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Optical Nonlinearity Caused by Charge-induced Field Screening in DC-Biased Quantum Well Structures

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We report the experimental results concerning the optical nonlinearity caused by charge-induced field screening in dc-biased quantum well structures designed to accumulate photo-excited carriers. The positive feedback can be established by the field screening, due to the photo-excited charges, and only by a self-contained capacitor, demonstrating the rapid change of the absorption coefficient at a low optical power level (~1W/cm^2) . The switching energy and response time are estimated to be 4.6fJ/μm^2 and 460nsec, respectively.

The quantum-confined Stark effect (QCSE)[1] has been receiving much attention from the stand points of the application of quantum wells to optical devices, actually applied to several electro-optic devices. One of the such devices is the self-electro optic device (SEED)[2)-6)], capable of optical bistable switching without any external optical feedback. The apparent advantages of the SEED are the simplicity of the structure and the low switching energy for attaining bistability[2)3)]. However, the SEED requires so large series resistance that the switching speed of the device is limited by a CR product of the *p-i-n* diode. Also, such a large resistance results in the complexity and difficulty in the integration of the device with the resistor on the practical applications.

We proposed a new scheme for attaining the optical bistability[7)]. The optical bistability can be obtained by the screening of the electric field, caused by the electric dipole created from the accumulation of photo-excited carriers in the multiple quantum well (MQW) structure. By the utilization of a self-contained capacitor instead of the external series resistor, the device characteristics are free from the CR product, that is, can be expected to have a faster switching speed and have much simpler structure than the SEED by excluding the resistor. We report the experimental results on the sample which realizes the proposed optical nonlinearity and discussing the switching speed and energy, based on those data.

The energy band diagram of the sample used in the experiments is shown in Fig.1. The sample was a *p-i-n* diode grown by molecular beam epitaxy , exhibiting a MQW structure inside the intrinsic region. The layer sequence is as follows. Starting with n-doped GaAs substrate, a 0.5μm-thick n-dope GaAs buffer layer was grown. Above this, $Al_{0.45}Ga_{0.55}As$ layers were grown, first a n-doped 1.0μm-thick layer and then a

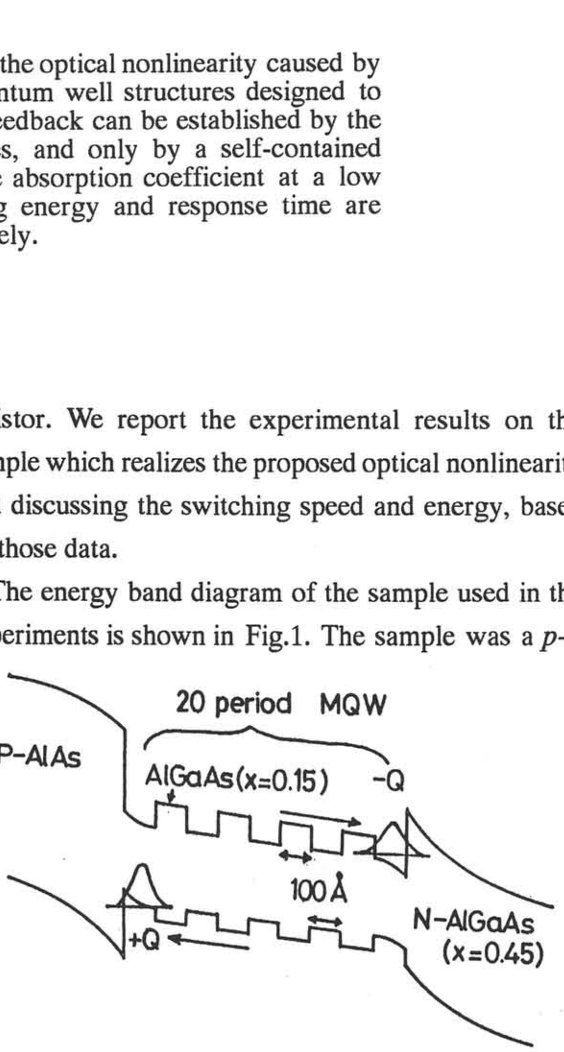

Fig.1. Energy band diagram of the sample used in the experiments. The structure was well designed to accumulate the photo-excited carriers.

