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Proposed Model of Electric Field Effects in High-Purity GaAs at Room Temperature

Durga Prasad Sapkota[1*], Madhu Sudan Kayastha[2], Makoto Takahashi[2], Koichi Wakita[2]

[1]Research and Development, Nepal Telecom, Kathmandu, Nepal
[2]Graduate School of Engineering, Chubu University, Kasugai, Japan
Email: [*]durga.sapkota@ntc.net.np

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Abstract

We have proposed a new model for the calculation of excitonic electroabsorption based on modified previously reported models for bulk structure. The excitonic absorption spectra in high purity GaAs have been theoretically studied in the presence of electric field at room temperature (RT). The Stark shift, linewidth broadening of exciton and extinction ratio have been calculated as a function of electric field. For the validity of our model we have compared with experimental result.

Keywords

Optoelectronics, Electroabsorption, Modulator

1. Introduction

Electroabsorption modulators are semiconductor devices which can be used for controlling the intensity of a laser beam via an electric voltage and have only been reported for waveguide configuration. Surface normal mode results in low extinction ratio due to short depletion width. We succeeded in growing high-purity epitaxial layers ($\sim 1 \times 10^{13}$ cm^{-3}) and obtaining high extinction ratio over 20 dB [1]. Based on the well known model [2] [3] (Franz-Keldysh effect) such large extinction ratio cannot be explained. We also observed clear exciton peak [4] and large red-shift associated with applying voltage as reported for quantum well structures. Therefore we propose a new model based on the experimental data.

Super-parallel and high speed operation that is characteristic of light can be realized by spatial light modulators (SLMs). However, at present a liquid-crystal light valve is only practically used with a low contrast ratio and low speed. Surface normal electroabsorption modulators are expected to be a next-generation SLMs with high speed and highly efficient SLMs.

[*]Corresponding author.

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The theoretical and experimental results have been reported [5]-[8]. Casey *et al.* [9] has discussed the strong relationship between the background impurities and optical absorption in bulk GaAs material. They pointed out that the contribution of exciton on absorption can be observed in high purity (5×10^{16} cm^{-3}) bulk GaAs even at RT. Dow and Redfield have theoretically studied about the importance of excitonic effects on electroabsorption [10]. The experimental result of high-purity GaAs epilayers has been succeeded with background impurity less than 1×10^{13} cm^{-3} at RT and Hall mobility of 312,000 cm^2 V^{-1}·s^{-1} at 77 K by using a liquid phase epitaxy (LPE) method [4]. A clear exciton absorption peak at RT is observed in this high purity epilayer which makes it possible to develop a spatial light modulator (SLM). This epilayer with large depletion layer over 30 μm is operated at surface normal configuration.

The experimental and theoretical study on excitonic electroabsorption in high purity GaAs at RT was realized [11], where F-K broadening has been used as Bottka *et al.* [7] and Sommerfeld factor was also not considered. In this work, we have proposed a new model for the calculation of excitonic electro absorption based on previously reported models. The Stark red-shifts, linewidth broadening of exciton and extinction ratio have been calculated. A new SLM with high speed and low driving voltage can be proposed by using these results. For the validity of our model we have compared with experimental result [12] and found the close agreement between them.

2. Theoretical Models

The absorption coefficient with exciton band and continuum band transition including Gaussian function and Sommerfeld factor at RT can be generalized based on [13] for bulk heavy hole only

$$\alpha(\hbar\omega) = \alpha_g \left(\frac{n_r E_g}{\hbar\omega}\right)\left[\alpha_e(x) + \alpha_c(x)\right] \quad (1)$$

where $\alpha_e(x) = G(x)$ and $\alpha_c(x) = H(x) + S(x)$

$$x = \frac{(\hbar\omega - E_{ex})}{\hbar\Gamma} \quad (2)$$

$$G(x) = Q_X e^{-\frac{x^2}{2}} \quad (3)$$

$$H(x) = \frac{1}{1+e^{x}} \quad (4)$$

$$S(x) = \frac{1}{1+e^{-2\pi x}} \quad (5)$$

$$\alpha_g = \left[\frac{|M_{cv}|}{\hbar k_{go} n_r}\right]^2 \left[\frac{(4\pi C_F)^2}{\varepsilon_s}\right]\left[\frac{(m_r)^2}{3(m_0)^2}\right]\left(\frac{n_r}{\lambda_{g0}}\right) \quad (6)$$

