Infrared absorption due to two-dimensional-electron-gas collective excitation in $GaAs/Al_xGa_{1-x}As$ multiple-quantum-well structures

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Infrared absorption due to a collective excitation of a two-dimensional electronic gas was observed in $GaAs/Al_xGa_{1-x}As$ multiple-quantum wells when the incident light is polarized parallel to the quantum-well plane. We attribute this phenomenon to a plasma oscillation in the quantum wells. The measured wavelength of the absorption peak due to the plasma oscillation agrees with our theoretical analysis. In addition, in this study the plasma-phonon coupling effect is also fitted to the experimental result. We show that the absorption is not related to the intersubband transitions but to the intrasubband transition, which originates from a plasma oscillation.

I. INTRODUCTION

Quantum-well infrared photodetectors (QWIP's) have attracted a lot of interest recently due to the fact that they can be used to produce large, two-dimensional imaging arrays. Most studies of QWIP's have concentrated on the intersubband transition in the $GaAs/Al_xGa_{1-x}As$ material system,[1–7] in which the selection rules forbid intersubband infrared (IR) absorption at normal incidence. In order to couple the IR radiation into the structure, optical gratings, usually metallic, or waveguides have been used. As an exception, Rosencher *et al.*[8] observed intrasubband photoconductivity for parallel-polarized light in $GaAs/Al_xGa_{1-x}As$ multiple quantum wells for the case of normal incidence. They attributed the intrasubband transition to a hot-electron bolometric effect. In this paper, we show another intrasubband transition in $GaAs/Al_xGa_{1-x}As$ multiple quantum wells which also occurs for light polarized to the quantum-well plane, and attribute this phenomenon to a plasma oscillation mechanism.

II. EXPERIMENT

A. Sample preparation

The samples used were grown by conventional molecular-beam epitaxy (MBE) in a VG-80H MBE system. The substrates were undoped, semi-insulating (100) GaAs. A buffer, consisting of undoped 2000-Å GaAs, and 1-μm n^+ GaAs with a Si concentration of 3×10^{18} cm^{-3}, and followed by 50 Å-undoped GaAs, was grown at a substrate temperature of 690 °C. The active region, consisting of a stack of 50 quantum wells each with a width of 52 Å, separated by 500-Å-thick $Al_xGa_{1-x}As$ ($x=0.22$) barriers, was next grown at a substrate temperature of 610 °C. The wells were doped in the center 32 Å with a Si concentration of 2×10^{18} cm^{-3}. The samples were capped by 50 Å of undoped GaAs and finally by 0.5-μm n^+ GaAs with a Si concentration of 3×10^{18} cm^{-3}.

B. Measurement

Absorption spectra were measured at room temperature using a Fourier transform infrared (FTIR) spectrometer. The samples are typically 4 mm long and 0.35 mm thick, and have their ends beveled at 45°. In this case, nine double passes are made through these quantum wells as the light passes down the length of the samples. The scan of the incident light covers a wave number range from 700 (14.3 μm) to 1400 cm^{-1} (7.1 μm). A polarizer was introduced to polarize the incident infrared light. The light is polarized parallel or perpendicular to the plane of the quantum well to measure intrasubband and intersubband transitions, respectively.

III. THEORETICAL CONSIDERATIONS

For a Si-doped n-type GaAs quantum well, the electrons in the well act as a quasi-two-dimensional plasma. The quantized plasma is represented by an anisotropic plasma slab with an effective thickness d^* and a spatially uniform effective dielectric tensor whose principal components are given as[9]

$$\varepsilon_x(\omega)=\varepsilon_x[1-4\pi n_s e^2/\varepsilon_x m_x^* d^* \omega(\omega+i\gamma x)] , \quad (1)$$

$$\varepsilon_z(\omega)=\varepsilon_z+\sum_{ij}4\pi n_s e^2 f_{ij}/m_{ij}^* d^*(\omega_{ij}^2-\omega^2-i\gamma_{ij}\omega)\ , \quad (2)$$

$$\varepsilon_y(\omega)=\varepsilon_x(\omega)\ , \quad (3)$$

where x, y, and z are the directions of propagation of the modes. x and y axes are defined to be parallel to the quantum-well plane, and the z axis is parallel to the growth direction (because the x-y plane is parallel to the well, the choice of x and y axes used in the present case is arbitrary). γ_x is the damping constant of the carriers for motion in the x or y direction. ε_x, ε_y, and ε_z are the optical dielectric constants parallel and perpendicular to the quantum-well plane in the GaAs active layers, respectively ($\varepsilon_x=\varepsilon_y$). n_s is the effective two-dimensional charge density. ω_{ij}, f_{ij}, and γ_{ij} are the frequency, oscillator strength, and damping constant of the i-j intersubband electronic excitations.

