Electroreflectance bias-wavelength mapping of the modulation Si δ-doped pseudomorphic GaAs/InGaAs/AlGaAs structure

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The electroreflectance bias-wavelength mapping is proposed as a tool for characterization of low-dimensional structures. The results of room-temperature measurements on modulation Si δ-doped pseudomorphic GaAs/InGaAs/AlGaAs heterostructure with high mobility two-dimensional electron gas are presented. Franz–Keldysh oscillations (FKO) in GaAs layer are analyzed using fast Fourier transform (FFT) mapping in order to find an electric field in the GaAs layer. Two frequencies of FKO are identified in the FFT spectra, which are attributed to transitions involving heavy and light holes. Two transitions within the InGaAs quantum well are found at zero bias and an additional transition becomes apparent in reversely biased structure. Spectral features due to spin-orbit split holes in GaAs, back AlGaAs barrier, and AlGaAs/GaAs superlattice are also identified. © *1999 American Institute of Physics.* [S0003-6951(99)02540-1]

Modulation techniques proved to be a very effective way of semiconductor structures investigation.[1] The reflectance spectra obtained with either optical or electrical modulation provide detailed information on optical functions of semiconductors. It is possible to observe very sharp features due to optical transitions even at room temperature. An analysis of those spectra provides information on the structure properties.[2] However, especially in the case of multilayered structures, it is often difficult to attribute particular features to a specific layer in such a structure. We propose a new approach to that problem, which uses the quasicontinuous change of the structure bias. We will show how the resulting electroreflectance bias-wavelength (ERBW) map makes the attribution of spectral features more clear.

A structure investigated was a pseudomorphic GaAs/$\mathrm{In_{0.2}Ga_{0.8}As}$/$\mathrm{Al_{0.2}Ga_{0.8}As}$ quantum well (QW) with modulation Si δ doping, grown by metalorganic vapor phase epitaxy at the Australian National University[3] (see Fig. 1). The structure was grown on SI GaAs substrate, and consisted nominally of a 600 nm GaAs buffer layer (BL), followed by 90 nm of (5 nm $\mathrm{Al_{0.2}Ga_{0.8}As}$/5 nm GaAs) superlattice (SL), 310 nm of $\mathrm{Al_{0.2}Ga_{0.8}As}$ back barrier, 10 nm of $\mathrm{In_{0.2}Ga_{0.8}As}$ QW, and 205 nm GaAs top barrier. The Si δ-doping ($n_D = 2.3\times10^{12}\,\mathrm{cm^{-2}}$) was placed 10 nm from the QW in the back $\mathrm{Al_{0.2}Ga_{0.8}As}$ barrier. There was a similar δ doping 2 nm below the structure surface in order to saturate the surface states. A Au/Ge ohmic contact was evaporated on the sample surface and alloyed. A semitransparent Au layer, evaporated on the sample surface, was used as a Schottky gate. Electron Hall density and mobility at RT were equal to $1.9\times10^{12}\,\mathrm{cm^{-2}}$ and 5320 $\mathrm{cm^2/V\,s}$, respectively. A high electron mobility at RT suggests that most electrons occupy the QW. This was confirmed by low temperature measurements. At $T=4.2\,\mathrm{K}$, the electron Hall density ($1.11\times10^{12}\,\mathrm{cm^{-2}}$) was approximately equal to the two-dimensional electron gas (2DEG) density found from Shubnikov–de Haas oscillations of magnetoresistance ($1.08\times10^{12}\,\mathrm{cm^{-2}}$). An additional conductivity channel of much lower electron mobility and density existed in the GaAs BL, which was established from electrochemical capacitance–voltage profiling of the investigated structure. Ohmic contact made on investigated sample short circuited both the high mobility channel in the QW and the low mobility channel in the GaAs BL (see Fig. 1).

The measurement was carried out at room temperature. The Schottky gate on the structure, biased with a sum of dc voltage U_i and ac modulation signal ΔU, was illuminated with a monochromatic light of wavelength λ. The electroreflectance (ER) signal was measured using a lock-in amplifier. In the next step the bias voltage was changed to U_{i+1}. After

