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# Below-Gap Levels in InGaAs High-Electron-Mobility Transistors Observed by Two-Wavelength Excited Photoluminescence

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## 1. Introduction

The InGaAs-channel layer on GaAs or AlGaAs within the critical thickness against lattice relaxation has smaller effective mass and larger carrier-confinement properties than a lattice-matched GaAs-channel layer. Since lattice defects and residual impurities in a crystal form below-gap levels acting as carrier traps, the characterization of below-gap levels [1, 2] and optimization of growth conditions for eliminating them in such pseudomorphic high-electron-mobility transistors(p-HEMTs) are becoming more and more crucial for improving device performance.

Though below-gap levels of InGaAs were measured by a deep level transient spectroscopy (DLTS) [3], such an electrical measurement becomes difficult as the layer thickness decreases. In this paper, we investigated below-gap levels of p-HEMTs by the optical method of a two wavelength excited photoluminescence (TWEPL). Below-gap levels in InGaAs-channel layer were detected separately from those in outer layers by selecting the energy of the excitation light, while the trap-filling effect was observed by changing the excitation intensity quite similar to the previous GaAs- and GaN-based quantum well structures [4-7]. The non-distractive and non-contacting merit of this technique without electrode is considered to be important for optimizing process conditions.

## 2. Experimental

Figure 1 shows the schematic configuration of an experimental setup for the TWEPL method. We used two laser diodes as excitation sources, called as an above-gap excitation (AGE) and a below-gap excitation (BGE), respectively. The photon energy of the AGE light (NEL, NLK 1001TOL) which yields inter-band absorption and band-to-band photoluminescence (PL) is 1.37 eV, while that of the BGE light (Anritsu, AF5A3102C50L) is 0.80 eV, lower than the band gap energy of InGaAs.

The structure of p-HEMT was grown on a GaAs substrate as AlGaAs/GaAs (800 nm)/$Al_{0.24}Ga_{0.76}As$ (9.0 nm)/$In_{0.20}Ga_{0.80}As$ (13.5 nm)/$Al_{0.24}Ga_{0.76}As$ (25.0 nm) /$In_{0.48}Ga_{0.56}P$ (10.0 nm)/GaAs (100 nm) in sequence. The p-HEMT sample was placed in a temperature-controlled cryostat, and was irradiated by both continuous AGE and chopped BGE with the frequency of 300 Hz at the same point. The PL from the sample was led to a photomultiplier tube (PMT) via an objective lens and a monochromator (M.M) set at the maximum wavelength of each spectrum. The PL intensity under both the AGE and the BGE, $I_{AGE+BGE}$ corresponding to the region A in Fig. 2, was lower than that without the BGE, $I_{AGE}$ corresponding to that of B, and we defined the normalized PL intensity by $I_{AGE+BGE}/I_{AGE}$. Its shift from unity implies the presence of below-gap levels at the present BGE energy. The energy distribution of below-gap levels can be obtained simply by tuning the BGE energy, while selecting the AGE determines the layer of optical excitation.

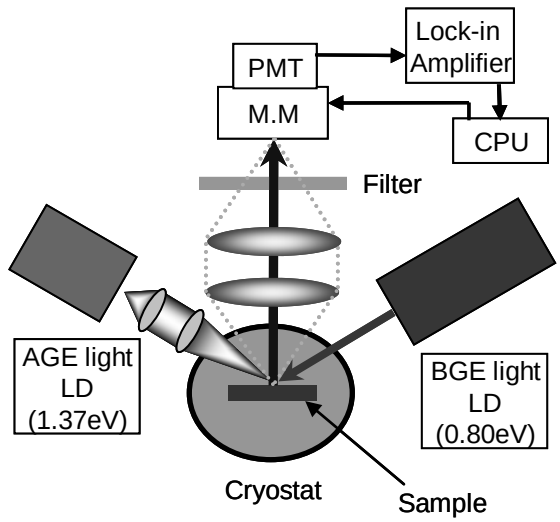


Fig. 1 The experimental setup for the TWEPL method.

