Detection of NRR Centers in InGaAs/AlGaAs HEMTs: Two-Wavelength Excited Photoluminescence Studies

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Non-radiative recombination (NRR) centers in a pseudomorphic \(\text{In}_{0.40}\text{Ga}_{0.60}\text{As}/\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}\) high electron mobility transistor (HEMT) grown by metal organic vapor phase epitaxy (MOVPE) have been studied by a purely optical, non-contacting technique of two-wavelength excited photoluminescence (TWEPL). By superposing a chopped below-gap excitation (BGE) light of 0.80 eV with an above-gap excitation (AGE) light of 1.37 eV, we have detected a pair of NRR centers in InGaAs channel layer whose transition energy corresponds to that of the BGE. The PL intensity change due to AGE-density, BGE-density and the temperature were examined and attributed to trap-filling effect of NRR centers, which can be utilized for the quantitative determination of NRR parameters.

Field of Research: Electrical and Electronic Engineering

1. Introduction

Indium gallium arsenide (InGaAs) ternary compound is an attractive material for high-power and high-speed electronic devices such as cell phones, satellite television receivers, radar equipment and so on. The use of InGaAs channel layer in high electron mobility transistor (HEMT) structures offers the advantages of smaller effective mass, higher mobility, superior saturation velocity of electrons and larger conduction band offset at channel/barrier interface with respect to the more common semiconductors like silicon and gallium arsenide (Sze, 2007; Ketterson et al., 1985). Though the introduction of indium in InGaAs causes lattice mismatch to the GaAs substrate, growth of good quality heteroepitaxial layer is still possible provided the thickness of the epitaxial-layer is kept under the critical thickness, which yields a pseudomorphic InGaAs channel layer and the device is called pseudomorphic HEMT (p-HEMT).

Further improvements in the performance of InGaAs-based p-HEMT hinge on understanding and reduction of point defects, such as native lattice defects, residual impurities and their complexes, which are introduced during the crystal growth and device processing steps. The presence of such defects in a crystal form below gap

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states, acting as nonradiative recombination (NRR) centers or trap centers and degrades the efficiency and reliability of the devices. Hence it is crucial to quantitatively characterize below-gap levels (Batista et al., 2003; Monte et al., 1999) and optimize the growth conditions for eliminating them in p-HEMT structures. Previous studies have used some electrical methods such as Deep-level transient spectroscopy (DLTS) for characterizing deep trap levels in InGaAs of AlGaAs/InGaAs/GaAs p-HEMT structure (Lu et al., 1996; Dermoul et al., 2001), but their applications are restricted due to the necessity of preparing suitable samples for the measurements like Schottky contacts or appropriate p-n junction. In the present work, a purely optical characterization technique of two-wavelength excited photoluminescence (TWEPL) (Kanoh et al., 1995; Kamata et al., 1999 and Yamaguchi et al., 2008) has been used for the detection and characterization of NRR centers in an In_{0.40}Ga_{0.60}As/Al_{0.24}Ga_{0.76}As p-HEMT structure as a measure for characterizing below-gap levels. Under selective excitation (Yamaguchi et al., 2008), below-gap levels in InGaAs channel layer were detected separately from those in the outer layers.

The structure of the investigated p-HEMT sample and the principle of TWEPL measurement are discussed in Section 2. The probable changes in PL intensity due to the sample irradiation with BGE are explained in Section 3 with the employment of One level and Two levels models. In Section 3, experimental results are presented and discussed. The conclusions of the present work are summarized in section 4.

2. Experimental

2.1 Sample Structure

We have studied a pseudomorphic (p-) InGaAs/AlGaAs high electron mobility transistor (HEMT) structure with indium content in the In_{x}Ga_{1-x}As channel layer of 0.40. The thickness of the well and barrier layers is adjusted to make the sample pseudomorphic. The sample was epitaxially grown on the GaAs substrate by metal organic vapor phase epitaxy (MOVPE). Figure 1 schematically shows the type of sample structure used in the present study. The structure consists of 800 nm thick Al_{0.25}Ga_{0.75}As/GaAs buffer layer, In_{0.40}Ga_{0.60}As/Al_{0.24}Ga_{0.76}As single quantum well, 10 nm thick In_{0.48}Ga_{0.52}P and 100 nm thick GaAs cap layers in sequence. A portion of the barrier layers, the InGaP and GaAs cap layers are doped with silicon of the order of 10^{18} cm^{-3}.