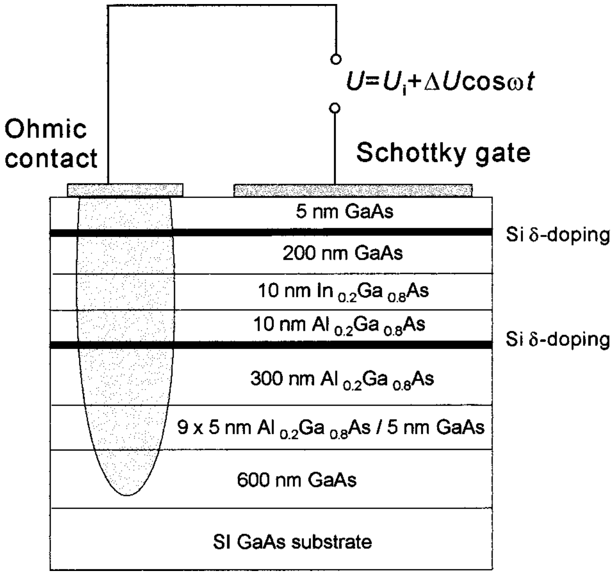

FIG. 1. A schematic sample structure with contact configuration.

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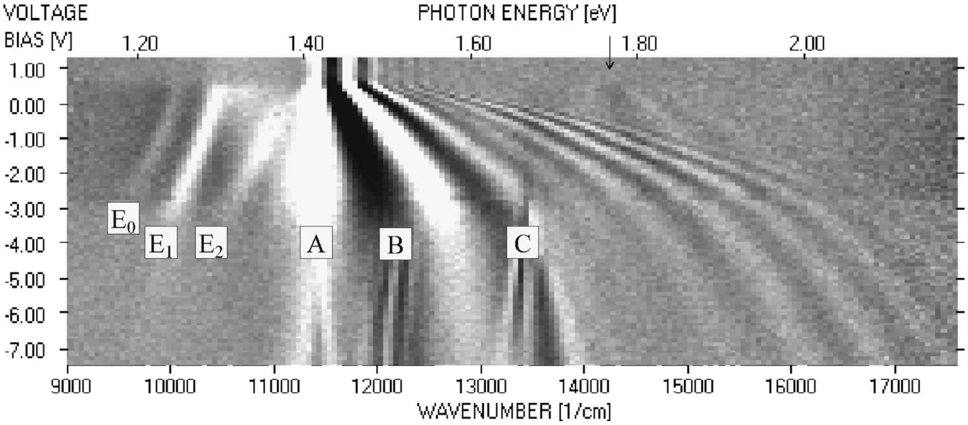

FIG. 2. The electroreflectance bias-wavelength (ERBW) map of the Si δ-doped pseudomorphic GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ structure. Brighter and darker regions of the ERBW map represent, respectively, a positive and negative ER signal. Usual ER spectrum can be extracted from a horizontal cross section of this map.

the full bias range was covered, the illuminating light wavelength changed to $\lambda + d\lambda$ and the whole procedure was repeated. If the bias difference $U_i - U_{i+1}$ is small enough, the ERBW map can be obtained from measured ER spectra, as it is shown in Fig. 2. The conventional ER spectrum measured at $U = 0$ V is shown for comparison in Fig. 3.

Two ER features (denoted as E_0 and E_1 in Fig. 2) can be seen below the GaAs band gap. Those are due to optical transitions within the QW. It is interesting to note that they disappear for $U > 0.5$ V, which is probably due to occupation of their final states by electrons. The E_0 and E_1 features redshift with increasing electric field, which results from the quantum confined Stark effect (QCSE)[4]—the spatial separation of electron and hole wave functions leading to a decrease of transition energy. A schematic potential diagram for those experimental conditions is shown in Fig. 4(a). An additional feature denoted in Fig. 2 as E_2 can be observed at $U < -0.5$ V. It must be due to a resonant electronic state, which becomes confined in the triangular well formed under high electric field [see Fig. 4(b)]. An electric field dependence of this feature is stronger than in the case of E_0 or E_1 transitions. This suggests that the spatial extent of the E_2 related wave function in the z direction is larger than the spatial extent of the E_0 or E_1 related wave functions, which is in agreement with our attribution.

Franz–Keldysh oscillations (FKO)[5] from the GaAs barrier can be clearly seen in the central part of the ERBW map. Their detailed analysis will be presented later in this letter. Another group of very weak features can be seen around $U = 0$ V in the energy range 1.7–1.9 eV, (see arrow in Fig. 2). Those are the FKOs involving the GaAs spin-orbit split holes at $E_g + \Delta_{so}$. Those features are very weak and they are difficult to detect in a usual ER spectrum (compare Fig. 3).

