Fast Fourier Transform Photoreflectance

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Abstract: The electric fields in semiconductor were investigated by using fast Fourier transform photoreflectance (FFT PR) techniques. The Aspnes derivative function was introduced to analyze the PR spectra as a function of photon energy. Using the Airy function at several different electric fields in GaAs, the Franz-Keldysh Oscillations (FKO) above the band-gap energy (Eg) of PR spectra was generated. It was confirmed that FKO period increased with increasing electric field. The application of FFT to the PR spectra was demonstrated to be able to calculate the electric field from FKO period under uniform electric field.

บทคัดย่อ: สนามไฟฟ้าที่เกิดขึ้นภายในสารกึ่งตัวนำ สามารถตรวจสอบได้โดยเทคนิคฟูเรียร์ทรานส์ฟอร์มโฟโตรีเฟลกแตนซ์ ฟังก์ชันของAspnes derivative ถูกนำมาใช้ในการวิเคราะห์สเปกตรัมของโฟโตรีเฟลกแตนซ์กับพลังงานโฟตอน การแกว่งของ Franz-Keldysh ปรากฏในสเปกตรัมของโฟโตรีเฟลกแตนซ์เหนือค่าของแถบพลังงานต้องห้ามของสารกึ่งตัวนำแกลเลียมอาร์เซไนด์ได้ถูกสร้างจำลองขึ้นโดยใช้ฟังก์ชัน Airy ที่ค่าสนามไฟฟ้าต่างๆ คาบการแกว่งของสเปกตรัมมีค่าเพิ่มขึ้นเมื่อสนามไฟฟ้ามีค่าเพิ่มขึ้น การประยุกต์ใช้เทคนิคฟูเรียร์ทรานส์ฟอร์มกับสเปกตรัมของโฟโตรีเฟลกแตนซ์ถูกแสดงให้เห็นว่า สามารถหาค่าสนามไฟฟ้าได้จากคาบการแกว่งของ Franz-Keldysh ภายใต้สนามไฟฟ้าที่เกิดขึ้น

1. Introduction

With the development and application of high-quality thin-film growth techniques such as molecular-beam epitaxy (MBE) and organometallic vapor phase epitaxy (OMVPE), groups of new materials such as semiconductor heterostructures including superlattices (SLs), single quantum wells (SQWs), and multiple quantum wells (MQWs) have been produced because of their new physical properties and device applications. A variety of characterization methods including photoluminescence (PL), photoluminescence excitation (PLE) spectroscopy, modulation spectroscopy, Raman and resonant Raman spectroscopy, absorption spectroscopy, transmission electron microscopy (TEM), Hall measurements, etc., have been applied to exploit various physical information from those structures, but most of the methods mentioned above must work under specific conditions such as low temperature, e.g., PL, PLE, or special sample preparation, e.g., TEM, etc. In experiments, the most popular methods should be simple as well as informative. This aim is satisfied in photoreflectance (PR), one of the powerful contactless modulation spectroscopy suggested by Wang, Albers, and Bleil in 1967 [1]. It was widely used in extraction of semiconductor band-structure parameters [2] in the 1970s.

Since the first report on the application of the PR technique to semiconductor heterostructure studies by Glembocki et al [3] in 1985, hundreds of papers have been published on this subject. PR is contactless, requires no special mounting of the sample, can be performed in a variety of transparent ambients and is sensitive to surface and interface electric fields. It is well known that at high electric fields Franz-Keldysh oscillation (FKO) appears in the PR spectra above the band-gap energy. The period of oscillations is directly related to the electric field at the surface or interface. Another more important feature of this technique is that even at room temperature, it can still provide as much information as other methods, i.e., PL, PLE, etc., at very low temperature [3]. For example, by using PR at 300 K, it is possible to determine the interband transition energies in semiconductor heterostructures (SLs, SQWs and MQWs) with an accuracy within a few meV. By analyzing the PR spectra, one can obtain even more information about any interested transition and can obtain even more information about the electric fields at surface or interface of semiconductor heterostructures.