2.2 TWEPL Measurement Scheme

Two-wavelength excited photoluminescence (TWEPL) is a purely optical, non-destructive and non-contacting technique. It has no limitation on the sample structure and size as long as appropriate light sources for above-gap excitation (AGE) and below-gap excitation (BGE) are provided. TWEPL also facilitates to quantitatively determine trap parameters of NRR centers, and their AGE and BGE spectroscopies. In AGE spectroscopy, AGE energy determines the layer of the observation whereas in BGE spectroscopy BGE energy determines the energy distribution of the observing levels. The method of TWEPL was initially used by Grimmeiss and Monemar (1973) to detect deep levels in Cu-doped bulk n-type GaP. Tajima (1985) introduced a systematic time modulation (chopping) of the AGE and BGE for characterizing deep levels in bulk GaAs. By observing a saturating behavior of the
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BGE effect with increasing BGE density, Kamata group (Kanoh et al., 1995; Kamata et al., 1997, 1999) has improved the method to a quantitative one and successfully determined NRR parameters such as trap density, carrier capture rates, spatial and energy distribution of NRR centers by expanding the analysis of the BGE density dependence for the first time. They optically characterized bulk GaN and several quantum well (QW) structures like GaAs/AlGaAs QWs, InGaN/GaN QWs, GaN/AlGaN QWs.

| n-GaAs cap | 100nm |
| n-In$_{0.48}$Ga$_{0.52}$P cap | 10nm |
| Al$_{0.24}$Ga$_{0.76}$As barrier | 29nm |
| In$_{0.40}$Ga$_{0.60}$As well | 5.5nm |
| Al$_{0.24}$Ga$_{0.76}$As barrier | 13nm |
| i-Al$_{0.25}$Ga$_{0.75}$As/i-GaAs buffer | 800nm |
| GaAs Substrate |

**Fig.1: Structure of In$_{0.40}$Ga$_{0.60}$As/Al$_{0.24}$Ga$_{0.76}$As p-HEMT.**

Figure 2 shows the experimental setup used for the TWEPL measurement. The sample was mounted in a temperature controlled cryostat. A BGE light ($h\nu_B < E_g$) is superimposed on a conventional AGE light ($h\nu_A > E_g$) by focusing them on the same spot on the sample surface. Here $E_g$ denotes the band gap of InGaAs channel layer. A semiconductor laser of wavelength 904nm ($h\nu_A = 1.37$ eV) was chosen as the AGE source to continuously excite the In$_x$Ga$_{1-x}$As channel layer only (Yamaguchi et al., 2008). A chopped BGE light was supplied by another semiconductor laser of wavelength 1.55µm ($h\nu_B = 0.80$ eV). The BGE changes the electronic population of an energy-matched below-gap state in the sample, which shift the balance between radiative and non-radiative recombination rates and hence modulates the band-edge PL intensity originating from the AGE. The arising modulated PL signal from the sample was guided by a set of objective lenses into the monochromator and measured by a near-IR sensitive photomultiplier (Hamamatsu H10330 A-75) at the temperature between 10 and 70K. The electrical signal from the photomultiplier output was fed to a digital lock-in amplifier for the detection purposes. An optical chopper was placed along the path of the PL signal and maintained at a frequency of 80 Hz. The chopper output was also served as a reference signal of the lock-in amplifier. The PL intensities with and without the BGE, $I_{AGE+BGE}$ and $I_{AGE}$, respectively were measured by observing the PL peak wavelength at each temperature. The normalized PL intensity, $I_n$, was defined by the ratio of $I_{AGE+BGE}$ to $I_{AGE}$. The study of the normalized PL intensity change, $I_n$, gives an observable measure of the NRR process selected by the BGE energy.
2.3 PL Intensity Change Due to BGE

Experimentally, three cases can arise due to the addition of BGE: no change in PL intensity, an increase or a decrease of PL intensity. The increase or decrease of PL intensity can be attributed to the one level model or two levels model, respectively, based on Shockley-Read-Hall (SRH-) statistics (Shockley and Read, 1952) which are explained as follows:

2.3.1 No Change in PL Intensity

When there are no NRR centers exist in the sample whose transition energy corresponds to the BGE energy, the addition of BGE light on the sample results in no change in PL intensity. Hence, $I_{\text{AGE+BGE}} = I_{\text{AGE}}$, i.e., $I_N = 1$.