$$C_F = \frac{2\pi\mu_0 c_0 e^2}{2\hbar} \quad (7)$$

where n_r is refractive index at bandgap, $\hbar\omega$ is photon energy, E_{ex} is exciton transition energy, c_0 is velocity of light, ε_s is static dielectric constant, μ_0 is vacuum permeability, M_{cv} is dipole matrix element, $k_{g0} = 2\pi/\lambda_{g0}$, where λ_{g0} is free space bandgap wavelength, e is electron change, C_F is fine-structure constant, m_r is reduced mass of electron and hole, m_0 is free electron mass, $G(x)$ is Gaussian function, Q_X is exciton quenching factor, $S(x)$ is three dimensional Sommerfeld factor and $H(x)$ is Heaviside function.

3. Result and Discussion

Equation (1) is divided into two parts: one is absorption spectra with excitonic transition (α_e) which is represented by Gaussian function and the other is band continuum absorption spectra (α_c) which is represented by Heaviside and Sommerfeld factor. The Sommerfeld factor was considered for fitting with the experimental re-

sult. The optical matrix element has been calculated as defined in the Ref. 13.

The absorption spectra with excitonic effects for high-purity GaAs with 5µm thick with background impurity of 10^{14} cm^{-3} at various electric fields are shown in **Figure 1**. The Stark red-shift of exciton peak with and with out external applied voltage has been included as $\Delta E = -6\times10^{-3}\frac{9}{8}f^2$ meV and $\Delta E = -19\times10^{-3}\frac{9}{8}f^2$ meV where f is reduced electric field which is defined as $f = F/F_i$ where F_i is ionization field and F is electric field, respectively. The inhomogeneous exciton linewidth broadening due to variation of electric field causing from background impurity in intrinsic region is also included according to the [14] by fitting with the experimental results as $\hbar\Gamma = 26\times6.5\times10^{-3}\frac{1}{f}e^{\frac{-10}{3f}}$ meV.

The electroabsorption spectrum broadening due to continuum band transition (F-K effect) has been included as 2.6 times smaller than that of Bottka *et al.* [7] for fitting with the experimental result. In zero external voltage, the loss is estimated to be about 0.09 dB at photon energy of 1.404 eV. In our model, we have not considered the reflection loss, coupling loss and substrate loss due to which the absorption spectra are slightly higher in experimental result than that of the theoretical result at photon energy below 1.38 eV. In **Figure 1** the gap of absorption tail between experimental and theoretical results without external applied voltage starts at photon energy of 1.415 eV, on the other hand, the gap with external applied voltage nearly starts at 1.38 eV.

The reason behind this is that the contribution of the F-K effect dominates the excitonic effects at high electric field. The electric field induced Stark red-shift of exciton resonance remains stable toward the lower energy even at electric field of 70 kV/cm indicating that the electric field is uniformly distributed inside the active layer, which predicts very high-purity thin layer. It is fortunate that the large amount of Stark red-shift of 20 meV was obtained, which nearly conceded with the experimental results as shown in **Figure 2**. The maximum change in absorption coefficient is obtained roughly about 7000 cm^{-1} at 1.404 eV. In bulk GaAs, it is first time reported that the large red-shift and much change in absorption in EA modulation are obtained for surface normal configuration. Up to a field of 25 kV/cm, the shift of exciton resonance follows slightly and then abruptly after this electric field. This is due to the starting of the degeneration of mixing of excitonic band and continuum band at high electric field. At field of 70 kV/cm, the exciton absorption red-shift exceeds to the exciton binding energy experimentally measured as 6.5 meV at zero external applied voltage.

