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Observation of Giant Electrorefractive Effect in Five-Layer Asymmetric Coupled Quantum Wells (FACQWs)

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The five-layer asymmetric coupled quantum well (FACQW) is a new potential-tailored quantum well (QW) that is promising for ultrafast and ultralow-voltage optical modulators and switches. We fabricated a waveguide phase modulator with a core layer of GaAs/AlGaAs multiple FACQWs, and a giant electrorefractive (ER) effect in the FACQW was measured for the first time. The ER sensitivity $\Delta n/\Delta F$ measured by the Fabry-Perot resonance method was as large as 1.7×10^{-4} cm/kV at around an electric field of 40 kV/cm. This giant sensitivity is in fair agreement with the theory. This result shows that the FACQW is promising for realizing ultrawide-band, ultrafast and low-voltage optical modulators and switches.
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KEYWORDS: quantum well, five-layer asymmetric coupled quantum well (FACQW), optical modulator, optical switch, phase modulator, electrorefractive index change, molecular beam epitaxy, Fabry-Perot resonance method

For optical waveguide modulators and switches based on phase modulation, a large electrorefractive index change Δn with small absorption loss is required. Several types of such optical modulation devices employ the quantum-confined Stark effect (QCSE) in rectangular quantum wells (RQWs), however, the region of large Δn is usually very close to the absorption edge of the e1 (the ground state of an electron)-hh1(the ground state of a heavy hole) transition (e1-hh1). Hence, in that region, Δn cannot be used because the absorption loss is too large. In the longer operation wavelength region, Δn of the RQW decreases sharply[1] because the positive and negative absorption coefficient changes cancel each other in the integral of the Kramers-Kronig relation.[2,3]

A group with one of the present authors previously proposed a five-layer asymmetric quantum well (FACQW) as a novel potential-tailored quantum well structure.[4] The FACQW can produce a giant electrorefractive index change in the transparent-wavelength region. The electrorefractive sensitivity $\Delta n/\Delta F$ (where F is an electric field applied normal to the quantum well plane) is expected to be much larger than that in RQWs or bulk GaAs. If the FACQW is applied to optical modulation devices such as optical modulators and switches, ultrafast and ultralow-voltage operation can be realized over a very wide wavelength range. It has been demonstrated that a Mach-Zehnder interferometer traveling-wave optical modulator with multiple FACQW structures could achieve a modulation bandwidth of over 50 GHz.[5] The physical origin of an abrupt electrorefractive index change at a positive bias[6] and the influence of layer thickness fluctuations of the FACQW on Δn[7] have also been studied.

In this letter, we report the fabrication of a waveguide phase modulator with a core layer of GaAs/AlGaAs multiple FACQWs and the measurement of the electrorefractive index change Δn as a function of applied electric field F.

The GaAs/AlGaAs FACQW structure[4] is shown in Fig. 1. It consists of a 16-monolayer (ML) quantum well (QW1) and a modified 16 (= 4 + 12)-ML QW (QW2) with a 3 ML $Al_{0.3}Ga_{0.7}As$ barrier layer inserted for potential modification. This thin AlGaAs barrier layer renders the structure asymmetric, and the barrier height of QW2 is effectively lower than that of QW1. The two QWs couple with each other through a 3 ML AlAs barrier layer at the center. Here, the positive direction of electric field F is defined as shown in the figure. At zero bias ($F = 0$), the wavefunctions of hh1 and hh2 are dominantly in QW1 and QW2, respectively, due to the asymmetry of the structure and isolation by the high AlAs barrier. The wavefunctions e1 and e2 (the first excited state of an electron) are uniformly distributed in QW1 and QW2. In the negative bias state ($F < 0$), the wavefunction of e1 is concentrated in QW2 and that of e2 in QW1, while those of hh1 and hh2 (the first excited state of a heavy hole) maintain the positions shown above. This change of distributions of electrons in the FACQW is very sensitive to electric field. As a result, when electric field $|F|$ is increased, the exciton absorption strengths and binding energies of e1-hh1 and e2-hh2 rapidly decrease while those of e1-hh2 and e2-hh1 rapidly increase. The transitions of e1-hh2 and e2-hh1 have similar transition energies, therefore, a strongly combined exciton absorption peak is caused by the e1-hh2 and e2-hh1 transitions in the

