PHOTOLUMINESCENCE CHARACTERISATION OF GaAs/AlGaAs STRUCTURES DESIGNED FOR MICROWAVE AND TERAHERTZ DETECTORS

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The photoluminescence (PL) spectra of GaAs/AlGaAs structures designed for microwave and terahertz detectors were investigated. Detailed experimental results of PL were obtained both before and after etching of the heavily doped layers. Possible mechanisms of carrier recombination are discussed and certain emphasis is put on the up to 20 times enhancement of the PL intensity observed in these detector structures.

Keywords: GaAs, AlGaAs, homojunction, photoluminescence, exciton, PL enhancement

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1. Introduction

The current research in the field of communication technology aims to increase the operational bandwidth of emitters and detectors. The greatest achievements have been reported in the visible, near-infrared and microwave (MW) bands. However, the performance of already existing devices in the high frequency MW region as well as in the terahertz (THz) range is still considered as being modest. Therefore, a new generation of emitters [1, 2] and detectors [3] based on n^+/n, n^+/i or p^+/i homojunctions, has been proposed for operation in MW and THz ranges. The characteristics of these devices have not been fully investigated so far.

We have designed a novel device model based on GaAs and AlGaAs structures for the implementation in the MW and THz range for broad band detection [4]. In this paper we present a photoluminescence characterisation of these structures. We discuss possible mechanisms of carrier recombination and put an emphasis on the enhancement of photoluminescence (PL) that is observed in these structures.

2. Samples and measurement technique

The structures were grown by molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate. The active region consisted of two homojunctions: Si doped n^+/n $Al_xGa_{1-x}As$ and n/n^+ GaAs. The layered composition of the GaAs/$Al_xGa_{1-x}As$ structure is shown in **Fig. 1**. Samples #1, #2, #3, #4 were grown with a different aluminium mole fraction in the active region containing, respectively, x = 0.3, 0.25, 0.2, 0.1.

An argon-ion laser operating in a continuous wave mode was used for the sample excitation with a photon energy ranging from 2.4 to 2.7 eV. The PL signal was dispersed by a monochromator and detected by a thermoelectrically cooled GaAs photomultiplier operating in the photon counting regime. The PL spectra of the structures were

Fig. 1. The structure of the GaAs/Al$_x$Ga$_{1-x}$As sample.

measured using various excitation intensities in the range from 2 mW/cm^2 to 6.8 W/cm^2. The laser excitation intensity was changed by using neutral glass filters or by varying the output power of the laser by controller. A closed cycle helium optical cryostat enabled the sample temperatures to be changed from an ambient 300 K down to 3.6 K.

The chemical etching of the top layers was performed using a H$_3$PO$_4$: H$_2$O$_2$: H$_2$O = 1 : 1 : 50 solution. The etching was controlled with a profilometer by leaving some part of the sample unetched.

3. Experimental results

The PL spectra of GaAs/Al$_x$Ga$_{1-x}$As structures with a different Al mole fraction x at a temperature of 3.6 K and a laser excitation intensity of $I = 1.36$ W/cm^2 are presented in Fig. 2. One can resolve two parts of the spectra indicated by segments. The first one, below 1.57 eV, is attributed to the GaAs layers. An emission below the forbidden energy gap, E_g(GaAs) =1.519 eV, is related to the lightly doped GaAs layer. The lower energy transitions at 1.49 eV, labelled A, are the recombination of free electron with the residual acceptor. The transition at 1.515 eV

is a well-known free exciton line [5] (marked as X in Fig. 2). The broad band from 1.5 to 1.57 eV is attributed to the emission from the heavily doped GaAs layer (n^+-GaAs). This broad band nearly disappeared from the spectra when the top n^+-GaAs layer was removed by etching. The radiation of multiple quantum wells (QWs) in the buffer layer at 1.547 eV is not clearly distinguished in Fig. 2. Clear excitonic lines radiating from QWs were only observed after the etching of all the top layers.

