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Enhanced two-photon absorption in a GaAs/AlAs multilayer cavity

Toshiyuki Kanbara, Shoya Nakano, Shinsuke Yano, Ken Morita, Takahiro Kitada and Toshiro Isu

Center for Frontier Research of Engineering, Institute of Technology and Science, The University of Tokushima
2-1, Minami-Josanjima-Cho, Tokushima 770-8506, Japan
Phone: +81-88-656-7671 E-mail: kanbara@frc.tokushima-u.ac.jp

1. Introduction

Strong optical nonlinearity of a semiconductor multilayer structure is useful for achieving planar-typed ultrafast all-optical switching devices with high switching efficiency. Recently, sub-picosecond responses of the optical Kerr signal of AlGaAs/AlAs multilayer were reported using the enhanced electric field of transmission modes [1]. It is also known that more enhanced internal field can be realized in a λ/2 cavity structure sandwiched by GaAs/AlAs multilayers comparing to a transmission mode of the plane periodic DBR multilayers, therefore much stronger optical Kerr signal can be expected using the cavity mode. In this work, we experimentally evaluated the electric field enhancement in the GaAs/AlAs multilayer with the λ/2-layer by using the time-resolved two-photon absorption (TPA) measurements. In order to evaluate TPA in the multilayer structure, the GaAs substrate has to be removed perfectly with keeping mirror surface. We propose an AlAs/$Al_{0.3}Ga_{0.7}As$ double etch-stopper structure for selective wet etching of the GaAs substrate.

2. AlAs/AlGaAs double etch-stopper structure

A number of works has been reported on selective removal of GaAs over $Al_xGa_{1-x}As$ using citric acid-based etchant. It was reported that the highest selectivity can be obtained when $x = 1$ (AlAs). [2] However, cracked structures caused by volume expansion of the AlAs oxides seriously degrade etching selectivity when a 200-nm-thick AlAs layer is used as the etch-stopper. Thus, we propose a double layer structure consisting of thin AlAs (5 nm) and thick $Al_{0.3}Ga_{0.7}As$ (200 nm) layers for selective removal of the GaAs substrate. Figure 1 shows time-dependent etch depths of etch-stopper structures with 50-nm-thick GaAs capping layers using citric acid-based etchants ($C_6H_8O_7$: H_2O_2 = 4:1). A 200-nm-thick $Al_{0.3}Ga_{0.7}As$ single layer and the AlAs/$Al_{0.3}Ga_{0.7}As$ (5 nm/200 nm) double layers were examined as etch-stopper structures. The GaAs capping layer was etched within first several seconds, because the etch rate of GaAs was about 400 nm/min. For the single $Al_{0.3}Ga_{0.7}As$ etch-stopper layer, the etching gradually proceeded, and all the layers were removed after 70 minutes. On the other hand, for the AlAs/$Al_{0.3}Ga_{0.7}As$ (5 nm/200 nm) double etch-stopper structure, etching was stopped at the AlAs layer for more than 20 minutes, indicating higher selectivity than the single AlGaAs etch-stopper. Extremely smooth mirror surface was obtained after selective removal of GaAs layer using the double etch-stopper structure.

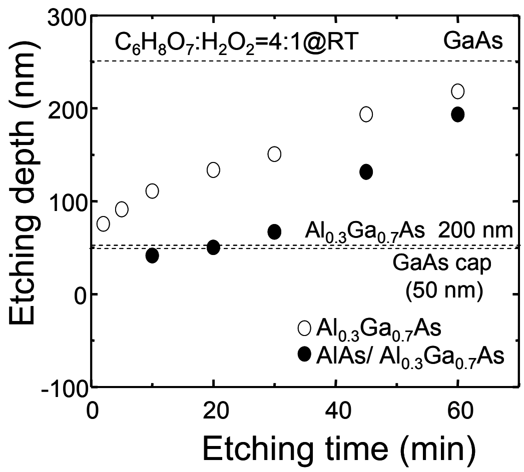

Fig.1 Time-dependent etching depth of $Al_{0.3}Ga_{0.7}As$ and AlAs/$Al_{0.3}Ga_{0.7}A$ etch-stopper structures.

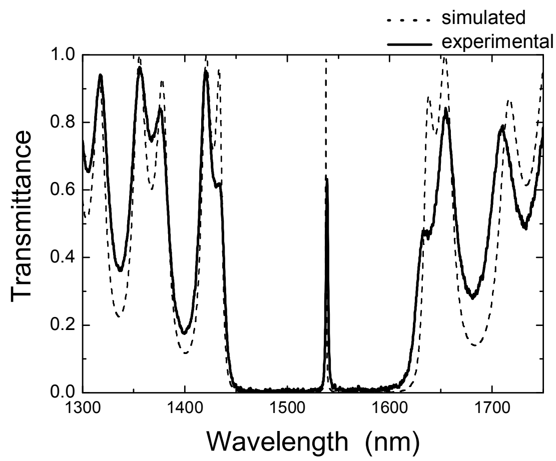

Fig. 2 Transmission spectra of GaAs/AlAs multilayer structures. Solid and dotted lines indicate the experimental and simulated results, respectively.