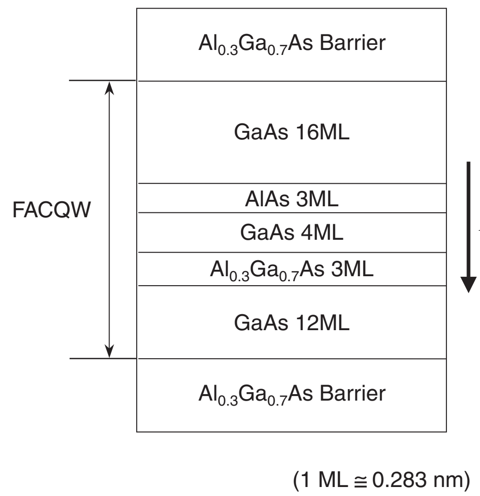

Fig. 1. Schematic diagram of layer structure of the FACQW.

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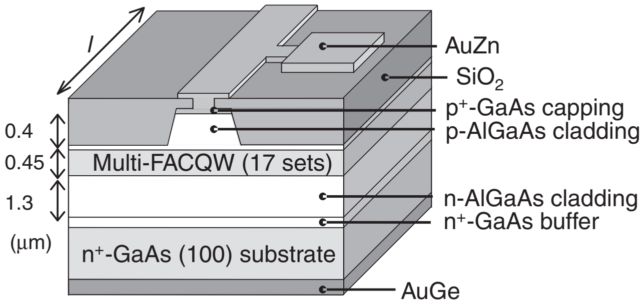

Fig. 2. Schematic diagram of the optical phase modulator with GaAs/AlGaAs multiple FACQWs in the core layer.

TE mode at a small applied electric field. Due to the Kramers-Kronig relations, the above-mentioned large absorption coefficient change at the absorption edge produces an almost linear, giant electrorefractive index change ($|\Delta n/\Delta F| \sim 2 \times 10^{-4}$ cm/kV). This value is over one order of magnitude larger than that of conventional RQWs in the transparent-wavelength region.[4)]

We fabricated a *p-i-n* strip-loaded waveguide phase modulator with GaAs/AlGaAs multiple FACQWs in the core layer, as shown in Fig. 2. The layered structure for the modulator was grown by solid-source molecular beam epitaxy on an n^+-GaAs (100) substrate. The core layer consists of 17 sets of undoped GaAs/AlGaAs FACQWs, and the total thickness of the core layer is 0.45 μm. The lower cladding layer is 1.3-μm-thick n-$Al_{0.35}Ga_{0.65}As$ (2×10^{17} cm^{-3}) and the upper one is 0.5-μm-thick p-$Al_{0.35}Ga_{0.65}As$ (2×10^{17} cm^{-3}). The FACQW layers were grown with atomic-layer precision by monitoring the reflection high-energy electron diffraction (RHEED) specular beam intensity oscillation during growth.[8)] An electric field can be applied through the *p-i-n* diode structure. A single-mode strip-loaded waveguide was formed by photolithography and wet etching. AuZn and AuGe were evaporated for upper and lower electrodes, respectively. The mirrors of the resonator were formed by cleaving. The cavity length of the sample is 1.2 mm and the width of the ridge is 3 mm.

The properties of electrorefractive index change in the FACQW phase modulator were measured by the Fabry-Perot (FP) resonance method.[9,10)] A tunable Ti:sapphire laser ($\lambda = 700$–850 nm) was used as a light source. The laser light entered the phase modulator through a polarization maintaining single-mode fiber. The intensity of transmitted light was observed using an optical spectrum analyzer or an infrared vidicon camera via a near-field-pattern measurement system (Hamamatsu A4859-03). Phase modulation was observed by means of the FP etalon resonance of the optical output power. When reverse bias is applied to the phase modulator, the optical output power has peak or valley values at every phase change of $\pi/2$, which corresponds to a refractive index change of

$$\Delta n = \frac{\lambda_o}{4l\Gamma P},$$

where λ_o is the operation wavelength, l is the cavity length, Γ is the confinement factor of light, and P is the filling factor of the FACQW structures in the core layer.