The second part of the PL spectra is associated with the Al$_x$Ga$_{1-x}$As layers. It can be shown that the PL intensity from Al$_x$Ga$_{1-x}$As decreases with the decrease of the Al mole fraction. This part of the PL spectrum can be interpreted as the superposition of
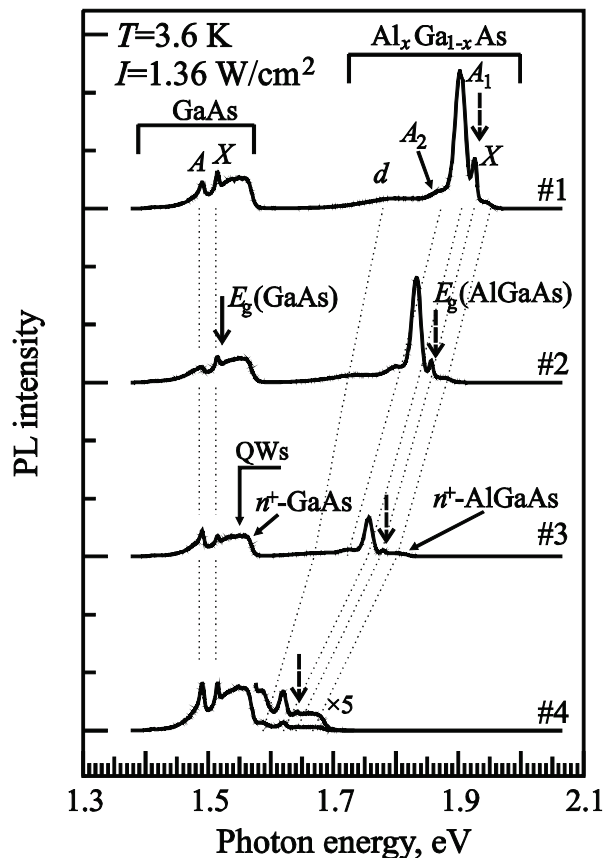

Fig. 2. The PL spectra of GaAs/Al$_x$Ga$_{1-x}$As structures at a temperature of 3.6 K and a laser intensity of $I = 1.36$ W/cm^2 for samples with different Al mole fraction x (0.3 in #1, 0.25 in #2, 0.2 in #3, 0.1 in #4). The spectra are shifted along the vertical axis for clarity. The scale for all the spectra is the same. The dotted lines act as guidelines for the eyes.

two separate spectra arising from both the n^+-type and the n-type $Al_xGa_{1-x}As$ layers. As Fig. 2 shows, this part of the spectrum consists of five broad peaks for the samples #1, #2, #3. Only four peaks are observed in the spectrum of the $Al_xGa_{1-x}As$ sample #4.

In order to interpret the nature of the PL spectra lines from the $Al_xGa_{1-x}As$ layers, the PL spectra was first measured after removing the two upper (n^+-GaAs and n^+-$Al_xGa_{1-x}As$) layers by chemical etching. Comparing the spectra obtained from samples with and without the (second) n^+-$Al_xGa_{1-x}As$ layer demonstrates that both of the corner broad peaks (d and n^+-AlGaAs in Fig. 2) are related to the radiation from n^+-$Al_xGa_{1-x}As$. Secondly, we have performed the PL investigations of the as grown samples in a temperature range of 3.6–300 K using various excitation intensities. The results obtained for sample #1 at different temperatures are shown in Fig. 3, and similar results were obtained for the other samples. The PL
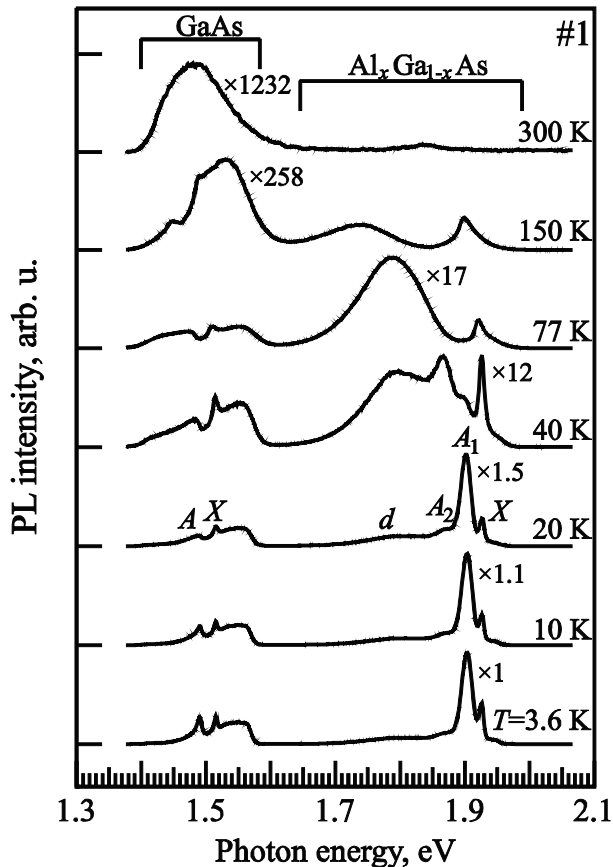
intensity of the peak around 1.926 eV at 3.6 K increases with temperature. It is a specific feature of the excitonic line. Two other peaks, labelled A_1 and A_2, of around 1.903 and 1.870 eV at 3.6 K saturate and disappear above temperatures of 40 K and 60 K, respectively. Consequently, they should be related to two different shallow impurities. The nature of the lowest energy broad peak, which dominates at the temperature of liquid nitrogen (77 K), can also be related to defects and will be discussed below.