The longitudinal plasma eigenmodes (plasmons) are obtained from

$$\varepsilon(q,\omega)=0\ , \quad (4)$$

namely,

$$\varepsilon_y(\omega)=\varepsilon_x(\omega)=0\ , \quad (5)$$

$$\varepsilon_z(\omega)=0\ . \quad (6)$$

Then we can obtain the plasma frequency

$$\omega_y^2=4\pi n_s e^2/(m_y^* d^* \varepsilon_y)\ , \quad (7)$$

where m_y^* is the effective mass in the y direction. Letting d be the well width and d^* the effective well width, and defining a ratio $\xi=d^*/d$, the plasma frequency can be rewritten as

$$\omega_y^2=4\pi N_d e^2/(m_y^* \xi \varepsilon_y)\ , \quad (8)$$

where N_d is the three-dimensional average doping density given by $n_s=N_d\times d$. In the case of infinite barrier height, $\xi=0.58$,[10] while in the case of finite barrier height $0.58<\xi\leq 1$. The frequency of the collective intersubband mode can be expressed as

$$\omega_{01}^{*2}=\omega_{01}^2+4\pi n_s e^2 f_{01}/m_{01}d^*\varepsilon_z=\omega_{01}^2+\Omega_{01}^2\ , \quad (9)$$

where

$$\Omega_{01}^2=4\pi n_s e^2 f_{01}/m_{01}d^*\varepsilon_z$$

and

$$f_{01}=(2m\omega_{01}/h)|\langle 0|z|1\rangle|^2\ .$$

Ω_{01} represents the contribution to Ω_{01}^* from the polarization field ($E_z=4\pi P_z$) of the intersubband excitation. f_{01} is the intersubband transition oscillator strength. The expected value of f_{01} is 0.96.[12]

If the incident wave includes an electric-field component of E_z in the z direction (perpendicular to the quantum-well plane), the electric radiation field can be coupled to the z-direction oscillation mode and provides wave energy to the plasma oscillation. When $\omega=\omega_{01}^*$, plasma resonance in the z direction will occur, and then an absorption peak can be observed at this frequency. On the other hand, if the incident wave has an electric-field component E_y, the radiation field can be coupled to the y-direction oscillation mode and provides wave energy to the y-direction plasma oscillation. When $\omega=\omega_y$, resonance in the y direction will occur, and then the absorption peak can be observed at the frequency ω_y.

IV. RESULTS AND DISCUSSION

Figure 1 shows the measured absorption of a structure containing 50 Si-doped quantum wells at room temperature for a typical sample without using a polarizer. Three main peaks, labeled A, B, and C, with wave numbers 843 ($\lambda_a=11.9$ μm), 966 ($\lambda_b=10.1$ μm), and 1084 cm^{-1} ($\lambda_c=9.2$ μm), respectively, are observed. However, when the incident wave is polarized perpendicular to the quantum-well plane, only two strong absorption peaks B and C are observed, as shown in Fig. 2. In order to identify the origins of peaks B and C, we have calculated the subband energies in the well. For the $GaAs/Al_{0.22}Ga_{0.78}As$ system at 300 K, the band offset ΔE_c is 168 meV. The first and second subbands are, respectively, 40 and 160 meV above the bottom of the well. These calculated data are in good agreement with the measured energies for peaks B in Figs. 1 and 2, where we propose that peak B corresponds to the intersubband transition from the first subband to the second one.

