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Carrier Induced Change in Refractive Index of Modulation Doped n-AlGaAs/GaAs Quantum Wells and Its Application

Hisao YOSHIMURA, Toshio MATSUSUE and Hiroyuki SAKAKI
Institute of Industrial Science, University of Tokyo,
7-22-1, Roppongi, Minato-ku, Tokyo 106, Japan

The change Δn_{CI} in refractive index induced by the introduction of electrons into quantum wells(QWs) is semiempirically calculated from measured absorption spectra of modulation doped QWs. Calculated Δn_{CI} is comparable to the refractive index change Δn_{SE} caused by quantum confined Stark effect and Δn_{CI} gets even greater than Δn_{SE} at the wavelength below the absorption edge. The application of Δn_{CI} for optical modulators is proposed. Effect of Δn_{CI} on the chirping of quantum well lasers is also discussed.

Recently there has been a considerable interest in optical properties of semiconductor quantum wells(QWs) under electric fields[1-6]. So far field induced changes in absorption $\alpha(\hbar\omega)$[1] and refractive index spectra $n(\hbar\omega)$[3] have been examined mainly for QWs placed inside of reverse biased p-n or Schottky junctions, where carriers are nearly absent. Various applications of this Quantum Confined Stark Effect(QCSE) have been already reported[2].

It has been recently demonstrated that the introduction of carriers into QWs by doping or by a field effect transistor configuration leads to a substantial reduction of absorption spectra $\alpha(\hbar\omega)$ near the band gap[4-5]. This carrier induced bleaching(CIB) is due to the combined effects of exciton quenching and bandfilling effects which override the many body effect. An application of this effect to high speed optical loss modulator is proposed[5-6].

Since $\alpha(\hbar\omega)$ and $n(\hbar\omega)$ are inter-related by Kramers-Kronig(KK) relationship, CIB should be accompanied by changes in refractive index. In this paper, we study this effect first by calculating the carrier induced refractive index change (CIRIC) on the basis of previously measured optical absorption spectra of modulation doped quantum wells. We show, in particular, CIRIC is at least as large as the refractive index change Δn due to QCSE and even greater on the lower energy side of the band gap($\hbar\omega<E_g$). We examine also possible applications of this CIRIC for optical modulators and switches and discuss the contribution of this effect on the chirping phenomenon in QW lasers.

The refractive index $n(\hbar\omega)$ and absorption $\alpha(\hbar\omega)$ are related by Kramers-Kronig relation,

$$n(\hbar\omega)-1 = \frac{C}{\pi}\int_0^{\infty}\frac{\alpha(\hbar\omega')d\omega'}{(\omega')^2-\omega^2}$$

In principle the calculation of refractive index requires the knowledge of

$\alpha(\hbar\omega)$ over the entire energy range. But in order to know the carrier induced change $\Delta n(\hbar\omega)$ near the absorption edge, all we have to know is the carrier induced change $\Delta\alpha(\hbar\omega)$ of absorption near the band edge because $\Delta n(\hbar\omega)=(n(\hbar\omega,N_s)-n(\hbar\omega,N_s=0)$ can be calculated from $\Delta\alpha(\hbar\omega)$ by using the following dispersion relation

$$\Delta n(\hbar\omega) = \frac{C}{\pi}\int_0^{\infty}\frac{\Delta\alpha(\hbar\omega')d\omega'}{(\omega')^2-\omega^2} \quad (2)$$

In this paper we determine $\Delta\alpha(\hbar\omega)$ from our $\alpha(\hbar\omega)$ data measured on modulation doped GaAs quantum wells[5], which are shown in Fig 1(a) for T=77K. The samples studied are molecular-beam-epitaxially grown GaAs(L_z=90A)-AlGaAs(L_b=200 or 240A) quantum wells of 50 periods. The electron concentrations N_s(=0, $5x10^{10}$, $2x10^{11}$, $5x10^{11}$, $1x10^{12}cm^{-2}$) are controlled by doping the central part of AlGaAs with Si. The doped layer is sandwiched by two undoped spacers to minimize the Si segregation[7]. From the data of Fig. 1(a) we have determined $\Delta\alpha(\hbar\omega)$ and performed numerical integration of Eq(2) to get carrier induced change in refractive index $\Delta n(N_s)$. The result is shown in Fig. 1(b). Note that with the increase in carrier concentration N_s, exciton peak in absorption spectra is quenched and the band gap shifts to higher energy. Correspondingly CIRIC takes place with the peak of $\Delta n(\hbar\omega)$ appearing at $\hbar\omega$ where the absorption coefficient is equal to half of exciton peak. Note that Δn reaches 0.10 at h =1.55 eV and as large as that caused by QCSE[7]. Although the CIRIC $\Delta n(\hbar\omega)$ for the photon energy below the exciton decreases monotonically, $\Delta n(\hbar\omega)$ at energy 30meV below the exciton peak is still as large as 0.03, which is far bigger than that of QCSE.