500Å-thick undoped outer side barrier layer to form the start of the intrinsic region of the diode. Next, twenty 100Å-thick GaAs quantum well layers separated by 100Å-thick $Al_{0.15}Ga_{0.85}As$ barrier layers to form the MQW without intentional doping. Then, a 0.1μm-thick undoped to form the end of the intrinsic region and a 0.1μm-thick n-doped AlAs outer side-barrier layer and a 0.5μm-thick p-doped $Al_{0.45}Ga_{0.55}As$ cap layer were grown. Both n- and p-doping levels were $5\times10^{17}cm^{-3}$. A semi-transparent Au film was deposited on the top surface of the sample. The potential barriers at the interfaces between the well and inner barrier layers in the MQW were designed to be enough low for the photo-excited electrons and holes to fully transit across the MQW before recombination, while the potential barriers at the interfaces between the MQW and outer side-barriers were designed to be enough high to accumulate considerable amounts of the photo-excited carriers at the interfaces. The Al mole fraction of the p-side barrier layer was chosen to be 1.0, because of the largest discontinuity in the valence band at the interface between GaAs well layer and AlAs barrier layer. On the discontinuity in conduction band , the dependence of Al mole fraction is different from that in valence band, because the energy gap of the Γ-direct conduction band is larger than that of the X-indirect conduction band when the Al mole fraction is larger than 0.45. Thus, the conduction band discontinuity at the interface is rather reduced, being the fraction over 0.45 . Therefore, the 0.45-Al mole fraction for the n-side AlGaAs outer side barrier layer was chosen to maximize the accumulation of the drifted electrons.

The electric field across the MQWs could be varied by changing directly the bias voltage connected to the *p-i-n* diode. We estimated that the built-in electric field of the sample at zero bias voltage is about 3.6×10^4V/cm. The optical nonlinearity in absorption coefficient was observed with photocurrent (PC) measurements. In our experiments we have used a Argon-ion laser-pumped cw dye laser CR-599 whose powers and wavelengths are appropriate to the present work, and used a mechanical chopper, a neutral density filter for keeping incident powers constant, and a lock-in amplifier for detecting the signal. The diameter of the incident laser beam was 1mm. The PC spectra were measured in the condition of constant incident light intensity. We used a 100Ω series resistor for measuring the current, but the value is so small as negligible. A resistance contained in the *p-i-n* diode was clarified to be less than 10Ω with the current-voltage characteristics in a forward bias condition.

Figure 2 shows the PC spectra at room temperature at a bias voltage of -2.5V for various optical power densities. The PC spectra were normalized at 840nm-wavelength. With the lowest

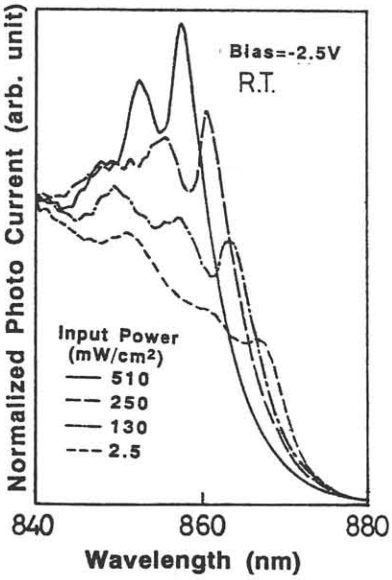

Fig.2. Photocurrent spectra at room temperature at a fixed bias voltage of -2.5V for various light input powers. The spectra were normalized at 840nm.

optical power, the exciton absorption peak in the PC spectra was shifted to longer wavelengths (lower energies) due to the QCSE, and the optical absorption was relatively low. When the intensity of incident light was increased, the Stark shift was systematically suppressed, and the optical absorption was considerably recovered. This means that a considerable portion of the applied bias is being screened by the electric dipole created from the photo-excited free charges (holes and electrons) which are accumulated separately near the interfaces. The voltage drop in the series resistor (100Ω) was enough small (for example, less than 50mV at an applied voltage of -3.5V) compared with the bias voltage drop across the *p-i-n* diode. To make sure of the constant bias condition for the sample, we monitored the bias voltage across the sample and confirmed it to have nothing to do with the incident light intensity. We also measured as well for the two different MQW samples whose Al mole fractions of both outer side barriers were 0.3 and 0.7, but did not show the clear suppression of the Stark shift at low input power less than $1W/cm^2$ as shown in Fig.3. Because these sample