In this paper, the application of fast Fourier transform (FFT) to the PR spectra is demonstrated to be able to calculate the electric field from FKO.

2. Fundamental PR Line shapes

The representation of the complex dielectric function ε of semiconductors and semiconductor heterostructures in a uniform electric field as a low-field perturbation expansion has proved to be particularly useful in the modulation spectroscopy such as photoreflectance and electroreflectance [4]. The low-field expression for $\Delta\varepsilon$, the field-induced change in ε, is related to the third derivative of the unperturbed dielectric function and is sufficiently simple to allow certain critical-point characterization to be obtained directly from low-field PR line shapes [4-7]. To consider the perturbation on the reflectivity R, when the electric field is applied to a sample, the reflectivity is changed through the change of the dielectric constants $\varepsilon 1$ and $\varepsilon 2$. The relative change of the reflectivity dR/R can be written as [6-7]

$$\frac{dR}{R}=\alpha(\varepsilon_1,\varepsilon_2)\Delta\varepsilon_1+\beta(\varepsilon_1,\varepsilon_2)\Delta\varepsilon_2\,, \qquad (1)$$

where α and β are the Seraphin's coefficients; $\varepsilon 1$, $\varepsilon 2$ and $\Delta\varepsilon 1$, $\Delta\varepsilon 2$ are the real and imaginary parts of the dielectric constant, respectively, and its variation, i.e., $\varepsilon = \varepsilon 1 + i\varepsilon 2$ and $\Delta\varepsilon = \Delta\varepsilon 1 + i\Delta\varepsilon 2$. The real and imaginary parts of the dielectric constants can be related with each other by Kramers-Kronig relations.

By first-order perturbation calculation, Aspnes [8] derived a result that dR/R is proportional to the third derivative of the unperturbed dielectric function, which depends on the joint density of states of a material, in the limit of low-field modulation. Here, the low-field limit means that the electro-optic $\eta\Omega \ll \Gamma$, where Γ is the broadening parameter of the optical feature, and $\eta\Omega$ is given by

$$(\eta\Omega)^3 = e^2\eta^2F^2/2\mu \qquad (2)$$

where F is the electric field in the sample which could be externally applied (or built-in) electric field. When $\eta\Omega \gg \Gamma$, the situation is in a high-field regime, where in bulk materials it appears as FKOs, which are described in section 3.

In the low electric field limit, i.e., the PR spectra as a function of photon energy can be analyzed using the Aspnes derivative function [7],

$$\frac{dR}{R}=\mathrm{Re}\sum_{j=1}^{p}C_j e^{i\theta_j}(E-E_{gi}+i\Gamma_j)^{-n}\,, \qquad (3)$$

Here, R is the reflectance, dR is the induced change in the reflectance by modulation light, E is the photon energy, p is the total number of spectral structures to be fitted, E_{gi},Γ_j,C_j and θ_j are transition energy, broadening parameter, amplitude and phase, respectively, of the feature corresponding to the jth critical point. The parameter n is a factor used to specify the critical point dimension.

3. Franz-Keldysh Oscillations in PR

When $\eta\Omega \gg \Gamma$, the situation is in a high-field regime, where in bulk materials it appears as FKOs. In the high-field limit, the FKO in PR spectrum is proportional to the product of Airy function such as Ai(x), Bi(x) and their derivatives such as Ai'(x), Bi' (x). The function describing the FKO in PR spectrum taking into account the mixing of both light and heavy hole signals [8]:

$$\frac{dR}{R}=\alpha_{lh}G[(E_g-E)/\eta\Omega]+\alpha_{hh}G[(E_g-E)/\eta\Omega], \qquad (4)$$

where G(x) is given by the Airy functions, G(x)=Ai'(x)Bi'(x) - xAi(x)Bi(x), $(\eta\Omega)^3=e^2\eta^2F^2/2\mu_{ih}$, (i=l or h). Here, E, Eg, and F are the photon energy, the band-gap energy, and the electric field strength, respectively. $\mu_{l(h)h}$ is the reduced light (heavy) hole mass : $\mu^{-1}_{l(h)h} = m^{-1}_{e} + m^{-1}_{l(h)h}$. The values for the effective electron and hole masses used here are in units of m_0. The α_{lh} and α_{hh} are coefficients containing the transition oscillation strength of the light and heavy hole.

