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# Time-resolved Photoluminescence Characterisation of GaAs/Al$_x$Ga$_{1-x}$As Structures Designed for Microwave and Terahertz Detectors

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The time-resolved photoluminescence of donor Si-doped GaAs/Al$_x$Ga$_{1-x}$As ($x$ = 0.3 0.25, 0.2, 0.1) structures designed for microwave and terahertz detectors have been investigated at $T$ = 3.6 K temperature. The excitonic, impurity and defect related emission lifetimes are revealed for these structures. Possible mechanisms of carrier recombination are discussed. Concentration of acceptor, carbon and silicon, are evaluated from measured lifetimes in the structures.
*Keywords*: GaAs, AlGaAs, heterostructures, photoluminescence, lifetime, exciton, time-resolved photoluminescence.

## 1. INTRODUCTION

The focus on radiation technology has shifted from frequencies in the infrared region to terahertz (THz) and microwave (MW) regions in recent years. These spectral ranges have enormous potential for applications in biology, medicine, security of wireless communications, etc. [1, 2].

However, the main challenge of utilising the radiation in this frequency range is lack of suitable and reliable terahertz sources and detectors. Recently we have developed a novel device design based on GaAs and AlGaAs structures for detection of radiation in broad band region from MW to THz [3]. This paper presents a continuous wave photoluminescence (PL) and time-resolved photoluminescence (TRPL) characterisation of these structures. The excitonic, impurity and defect related emission lifetimes are revealed. The possible mechanisms of carrier recombination are discussed.

## 2. SAMPLES AND EXPERIMENTAL DETAILS

The structures were grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The active region consisted of two homojunctions: Si doped $n^+$ ($N_D = 3 \times 10^{18}$ cm$^{-3}$, $d$ = 100 nm) / $n$ ($N_D = 1 \times 10^{16}$ cm$^{-3}$, $d$ = 300 nm) Al$_x$Ga$_{1-x}$As and $n$ ($N_D = 1 \times 10^{16}$ cm$^{-3}$, $d$ = 300 nm) / $n^+$ ($N_D = 3 \times 10^{18}$ cm$^{-3}$, $d$ = 300 nm) GaAs. To delimit the detector structure and the substrate, 200 nm $i$-GaAs layer and $N$ = 20 GaAs/Al$_{0.25}$Ga$_{0.75}$As ($L_W = L_B$ = 10 nm) quantum wells (QW) were inserted. The particular composition of GaAs/Al$_x$Ga$_{1-x}$As layered structure is presented elsewhere in [4]. The samples #1, #2, #3, #4 were grown with different AlAs mole fraction in the active region containing $x$ = 0.3, 0.25, 0.2, 0.1, respectively.

Continuous wave PL was measured using a grating monochromator and an Ar-ion laser as the excitation source. The PL was detected by a thermoelectrically cooled, metal packaged, GaAs photomultiplier operating in a photon counting regime.

TRPL was induced using a frequency doubled diode pumped Nd:LSB microchip solid-state laser with a 400 ps FWHM pulse width. The pulse repetition rate was 10 kHz with an average output power of 40 mW, and the excitation wavelength was 531 nm. The TRPL measurements were performed with a thermoelectrically-cooled, high efficiency photomultiplier with an internal GHz preamplifier using a time correlated single photon counting (TCSPC) system [5]. The closed cycle helium optical cryostat enabled us to control the sample temperatures from ambient room temperature (300 K) down to 3.6 K. More details about experimental equipments and measurement schemes are presented in [6].

The PL decay transient curves were fitted by incorporating one or two exponential decay constants, and the characteristic decay times were extracted. Short lifetimes were extracted after application of deconvolution algorithm for signal processing.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

To exclude absorption of incident light and reabsorption of emitted light from the structure, the $n^+$-GaAs top contact layer was removed by chemical etching.