## 3. Results and Discussion

Figure 3 shows the conventional PL spectra of the p-HEMT sample under the temperature range between 15 and 300 K. Here the AGE energy was 1.37 eV with the density of 1.48 mW/cm$^2$. There were no excitations inside GaAs and $Al_{0.24}Ga_{0.76}As$, since their forbidden-gap energies are at most 1.42 and 1.72 eV at room temperature, respectively. Thus PL spectra shown in Fig. 3 originate from InGaAs-channel layer: Two components of 1.19 and

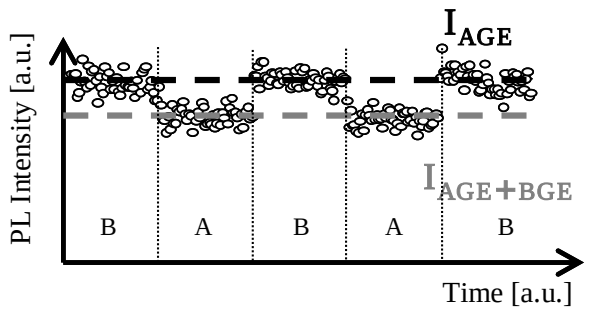


Fig. 2 The variation of PL peak intensity in response to the chopped BGE light.

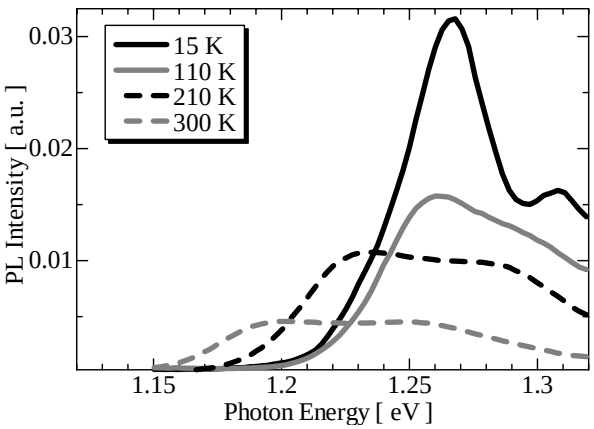


Fig. 3 PL spectra of the InGaAs p-HEMT at the temperature between 15 and 300 K.

1.26 eV at room temperature coincide with calculated ground and first excited states of the AlGaAs/InGaAs/ AlGaAs quantum well. With decreasing temperature, the PL intensity increases with the shift of peak energies.

In Fig. 4, the relationship between the normalized PL intensity at 15 K, $I_{AGE+BGE}/I_{AGE}$, and the BGE density was shown. The BGE effect appeared as the decrease of the $I_{AGE+BGE}/I_{AGE}$ from unity in this case. The amount of the PL quenching became pronounced with increasing the BGE density, but tended to saturate in the region above 100 mW/cm$^2$. The saturating tendency of the PL quenching was well explained by the trap-filling of the two-levels model in the rate-equation analysis based on SRH statistics [4]. Our present result of p-HEMT was quite similar to those of GaAs/AlGaAs QW structures as described in the previous paper [4-7].

The asymptotic value of the $I_{AGE+BGE}/I_{AGE}$ gives us an important condition for determining density, electron and hole capture rates of the below-gap levels detected by the BGE energy of 0.80 eV. With decreasing the AGE density from 2.36 to 0.76 mW/cm$^2$, the BGE effect increases since the excitation via the below-gap levels relative to band-to-band excitation increases.

Though electronic devices are naturally not optimized to enhance PL intensity, the structure of the present p-HEMT provides carrier confinement at the InGaAs-channel layer as a quantum well at the same time. This unintentionally emissive nature is beneficial for the TWEPL characterization from grown wafers to final device structures without the necessity of electrodes.

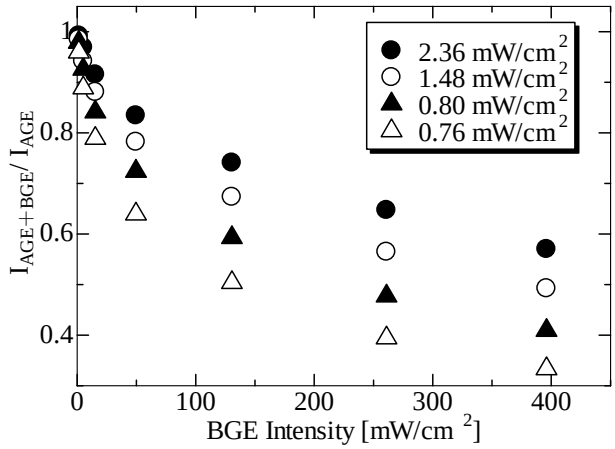


Fig. 4 The normalized PL intensity as functions of both the BGE (abscissa) and AGE (inserted captions) densities.

## 4. Summary

We have observed below-gap levels of the InGaAs-channel layer in a p-HEMT by the TWEPL of 0.80 eV BGE energy for the first time. The BGE-density dependence of the normalized PL intensity showed saturation because of the trap filling effect in the InGaAs layer. The result indicates that the optical spectroscopy of the TWEPL method is effective for characterizing defect levels not only of previous optical devices but also of electronic devices.


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