

## Effect of electric field on the probability of optical transitions in InGaAs/GaAs quantum wells observed by photo- and electroreflectance methods

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The influence of an electric field on the energy spectrum and the probability of optical transitions in InGaAs/GaAs single quantum wells (QWs) of different widths has been investigated with photo- and electroreflectance techniques. The electric field in the area of a QW is varied in a wide range and controlled by well-defined Franz–Keldysh oscillations. A quadratic red shift of electroreflectance features concerned with interband excitonic transitions in QWs is observed. The electric field dependence of the intensity of these features and calculated data for the probability of optical transitions are compared. There are some field values when transitions that are symmetry-forbidden in zero field are much stronger than symmetry-allowed transitions.

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### 1 Introduction

The optical transition probability in quantum wells (QWs) strongly depends on electric field. This dependence has been calculated numerically a few years ago [1]. Besides the influence on the position and width of quantum-well levels, the electric field causes the transformation of the envelope wave functions. It can result in the existence of some maxima in the field dependence of the optical transition probability. The absolute value of the maxima may be comparable with unity even for transitions “forbidden” in zero field. This phenomenon is observed for some excited states of QWs only. We do not know of any experiments that have clearly defined it.

At present, there are some optical techniques which may be used to investigate the interband energies and thus the optical properties of QWs. Probably the most popular are luminescence techniques such as photoluminescence (PL), which is mostly used at low temperatures. The ground-state transition energies of QWs may be determined from PL spectra while, for the higher states, another technique is required.

To get full information about the excitonic spectrum of QWs we use such kinds of modulation spectroscopy as photorefectance (PR) and electroreflectance (ER). These techniques have become important in the accumulation of band-structure parameters of both single and multiple quantum wells for a variety of material systems. Unlike luminescence techniques, PR and ER have been particularly successful at room temperature where they can produce sharp spectral features associated with all transitions in QWs, which is a very important aspect of quantum dimensional structure characterization since devices normally operate around room temperature.

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The possibility of modifying the electron wave function and the optical transition probability by an electric field in QWs has opened up fresh opportunities for nano- and optoelectronic devices. For example, it will be possible to tune characteristics of resonant tunneling devices, intersubband photodetectors, and cascade lasers.

## 2 Experimental

The investigated samples consisted of  $\text{In}_{0.225}\text{Ga}_{0.775}\text{As}/\text{GaAs}$  single quantum wells. All these high-quality samples were grown by metalorganic vapor-phase epitaxy [2]. Single QWs had different widths from 11 nm to 23 nm. The GaAs cap layer had a width of 110 nm and the donor concentration was about  $10^{16} \text{ cm}^{-3}$  to put the QW into the area of the surface space-charge electric field.

In our photoreflectance system the built-in field was modulated by a chopped pump He–Ne laser beam ( $\lambda = 632.8 \text{ nm}$ ). The pump and probe illuminations were arranged to overlap each other on the sample surface with identical areas. The probe beam was provided by a halogen lamp and a computer-controlled spectrometer. The energy of the probe beam was scanned as a function of photon energy from 1.14 to 1.66 eV.

It was necessary to make metallic contacts on the surface of the samples for ER measurements. A thin Ag film was deposited on the GaAs cap layer and formed a Schottky barrier. The ohmic contact to the GaAs substrate was fabricated by a laser technique [3]. So, the probe beam in ER was transmitted through the semitransparent Schottky contact. The built-in electric field in this technique was directly modulated by an ac voltage. Besides, different dc biases were applied to the structures to vary the internal electric field in a wide range.

## 3 Results and discussion

At first, each investigated sample was measured by the PR method. These spectra yielded the first information about QW excitonic transitions. Then ER spectra were measured with different dc biases. Photoreflectance and electrorefractance spectra were similar. Each of them could be divided into two parts; the first part was due to InGaAs QW excitonic transitions and the second was due to GaAs. Figure 1 shows typical ER spectra for two samples with 15- and 18.5-nm-thick QWs, measured at 300 K.

The spectra above the GaAs energy gap at room temperature (1.424 eV) exhibit well-defined Franz–Keldysh oscillations (FKOs) from the GaAs interface. The electric field in a QW was determined from the period of these FKOs. We used the graphical technique of Aspnes and Studna [4], which has formed the basis of the FKO analyses performed to date. The asymptotic form for  $dR/R$  has a relatively simple expression:

$$\frac{dR}{R} \propto \cos \left( \frac{2}{3} \left[ \frac{E_n - E_g}{\hbar\Omega} \right]^{3/2} + \psi \right), \quad (1)$$

