Quantum-confined Stark effect in InGaAs/InP quantum wells grown by organometallic vapor phase epitaxy

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(Received 13 October 1986; accepted for publication 11 February 1987)

We report the first observation of the quantum-confined Stark effect in InGaAs/InP multiple quantum wells grown by organometallic vapor phase epitaxy. The effect is observed both in transmission and photoconductivity measurements. The observed spectral shift agrees with the theory.

Quantum well structures, composed of alternate very thin layers of two different semiconductors, show unusual optical properties at room temperatures associated with their remarkable exciton absorption resonances. One affect of particular recent interest is the quantum-confined Stark effect (QCSE).[1,2] In the QCSE, electric fields applied perpendicular to the quantum well (QW) layers can shift the optical absorption edge to lower photon energies with the exciton absorption peaks remaining clearly resolved. This electroabsorptive effect has been applied to make small, high-speed optical modulators,[3,4] and optical switching and signal-processing devices.[5,6] In GaAs/GaAlAs QW, the theory and experiment show very good agreement for QCSE.[1,2,4] It is very important for light wave communications to develop materials able to show this effect in the region of minimum fiber losses (wavelength $\lambda \sim 1.5\ \mu$m). It is also desirable that these materials could be grown on substrates transparent at those wavelengths.

Perpendicular-field electroabsorption has recently been studied in InGaAs[7–11] and GaSb[12,13] QW, both at long ($\lambda \sim 1.5\ \mu$m) and short wavelength ($\lambda \sim 0.95\ \mu$m). The GaSb wells show relatively clear shifts of the exciton peaks with field, characteristic of the QCSE, but the GaSb substrate is unfortunately opaque at the wavelengths of interest. The InP substrate used with long-wavelength InGaAs QW is transparent; however, the electroabsorption that has been reported[8–11] shows large broadening of the exciton peaks with field compared to that reported for GaAs and GaSb QW. There is some shift of the peaks to lower energies with field, but it is comparable to or less than the width of the peaks. Furthermore, the forbidden transitions that should appear when a perpendicular field is applied[4] are not resolved at all. The broadening makes any quantitative test of QCSE theory in this material difficult, and reported comparisons with theory[11] show experimental shifts significantly less than calculations predict. It also limits the practical usefulness of the electroabsorption for light modulation. The scaling of theory to other material systems has also not been successfully proved as far as we are aware. Furthermore, with few exceptions,[14] QW electroabsorption material has been grown by molecular beam epitaxy, and it is practically important to know if other growth techniques can be used.

In this paper, we report the first observation of the QCSE in InGaAs QW with InP barriers in material grown by organometallic vapor phase epitaxy (OMVPE). In contrast to previous InGaAs/InAlAs QW results, the exciton peaks shift strongly with field, we can resolve forbidden transitions, the large broadening of the absorption edge below the gap is absent, and we can make a quantitative comparison with QCSE theory.

The samples were grown in a horizontal OMVPE system at atmospheric pressure. The growth chamber has a run-vent system with very fast switching and low dead volumes as well as other features that allow the growth of QW as narrow as 10 Å with an average roughness of half the lattice constant of InGaAs.[15] The epitaxial layers were grown on a [100] p^+-InP($p = 3\times10^{18}$ cm^{-3}) substrate at 625 °C using trimethylindium and trimethylgallium as sources of group III elements and pure AsH_3 and PH_3 as the group V sources. The doping gases were diethylzinc and H_2S for p and n doping, respectively. Typical growth rates are ~10 Å/s for InGaAs and ~5 Å/s for InP. The InGaAs without intentional doping is slightly n type with small residual concentration of $n_{300\,K} \sim 2$–3×10^{15} cm^{-3} and has a 77 K mobility of $\mu_{77\,K} \sim 4.5\times10^4$ cm^2 V^{-1} s^{-1}. For the InP layers $n_{300\,K} \sim 10^{16}$ cm^{-3} and $\mu_{77\,K} \sim 1$–1.5×10^4 cm^2 V^{-1} s^{-1}. The sample structure is shown in the insert of Fig. 1. The multiple quantum wells (MQW's) form the intrinsic region of a p-i-n diode. A 0.5-μm-thick p-doped (2×10^{17} cm^{-3})InP buffer layer separates the MQW from the p^+ substrate. The MQW's consist of 100 periods of alternate InGaAs QW's and InP barriers each 100 Å thick. Finally a 0.3-μm-thick n-doped (2×10^{17} cm^{-3})InP buffer layer and a 1-μm n^+-doped (2×10^{18} cm^{-3})InP contact layer complete the p-i-n diode. The samples are processed to form rectangular mesas (200 μm$\times$200 μm) with an Au contact as shown in the figure. The substrate was thinned down to 100 μm to reduce free-carrier absorption in the substrate.

