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Electrical Evaluation of Energy Distribution of State Density for Embedded Quantum Dot Single Layer

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Abstract

In this study, the electrical state of single-layer self-assembled InAs quantum dots (QDs) embedded in the GaAs layer is evaluated using potential modulated admittance method (PMAM). PMAM result shows the interfacial state existence in the depletion layer. Also, in evaluation using energy at the QD layer, the energy distribution of states is consistent with the DLTS result, which proves the interfacial signal originates from the QD layer. As a result, energy distribution of state density in QD layer is evaluated electrically.

1. Introduction

The quantum nature of quantum dots (QDs) are promising candidate to realize superior devices such as photovoltaic devices with high efficiency [1]. For the photovoltaic applications, the carrier dynamics concerned with QDs including carrier escape from the quantum states are important issue, meaning that methods to evaluate the states in QDs can be another important issue. Deep level transient spectroscopy (DLTS) [2] is well-known method to evaluate electronic states in the energy gap of semiconductors by the thermal escape of carriers. However, the conventional spatial depth profile is difficult for QD evaluation because of the resolution. On the other hand, temperature modulated admittance spectroscopy [3] is possible to evaluate electrical states in the band gap without using transient reaction while it is difficult to evaluate interfacial states localized in the depth direction as a QD layer. Therefore, potential modulated admittance method (PMAM) is employed to evaluate the energy distribution of state density of embedded QD single layer in this study. As a result, PMAM signal shows the existence of interfacial states and the distribution is found to be consistent with the DLTS result.

2. Experimental method

2.1. Sample Structure

Single-layer self-assembled InAs QDs were embedded in Si-doped GaAs Schottky barrier diodes grown on (100) n-GaAs substrates by molecular-beam epitaxy (MBE). In order to avoid charging into QDs from upper GaAs layer, 2 nm $Al_{0.30}Ga_{0.70}As$ was embedded in the GaAs layer at the position of 9 nm above the QD layer. Schottky barriers were fabricated on the MBE layers by evaporating Ni films. The carrier concentration of ~3 $\times10^{16}$ cm^{-3} was evaluated from the C-V characteristics at 300 K for the GaAs layers. The dot layer is located 300 nm below the gate. For the QDs, the density of 3.6 $\times10^{10}$ cm^{-2}, diameter of 26.8 nm and height of 7.5 nm were determined using atomic-force microscope (AFM) for surface QDs grown on another (100) GaAs substrate using same growth condition.

2.2. Potential Modulated Admittance Method (PMAM)

Agilent E4980A was used for the measurement. PMAM is a method based on admittance method [3] and arranged to evaluate embedded interfacial states. PMAM signal is defined as $\delta C/\delta \ln(\omega)$ from *C-f* measurement. In admittance method, states crossing the Fermi level can be detected, and the evaluation frequency changes detectable time constant. For conventional temperature modulated admittance method, it is difficult to evaluate interfacial states because the Fermi level has to be fixed on the interfacial state in temperature sweep. On the other hand, potential modulation is suitable for the evaluation of QD states. The signal intensity of layer states meaning those distribute in the epitaxial layer is affected by electrical field where the Fermi level crosses the states. As a result, higher external voltage which leads larger electrical field in the depletion layer decreases the signal intensity of layer states. On the other hand, the signal intensity from interfacial states has a peak when the Fermi level crosses the states. A peak structure of the admittance signal in the external voltage sweep indicates interfacial states. Also in increasing evaluation frequency or decreasing measurement temperature, state density at shallower energy can be detected.

2.3. Deep Level Transient Spectrascopy (DLTS)

In this study, Agilent/HP 4280A was used for the DLTS measurement. The DLTS signal is determined for each rate window as the Fourier coefficient of the capacitance transient at various temperatures. Here, simple DLTS assumes single levels in the energy gap, while the electronic states in QDs are expected to have energy distribution due to the size fluctuation of QDs. Therefore, in order to evaluate the density of the states in QDs precisely, the energy distribution of the electronic states is included in the theoretical curve for the fitting of DLTS spectra in this study.

3. Result

3.1. PMAM result

PMAM signals were obtained using external voltage ranging from -0.35 to -1.90 V at several temperature. Fig. 1 shows the PMAM signals versus the Fermi energy at QD layer as a parameter of evaluated frequency at 200 K. Here, the Fermi energy at QD layer is determined from the C-V characteristic for each external voltage. As a result, peak is observed clearly in the signal which indicates the existence of interfacial states in the depletion layer. Also, the energy distribution of states can be evaluated from the peak energy and the signal intensity as shown later (Fig. 3).