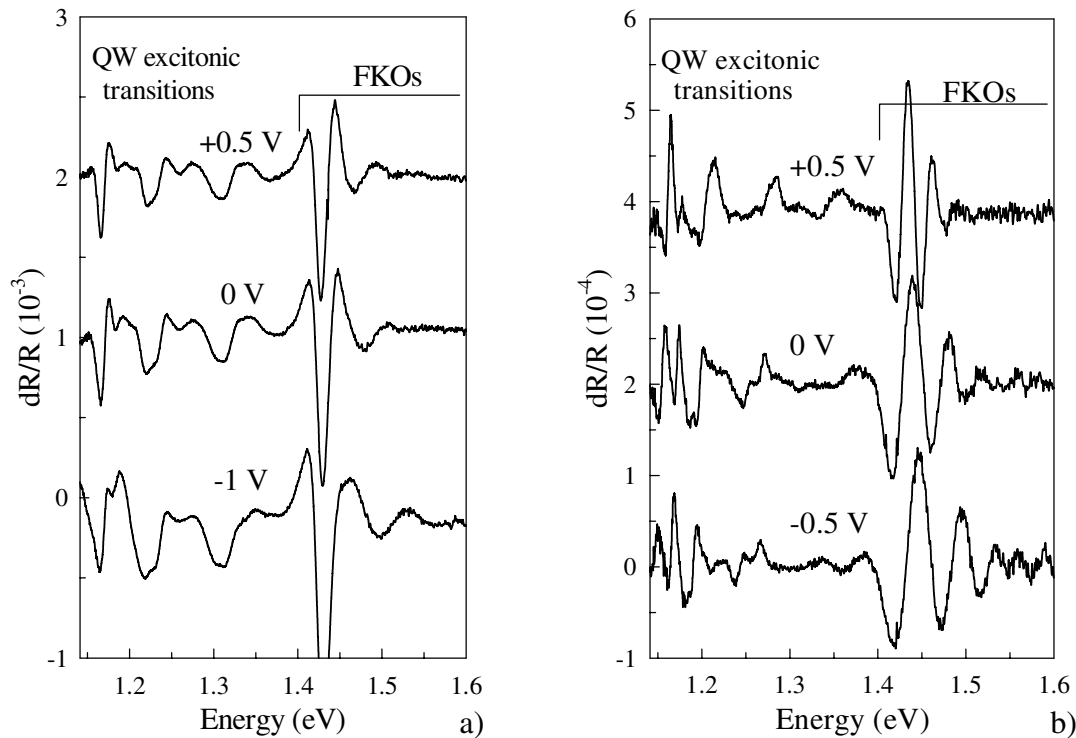
where  $E_n$  is the photon energy of the  $n$ -th extremum,  $E_g$  is the band-edge transition energy,  $\psi$  is a phase factor, and

$$\hbar\Omega = \left( \frac{e^2 \hbar^2 F^2}{8\mu} \right)^{1/3} \quad (2)$$

is the electro-optic energy, where  $F$  is the electric field and  $\mu$  is the interband reduced mass in the direction of  $F$ . For the FKOs near 1.42 eV here,  $\mu$  relates to transitions from the heavy-hole valence band in GaAs and is given by  $\mu = 0.055 m_0$  [5].

From Eq. (1), the extrema in the FKOs are given by

$$\frac{2}{3} \left[ \frac{E_n - E_g}{\hbar\Omega} \right]^{3/2} + \psi = n\pi. \quad (3)$$



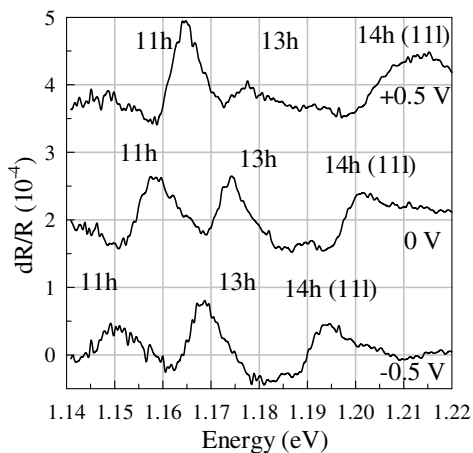
**Fig. 1** Electroreflectance spectra for 15- (a) and 18.5-nm-thick (b)  $\text{In}_{0.225}\text{Ga}_{0.775}\text{As}/\text{GaAs}$  single QWs with different dc biases, measured at 300 K.

A plot of  $(2/3\pi) [E_n - E_g]^{3/2}$  vs. the index number  $n$  yields a straight line with a slope of  $(\hbar\Omega)^{3/2}$ . This slope and Eq. (2) give the electric field  $F$ .

Having applied different external potentials, the electric field in the QW was varied. Figure 1 shows electroreflectance spectra for two samples with three different dc biases. For a 18.5-nm-thick QW they were equal to +0.5, 0, and -0.5 V. The electric field inside this QW directly obtained from the period of the FKOs was 19, 31, and 42 kV/cm, respectively.