Transmission and photoconductivity measurements are performed using conventional lock-in techniques, with a total resolution of $\lesssim 4$ nm. The transmitted and the reference beams are detected by PbS photoresistors. The transmission and photocurrent spectra are normalized to the reference beam. The transmission is corrected for reflection and substrate losses, determined in an independent experiment.

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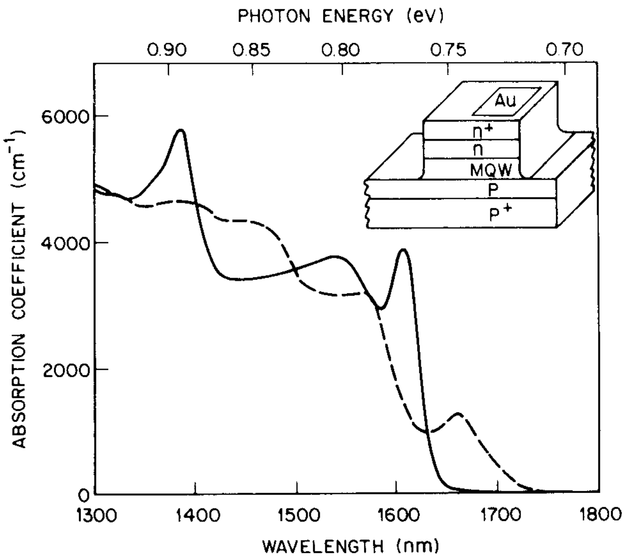

FIG. 1. Observation of quantum-confined Stark effect in InGaAs/InP quantum wells. The room-temperature absorption spectra are measured at 0 V (solid line) and 30 V (dashed line). The sample structure is shown in the insert; the quantum wells consist of 100 periods of alternating 100-Å InGaAs and 100-Å InP layers.