4. Simulation with Airy function

The Airy function in Eq. (4) was used to simulate the FKO in the PR spectrum of a GaAs sample. The Airy function program was written by using C language run on UNIX systems such as Linux UNIX and FreeBSD UNIX. The FKOs of various electric fields from 20 to 80 kV/cm with a fixed α_{lh} and α_{hh} are shown in Figure 1. The periods of FKOs increase clearly with electric fields. When the electric fields are fixed at 40 kV/cm, the FKOs in PR spectra depend on the α_{lh} and α_{hh}, as shown in Figure 2. The amplitudes of FKOs increase with α_{lh} and α_{hh}, while the periods have not change in the PR spectra.

5. Fast Fourier transform PR

Fast Fourier transform (FFT) is applied to the PR spectra in the energy (E) region higher than the band-gap energy Eg to obtain the FKO period and then the electric field in the sample. The horizontal-axis variable is transformed from $\varepsilon=(E-Eg)^{3/2}$ to the inverse of ε as t, while the vertical-axis variable is from dR/R to G(t) that can be written as [9]

$$G(t)=\int (dR/R)\exp(-i2\pi\varepsilon t)d\varepsilon. \qquad (5)$$

The main peak (t_0) evaluated from the Fourier transform is related to the electric field by

$$t_0 = (2/3\pi)(2\mu)^{1/2}(1/e\eta F), \qquad (6)$$

where μ is the reduced effective mass and F is the electric field [10]. The FFT PR program was written by using C language run on UNIX systems such as Linux UNIX and FreeBSD UNIX .

As seen in Figure 3, the transformed results of the simulated FKOs in PR spectra shown in Fig.1 exhibit clearly two peaks. High-t peak corresponds to the FKOs of heavy hole, while lower-t peak to the FKOs of light hole. The values of the electric fields of light and heavy holes calculated from the peak position are, of course, the same as the electric field values of simulated FKOs in the section 4.

