# Control of carrier relaxation for suppression of optical gain damping by using Well-in-Well structure

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***Abstract*- A quantum well design for controlling of the carrier dynamics was investigated for high speed direct modulation semiconductor lasers. The proposed Well-in-Well structure decreases the carrier relaxation time into an active well by designing the wave function which relates to the LO phonon scattering rate. By analyzing the scattering rate of each energy state, the electron relaxation time was estimated to be a few picoseconds which is 2-10 times smaller than that of a conventional quantum well structure. The result is desirable for improving the modulation damping effect which limits the modulation band width. f-3dB is expected above 50GHz. The effect of an asymmetrical Well-in-Well structure was also discussed.**

## I. INTRODUCTION

Quantum well (QW) lasers have been progressed and the direct modulation speed has become fast up over 20GHz. However, increase of the modulation speed by structural optimization methods is limited by the damping effect of the optical gain. To suppress the dumping effect due to the finite carrier relaxation time, a tunnel injection quantum well (TI-QW) structure (Fig. 1(a)) was proposed [1,2]. The TI-QW structure can control the carrier relaxation time into an active well by designing the wave function which relates to the LO-phonon scattering.

In this paper, a Well-in-Well (WWell) structure is proposed for controlling the carrier relaxation time to improve the modulation band width. The WWell has the same elemental functions as the TI-QW and a simple layer structure. It is noted the WWell is proposed to increase the LO phonon scattering by designing the quantum structure in detail and is different from the conventional GRIN-SCH which has similar potential steps. The electron relaxation characteristics dependence on the structure was analyzed numerically and modulation bandwidth was investigated.

## II. CONCEPT OF WWELL AND ANALYSIS MODEL

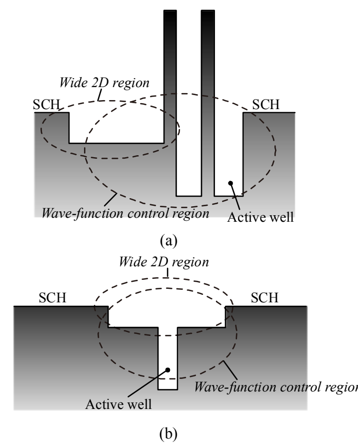


Fig. 1. Schematic models of single quantum well structure, (a) tunnel injection quantum well (TI-QW) structure, (b) Well-in-Well (WWell) structure.

Figure 1 shows the conventional TI-QW structure and the proposed WWell structure. The fundamental feature of the TI-QW is design of the wave functions in order to increase the LO-phonon scattering. The WWell structure is composed of the active inner well and the outer well. The outer well is designed for decreasing the LO-phonon scattering time from the outer well to the active inner well. The outer well is also designed to be a relatively wide 2D region to inject the carriers from the 3D-SCH region as the same reason as the TI-QW. Thus the WWell structure has the same elemental functions as the TI-QW. The WWell is formed with a simple structure and the charge non-neutrality effect which may be caused in the TI-QW will be relaxed.

For investigation of the characteristics of the WWell, the carrier relaxation time was analyzed. Here the carrier relaxation time means the ensemble time of the electron scattering from a SCH energy state to a ground state of the active well through the various energy state. This relaxation time was derived by rate equation with 6,000 variable numbers of energy and quantized states. The carrier scattering rate was calculated assuming the LO-phonon scattering by designing the wave function [3] because the LO-

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phonon scattering is a dominant mechanism. The assumed potential structure had a conduction band discontinuity of 0.31eV between a SCH region and an inner active well, and 0.23eV between an outer well and an inner active well. The width of the inner active well was fixed to 8nm. The potential structure can be composed by the GaAlAs and GaInAs. In the numerical analysis, 10 quantized states and these wave functions through the whole structure including SCH were derived by Schrödinger equation.