At high reverse bias three additional features denoted in Fig. 2 as A, B, and C can also be observed. In this bias region the QW is probably depleted of electrons and the parallel conduction channel in the GaAs BL acts as a back contact [see Fig. 4(c)]. This results in extension of the electric field modulation region to the AlGaAs back barrier and AlGaAs/GaAs SL. We attribute the B transition to the confined states in the AlGaAs/GaAs SL and the C feature to the

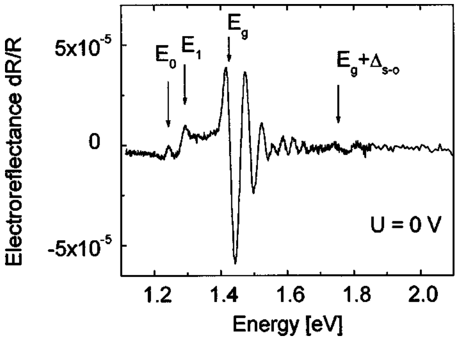

FIG. 3. Electroreflectance spectrum measured at $U = 0$ on the Si δ-doped pseudomorphic GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ structure.

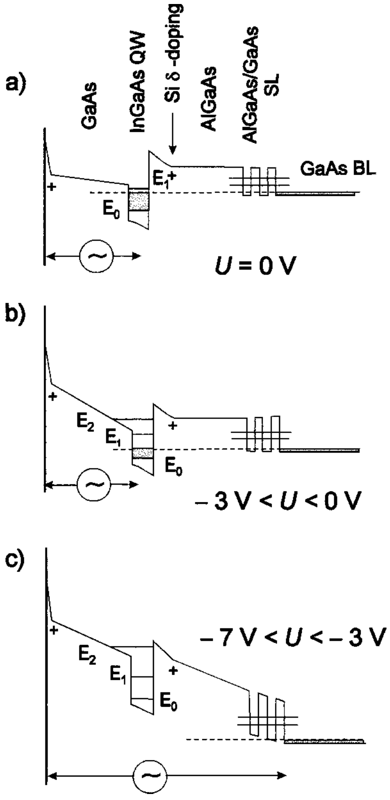

FIG. 4. Schematic potential diagram of the Si δ-doped pseudomorphic GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ structure investigated by ERBW mapping. (a) $U = 0$ V. The 2DEG in the QW acts as a back contact for electric field modulation. E_0 and E_1 features, as well as the FKO from the top GaAs layer can be seen in the ERBW map; (b) $-3\ \mathrm{V} < U < 0$ V. The E_2 feature due to electronic state confined in the triangular potential well over the $In_{0.2}Ga_{0.8}As$ QW becomes apparent in the ERBW map. (c) $-7\ \mathrm{V} < U < -3$ V. The $In_{0.2}Ga_{0.8}As$ QW is depleted and a parallel conduction channel in the GaAs BL serves as a back contact for electric field modulation. The features B and C due to transitions within the $Al_{0.2}Ga_{0.8}As$/GaAs SL and band-to-band transition from the $Al_{0.2}Ga_{0.8}As$ back barrier, respectively, can be seen in the ERBW map.

transitions from the AlGaAs barrier. The energy position of those features agree very well with values found from photovoltaic measurements, which backs up our attribution. The attribution of the feature A seen in Fig. 2 is less straightforward. A split character of this feature may result from the strain-induced splitting of heavy and light holes in the GaAs top barrier, grown on strained InGaAs QW or from an additional electronic state confined in the triangular well over the InGaAs QW.

The FKOs in GaAs can be analyzed in more detail using the ERBW map. It is well known that the ER line shapes can be described by Airy functions.[6] However, it can be shown that using asymptotic expansions for Airy functions:[7]

$$\frac{dR}{R} \sim \frac{1}{E^2(E-E_g)} \exp\left(-2 \frac{(E-E_g)^{1/2}}{(\hbar\Theta)^{3/2}} \Gamma \right) \times \cos\left[\frac{4}{3} \frac{(E-E_g)^{3/2}}{(\hbar\Theta)^{3/2}} + \Phi \right], \tag{1}$$

where electro-optical energy $\hbar\Theta$ is given by $\hbar\Theta = [(e^2F^2\hbar^2/2\mu)]^{1/3}$, F is a surface electric field, μ is reduced effective mass of the electron-hole pair, E_g is energy gap, Φ is a phase factor, and Γ is a broadening factor. It can be seen from Eq. (1) that the period of FKOs is proportional to $(E-E_g)^{3/2}$. Therefore the formula [Eq. (1)] can be rewritten as:

$$\frac{dR}{R} = f(E,F)\cos[c\Lambda + \Phi], \tag{2}$$

with $\Lambda = (E-E_g)^{3/2}$, $c = 4/3(\hbar\Theta)^{-3/2}$, and $f(E,F)$ is the slowly varying envelope function. The c factor determines the surface electric field F in the layer under investigation.