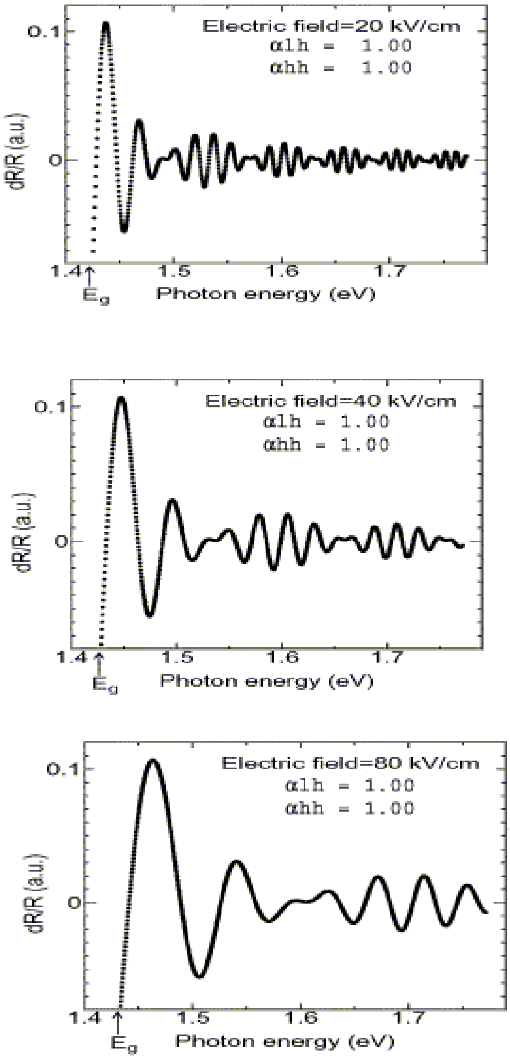
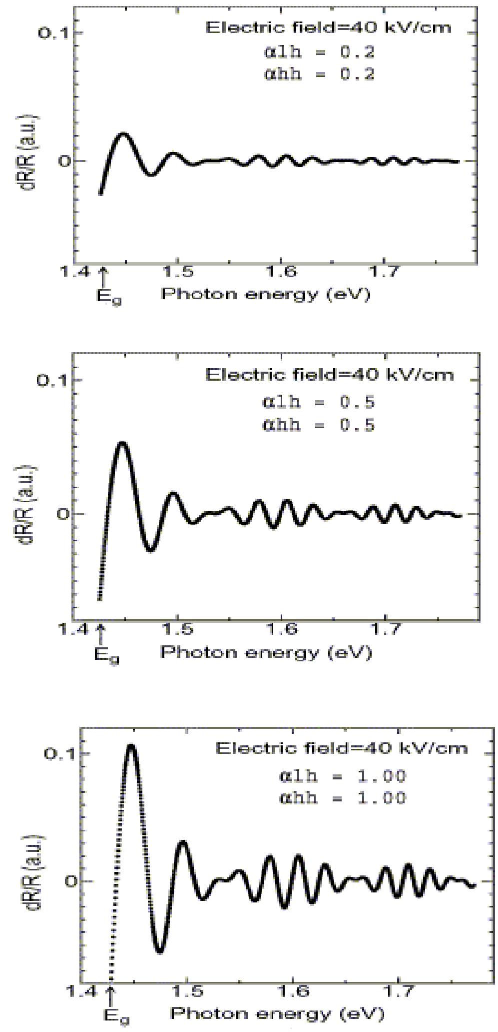


Figure 1. The FKOs due to various electric fields from 20 to 80 kV/cm with Fixed α_{lh} and α_{hh} are simulated by using the Airy function.

6. Discussions

J. Nukeaw *et al.* [11] have reported the electric fields at the surface and interface of doped GaAs/Si-GaAs structures grown by MBE. The electric fields were investigated using room-temperature PR spectroscopy. In the original PR spectra measured using a He-Ne laser as the pump light that had a modulation effect through out the doped layer, two different FKO periods could not be distinguished from each other. The application of FFT to the PR spectra can be used to calculate the electric field for each of the two periods involved in the original PR spectra. The transformed spectra clearly exhibited two peaks. By using an Ar laser as the pump light, the FFT-PR spectra showed only one peak. Because the Ar laser light was absorbed near the surface region. The resultant surface electric fields increased with increasing carrier concentration, while the change of the interface electric field was small. The behavior agreed qualitatively with the results of the model calculation, although there was a small discrepancy at higher carrier concentrations. The discrepancy was explained the field strength derived from PR measurement was not their maximum, but the average value for high electric fields.



Figurer 2. The FKOs for various α_{lh} and α_{hh} with a fixed electric field are simulated by using the Airy function.

J. Nukeaw *et al.* [12] also reported the electric fields of InP Er delta-doped grown by OMVPE. The electric fields were systematically investigated by room-temperature PR spectroscopy. The PR spectra were characterized by FKO above the band-gap energy due to an internal electric field in the epitaxial layer. FFT was applied to the PR spectra to calculate strength of the electric field from the FKO. The resultant electric field decreased with increasing Er-exposure duration. The dependence of the electric field on the Er-exposure duration was interpreted by change in size of the ErP clusters with the Er-exposure duration. The dependence of the electric field on the cap-layer was explained by the Er atoms easily reach to the surface with the thin cap-layer and react with O atoms in air to form Er_2O_3 after growth, resulting in increase of electric field.