2.3.2 Increase in PL Intensity: One Level Model

The increase in PL intensity due to the BGE is explained by one level model that includes one NRR center (trap state 1) located inside the forbidden gap of the material shown in Fig. 3(a). When a BGE light of suitable energy is added, either electrons are excited from the valence band to the trap center or from the trap center to the conduction band. As a consequence, the hole density ($p$) in the valence band or electron density ($n$) in the conduction band correspondingly increases, and the PL intensity increases due to its direct proportional relationship with the product $np$. Hence, $I_{\text{AGE+BGE}}$ becomes higher than $I_{\text{AGE}}$ (Kamata et al., 1999), i.e., $I_N > 1$.

2.3.2 Decrease in PL intensity: Two Levels Model

The decrease in PL intensity due to BGE is explained by a two levels model that includes two NRR centers (trap states 1 and 2) inside the forbidden gap of the
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material as shown in Fig. 3(b). When the BGE energy corresponds to the energy difference between the two coexisting traps, electrons in state 1 are excited to the state 2, from which they recombine non-radiatively with holes in the valence band, reducing the hole density in the valence band (-Δp). Correspondingly, a decrease of the number of electrons in state 1 allows an increase of NRR from the conduction band to the state 1, reducing the electron density in the conduction band (-Δn). The combination of both of these effects resulting in a decrease of the number of electron-hole pairs available in the bands for radiative recombination. Hence the addition of BGE results in an increase of NRR rate, decreases the PL intensity and I_{AGE+BGE} becomes lower than I_{AGE} (Kanoh et al., 1995), i.e., I_N < 1.

Therefore the deviation of I_N from unity (either increase in the one level model or decrease in the two levels model) represents the presence of NRR centers.

3. Results and Discussion

The conventional PL spectrum of the In_{0.40}Ga_{0.60}As/Al_{0.24}Ga_{0.76}As p-HEMT sample observed at 10 K under the AGE excitation density of 0.21 mW/cm^2 is shown in Fig. 4. Emission of PL signal from the InGaAs channel layer was confirmed by selective excitation (Yamaguchi et al., 2008). The Sample showed band-edge PL peak at 1124 nm with FWHM of 20 nm.
After determining the spectral position of the conventional PL peak intensity, we proceeded to observe the BGE effect by fixing the detection wavelength for TWEPL at that point. A typical recorded result of TWEPL at 10 K is shown in Fig. 5. The horizontal time axis is divided into five segments of 50 s each. A considerable decrease in the PL peak intensity ($I_n < 1$) is clearly observed when the BGE light was superposed on the AGE in the second and fourth segment indicating the presence of a pair of NRR centers in the sample whose energy difference corresponds to that of BGE, 0.80 eV in the two levels model. A statistical time average of these results of PL peak intensity as a function of time for each segment of the abscissa allows us to acquire $I_{AGE}$ and $I_{AGE+BGE}$, which are necessary to calculate the value of the normalized PL intensity, $I_n$, introduced as experimental results in Figs. 6 to 8, where the solid lines are used as a guide to the eye.
Fig. 5: A Typical Recoded Data of TWEPL: the PL Peak Intensity with AGE only, $I_{AGE}$ and with both the AGE and BGE, $I_{AGE+BGE}$, were Acquired by Calculating a Statistical Time Average for Each Segment of the Abscissa.

We examined AGE power dependence of the sample at 10 K as shown in Fig. 6. It is seen that with decreasing AGE density from 0.47 to 0.06 mW/cm$^2$ under a fixed BGE density of 129 mW/cm$^2$, the value of normalized PL intensity decreased from 0.86 to 0.69. The decrease of $I_N$ from unity indicating the presence of NRR centers in the sample. Since the PL intensity change, in general, depends on the interaction between below-gap states excited by the BGE and the AGE density of the band-to-band PL, an enhancement of the PL intensity change with decreasing AGE density resulting from the fact that at lower AGE excitation, the excitation via the below-gap levels relative to band-to-band excitation increases (i.e., BGE effect increases). The present result of AGE power dependence of the normalized PL intensity is quite similar to those of GaAs/AlGaAs QW structures (Hoshino et al., 1998a, 2000; Kamata et al., 1995).