The PL spectra of GaAs/Al$_x$Ga$_{1-x}$As structures with different AlAs mole fraction $x$ at $T$ = 3.6 K temperature and $I$ = 1.36 W/cm$^2$ laser excitation intensity are presented in Fig. 1, a. One can resolve two parts of the spectra indicated by segments. The first one is attributed to GaAs layers, and the second part of the PL spectra is associated with the

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$Al_xGa_{1-x}As$ layers. Mark $d$ means defect related emission bands. Exitonic emission is marked as $X$ (for more details see [4]). The excitonic radiation of multiple QWs in the buffer layer is at 1.547 eV. The transitions $A$, $A_1$ and $A_2$ are recombinations related with the residual acceptors. Band $A$ consists of two parts which cannot be resolved in Fig. 1, a. In emission spectra of $n$-GaAs and $n$-$Al_xGa_{1-x}As$ we observe emission transitions related with two kinds of acceptor impurities. The first transition is related with carbon C residual acceptor. This impurity is characteristic for MBE grown AlGaAs crystals. The carbon ionization energy is 26 meV in GaAs [7]. $n$-GaAs and $n$-$Al_xGa_{1-x}As$ layers are also doped with silicon impurity. The silicon impurity in GaAs structures behaves as donor impurity. However, the silicon is an amphoteric impurity in GaAs, therefore a part of Si impurities becomes acceptors with the ionization energy of 34.5 meV [7].

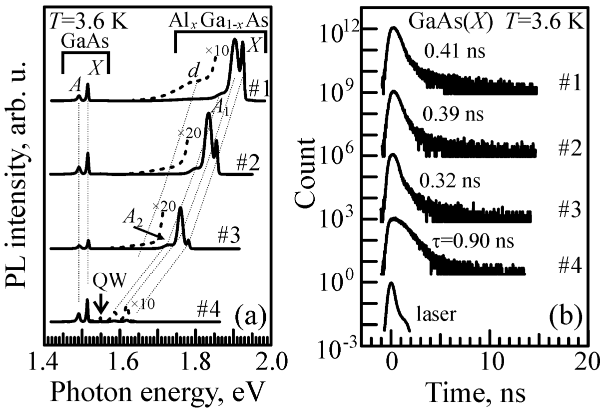


**Fig. 1.** (a) The PL spectra of $GaAs/Al_xGa_{1-x}As$ structures with different AlAs mole fraction $x$ (#1 – 0.3, #2 – 0.25, #3 – 0.2, #4 – 0.1). The scale for all the spectra is the same. (b) The PL decay transients of excitonic emission lines of $n$-GaAs at emission energy $E = 1.515$ eV for different samples #1 – #4 at $T = 3.6$ K lattice temperature. The curves are shifted vertically for clarity

Figure 1, b, shows the PL decay transients of excitonic emission lines of $n$-GaAs layers in different samples #1 – #4 at emission energy $E = 1.515$ eV and $T = 3.6$ K lattice temperature.

The radiative lifetime of free excitons in ultrapure GaAs is 3.3 ns at the threshold of very low temperatures (1.7 K) [8]. The GaAs free exciton radiative characteristic time constant in our investigated structures is between 0.32 ns – 0.90 ns. This behaviour implies the existence of other recombination channels, for example, nonradiative.