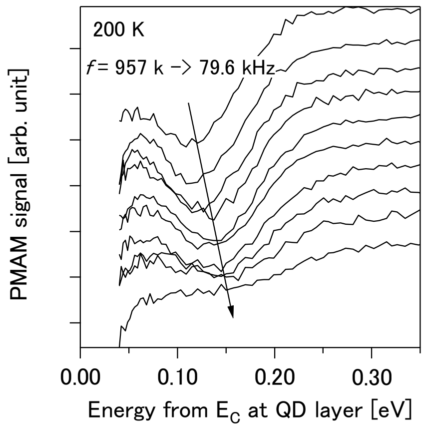

Fig. 1 PMAM signals for the GaAs Schottky diode with InAs QD layer measured at 200 K.

3.2. Analysis of DLTS

The DLTS was performed using the measurement voltage of -4.1 V, pulse voltage of +0.1 V, pulse width of 10 ms, and measurement step of 100 μs. The spectra show majority carrier (electron) emission as shown in Fig. 2. Here, in this condition, the depletion layer changes from 273 to 513 nm. Using Arrhenius analyses for obtained spectra, 4 signals are detected as listed in Table 1. Three peaks in lower temperature is considered to be derived from the QDs while the other peak in higher temperature shows good agreement with a defect reported for GaAs layers as EL4 [4].

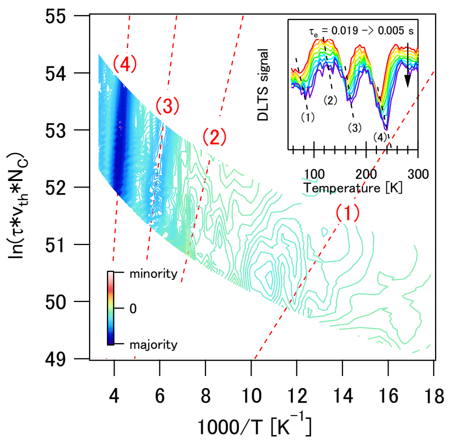

Fig. 2 Color mapping of DLTS specrta (main) and DLTS signal for different rate window (inlet). Detected states are assigned as shown in Table I.

3.3. Complementary Evaluation of Interfacial States

Fig. 3 shows energy distribution of state density evaluated by the PMAM assumed the QD layer as the interface position (dots) and calculated into the in-plane density from the DLTS result (lines). The distribution evaluated using PMAM is consistent with the DLTS result, which proves the validity of the assumption that the interfacial PMAM signals originate from the QD layer.

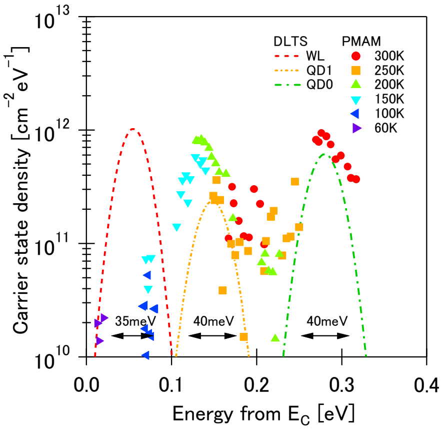

Fig. 3 In-plane energy state density evaluated by the PMAM (dots) and DLTS (lines).

Table I Electrical states evaluated using PMAM and DLTS

		PMAM	DLTS		
		$D_{T(peak)}$ [cm^{-2}eV^{-1}]	E_a [eV]	FWHM [eV]	D_T [cm^{-3}]
(1)	WL	-	0.055	0.035	2.7×10^{14}
(2)	QD1	8.3×10^{11}	0.148	0.040	(7.6×10^{13})
(3)	QD0	9.4×10^{11}	0.280	0.040	(2.2×10^{14})
(4)	EL4	-	0.510	0.070	2.9×10^{14}

4. Conclusions

The energy distribution of state density in embedded InAs QD layer is evaluated using PMAM. The peak density of PMAM result is more reliable because the state density evaluated by DLTS can be affected by the carrier interaction between QD states. Therefore, considering the FWHM from DLTS and the peak density of state from PMAM, it is found that the density of QD1 and QD0 is evaluated as 3.5 $\times 10^{10}$ and 4.0 $\times 10^{10}$ cm^{-2}, respectively. PMAM can be a method to evaluate the density of state for embedded interfaces.

Acknowledgements

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