Similar to the above analysis for peak B, we also calculated the energy of peak C. We found that the corresponding energy is much higher than the measured value, i.e., such a transition occurs from the first subband to a state out of the well. Therefore , peak C seems to originate from the lowest subband to the continuum state transition. If so, the width of the absorption peak must be quite broad. However, peak C shown in Figs. 1 and 2 is quite sharp. We also presumed that the final state is not the continuum state, but a third subband within the well. But the transition from the first subband to the third one is forbidden. It implies that there may be an unknown resonance process occurring in the quantum

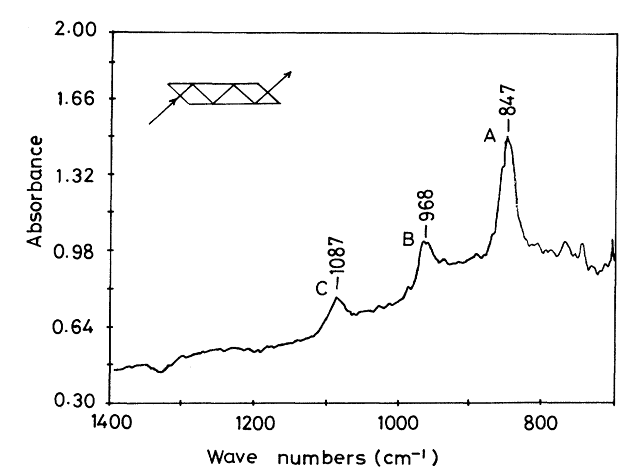

FIG. 1. Absorbance spectrum for a typical sample measured in a unpolarized 45° incidence configuration (without using a polarizer). Three peaks, labeled A, B, and C, are observed.

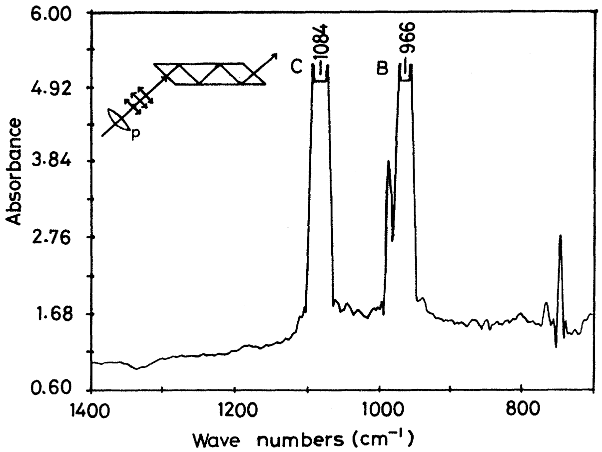

FIG. 2. Absorbance spectrum for the same sample measured in a polarized 45° incidence configuration. The incident light is polarized perpendicular to the quantum-well plane. Two strong absorption peaks B and C due to intersubband transition appear, and peak A completely disappears. In the inset, P denotes the polarizer.

wells. At the present time, the origin of peak C remains unknown.

On the other hand, when the incident light is polarized parallel to the quantum-well plane, only one strong absorption peak A appears, as shown in Fig. 3, in which both absorption peaks B and C completely disappear.

We also measured another ten samples with different well widths and molar fractions x, and found that they show the same behavior. The positions of peaks A, B, and C for a sample with the same well width and molar fraction x are very close to those of the typical sample as shown in Figs. 1, 2, and 3.

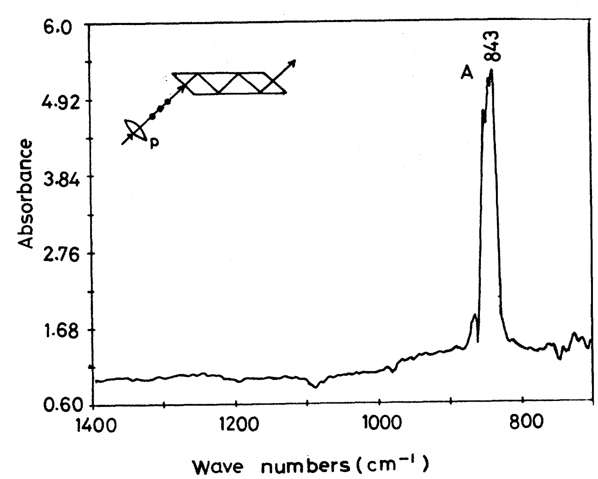

FIG. 3. Absorbance spectrum for the same sample measured in a polarized 45° incidence configuration. The light is polarized parallel to the quantum-well plane. The strong peak A due to plasma oscillation appears, and peaks B and C completely disappear. In the inset, P denotes the polarizer.

It is worth noting that the samples used in this study have 1.5 μm of heavily doped top and bottom contacts. They comprise a greater width than the total width of the quantum wells. One should expect plasma oscillation from these bulklike contacts. To clarify this thought, we measured the same sample without the multiple quantum wells, i.e., the multiple quantum wells were removed by a chemical etching, leaving behind only a 1-μm-thick heavily doped GaAs layer on the substrate. We found that no absorption signal appeared in the wave-number range from 700 to 1400 cm^{-1}. Thus we believe that signals A, B, and C, as shown in Fig. 1, are not induced by the n^+-GaAs bulklike contact layers.