We obtained relatively large value of exciton binding energy and small value of Bohr radius as a result the exciton resonance is slightly broadened up to 14 times of classical ionization field as shown in **Figure 3**. In this study, the obtained ionization field is only 1.26 times smaller than GaN, whereas, it was reported about 17 times smaller [15]. We predict that the exciton peak after the electric field of 70 kV/cm may be completely dominated by F-K effect. We have calculated the extinction ratio by using the relation $10\log\left(e^{-\Delta\alpha d}\right)$ as a function of electric field strength at detuning energy of 25 meV. **Figure 4** shows that the gap of curve between the extinct-

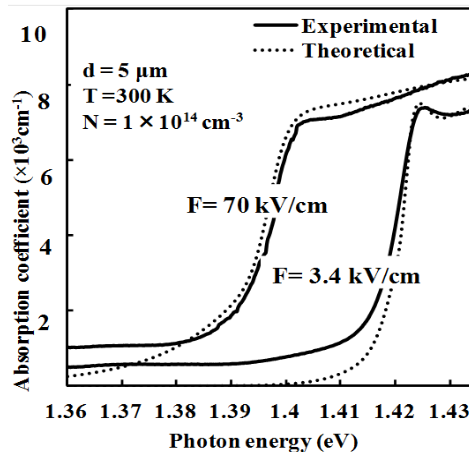

Figure 1. The comparison of excitonic absorption spectra between experimental and theoretical result.

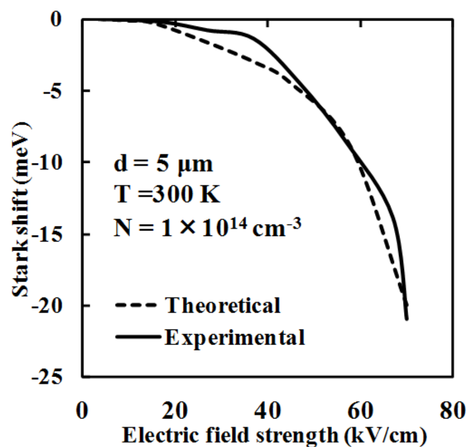

Figure 2. Theoretical and experimental results of Stark red-shift as a function of electric field.

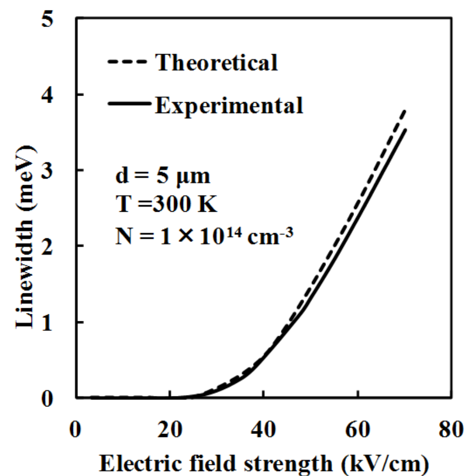

Figure 3. Theoretical and experimental results of linewidth as a function of electric field.

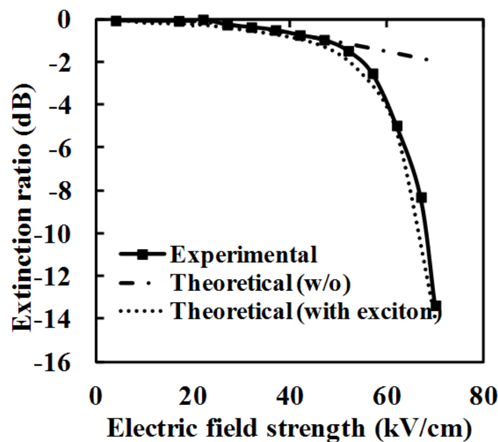

Figure 4. The extinction ratio as a function of electric field strength. The solid line, dot line and dash dot line represent the experimental, theoretical (with exciton) and theoretical (w/o exciton), respectively.

tion ratio with and without exciton is very small at low electric field. The separation increases with the increasing of electric field. The extinction ratio is estimated to be about 7 times higher in the case of exciton absorption than that of without exciton at 70 kV/cm. This is due to the advantage of enhancement of absorption with exciton as a result; we obtained the large absorption coefficient change in high-purity GaAs material. The extinction ratio is estimated to be 14 dB for high speed device at 70 kV/cm, however the applied voltage is comparatively high due to relatively large background impurity.

4. Summary

We have developed a new model for excitonic electroabsorption spectra, Stark red-shift, and inhomogeneous linewidth broadening in the presence of electric field strength based on previously reported result. We also obtained the large red-shift about 3 times higher than the exciton binding energy without excessive exciton linewidth broadening. This is appreciable result in bulk structure. The performance characteristic is determined to be an extinction ratio of 14 dB.

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