The long-wave part of the PR and ER spectra at a photon energy less than the GaAs fundamental band gap comes from an InGaAs single QW. An applied ac voltage causes the modulation of the energy position and a broadening of the excitonic spectra. At first, we supposed that only this modulation brings into existence the ER signal. The QW excitonic transition part of the spectra in Fig. 1 is quite complicated. Both the symmetry-allowed and the symmetry-forbidden optical transitions are observed. An intrinsic electric field or an irregularity of the QWs interfaces is responsible for the presence of symmetry-forbidden transitions. They were observed for a GaAs/AlGaAs multiple QW by the PR method [6] before. Besides, weak signals in the area of the parity-forbidden transitions were observed in  $\text{In}_{0.045}\text{Ga}_{0.955}\text{As}/\text{GaAs}$  coupled QWs by photoluminescence excitation spectroscopy [7, 8], where it was confirmed that the appearance of the transitions is due to the strong mixing of the heavy-hole and light-hole excitons. Şek et al. [9] showed that, although this mixing is still important, a very weak built-in electric field can be dominant in the observation of forbidden excitonic transitions in a double QW. In our experiments the external electric field varied the probability of symmetry-forbidden optical transitions in the single QW and their intensity was higher than symmetry-allowed ones, in accordance with theoretical calculations [1, 10].

For a 18.5-nm-thick QW, excitonic transitions are shown in Fig. 2. It was assumed that the first spectral feature is concerned with 11 h. Its energy is in good agreement with photoluminescence data at the same temperature (300 K). Other transitions' energies were calculated and are shown in Fig. 2.



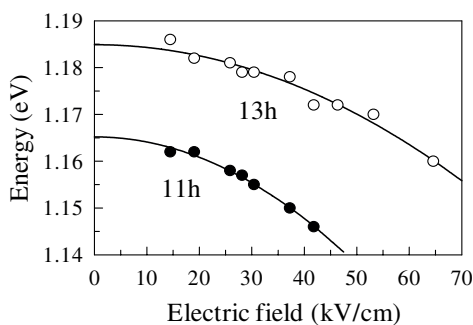
**Fig. 2** Electroreflectance features of some excitonic transitions in a 18.5-nm-thick  $\text{In}_{0.225}\text{Ga}_{0.775}\text{As}/\text{GaAs}$  single QW with different dc biases: +0.5, 0, and -0.5 V.

The shift to lower energy with an increasing electric field was observed for ground excitonic transitions in  $\text{GaAs}/\text{GaAlAs}$  [11] and  $\text{In}_{0.08}\text{Ga}_{0.92}\text{As}/\text{GaAs}$  [12] single QWs. We observed this red shift not only for ground but also for excited excitonic transitions in  $\text{In}_{0.225}\text{Ga}_{0.775}\text{As}/\text{GaAs}$  QWs. Figure 3 shows the energy shift of electroreflectance features concerned with 11 h and 13 h in the 18.5-nm-thick QW vs. intrinsic electric field, obtained from the period of FKOs. This effect is mostly due to a quadratic Stark shift of the first confined electron state. The shift was different for different transitions. It influences the amplitude of respective electroreflectance features. This effect can only result in their monotonic modification with an external potential increase, but in the ER spectra another variation of the features' amplitudes was clearly observed. Figure 4 shows the amplitudes of the ER features, concerned with the 11 h optical transition (closed circles) and the symmetry-forbidden 13 h optical transition (open circles) vs. the electric field.

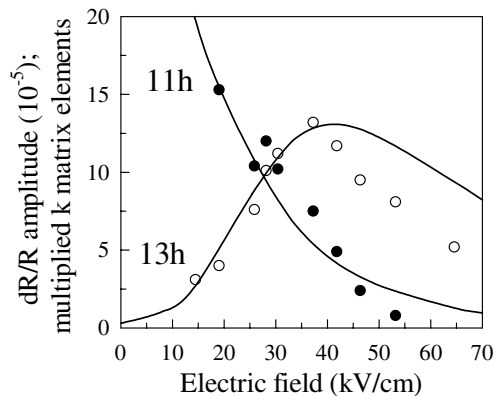
One can see that there are some values of the electric field when spectral features belonging to transitions symmetry-forbidden (13 h) in zero field are much stronger than symmetry-allowed transitions (11 h). Further increasing of the electric field leads to a decreasing of the 13 h amplitude. These experimental results were compared with the theoretical data for the electric field dependence of the probability of the same optical transitions. The optical matrix element dependence on electric field was calculated as had been done in [1]. To fit the experimental results these calculated matrix elements were multiplied by a variable parameter  $k$ . This parameter was the same for both transitions. Theoretical optical matrix elements vs. the electric field are shown in Fig. 4 by lines. The fitting proves that besides the influence on the position and broadening of QW levels, the electric field varies the probability of optical transitions.

#### 4 Conclusion

In this work a non-monotonic electric field dependence of the optical transition probability was experimentally observed in QW structures by photo- and electroreflectance methods. The obtained results



**Fig. 3** Energy shift of electroreflectance features concerned with 11 h and 13 h excitonic transitions in the QW vs. intrinsic electric field, obtained from the period of FKOs.



**Fig. 4** Electroreflectance features' amplitudes (circles) and theoretical optical matrix elements (lines) vs. the electric field.

confirm that at some values of the electric field transitions that are symmetry-forbidden in zero field are much stronger than symmetry-allowed transitions. The possibility of varying the optical transition probability by an external electric field creates a novel way to design new QW-based devices of nanoelectronics and optoelectronics.

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