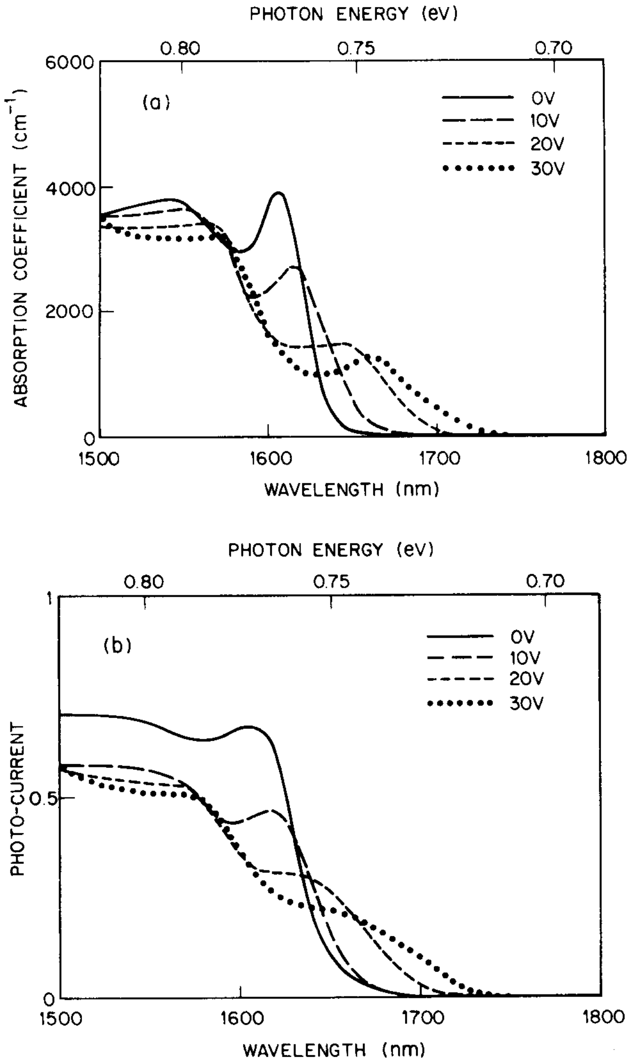

FIG. 2. Detail of (a) the absorption and (b) the photocurrent spectra in the vicinity of the $n_z = 1$ transition for four applied voltages.

Room-temperature absorption spectra at 0 and 30 V are shown in Fig. 1. At 0 V, the $n_z = 1$ heavy (hh) and light (lh) hole exciton peaks can be clearly resolved, as well as a strong resonance at the $n_z = 2$ transition edge. The $n_z = 1$ hh exciton peak is broader than in GaAs MQW's, presumably due to alloy disorder in the wells. The energies of these $n_z = 1$ transitions are slightly smaller than that expected for the InP lattice-matched composition; the small difference can be explained by strain in the sample. The mean absorption coefficient in the MQW is 4400 cm^{-1} in good agreement with Ref. 16. The residual absorption at the band gap is hard to determine because of free-carrier absorption at the substrate, and is arbitrarily set to zero. The 30-V spectrum clearly shows the dramatic changes produced by the electric field. The $n_z = 1$ hh exciton peak strongly red shifts to the point that it appears almost separated from the rest of the spectrum. The $n_z = 1$ lh and $n_z = 2$ transitions present less pronounced shifts and a new feature appears around 0.84 eV. It is located close to the calculated $n_z = 3$ hh to $n_z = 1$ electron "forbidden" transition, which becomes allowed in the presence of a perpendicular field.[4]

These data represent the first observations of the QCSE in the infrared gap InGaAs/InP MQW. In Fig. 2, we present the details of the QCSE close to the $n_z = 1$ transitions, in the absorption [Fig. 2(a)] and photocurrent [Fig. 2(b)] spectra. This is the region of interest for applications to optical modulation. The heavy-hole absorption peak shifts from 0.77 to 0.74 eV, or about six times the exciton binding energy. The height of the absorption resonance decreases from 4400 to 1250 cm^{-1} because of the reduced overlap between the electron and hole wave functions,[4] and the linewidth roughly doubles.[17] The photocurrent spectra closely follow the absorption although the features are less pronounced. The large band-gap difference between $In_{0.47}Ga_{0.53}As$ (0.7 eV) and InP (1.35 eV) results in a very strong confinement which enables us to apply high fields. We have tested that the exciton remains resolved and continues to shift with field even up to 60 V.

In the limit of strong quantum confinement, the calculation of the QCSE shifts for the 1S exciton reduces approximately to the sum of the shift of the single-particle electron and hole states, and the shift in the binding energy of the exciton. We use exactly the same calculation techniques as used previously.[1,2] The single-particle levels are calculated using the tunneling resonance (TR) method, which includes the effects of the quasi-bound nature of the single-particle states, and the exciton binding shift is calculated variationally.