## III. Analysis and Results

Figure 2 shows the carrier relaxation time dependence on the width of the outer well. In the numerical analysis, the SCH layer thickness of one side was assumed to be 30 nm. It is noted that the structure whose outer well width was 0 nm and 30 nm correspond to the conventional QW structures of shallow and deep well depth, respectively. The relaxation time is reduced when the outer well width is approximately 10nm. The minimum relaxation time was 3.7ps and corresponding K-factor was 0.15ns at typical laser parameter.

Figure 3 shows the carrier relaxation time dependence on the well depth. In the case of conventional QW structures, the relaxation time showed a large dependence on the well depth with the range of over ten times. On the other hand, the WWell structures showed small relaxation time dependence on the well depth and it was shorter than that of the conventional QW. It is noted that a shallow well (<0.2eV) caused short relaxation time, however the optical gain will be degraded because of the broadening of the electron wave function. Thus such a shallow well is not appropriate to a high speed modulation laser.

In case of the symmetric potential structure of the WWell shown in Fig. 1 (b), the peak probability of the wave function of the outer well doesn't exist in the center of the inner active well though that of the inner well exists at the center. In order to increase the overlap between these wave functions, a "shifted WWell" structure was investigated. The shifted WWell structure had an asymmetric potential structure by shifting the inner well from the center of the outer well. The analyzed result is shown in Figure 4. The total thickness of outer wells was fixed to be 20nm. From the result, the relaxation time became faster in the shifted WWell structure than the symmetric potential structure shown as "10nm:10nm".

In conclusion, a novel quantum well active region "WWell" was proposed to reduce the electron relaxation time. The WWell is advantageous to improve the direct modulation response of the semiconductor lasers by suppression of the gain damping. The modulation response was also analyzed and over 50GHz of f-3dB can be expected by this structure. Detail will be shown in the presentation.

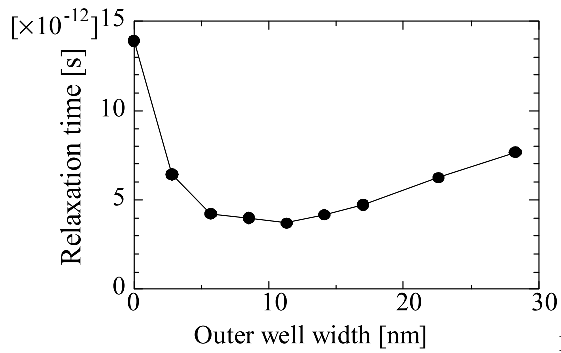


Fig. 2. Relaxation time dependence on outer well with of WWell structures. The width means the one side.

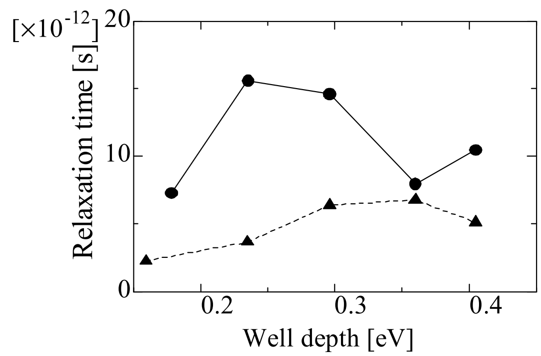


Fig. 3. Relaxation time dependence on the well depth of the conventional QW and WWell structure.

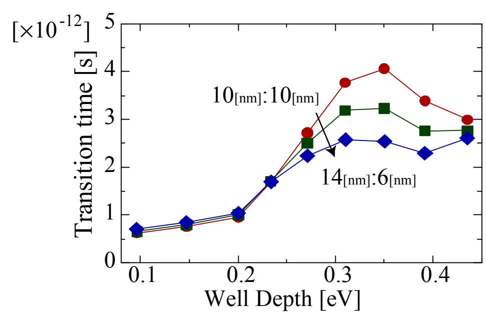


Fig. 4. Dependency of relaxation time on the degree of shift of active well.

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