Semicond. Sci. Technol. **21** (2006) 1069–1072 doi:10.1088/0268-1242/21/8/015

A study on the energy bands of multi-quantum wells in the quantum cascade laser structure by deep-level transient spectroscopy

Jin Soak Kim[1], Eun Kyu Kim[1], Il Ki Han[2], Jin Dong Song[2], Jung Il Lee[2], Sejoon Lee[3], Yoon Shon[3] and D Y Kim[3]

[1] Quantum-Function Spinics Laboratory and Department of Physics, Hanyang University, Seoul 133-791, Korea
[2] Nano Device Research Center, Korea Institute of Science and Technology, Seoul 130-650, Korea
[3] Quantum Functional Semiconductor Research Center, Dongguk University, Seoul 100-715, Korea

E-mail: ek-kim@hanyang.ac.kr

Received 26 January 2006, in final form 16 May 2006
Published 28 June 2006
Online at stacks.iop.org/SST/21/1069

Abstract
We have investigated the defect states and confined energy levels of three quantum wells (QWs) in the quantum cascade laser (QCL) structure by capacitance–voltage and deep-level transient spectroscopy methods. Defect states with activation energies in the range of 0.49–0.88 eV were obtained in the GaAs capping layer, and their origins were considered as EL3 and EL2 families, which are well-known deep levels of GaAs materials. The densities of these defects in the GaAs capping layer of the QCL structure were about 3–12% of the donor concentration. The confined energy levels of QWs showed activation energies of about 130 meV and 230 meV from the top of the AlGaAs barrier, and their carrier confinement ability was measured to be about 0.5% of the donor concentration.

1. Introduction

Quantum cascade lasers (QCL) are very much applicable to a gas sensor system for high sensitivity and free space communication at the atmospheric windows [1–3]. The structure of a QCL for the lasing wavelength of the mid-infrared range consists of several ten times repetition of the active region. The active region also consists of emission and injector regions. Each of the emission and injector regions is formed by multi-quantum wells (MQWs) or superlattices in the basis of GaAs/AlGaAs or InAlAs/InGaAs. After the successful suggestion of diagonal transition in the emission region, which has been adopted in the first successful QCL, more useful structures such as vertical transition and mini-band transition have been developed to improve the performance of QCLs [4–6]. In spite of successful development of QCLs, enough to be lased in room temperature and continuous wave operation [7], analysis of the QCL structures has mostly been focused on the optical properties by Fourier transform infrared or crystal properties by x-ray diffraction [8, 9]. There have been some reports on the electrical properties of the QCL structure such as capacitance–voltage (C–V) and current–voltage (I–V) [10, 11], but deep-level transient spectroscopy (DLTS) studies for the QCL structure can supplement more precise information on its electronic structure.

In this study, we investigated the electrical properties of the three-QW (3QW) emission region in the QCL structure by performing capacitance–voltage (C–V) and DLTS measurements. The emission region with GaAs/AlGaAs 3QWs was grown by molecular beam epitaxy (MBE) on an n^+-GaAs substrate, except other complex regions in the QCL structure. The emission mechanism in the 3QW region was discussed with quantum confined levels and barrier tunnelling.

Figure 1. Sample structure of GaAs/AlGaAs three quantum wells in the emission region of the QCL structure.

2. Experimental details

As mentioned before, the QCL structure is made up of several tens of periods of the active region, but this structure is too complicated to analyse the electrical properties by *C–V* and DLTS measurements. Thus, we used in this study a simple structure with an emission region. The GaAs/AlGaAs 3QW structure was grown by a MBE system. The GaAs buffer layer with a thickness of 500 nm was grown on the n^+-GaAs substrate, and then the GaAs and AlGaAs layers were grown alternatively in order to make the 3QWs. Nominal thicknesses of the GaAs QWs are 4.8 nm, 5.4 nm and 1.9 nm, and those of the AlGaAs barrier layers are 2.8 nm, 1.1 nm, 1.1 nm and 4.6 nm in the same sequence of the QWs. The ratio of Al and Ga in the AlGaAs is 3:7; thus, $Al_{0.3}Ga_{0.7}As$ was used as a barrier material. Very similar emission structures to our 3QWs have been adopted in the QCL which have been lased at a wavelength around 9.8–11 μm [12, 13]. The ratio was confirmed by performing double-crystal x-ray spectroscopy. Finally, the GaAs capping layer with a thickness of 200 nm was grown on the 3QW structure.