Thus, FFT is successfully applied to the PR spectra to calculate the electric field from the FKO.

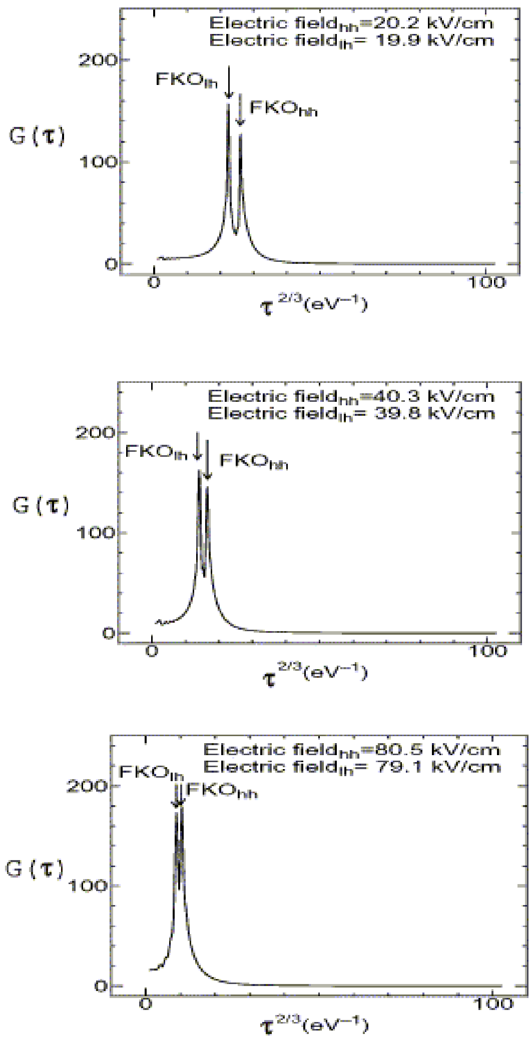


Figure 3. Transformed results of the PR spectra shown in Figure 1. From the peak positions the electric fields were obtained using eq. 6.

7. Conclusions

The FKO was generated using the Airy function at several different electric fields in GaAs. It was confirmed that FKO period increases with electric field. It was demonstrated that the application of FFT to the PR spectra can be used to calculate the electric field from the FKO under uniform electric fields.

References

[1] E. I. Wang, W. A. Albers, and C. E. Bleil, II-VI Semiconducting Componds, edited by D. C. Thomas (Benjamin, New York, 1967), p. 136.

[2] M. Cardona, Advances in Solid State Physics, Vol. X (Pergamon, Vieweg, 1970), p.125.

[3] O. J. Glembocki, B. V. Shanabrook, N. Bottka, W. T. Beard, and J. Comas, *Appl. Phys. Lett.* **46**,976 (1985).

[4] D. E. Aspnes and J. E. Rowe, *Solid State Commun.* **8**, 1145 (1970).

[5] D. E. Aspnes and J. E. Rowe, *Phys. Rev.* **B5**, 4022 (1972).

[6] J. E. Rowe, D. E. Aspnes, *Phys. Rev. Lett.* **25**, 162 (1970).

[7] D. E. Aspnes, *Surf. Sci.* **37**, 418 (1973).

[8] D. E. Aspnes, *Phys. Rev.* **B12**, 2297 (1975).

[9] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, Numerical Recipes in C (Cambridge University Press, Cambridge, 1994) p.496.

[10] D. P. Wang and C. T. Chen, *Appl. Phys. Lett.* 67, 2069 (1995).

[11] J. Nukeaw, Y. Fujiwara, and Y. Takeda, *Jpn. J. Appl. Phys.* 36, 7019 (1997).

[12] J. Nukeaw, N. Matsubara, Y. Fujiwara, and Y. Takeda, *Appl. Surf. Sci.* 117/118, 776 (1997).

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