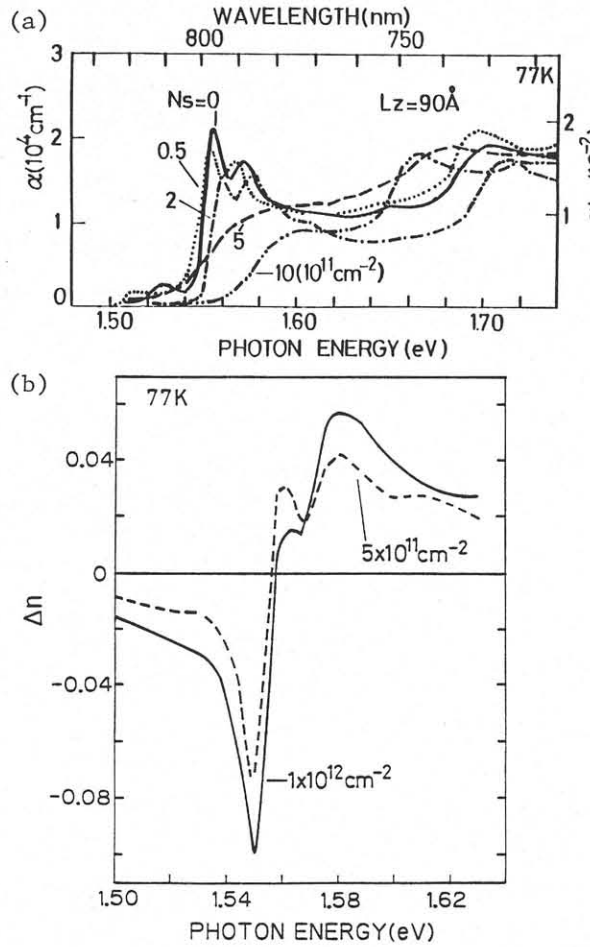

Fig.1 Absorption spectra of modulation doped N-AlGaAs/GaAs QWs(L_z=90A) with various N_s, ranging from 0 to $10^{12}cm^{-2}$ measured at 77K(a) and refractive index change $\Delta n=n(N_s)-n(N_s=0)$ (b) calculated by Eq.(2) at $N_s=5x10^{11}cm^{-2}$(broken line) and $1x10^{12}cm^{-2}$(solid line).

The reason for CIRIC to be quite high in this energy range can be understood by the following consideration. For the QCSE, the change $\Delta\alpha(\hbar\omega)$ occurs mainly due to the shifts of exciton peaks. Hence the integrated area of absorption does not change. In other words, $\Delta\alpha$ gets both positive and negative depending on the energy as shown by the broken line in Fig. 2. For the carrier induced change of $\Delta\alpha(\hbar\omega)$, however, exciton peak quenches and the absorption edge shifts towards higher energy, which leads to the decrease in integrated area of absorption spectra. Hence $\Delta\alpha$ is always negative as shown by solid line in Fig. 2. If we consider these features of $\Delta\alpha$ and substitute them to Eq(2), we expect that Δn is quite different for two cases. For QCSE case, the contribution of $\Delta\alpha$ to $\Delta n(\hbar\omega)$ is positive in the lower energy side of the exciton but gets negative in the higher energy side of the peak. Hence these two terms cancel each other, leading to a small $\Delta n(\hbar\omega)$. In CIRIC case, $\Delta\alpha$ around the bandgap is always negative. Hence the contribution of $\Delta\alpha$ to Δn is additive even when the photon energy deviates from the exciton, leading to a large change in refractive index. This high Δn expected for CIRIC process suggests various possibilities of electro-optic (EO) device application. For instance, at $N_s = 1\times10^{12}/cm^2$, the maximum value Δn is calculated to be 0.10. Since electric field F to induce $1\times10^{12}cm^{-2}$ charge is eN_s/ε, $(\Delta n/n)/F$ is calculated to be 2.01×10^{-9} m/V, which is about 100 times larger that of $L_iN_bO_3$. At 300K $(\Delta n/n)/F$ becomes slightly smaller, and is 1.2×10^{-9}m/V, as will be discussed elsewhere.