The PL decay transients for free electron-carbon acceptor ($e$-C) transition, which is marked as $e$-$A_1$, were measured at photon energy $E = 1.497$ eV and are shown in Fig. 2, a. There are exponential decay transients with lifetime about 17 ns. The PL decay transients for free electron-silicon acceptor transition $e$-Si(acceptor), which is marked as $e$-$A_2$, were measured at photon energy $E = 1.4916$ eV. They are shown in Fig. 2, b. We observe two exponential decays of the emission since the $e$-$A_2$ emission overlaps with Si(donor)-C transitions marked as $D$-$A_1$. The estimated donor-acceptor recombination characteristic time $\tau(D\text{-}A_1)$ is in the range from 0.11 μs to 0.12 μs and $\tau(e\text{-}A_2)$ varies from 23 ns to 25 ns. The donor-acceptor pair lifetime depends on pair distance or emission wavelength or energy. The lifetime is longer at lower spectral energies. For example, recombination characteristic time $\tau(D\text{-}A_2)$ measured in the sample #3 at energy $E = 1.488$ eV is 0.16 μs (gray line in Fig. 2, b), $\tau(D\text{-}A_2) = 0.18$ μs at $E = 1.4862$ eV and $\tau(D\text{-}A_2) = 0.19$ μs at $E = 1.4844$ eV. The energy dependence of recombination characteristic time is weak. It is shown that nonradiative recombination is also important in donor-acceptor pair recombination [9]. We can suppose that nonradiative $D$-$A$ recombination rate is of the same order as the radiative $D$-$A$ recombination in the investigated samples.

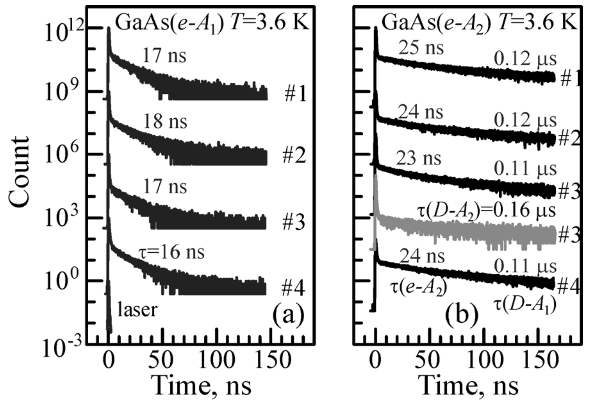


**Fig. 2.** The PL decay transients of free electron-acceptor (a) $e$-$A_1$ measured at energy $E = 1.497$ eV and (b) $e$-$A_2$ measured at energy $E = 1.4916$ eV of GaAs layers for #1-#4 samples at $T = 3.6$ K. The symbol $D$-$A_2$ denotes donor-acceptor related transitions measured at energy $E = 1.488$ eV (gray line). The curves are shifted vertically for clarity

Experimental results enable us to estimate concentration of acceptor impurities in $n$-GaAs layer. Free electron-acceptor recombination consists of two parts: i) free electron-acceptor radiative recombination with recombination coefficient $W_{eA}$, and ii) nonradiative free electron-acceptor recombination with recombination coefficient $B_{eA}$. Experimentally observed free electron-acceptor lifetime can be calculated

$$\frac{1}{\tau(e-A)} = \frac{1}{\tau(W_{eA})} + \frac{1}{\tau(B_{eA})} = N_A(W_{eA} + B_{eA}), \qquad (1)$$

where $N_A$ is acceptor concentration. The coefficients are $W_{eA} = 8.9 \times 10^{-10}$ cm$^3$/s and $B_{eA} = 1.7 \times 10^{-8}$ cm$^3$/s at liquid helium ($T = 4.2$ K) temperature [10, 11]. Assuming that the measured $e$-$A_2$ recombination lifetime is about 24 ns, then the estimated Si acceptor concentration is approximately equal to $N_A(\mathrm{Si}) = 2.3 \times 10^{15}$ cm$^{-3}$. The lifetime $\tau(e\text{-}A_1) = 17$ ns gives carbon acceptor concentration value $N_A(\mathrm{C}) = 3.3 \times 10^{15}$ cm$^{-3}$.

Figure 3, a, shows the PL decay transients of excitonic emission lines of $n$-$Al_xGa_{1-x}As$ layers in different samples #1 – #4 at lattice temperature $T = 3.6$ K. The characteristic recombination lifetime is similar for all samples and equals about 0.3 ns.

Figure 3, b, shows the PL decay transients of defect-related transitions of $n$-$Al_xGa_{1-x}As$ layers in different samples #1 – #3 at lattice temperature $T = 3.6$ K. The transients are nonexponential. We approximated the middle part of the decay curve with a single exponential decay. Lifetime values were found to vary from 54 ns to 93 ns.