Figure 3 shows the intensity modulation waveforms of transmitted light (TE mode) at $\lambda = 850$ nm (60 nm from the absorption edge) through the phase modulator (resonator) under various applied reverse voltages. Fringes of the FP resonance were scanned by applying a 1 Hz ac signal of a triangular wave to the modulator. The applied field F was changed by varying peak-to-peak voltage $V_{p\text{-}p}$. Sudden changes in the period of transmitted light intensity variation indicate us the positions of the resonance peak and valley as a function of applied voltage. Unlike the QCSE in conventional RQWs, the QCSE in FACQWs shows no redshift of the absorption edge, and there is little change of absorption at 850 nm.

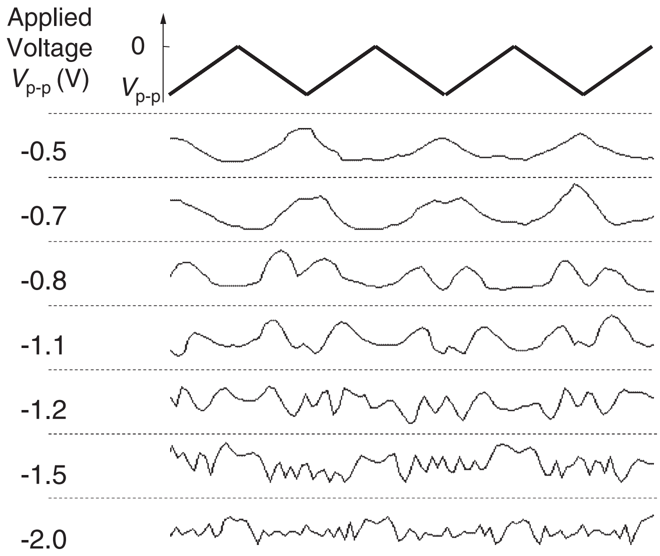

Fig. 3. Intensity modulation waveforms of transmitted light (TE mode) at $\lambda = 850$ nm (60 nm from the absorption edge) through the phase modulator (resonator) with the GaAs/AlGaAs FACQW core layer under various applied reverse voltages.

Thus, electrorefractive index change Δn in the FACQWs was measured as a function of the change in reverse voltage, as shown in Fig. 4. The theoretical curve is also shown. The value of Γ of the waveguide used in our experiments was approximately 0.7 for the TE mode, and the filling factor P was 0.4. Here the electric fields F were defined as average values in the core layer, and the electric field caused by the built-in potential was also considered. The ER sensitivity $|\Delta n/\Delta F|$ of TE-mode light was as large as 1.7×10^{-4} cm/kV at approximately $F = -40$ kV/cm.

The theoretical curve of Δn in Fig. 4 is calculated from absorption spectra using the Kramers-Kronig relations. The calculation method of absorption spectra is the same as that in ref. 11. The wavefunctions and exciton binding energies are calculated by the propagation matrix method and a variational computation.[12)] The exciton absorption spectra are calculated by employing Lorentzian line shape functions with a semi-empirical formula for the half-width at half-maximum (HWHM). In the calculation, the nonuniformity of the distributions of electric field F and light intensity in the core layer is also considered. Because a giant refractive index change is expected to occur under a very small electric field, $\Delta n/\Delta F$ is much larger than those in RQWs or bulk materials. In this calculation, the carrier concentration of the core layer is assumed to be 1×10^{16} cm^{-3}. As shown in the