The change of normalized PL intensity as a function of BGE density of the p-HEMT sample at 10 K is shown in Fig. 7. With increasing the BGE power from 5.46 to 213 mW/cm$^2$ at a fixed AGE density of 0.14 mW/cm$^2$, the normalized PL intensity decreased from 0.94 to 0.71, the amount of PL quenching became pronounced with increasing BGE density showing a slightly saturating tendency. The decrease of $I_N$ from unity represents the presence of a pair of NRR centers in the two levels model. The saturating tendency in the BGE density dependence is attributed to the trap filling effect of the two levels model in the rate equation analysis based on SRH.
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Fig. 6: AGE Power Dependence of the Normalized PL Intensity of In$_{0.40}$Ga$_{0.60}$As/Al$_{0.24}$Ga$_{0.76}$As p-HEMT.

![Image of Fig. 6](image)

Fig. 7: BGE Power Dependence of the Normalized PL Intensity of In$_{0.40}$Ga$_{0.60}$As/Al$_{0.24}$Ga$_{0.76}$As p-HEMT.

![Image of Fig. 7](image)

statistics (Kanoh et al., 1995). The present result of PL quenching saturation is similar to that of undoped and Se-doped GaAs/AlGaAs QW structures (Kanoh et al.,
The saturating tendency of $I_N$ can be utilized for the quantitative determination of NRR parameters such as trap density, electron and hole capture rates by using the trap filling condition (Kanoh et al., 1995; Hoshino et al., 2000).

The above experimental results of the PL intensity quenching and its saturation with increasing BGE power can be explained by a two levels model as schematically shown in Fig. 3. Under the AGE, electrons are excited from the valence band to the conduction band from which they recombine with holes in the valence band either radiatively or non-radiatively through the trap state 1. The electron occupation function of the trap state 2 is negligible under the irradiation with AGE only. When the BGE energy matches the energy difference between two coexisting band-gap states, electrons in state 1 are excited to state 2, from which they recombine non-radiatively with holes in the valence band, reducing hole density in the valence band $p$ by an amount $\Delta p$. Similarly, electron vacancies in state 1 allow an increase of NRR from the conduction band, reducing the electron density in the conduction band $n$ by an amount $\Delta n$. The decrease in both electron and hole densities results in the band-edge PL intensity quenching. In the region of low BGE densities, the electron occupation function of trap state 2, $f_2$, remains considerably lower than 1, and an increase in BGE power yields almost proportional increase in the $f_2$, which results in the linear PL quenching. On the other hand, in the region of higher BGE densities, the $f_2$ approaches closely 1 and becomes insensitive to the increase in BGE density and, thus, the amount of PL quenching shows saturation. Therefore the saturation of the PL quenching can be attributed to the trap filling effect of electrons in the trap state 2.

![Fig. 8: Temperature dependence of the normalized PL intensity of the In$_{0.40}$Ga$_{0.60}$As/Al$_{0.24}$Ga$_{0.76}$As p-HEMT.](image)

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<thead>
<tr>
<th>$P_{AGE}$</th>
<th>0.14 mW/cm$^2$</th>
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<tr>
<td>$P_{BGE}$</td>
<td>129.3 mW/cm$^2$</td>
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$\frac{I_{AGE}}{I_{BGE}}$
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Temperature dependence of the In\textsubscript{0.40}Ga\textsubscript{0.60}As/Al\textsubscript{0.24}Ga\textsubscript{0.76}As p-HEMT sample was observed by measuring the normalized PL intensity in the temperature region between 10 to 70 K at a fixed AGE and BGE densities of 0.14 and 129 mW/cm\textsuperscript{2}, respectively as shown in Fig. 8. It is seen that I\textsubscript{N} decreased with increasing temperature. This temperature dependence is different from previous results of GaAs/AlGaAs and InGaN/GaN quantum wells in which the curve showed monotonic increase of I\textsubscript{N} with increasing temperature (Kanoh et al., 1995; Klausing et al., 2003 and Kamata et al., 1999, 2002a, 2002b) and was attributed to the thermal emission of electrons from the second state to the conduction band in a two levels model (Kamata et al., 2002a).

4. Conclusions

Non-radiative recombination (NRR) centers in a MOVPE grown In\textsubscript{0.40}Ga\textsubscript{0.60}As/Al\textsubscript{0.24}Ga\textsubscript{0.76}As p-HEMT structure were studied by the optical method of two-wavelength excited photoluminescence (TWEPL). A pair of NRR centers whose transition energy matches that of BGE, 0.80eV, was detected in the InGaAs-channel layer separately from those in the outer layers under selective excitation. Results of AGE-density, BGE-density and temperature dependence of the normalized PL intensity was attributed to the trap-filling effect of NRR centers, which can be utilized for determining density, electron and hole capture rates of the NRR centers quantitatively.

References


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