As one practical device application, we show in Fig.3 an optical modulator, where the transmission of guided waves is controlled by changing the electron concentration N_s in QWs. Since the use of the depletion mode FET configuration allows the depletion of carriers with N_s at least 5×10^{12} cm^{-2}, we consider here a waveguide with 5 QWs, each of which has N_s of $1\times10^{12}/cm^2$. For this configuration, the refractive index change for a TE_0 mode is given by $\Gamma\Delta n$, where Γ is the confinement factor. When the thickness of the core is 5000A and the refractive index of the core and cladding layer is 3.47 and 3.37, respectively, then Γ of TE_0 mode is 12%. Hence the maximum change of Δn_{TE0} is expected to be 0.012 at hv=1.55eV. To use

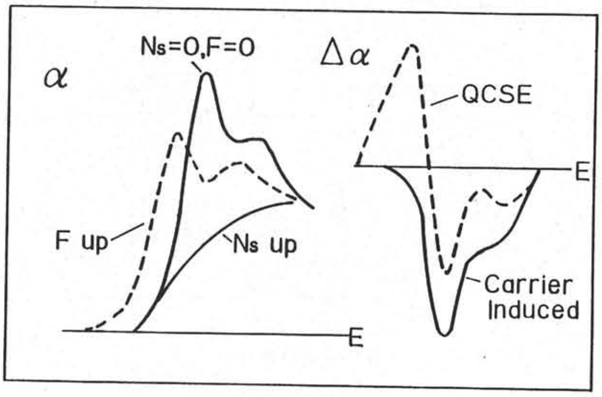

Fig.2 Schematic illustrations of the change of absorption spectra of quantum wells by quantum confined Stark effect(broken line) and by carrrier induced effect(solid line)

this kind of waveguide as one branch of Mach Zehnder interferometor and to achieve the phase shift of π, then the required length L is found to be 33um. Since the absorption at $\hbar\omega$=1.55eV is strong, it becomes more desirable to operate devices at lower photon energies where the residual absorption is smaller. For example, at $\hbar\omega$=1.505eV, 50meV below the exciton peak, α_{TE} is $27cm^{-1}$ and Δn_{TE} becomes 0.0015. The required length L is then 230um, which is still considerably smaller than that of $LiNbO_3$ devices. In this low absorption range, it is possible , of course, to construct not only Mach Zenhder interferometor but a cross-waveguide total reflector switch and a directional-coupler modulator. The switching speed of these CIRIC modulators, and switches is essentially the same as that of field effect transistors. Hence the ultimate speed is limited by the transit time τ_{tr} and as small as 5 psec, when the channel length or the width of the waveguide is 1um 2um. The cut off frequency is 15 to 30 GHz. As in the usual FET operation, the CR delay to charge up the waveguide with charge ΔQ may further reduce the switching speed. To minimize this delay, one must adopt a high

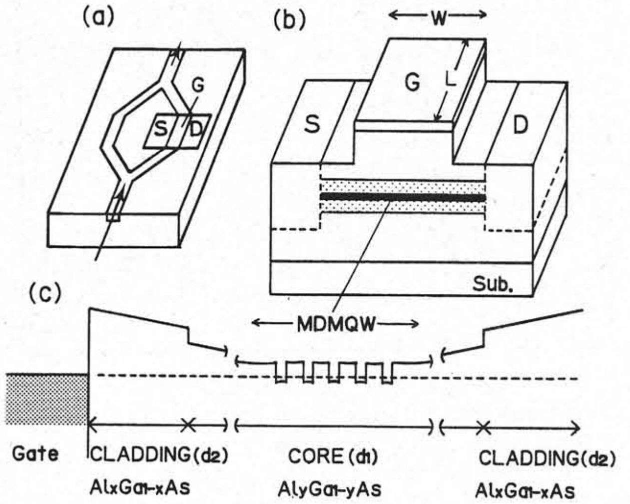

Fig.3 A proposed Mach Zehnder interferometor in which one branch consists of QW CIRIC modulator(a), its details(b), and its band diagram(c). Typical Dimensions: the source drain distance W(1~2um), the modulator length L (230um), the core thickness $2d_1$(5000A), the cladding thickness d_2(4000A), and the well width(90A). The Al mole fractions , x and y, of core and cladding layer are 0.24 and 0.38, respectively.
The lateral confinement is achieved by the ridge structure, in which d_2 is changed stepwise.

power FET driver which can supply the current J greater than $\Delta Q/\tau_{tr}$.

The results of Fig. 1(b) allows one to estimate roughly the chirping in QW lasers under current modulation, since the chirping results from the CIRIC process of holes and electrons. Since the state density of electrons is smaller than that of holes, the bandfilling effects takes place mainly in the conduction band. By considering that the lasing energy of SQW or MQW laser is about 20~25meV below the exciton peak and by assuming the variation of N_s is from $5x10^{11}$ to $1x10^{12}cm^{-2}$, the expected change in refractive index is 0.015. When the confinement factor is 2% for single QW and 20% for MQW, the calculated change in refractive index is $3.0x10^{-4}$ or $3.0x10^{-3}$, respectively. This should change the lasing wavelength $(\Delta n/n)\lambda$=0.67A~6.7A. Since the injection level for lasers depends on various parameters such as waveguide losses and mirror losses, the above discussion provides only a rough estimate on chirping. More rigorous analysis will be presented elsewhere.

In summary, the magnitude of carrier induced refractive index in QWs has been studied for the first time and their importance for device applications and the chirping in lasers are clarified.

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