We are now in a position to calculate the plasma wavelength. Using Eq. (8), we can calculate the plasma frequency ω_y. In this equation, $N_d = 2\times10^{18}\ cm^{-3}$, $m_y^* = 0.067 m_0$ (where m_0 is the free-electron mass), $\varepsilon_y = 10.2$,[11] and $\xi = 0.7$ for the Al molar fraction of $x = 0.22$ used in our calculation. As a result, we obtain 14.5 μm for the plasma wavelength. This value is in rough agreement with the measured value of $\lambda_a = 11.9\ \mu$m. The difference between the experimental and theoretical values may be due to the collective plasma-phonon coupling effect.

Now let us deal with the problem of the plasma-phonon coupling. The dielectric function, including the transverse-optic (TO) mode at frequency ω_t, is expressed as[13]

$$\varepsilon(\omega) = \varepsilon_y + (\varepsilon_0 - \varepsilon_y)\omega_t^2/(\omega_t^2 - \omega^2) \ . \tag{10}$$

Using the Lyddane-Sachs-Teller relation between ω_t and ω_l [ω_l is the longitudinal-optic (LO) mode frequency][14]

$$\omega_l = \omega_t \sqrt{\varepsilon_0/\varepsilon_y} \ , \tag{11}$$

and inserting the plasma term $-\omega_p^2/\omega^2$ into Eq. (10), we have

$$\begin{aligned}\varepsilon(\omega) &= \varepsilon_y - \omega_p^2/\omega^2 + (\varepsilon_0 - \varepsilon_y)\omega_t^2/(\omega_t^2 - \omega^2) \\ &= \varepsilon_y[1 - \omega_p'^2/\omega^2 + (\varepsilon_0/\varepsilon_y - 1)\omega_t^2/(\omega_t^2 - \omega^2)] \ ,\end{aligned} \tag{12}$$

where ω_p is the plasma frequency without the optic dielectric constant parameter ε_y, and ω_p' is equal to ω_y, as given by Eq. (8). By letting Eq. (12) equal 0, longitudinal plasma eigenmodes can be obtained. As a result, the coupling between the plasma and phonons can be expressed as

$$\omega_\pm^2 = \tfrac{1}{2}[\omega_l^2 + \omega_y^2 \pm \sqrt{(\omega_l^2 + \omega_y^2)^2 - 4\omega_y^2\omega_t^2}] \ . \tag{13}$$

This result has also been obtained by Warga[15] and Singui and Tosi[16] by different methods. In the present study, we are only interested in the ω_+ branch. In order to calculate the frequency ω_+, the electron density $N_d = 2\times10^{18}\ cm^{-3}$ and the frequencies $\omega_l = 8.88\times10^{10}$ Hz (corresponding to wave number 296 cm^{-1}) and $\omega_t = 8.19\times10^{10}$ Hz (corresponding to wave number 273 cm^{-1}) for GaAs (Ref. 17) were used. As a result, the wavelength λ_+ corresponding to the frequency ω_+ will shift from 14.5 [calculated from Eq. (8)] to 13.5 μm. This expected value is quite close to our experimental data ($\lambda_a = 11.9\ \mu$m). Thus, summarizing the discussion given above, we believe that the absorption peak A in Figs. 1 and 3 originates from the plasma oscillation and the plasma-phonon coupling effect.

We also consider another reason to explain the difference in the wavelength between the experimental and theoretical values: Experimentally, the true Si-doping density may be higher than the designed value of $N_d = 2\times10^{18}$ cm^{-3} in GaAs active layers. If so, the plasma oscillation peak would appear on the short-wavelength side.

V. CONCLUSION

In conclusion, we have observed that plasma oscillation occurs in GaAs/Al_xGa_{1-x}As multiple-quantum-well infrared photodetectors when the incident light is polarized in the direction parallel to the quantum-well plane. The measured wavelength of the absorption peak A due to plasma oscillation and plasma-phonon coupling is in good agreement with the theoretical result. Although infrared absorption occurs near the intersubband energy difference, the absorption mechanism is not due to direct intersubband transitions. Therefore, infrared absorption is detected even at normal incidence, which is remarkedly different from detectors based on intersubband transitions.

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