We have used $m_e = 0.041$, $m_{hh,z} = 0.377$, and $m_{lh,z} = 0.0516$ for the effective masses in InGaAs,[18] and $m_e = 0.077$, $m_h = 0.65$, and $m_l = 0.12$ in InP,[19] all in units of the free-electron mass. We have taken a 232-meV discontinuity in the conduction band and 382 meV in the valence band.[20] The mean dielectric constant was chosen as $\epsilon = 12$. Experiment and theory are compared in Fig. 3 for the hh exciton resonance. Only the zero-field peak position is ad-

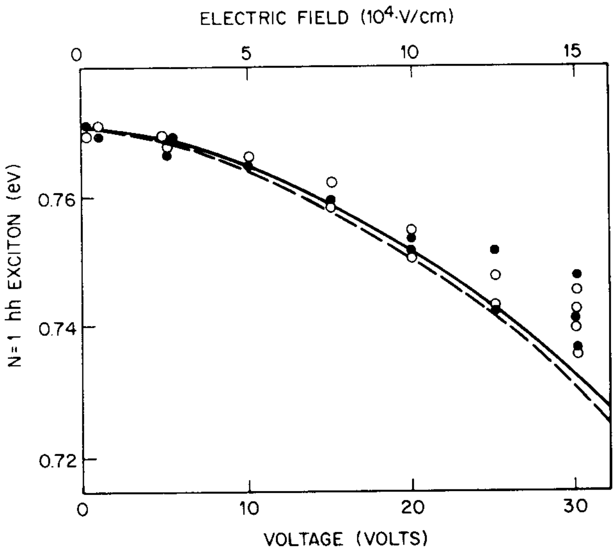

FIG. 3. Comparison of the measured shifts of the $n_z = 1$ hh-exciton vs the applied field. The open and black circles are, respectively, deduced from the absorption and photocurrent spectra. The dashed line is the sum of the calculated shifts of the appropriate single-particle states and the solid line includes the correction for the change in the exciton binding energy.

justed in the theory because of the unknown strain in the sample. The dashed line gives the sum of the calculated shifts of the single-particle states, and the solid line includes the exciton binding energy shift. To convert applied voltage to field, we assume that the total voltage drops homogeneously over the MQW, and neglect the built-in field. The open and black circles in Fig. 3 are deduced from the transmission and photocurrent data, respectively, for several mesas. We find an excellent agreement up to 20 V. Beyond this value the observed shift is smaller than calculated. This tendency to saturate varies from mesa to mesa, and remains to be explained.

One possible explanation as to why we observe clear shifts of the peaks with field in contrast to previous observations of strong broadening is related to the high purity of our samples (residual impurity concentrations $< 3\times 10^{15}$ cm^{-3}). When nominally intrinsic QW's are depleted, the residual impurities may be ionized, leaving a random field from these point charges. Such a field will have a component in the plane of the MQW layers, and it is known that such fields can readily broaden the exciton peak.[2] Thus high purity in the QW is very important for clear shifts without excessive broadening. This interpretation is supported by our observation that the photocurrent responsivity is substantially independent of the reverse bias for both InGaAs/InP and GaAs/GaAlAs QW's that show clear QCSE, as should be the case for a good diode. Conversely, in the reported InGaAs/InAlAs[11] QW's the photocurrent increases with increasing reverse bias, indicating a poor electrical behavior of the *p-i-n* diodes. We have also found this to be the case in our own InGaAs/InAlAs and GaAs/GaAlAs samples that show strong broadening with the field.

In conclusion, the large changes of the absorption spectrum with field clearly indicate that light modulators made of InGaAs/InP MQW's can be constructed. The results reported here show that (i) long-wavelength alloy quantum wells can show clear QCSE electroabsorption at room temperature, (ii) the QCSE theory does scale to material systems other than GaAs/GaAlAs, and (iii) OMVPE is a very attractive growth technique for sophisticated, long-wavelength quantum well devices. Importantly for possible devices, this material system also has transparent substrates. Possible extensions of this work include waveguide modulators to increase modulation depth[10,21] and reduce drive voltage,[22] and, because of the good photocurrent response, self electro-optic effect[5] switches and linearized modulators may also be achievable. Given the operating wavelengths, these conclusions are promising for modulators and optical switching devices that will also be directly compatible with optical fiber communications.