For *C–V* and DLTS measurements, we fabricated the metal–semiconductor contact diode. The 0.5 mm gold (Au) gates were fabricated by thermal evaporation with a shadow mask and the backside Ohmic contact was done by indium bonding. The final sample structure for the electrical measurements is shown in figure 1. The internal mode of a HP4280A capacitancemeter and a Boonton 7200 capacitancemeter with a HP8116A pulse generator, a SR640 low-pass filter and a data-acquisition system were used in order to measure capacitance–voltage and time-dependent capacitance transients. The measuring temperatures were changed from 10 K to 325 K by a liquid helium cryostat.

3. Results and discussion

Figures 2(*a*) and (*b*) show *C–V* characteristics measured at various temperatures and the carrier profiles extracted from

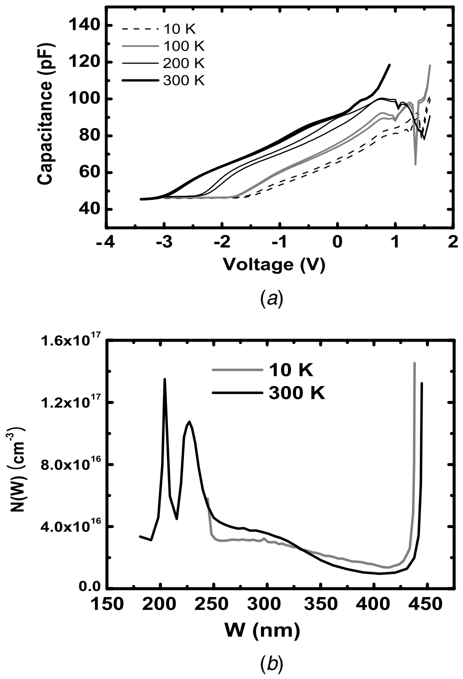

Figure 2. (*a*) *C–V* characteristics and (*b*) carrier depth profiles of the 3QW sample measured at various temperatures.

C–V measurements for the 3QW sample. Decreasing the measuring temperature, the *C–V* curves shift toward the higher voltage side. It implies that the *C–V* shift originated from the change of carrier concentration, depending on the temperature. Because the carrier concentration becomes smaller with the decrease of temperature, the depletion length at low temperature is larger than that at high temperature under the same bias conditions. In the carrier depth profile of figure 2(*b*), the peaks indicate the existence of a carrier confined level in quantum structures such as QW and quantum dots [14, 15]. Here, two peaks at 300 K imply the existence of QW layers. However, it shows only two peaks in 3QWs because of large zero-bias depletion. That is, the zero-bias depletions were expanded to near the first QW region at 300 K and contained whole QW layers at 10 K, respectively. Thus, the carrier profile at 10 K does not show any peaks. On the basis of this *C–V* result, the bias condition for the DLTS measurements of QW layers was decided.

Figure 3 shows DLTS spectra of the 3QW structure measured at a high-temperature region from 170 K to 340 K. Here, a rate window of 0.92 s^{-1} and a filling pulse width of 10 ms were used. There are three main signals named as A, B, C and C′, whose activation energies are obtained to be about 0.49 eV, 0.80 eV, 0.88 eV and 0.81 eV, respectively. Considering that the conduction band discontinuity of the GaAs/AlGaAs QW structure is slightly smaller than 295 meV [16], these activation energies cannot be related to the confined level of the QWs. Therefore, there may be well-known defects in GaAs such as EL3 family for the A signal and EL2 family for the B, C and C′ signals [17]. Concentrations of the defects were changed depending on the pulse and measuring bias conditions. The pulse and measuring biases represent the spatially scanned region during the DLTS measurements.

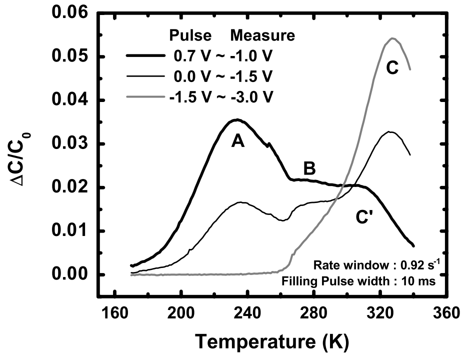

Figure 3. DLTS spectra of the 3QW sample measured at a high-temperature region from 170 K to 340 K under different bias conditions. Here, the rate window and the filling pulse width were 0.92 s^{-1} and 10 ms, respectively.