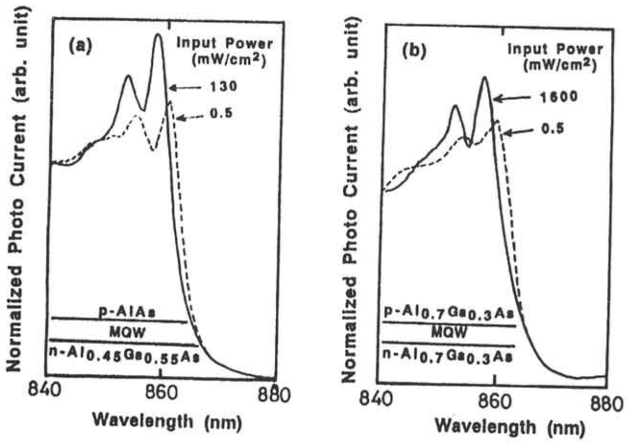

Fig.3. Photocurrent spectra at room temperature at a bias voltage of -1.0V (a) in the sample of Fig.1 and (b) in the sample whose Al mole fraction of both outer side barriers were 0.7. The former sample showed a clear suppression of the Stark shift at an input power as low as $130mW/cm^2$, while the latter one required a high input power, $1600mW/cm^2$, to show the same amount of suppression of the Stark shift as the former one showed.

structures were not designed to accumulate the photo-excited carriers at the interfaces. This means that the charge accumulation is the key to induce the field screening and that a possibility of the feedback due to the voltage drop in the series resistor like the SEED can be excluded from the principle of the former observed clear suppression of the Stark shift.

Based on the optical nonlinearity caused by the field screening, we can expect to establish a positive feedback as follows[7]. For a low optical input power, the significant fraction of the applied reverse-bias voltage is dropped across the MQW, resulting in an intense electric field. The electric field gives rise to a red-shift of the absorption edge and a reduction of oscillator strength due to spatial separation of carrier wavefunctions in the conduction and valence bands. Thus, the optical absorption is relatively low. Increasing the optical input power increases the excited carriers, resulting in the accumulations of the electrical charges near the interfaces between the MQW and the outer side barrier layers. The accumulated charges produce an electric dipole which screens, to some extent, the original applied field. When the light wavelength is chosen to be near to the lowest heavy hole absorption peak at a low field, the field screening efficiently causes increased absorption and the increase of oscillator strength for the input photons as the exciton resonances move back, resulting in further increased charges near the interfaces. The increased charges further screen the field. Thus, a positive feedback should be established.

Figure 4 shows the measured photocurrents as functions of the incident light intensity for several wavelengths at (a) room temperature and (b) 80K.

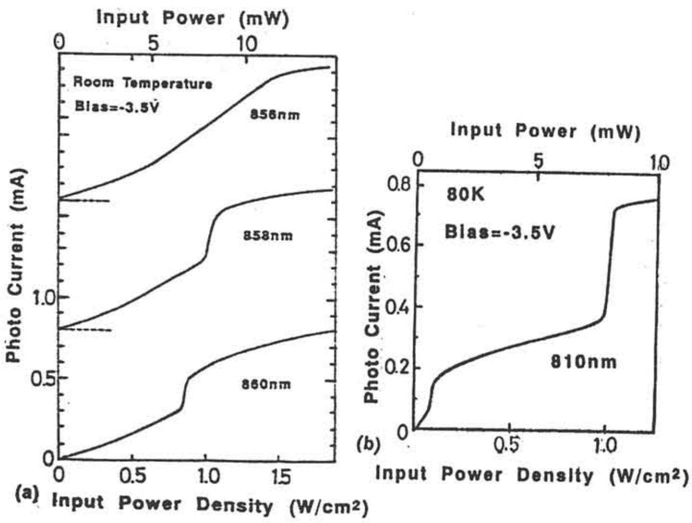

Fig.4 (a) Photocurrents as functions of the incident light intensity at room temperature for each wavelength of the input light. The wavelength of the lowest heavy hole exciton resonance at a low field was 858nm. (b) Photocurrents as functions of the incident light intensity at 80K. The wavelength was tuned to the heavy hole exciton resonance at a low field, 810nm.