We are pleased to acknowledge J. E. Henry for assistance in processing the samples.

[1]D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, Phys. Rev. Lett. **53**, 2173 (1984).
[2]D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, Phys. Rev. B **32**, 1043 (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).
[4]For a summary of work on quantum well electroabsorption and further discussion of QCSE theory see D. A. B. Miller, J. S. Weiner, and D. S. Chemla, IEEE J. Quantum Electron. **QE-22**, 1816 (1986).
[5]D. A. B. Miller, D. S. Chemla, T. C. Damen, T. H. Wood, C. A. Burrus, A. C. Gossard, and W. Wiegmann, IEEE J. Quantum Electron. **QE-21**, 1462 (1985).
[6]D. A. B. Miller, J. E. Henry, A. C. Gossard, and J. H. English, Appl. Phys. Lett. **49**, 821 (1986).
[7]K. Wakita, Y. Kawamura, Y. Yoshikuni, and H. Asahi, Electron. Lett. **21**, 340 (1985).
[8]K. Wakita, Y. Kawamura, Y. Yoshikuni, and H. Asahi, Electron. Lett. **21**, 574 (1985).
[9]Y. Kawamura, K. Wakita, Y. Itaya, Y. Yoshikuni, and H. Asahi, Electron. Lett. **22**, 242 (1986).
[10]K. Wakita, Y. Kawamura, Y. Yoshikuni, and H. Asahi, Electron. Lett. **22**, 907 (1985).
[11]K. Wakita, Y. Kawamura, Y. Yoshikuni, H. Asahi, and S. Uehara, IEEE J. Quantum Electron. **QE-22**, 1831 (1986).
[12]T. E. Van Eck, P. Chu, W. S. C. Chang, and H. H. Wieder, Appl. Phys. Lett. **49**, 135 (1986).
[13]T. Miyazawa, S. Tarucha, Y. Ohmori, Y. Suzuki, and H. Okamoto, Jpn. J. Appl. Phys. (Part 2), **25**, L200 (1986).
[14]C. Alibert, S. Gaillard, J. A. Brum, G. Bastard, P. Frijlink, and M. Erman, Solid State Commun. **53**, 457 (1985).
[15]B. I. Miller, E. F. Shubert, U. Koren, A. Ourmazd, A. H. Dayem, and R. J. Capik, Appl. Phys. Lett. **49**, 1384 (1986).
[16]J. S. Weiner, D. S. Chemla, D. A. B. Miller, T. H. Wood, D. Sivco, A. Y. Cho, Appl. Phys. Lett. **46**, 619 (1985).
[17]S. Hong and J. Singh, Appl. Phys. Lett. **49**, 331 (1986).
[18]K. Alavi and R. L. Aggarwal, Phys. Rev. B **21**, 1331 (1980).
[19]*Semiconductors—Physics of Group IV Elements and III-V Compounds*, Landolt–Bornstein, edited by O. Madelung (Springer, Berlin, 1982), Vol. 17 (A).
[20]M. S. Skolnick, P. R. Tapster, S. J. Bass, A. D. Pitt, A. Apsley, and S. P. Aldred, Semicond. Sci. Technol. **1**, 29 (1986).
[21]J. S. Weiner, D. A. B. Miller, D. S. Chemla, T. C. Damen, C. A. Burrus, T. H. Wood, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **47**, 1148 (1985).
[22]J. S. Weiner, A. C. Gossard, J. H. English, D. A. B. Miller, D. S. Chemla, and C. A. Burrus, Electron. Lett. **23**, 77 (1987).