The fast Fourier transform (FFT) analysis was previously[8] applied to the photoreflectance spectrum in order to find an electric field in multilayered structure. We developed a procedure, which can make use of the whole bias range of ER measurements. Therefore the quasicontinuous dependence of electric field on the bias can be obtained. We applied this FFT-based procedure to our ERBW map with the FKOs in GaAs. Results are presented in the form of a greyscale image (see Fig. 5). The darker areas represent high amplitude of the FFT spectrum. Two curves can be seen in Fig. 5. They are due to transitions involving heavy and light holes in GaAs.[9] For more clarity two scales of the vertical axis are shown, involving the light and heavy holes on the left- and right-hand side axis of Fig. 5, respectively. The value of an electric field deduced from both curves is the same within a good accuracy. This confirms that both light and heavy holes give a contribution to the FKOs observed in our structure.

The dependence of the electric field in the GaAs layer on bias voltage in the whole bias range can be easily examined in Fig. 5. At $U > +0.5$ V the electric field saturates at the value 30 kV/cm. A decrease of bias results in an increase of electric field in GaAs up to 300 kV/cm at $U = -7.5$ V.

In conclusion the results of ERBW mapping of the pseudomorphic $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW with modulation Si δ doping were presented in this study in order to present the capabilities of the new method. The FFT analysis of the FKOs from the GaAs barrier reveals (1) the contribution from light and heavy holes and (2) the bias dependence of the surface electric field in the GaAs layer. Spectral features due to quantum confined states in the QW and in the AlGaAs/GaAs SL, the electric field-induced confinement of a resonant electron state in the QW, and the FKO involving spin-orbit split holes in GaAs, and the AlGaAs barrier were also observed in the ERBW map. It has been shown that the ERBW mapping is an effective and very sensitive method of low dimensional structures investigation.

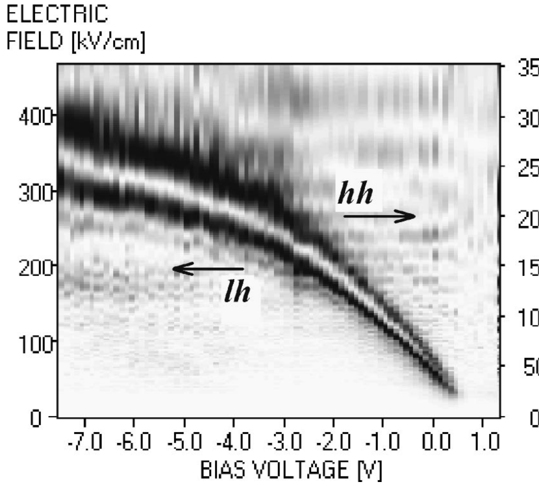

FIG. 5. The results of Fourier transform analysis of Franz–Keldysh oscillations based on ERBW map of the Si δ-doped pseudomorphic $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ structure. Dark regions represent the maxima of the power spectrum. Left- and right-hand side axis scales indicate the value of electric field obtained using masses of light and heavy holes, respectively.

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[1] See, for example, F. H. Pollak, in *Handbook on Semiconductors*, edited by T. S. Moss (Elsevier, New York, 1994), Vol. 2, p. 527.

[2] Y. S. Huang, W. D. Sun, L. Mailkova, F. Pollak, I. Ferguson, H. Hou, Z. C. Feng, T. Ryan, and E. B. Fanter, Appl. Phys. Lett. **74**, 1851 (1999); L. Aigouy, F. Pollak, and G. Gumbs, *ibid.* **70**, 2562 (1997); Y. Yin, H. Qiang, D. Yan, F. Pollak, and T. F. Noble, Semicond. Sci. Technol. **8**, 1599 (1993).

[3] G. Li, M. B. Johnston, A. Babinski, S. Yuan, M. Gal, S. J. Chua, and C. Jagadish, J. Cryst. Growth **195**, 54 (1998).

[4] G. Bastard and J. A. Brum, IEEE J. Quantum Electron. **QE-22**, 1625 (1986).

[5] F. H. Pollak, Superlattices Microstruct. **10**, 333 (1991).

[6] M. Cardona, *Modulation Spectroscopy*, Solid State Physics, Suppl. 11 (Academic, New York, 1969), pp. 55–65.

[7] D. E. Aspnes and A. A. Studna, Phys. Rev. B **7**, 4605 (1973).

[8] H. E. Scheibler, V. L. Alperovich, A. S. Jaroshevich, and A. S. Terekhov, Phys. Status Solidi **152**, 113 (1995).

[9] D. E. Aspnes, Phys. Rev. B **12**, 2297 (1975).