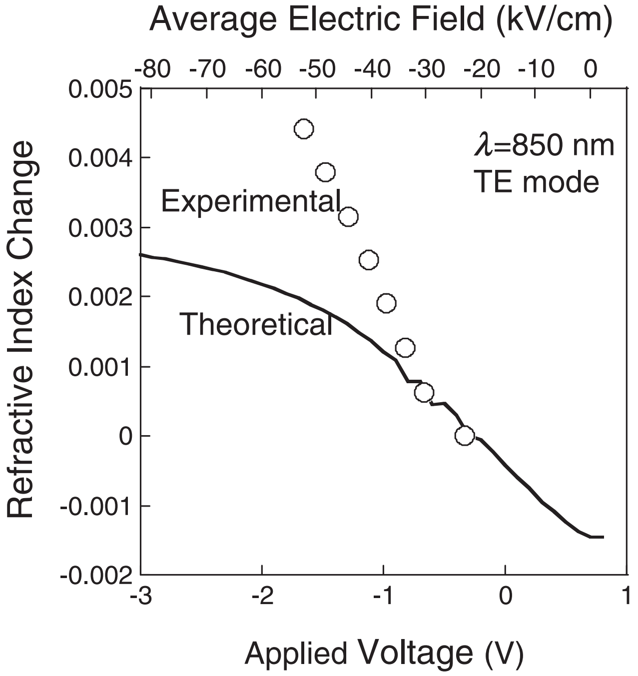

Fig. 4. Refractive index change Δn of the GaAs/AlGaAs FACQW as a function of applied voltage for TE mode. The solid curve is theoretical data calculated considering the nonuniform distributions of electric field and light intensity in the core layer.

figure, the ER sensitivity $|\Delta n/\Delta F|$ obtained experimentally is larger than that theoretically expected. One of the reasons for this discrepancy between the experimental and theoretical results may be a bulk electrooptic (Pockels) effect of the FACQW. In order to evaluate such a bulk effect in the FACQW, we measured $|\Delta n/\Delta F|$ of a bulk $Al_{0.1}Ga_{0.9}As$ waveguide with the same device structure except for the core layer. Bulk $Al_{0.1}Ga_{0.9}As$ has almost the same absorption edge wavelength (790 nm) as that of the FACQW. The measured $|\Delta n/\Delta F|$ of bulk AlGaAs was about 1.8×10^{-5} cm/kV at $\lambda = 850$ nm. This rather large refractive index change is caused by the Pockels effect and the Franz-Keldysh effect. The ER sensitivity resulting from the Pockels effect is estimated to be very small ($\sim 2.5 \times 10^{-6}$ cm/kV using the electrooptic coefficient in GaAs, $r_{41} = 1.2 \times 10^{-12}$ m/V[13]). Therefore Δn of bulk $Al_{0.1}Ga_{0.9}As$ is considered to be caused mainly by the Franz-Keldysh effect. In fact, not only a refractive index change but also a fairly large absorption change due to the Franz-Keldysh effect occurred at $\lambda = 850$ nm in this experiment. In any case, the value $|\Delta n/\Delta F|$ of bulk $Al_{0.1}Ga_{0.9}As$ is one order of magnitude smaller than that of the FACQW. Therefore, the contributions of the Pockels effect and the Franz-Keldysh effect to the giant Δn in the FACQW is considered to be small.

The above results show, for the first time, that the giant Δn is actually produced in the FACQW, as predicted. This giant ER sensitivity in the FACQW is very promising for realizing high-performance optical modulation devices such as Mach-Zehnder modulators and switches.

In conclusion, we fabricated a waveguide phase modulator having a core layer of GaAs/AlGaAs multiple FACQWs with atomic-layer precision. The ER effect in the FACQW was measured for the first time. The ER sensitivity $|\Delta n/\Delta F|$ measured by the FP resonance method is as large as 1.7×10^{-4} cm/kV at around $F = -40$ kV/cm. This giant sensitivity is in fair agreement with the theory. This result shows that the FACQW is expected to realize ultrawide-band, ultrafast and low-voltage optical modulators and switches.

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