3. Two-photon absorption measurements

The cavity structure used in time-resolved TPA measurements was grown by molecular beam epitaxy (MBE). A GaAs cavity layer (222 nm) was inserted in the center of the 30 periods of GaAs(111 nm)/AlAs(130 nm) multilayer, and the double etch-stopper structures was also inserted between the substrate and the multilayer. The GaAs substrate was removed by selective wet etching after thinning to 100 μm by mechanical polishing. The solid line in Fig. 2

shows an experimental transmission spectrum of the sample. A strong cavity mode in the multilayer was observed at 1.54 μm. The width of the mode was ~2.6 nm, and it corresponded to ~1.3 ps in the time region. This transmission spectrum was well reproduced by a simulation based on the transfer matrix method (a dotted line in Fig. 2). Average internal field in the GaAs/AlAs multilayer structure at the cavity mode is estimated to be 45 times larger than that in a GaAs bulk.

TPA measurement was carried out by the time-resolved pump and probe method using ~100 fs pulses with 100 kHz reputation rate. The wavelength was tuned at the cavity mode (1.54 μm). The polarization directions of both the pump and probe beams were parallel to the [100] direction, and probe beam intensity was 0.1 mW. Figure 3 shows results of time-resolved transmission change of both the GaAs/AlAs multilayer and 350-μm-thick GaAs bulk. The strong transmission change due to TPA in the vicinity at $\Delta t = 0$ was obtained in both samples. The time width of transmission change in GaAs bulk was ~100 fs, which was limited to the laser pulse width. On the other hand, a time width of the GaAs/AlAs multilayer was about 1 ps, which was limited to the width of the cavity mode.

Transmission intensity of the probe beam is described by the following equation, when we assumed that the GaAs/AlAs multilayer is the homogeneous medium,

$$\frac{\Delta T}{T_0} = \frac{\beta Lsc^2 \mathrm{I}_{pu0}}{1+\beta Lsc^2 \mathrm{I}_{pu0}} \quad (1),$$

where I_{pu0} is the intensity of pump beam, β is two-photon absorption coefficient, L is the thickness of the medium, s is the transmission change on the surface and c is enhancement factor, which represents the enhancement of internal light intensity in the medium. Figure 4 shows the pump power dependence of $|\Delta T/T_0|$ at $\Delta t = 0$ in the GaAs/AlAs multilayer and GaAs bulk. We first determine the β of GaAs bulk by fitting of eq. (1) to the experimental result of the GaAs bulk with the use of $c = 1$, $L = 350$ μm and $s = 0.77$. We obtained $\beta = 16$ cm/GW for GaAs bulk, which was reasonable value in the literature reported previously [2]. In order to evaluate enhanced internal electric field effects of the GaAs/AlAs multilayer, we substituted $L = 7.5$ μm, $s = 0.79$ and $\beta = 16$ cm/GW in eq. (1), and fitted the enhancement factor c to the experimental result. We obtained $c = 37$ for our GaAs/AlAs multilayer sample. This shows that the average field in the GaAs/AlAs multilayer is 37 times larger than that in the GaAs bulk, which is well agreement with an estimated value (45 times larger) by the simulation of internal electric field.

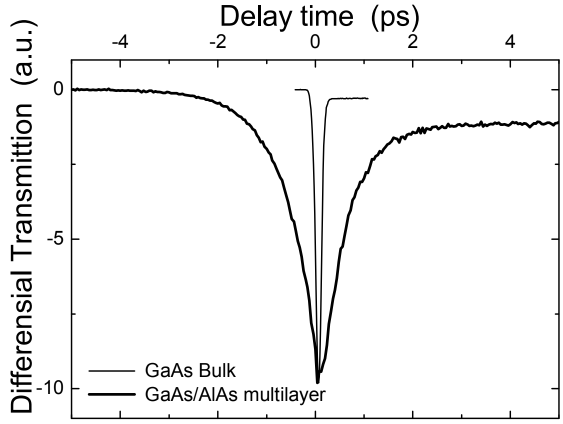

Fig.3 Time-resolved transmission change in the GaAs/AlAs multilayer sample and 350-μm-thick GaAs bulk.

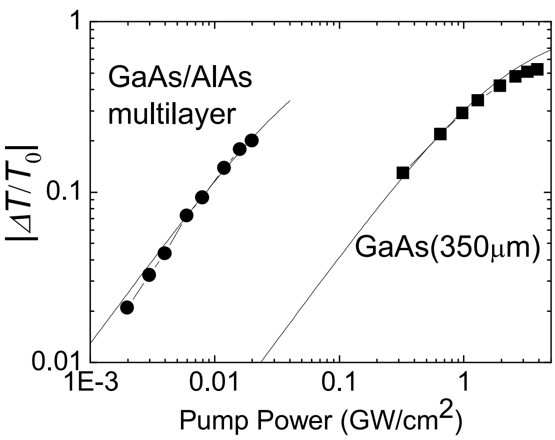

Fig.4 Pump power dependence of $|\Delta T/T_0|$ at $\Delta t = 0$ in the GaAs/AlAs multilayer sample and 350-μm-thick GaAs bulk.

4. Conclusions

We demonstrated strong enhancement of two-photon absorption in the GaAs λ/2-cavity structure sandwiched by GaAs/AlAs multilayers. Selective removal of the GaAs substrate from the multilayer sample for time-resolved TPA measurements was successfully achieved by using AlAs/$Al_{0.3}Ga_{0.7}As$ double etch-stopper structure. Time-resolved TPA measurements of the 30 periods GaAs/AlAs multilayer with the GaAs λ/2-cavity layer reveals that strong enhancement of TPA in the cavity structure comparing to the 350-μm-thick GaAs bulk. By analyzing the observed TPA results, the average electric field in the multilayer sample is 37 times larger than that in the GaAs bulk. The obtained enhancement factor is well agreement with an estimated value (45 times larger) by the simulation of internal electric field.

References

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