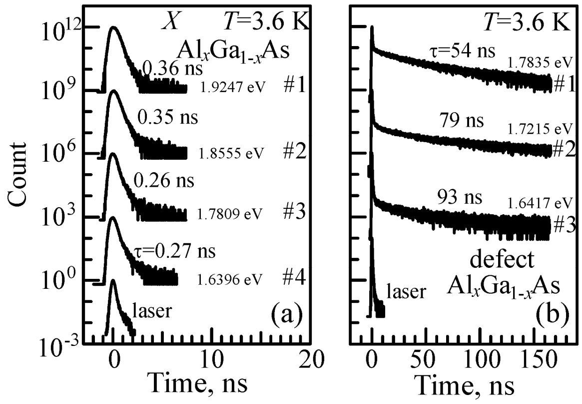


**Fig. 3.** The PL decay transients of (a) excitons $X$ and (b) defect-related transitions of $n$-Al$_x$Ga$_{1-x}$As layers for samples #1 – #4 at $T = 3.6$ K. The decay time constants and emission energies are indicated at each trace. The curves are shifted vertically for clarity

Figure 4 shows the PL decay transients of acceptor related bands of $n$-Al$_x$Ga$_{1-x}$As layers. Symbols $e$-$A_1$ and $e$-$A_2$ also denote free electron-acceptor transitions related with C acceptor and Si impurity part of which behaves as acceptor impurity. The emission transient character indicates that the shape of curve is determined by a number of processes which include donor acceptor emission processes as well.

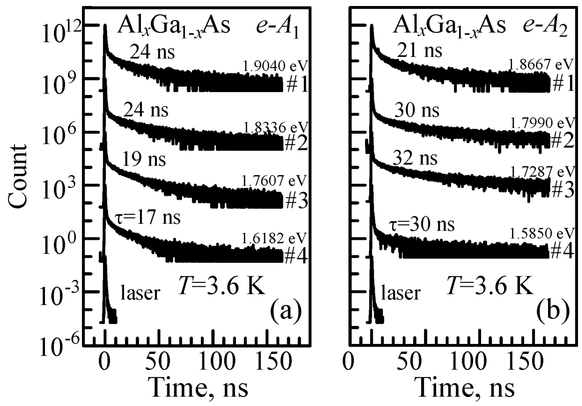


**Fig. 4.** The PL decay transients of acceptor related bands of $n$-Al$_x$Ga$_{1-x}$As layers for samples #1 – #4 at $T = 3.6$ K. The symbols $e$-$A_1$ (a) and $e$-$A_2$ (b) denote free electron-acceptor related transitions. The decay time constants and emission energies are indicated at each trace. The curves are shifted vertically for clarity

## 4. CONCLUSIONS

The time-resolved photoluminescence of donor Si-doped GaAs/Al$_x$Ga$_{1-x}$As ($x = 0.3$ 0.25, 0.2, 0.1) structures designed for microwave and terahertz detectors was investigated at $T = 3.6$ K temperature. The excitonic, impurity and defect related emission lifetimes were measured in these structures. We established that the exciton lifetime in $n$-GaAs layers is within the range of 0.32 ns – 0.90 ns, and it is approximately 0.3 ns in $n$-Al$_x$Ga$_{1-x}$As layers. Free electron-acceptor characteristic transition time is about 16 ns – 25 ns in $n$-GaAs layers, and it is 17 ns – 32 ns in $n$-Al$_x$Ga$_{1-x}$As layers. Defect related characteristic transition time in $n$-Al$_x$Ga$_{1-x}$As layers is of the order of 54 ns – 93 ns. Residual C and Si-as-acceptor concentrations estimated in GaAs layer of these structures are about $3.3 \times 10^{15}$ cm$^{-3}$ and $2.3 \times 10^{15}$ cm$^{-3}$ respectively.


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