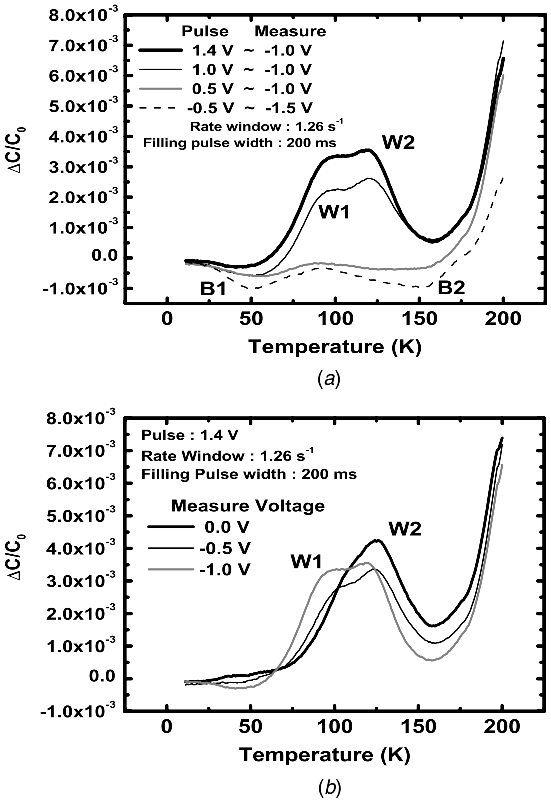

Figure 4. DLTS spectra of the 3QW sample measured at a low-temperature region from 20 K to 200 K under (*a*) different pulse amplitudes and (*b*) different bias conditions. Here, a rate window of 1.26 s^{-1} and a filling pulse width of 200 ms were used.

For example, a low reverse-bias voltage as measuring bias corresponds to the shallow region from the gate electrode and a high reverse-bias condition corresponds to the deep region. Because the 3QW layer appeared at about +0.5 V (small forward bias) in C–V measurements, signals A and B may be spatially located near the 3QW layer or the GaAs capping layer. On the other hand, signal C appeared in the QW region and the buffer layer. Concentrations of all kinds of signals were 3–12% of the donor concentration in the 3QW sample.

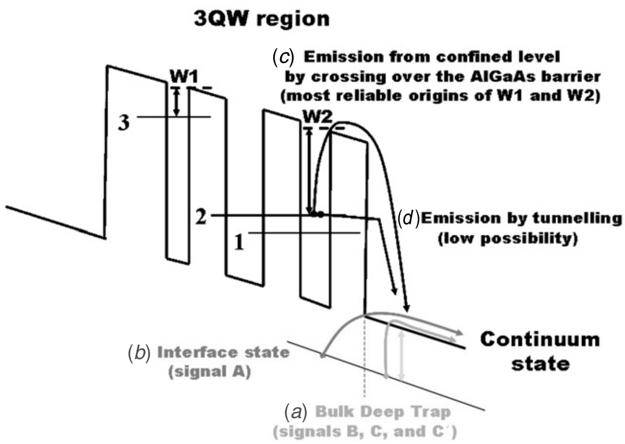

Figure 5. Schematic conduction band diagram of GaAs/AlGaAs 3QWs in the QCL emission region.

Table 1. DLTS parameters of the quantum well related signals detected at a low-temperature range (as shown in figure 4).

Signal	Measuring bias voltage (V)	Activation energy (eV)	Emission cross section (cm^2)
W1	0.0	0.13	5.77×10^{-19}
	−0.5	0.15	8.62×10^{-18}
	−1.0	0.10	1.16×10^{-19}
W2	0.0	0.23	8.86×10^{-16}
	−0.5	0.22	5.03×10^{-16}
	−1.0	0.18	2.75×10^{-17}

Figure 4 shows DLTS spectra of the 3QW structure measured at a low-temperature region from 20 K to 200 K. Here, a rate window of 1.26 s^{-1} and a filling pulse width of 200 ms were used. In this temperature region, W1 and W2 signals are found. In figure 4(*a*), the upper two spectra measured at larger than 1.0 V pulse under −1.0 V measuring voltage contain the 3QW region. Therefore, it is considered that signals W1 and W2 may be an energy level of the QWs, and then the activation energy difference between them is about 80–100 meV. Moreover, the activation energies were sensitively shifted with dependence on the provided electric field. Figure 4(*b*) shows the DLTS spectra measured under various bias conditions. In general, the point defects in GaAs have a Poole–Frenkel effect [14], showing the increase of emission rate with the increase of electric field. However, the shift of activation energy values of W1 and W2 signals was quite large compared to the typical Poole–Frenkel effect in point defects. Of course, the QCL structure should be designed with a sensitivity of the electric field [18].

