\parallel}$	$\frac{lh_\perp}{hh_\parallel}$
Theory	0	1/4	1/3	4/3
Experiment	0.05–0.1	0.44–0.56	0.56–0.79	1.1–1.5

The effective intensities producing the saturation in the waveguide were obtained by numerically correcting the incident intensities for the following factors: (i) spreading of the light in the plane of the layers and (ii) the leaky waveguide losses normal to the plane of the layers. Our results for the 64-μm-long sample are shown in Figs. 2(a) and 2(b) for $\hat{e}\|$plane and $\hat{e}\perp$plane, respectively. For $\hat{e}\|$plane both the hh and lh excitons are present at low intensities. For $\hat{e}\perp$plane only the lh exciton is observed. In both configurations as the intensity is increased the excitonic absorption is found to saturate. Our observation for $\hat{e}\perp$plane is the first in which the excitonic nonlinearity is seen in a configuration where only the lh exciton is present. The saturation occurs at the same intensity of approximately 300 ± 200 W/cm^2 in both incident polarizations. The uncertainty is due to the numerical corrections and averaging. This is in agreement with the saturation intensities obtained with MQWS's at normal incidence.

The excitonic saturation in semiconductors is governed by phase-space filling and screening. Due to the exclusion principle the screening consists of the short-range exchange interaction as well as the classical long-range direct screening. In three-dimensional semiconductors the dominant screening mechanism at high temperatures is the long-range direct screening. The observation that saturation effects are the same in SQWS's and in MQWS's shows that they are determined by the carriers in the same layer as the excitons. This indicates that even in multilayer structures direct screening is nearly two dimensional in character and is con-

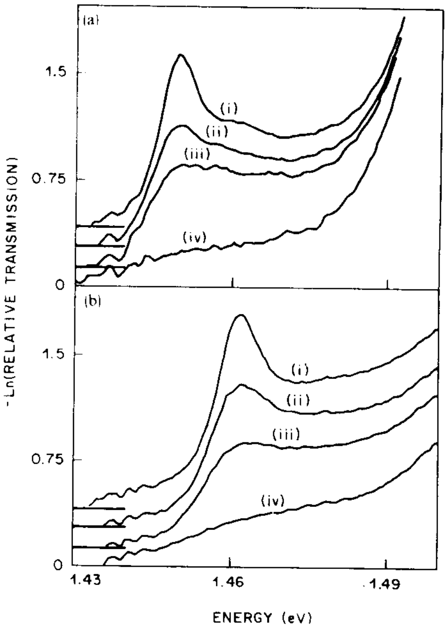

FIG. 2. Single quantum well absorption spectra obtained with incident polarization (a) parallel and (b) perpendicular to the plane of the layers at effective intensities of (i) 0.8 W/cm^2, (ii) 250 W/cm^2, (iii) 800 W/cm^2, and (iv) 8000 W/cm^2. The spectra are vertically offset for clarity.

sequently strongly reduced from the three-dimensional case.[20] It also suggests that exchange interactions may be relatively more important in quantum wells than in three-dimensional semiconductors for the excitonic saturation. Recent theoretical investigations have proposed such a mechanism[21] to explain the dynamics of excitonic saturation at room temperature under femtosecond excitation.[22]

In conclusion, we have observed a large anisotropy in absorption for light propagating along the plane of the layers of a SQW. This effect has potential application to polarization sensitive devices. The large room-temperature nonlinearities that we observe for light propagating along the layers should make possible the development of integrated optical devices such as high-speed modulators, optical switches, and passively mode-locked diode lasers similar to those already demonstrated using light propagating at normal incidence in MQWS's.[3–5] In addition, they provide important information on the basic physical mechanisms involved in linear and nonlinear optical effects in ultrathin semiconductor layers.

[1] D. A. B. Miller, D. S. Chemla, P. W. Smith, A. C. Gossard, and W. T. Tsang, Appl. Phys. B **28**, 96 (1982).

[2] J. S. Weiner, D. S. Chemla, D. A. B. Miller, T. H. Wood, D. Sivco, and A. Y. Cho, Appl. Phys. Lett. **46**, 619 (1985).

[3] T. H. Wood, C. A. Burrus, D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **44**, 16 (1984); T. H. Wood, C. A. Burrus, D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, and W. Wiegmann, IEEE J. Quantum Electron. **QE-21**, 117 (1985).

[4] D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, Appl. Phys. Lett. **45**, 13 (1984).

[5] Y. Silberberg, P. W. Smith, D. J. Eilenberger, D. A. B. Miller, A. C. Gossard, and W. Wiegmann, Opt. Lett. **9**, 507 (1984).

[6] D. D. Sell, S. E. Stokowski, R. Dingle, and J. V. DiLorenzo, Phys. Rev. B **7**, 4568 (1973).

[7] M. Yamanishi and I. Suemune, Jpn. J. Appl. Phys. **23**, L35 (1984).

[8] M. Yamada, S. Ogita, M. Yamagishi, K. Tabata, N. Nakaya, M. Asada, and Y. Suematsu, Appl. Phys. Lett. **45**, 324 (1984).

[9] R. Sooryakumar, D. S. Chemla, A. Pinczuk, A. C. Gossard, W. Wiegmann, and L. J. Sham, J. Vac. Sci. Technol. B **2**, 349 (1984).

[10] D. S. Chemla, D. A. B. Miller, P. W. Smith, A. C. Gossard, and W. Wiegmann, IEEE J. Quantum Electron. **QE-20**, 265 (1984).

[11] J. C. Hensel and G. Feher, Phys. Rev. **129**, 1041 (1963).

[12] R. C. Miller, D. A. Kleinman, W. A. Nordland, Jr., and A. C. Gossard, Phys. Rev. B **22**, 863 (1980).

[13] C. Weisbuch, R. C. Miller, R. Dingle, A. C. Gossard, and W. Wiegmann, Solid State Commun. **37**, 219 (1981).

[14] J. L. Merz, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **30**, 629 (1978); J. P. Van der Ziel and A. C. Gossard, J. Appl. Phys. **49**, 2919 (1978).

[15] E. Garmire, Appl. Phys. Lett. **23**, 403 (1973).

[16] D. B. Hall and C. Yeh, J. Appl. Phys. **44**, 2271 (1973).

[17] H. A. Haus and D. A. B. Miller, IEEE J. Quantum Electron (to be published).

[18] A. Fasolino and M. Altarelli, in *Proceedings of the Third International Winterschool on New Developments in Solid State Physics*, edited by G. Bauer, F. Kuchar, and H. Heinreich (Springer, New York, 1984), Vol. 53, p. 176.

[19] G. D. Sanders and Y. C. Chang (unpublished).

[20] A. L. Fetter, Ann. Phys. **88**, 1 (1974).

[21] S. Schmitt-Rink, D. S. Chemla, and D. A. B. Miller (unpublished).

[22] W. H. Knox, R. L. Fork, M. C. Downer, D. A. B. Miller, D. S. Chemla, C. V. Shank, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **54**, 1306 (1985).

0003-6951/85/190667-03$01.00