Tuning the wavelength of the incident light to the lowest heavy hole exciton resonance at a low field (858nm at room temperature and 810nm at 80K), a sudden increase of the photocurrent was observed at the incident power about $1W/cm^2$. These phenomena are considered to be the demonstration of above mentioned positive feedback. The wavelength of the incident light sensitively effect the positive feedback behavior, and selecting only between 857nm and 862nm around the exciton resonance at a low field

(858nm), the sudden increase of the photocurrents occurred, although the step height in the photocurrent lowered with being away from the wavelength of the exciton resonance. Especially, tuning the wavelength at the shorter wavelength of the exciton resonance, the positive feedback occurred only at the range less than 1nm. Also, a small hump in the photocurrent which seems to be concerned with the light hole exciton absorption was observed at lower incident power at 80K. We also observed the rapid change of the absorption coefficient with the transmission measurements. The sample was prepared by removing the GaAs substrate with a selective etchant. The sudden decrease of the transmission light intensity can be seen in Fig.5.

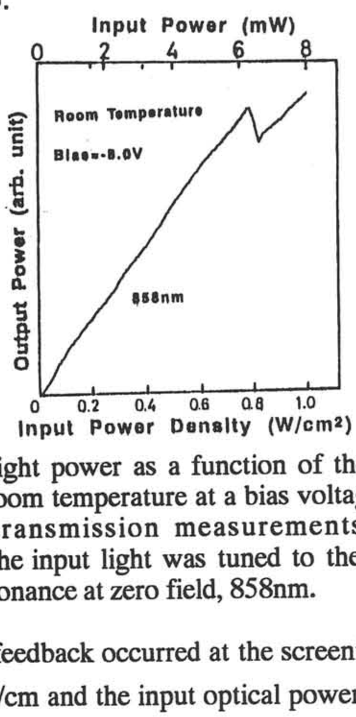

Fig.5 Output light power as a function of the input light power at room temperature at a bias voltage of -8.0V in the transmission measurements. The wavelength of the input light was tuned to the heavy hole exciton resonance at zero field, 858nm.

The positive feedback occurred at the screening field E_s ~0.5×10^5V/cm and the input optical power density Ip~$1W/cm^2$, so the switching energy and response time are estimated as follows. The surface density of carriers N_s accumulated at the interfaces between the MQW and outer barriers is, $N_s=(\varepsilon_0\varepsilon_s)E_s/e$ ~ 3.6×10^{11} $1/cm^2$,where $\varepsilon_0\varepsilon_s$ and e are the averaged dielectric constant in the MQW and electron charge, respectively. The surface carriers are created by an optical beam spending an energy, $(\hbar\omega_p)N_s$ ~0.83 $fJ/\mu m^2$. On the other hand, the over all generation rate of carriers per unit area is given by, $G= (I_p/\hbar\omega_p)(1-r)(1-\exp(-\alpha NL_z))$ ~ 7.9×10^{17} $cm^{-2}sec^{-1}$, where I_p, $\hbar\omega_p$, N, L_z, r and α are the input power density ~$1W/cm^2$, the photon energy ~1.45eV, the period of MQW, the thickness of GaAs well, the reflectivity for the light beam ~0.3, and absorption coefficient in each QW ~$1.5\times10^4cm^{-1}$.

Because of no recombination of carriers within the MQW, the response time are determined only by the escaping time τ of the accumulated carriers over the outer barriers. The life time τ is given by ,τ ~ N_s/G ~ 460nsec. Thus, the switching energy is estimated to be quite small $I_p\times\tau$ ~$4.6fJ/\mu m^2$ which is comparable to those in SEEDs, $5.3fJ/\mu m^2$, using the external series resistance of 22kΩ.[3]

So far, the sample has not shown the bistable switching. The bistable behavior depends on the existence of clear exciton resonances and on their sharp change induced by the field effect. Some improvements [7)9)10)-13)] are required to realize the bistablity.

In conclusion, we reported the optical nonlineality caused by the field screening in a dc-biased quantum well structures. The field-induced Stark shift was systematically reduced with increasing intensity of the incident light. The samples showed the rapid changes of the absorption coefficient at a low optical power level (~$1W/cm^2$), demonstrating a positive feedback. The switching energy and response time were estimated to be $4.6fJ/\mu m^2$ and 460nsec, respectively.

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