DLTS parameters of W1 and W2 signals in figure 4 are summarized in table 1. Here, the activation energy means typically a difference between the band edge and trap levels, and then the carrier emission processes in the 3QW emission region can be suggested as shown in figure 5; the carriers in QWs can have some kinds of routes to emission from the confined energy levels, and the reliable routes may be tunnelling through the AlGaAs barrier and crossing over the barrier. However, the possibility of the tunnelling process seems to be quite low because the activation energy of

230 meV for signal W2 is a relatively large value compared to the conduction band discontinuity of 290 meV. Thus, it is expected that the activation energies of W1 and W2 mean differences between conduction band edge of the AlGaAs barrier and confined energy level of the GaAs QWs. From the activation energies of W1 and W2, the origin of W1 seems to be a ground energy level of the narrow QW (level 3 in figure 5) and that of the W2 seems to be ground energy levels of two wide QWs (levels 1 and 2 in figure 5). Levels 1 and 2 in figure 5 are very close enough to tunnel each other. Thus, W2 appeared as only one peak. In the QCL, transition of electrons between levels 1 and 2 in figure 5 corresponds to emission. The 3QW sample used in this study was very similar to the previously reported QCL structure [12, 13]. In these reports, the wavelength of the QCL structure was reported as 11.3 μm (110 meV) at 77 K. The obtained energy difference of W1 and W2 is estimated as 80–100 meV which corresponds to the wavelength of the previously reported QCL structure. Signal magnitudes of W1 and W2 correspond to carrier confinement abilities of QWs. As a result, we estimated that the carrier confinement of 3QWs was calculated to be about 0.5% of the donor concentration. But an extremely careful analysis and more experiments are needed to clarify the relation between the emission process and the activation energy.

4. Conclusion

The defect states and confined energy levels in the 3QW emission region of the QCL structure were successfully analysed by *C*–*V* and DLTS measurements. The defect states with activation energies ranging from 0.49 eV to 0.88 eV appeared in the GaAs capping layer and they were considered as well-known deep levels such as EL3 and EL2 families. The concentrations of these defects were in the range of 3–12% of the donor concentration. It also appeared that the confined energy levels of QWs have activation energies of about 130 meV and 230 meV from the top of the AlGaAs barrier, and their confinement ability was about 0.5% of the donor concentration.

Acknowledgments

This work was supported by the NRL Program and KOSEF q-Psi at Hanyang University, the Dual Project of the Ministry of Commerce, Industry and Energy of Korea and the second step Brain Korea 21 project in 2006.

References

[1] Kosterev A A, Curl R F, Tittel F K, Gmachl C, Capasso F, Sivco D L, Baillargeon J N, Hutchinson A L and Cho A Y 2000 *Appl. Opt.* **39** 4425
[2] Kosterev A A, Tittel F K, Gmachl C, Capasso F, Sivco D L, Baillargeon J N, Hutchinson A L and Cho A Y 2000 *Appl. Opt.* **39** 6866
[3] Blaser S, Hofstetter D, Beck M and Faist J 2001 *Electron. Lett.* **37** 778
[4] Capasso F, Cho A Y, Faist J, Hutchinson A L, Luryi S, Sirtori C and Sivco D L 1994 *Science* **264** 553
[5] Faist J, Capasso F, Sirtori C, Sivco D, Hutchinson A and Cho A 1995 *Appl. Phys. Lett.* **66** 538
[6] Helm M 1995 *Semicond. Sci. Technol.* **10** 557
[7] Beck M, Hofstetter D, Allen T, Faist J, Oesterle U, Ilegems M, Gini E and Melchior H 2002 *Science* **295** 301
[8] Liu F Q, Zhang Q S, Zhang Y Z, Ding D, Xu B and Wang Z G 2001 *Solid-State Electron.* **45** 1831
[9] Slivken S, Evans A, David J and Razeghi M 2002 *Appl. Phys. Lett.* **81** 4321
[10] Lu S L, Schrottke L, Teitsworth S W, Hey R and Grahn H T 2006 *Phys. Rev.* B **73** 033311
[11] Razeghi M and Slivken S 2003 *Optoelectron. Lett.* **11** 85
[12] Kruck P, Page H, Sirtori C, Barbieri S, Stellmacher M and Nagle J 2000 *Appl. Phys. Lett.* **76** 3340
[13] Green R P, Wilson L R, Carder D A, Cockburn J W, Hopkinson M, Steer M J, Airey R J and Hill G 2002 *Electron. Lett.* **38** 1539
[14] Blood P and Orton J W 1992 *The Electrical Characterization of Semiconductors: Majority Carriers and Electron States* (London: Academic) p 288
[15] Gombia E, Mosca R, Frigeri P, Franchi S, Amighetti S and Ghezzi C 2002 *Mater. Sci. Eng.* B **91** 393
[16] Sirtori C, Kruck P, Barbieri S, Collot P, Nagle J, Beck M, Faist J and Oesterle U 1998 *Appl. Phys. Lett.* **73** 3486
[17] Min S-K, Kim E K and Cho H Y 1988 *J. Appl. Phys.* **63** 4422
[18] Sirtori C, Capasso F and Faist J 1994 *Phys. Rev.* B **50** 8663