4. Discussion

The energetic positions of possible emission lines have been theoretically calculated and compared with experimental results. Due to an amphoteric character of Si impurity, the Si-acceptor on the As site can also be expected in the n-type Si-doped $Al_xGa_{1-x}As$. An unintentional impurity that is commonly observed in GaAs and $Al_xGa_{1-x}As$ alloys grown by MBE is carbon (C). Up until now it has been found only as an acceptor in $Al_xGa_{1-x}As$ [6]. Consequently, we used the dependence of impurity binding energy in $Al_xGa_{1-x}As$ in the composition range of $0 < x < 0.4$ as: $E_{Si}(D) = 6.0 + 8.8x + 7.2x^2$ (meV) [6], $E_{Si}(A) = 34.8 + 47.3x + 465x^{3.5}$ meV) [7], $E_C(A) = 26.7 + 5.56x + 110x^{3.4}$ (meV) [8]. The $Al_xGa_{1-x}As$ band-gap energies were calculated as $E_g^\Gamma(T = 0K) = 1.5194 + 1.36x + 0.22x^2$ (eV) [9], and the Varshni's equation coefficients were taken from Ref. [10]. The calculated E_g values at 3.6 K for different samples are shown in Fig. 2 as vertical arrows.

The excitonic lines were included in all of these calculations too. The free exciton binding energy was evaluated by a quadratic interpolation $E_x(\Gamma) = 4.1 + 5.5x + 4.4x^2$ (meV) [6]. The impurity bound exciton binding energies were described using Haynes' rule [11], and the above-mentioned impurity binding energies were approximated to the corresponding values in GaAs [12]. These led to the following two relationships:

$$E_{DX} = 1.2 + 1.8x + 1.4x^2 \text{ (meV)} \tag{1}$$

for donor bound exciton DX, and

$$E_{CX} = 2.9 + 0.62x + 12x^{3.4} \text{ (meV)} \tag{2}$$

for carbon acceptor bound exciton CX, respectively.

Fig. 3. The normalized PL spectra of a GaAs/$Al_{0.3}Ga_{0.7}As$ structure (sample #1) at different temperatures from 3.6 to 300 K at a laser excitation intensity of $I = 1.36$ W/cm^2. The spectra are shifted along the vertical axis for clarity.

A comparison of both the experimental and calculated results helped us to identify these lines. The A_1 and A_2 lines are related to the carbon and silicon-acceptor, respectively. The main part of the broad line is related to the free electron–neutral acceptor transitions. The donor–acceptor recombination is profound only at low temperatures and low excitation intensities due to donor ionisation. The highest energy edges are above the band gap energies and are related to the Fermi level in the n^+-$Al_xGa_{1-x}As$ layers.

The band X in $Al_xGa_{1-x}As$ is attributed to free and donor-bound exciton transitions at a temperature of 3.6 K. As the temperature increases to $T > 10$ K, the donor-bound exciton recombination disappears due to ionisation of the donors, and the free excitonic emission and (in part) band-to-band transitions begin to dominate.

The broad band d which is visible as the lowest energy line in the $Al_xGa_{1-x}As$ spectra shown in Figs. 2 and 3 has lower values than the minimum energy of transitions related to shallow impurity. This broad band emission is, therefore, attributed to point defects or complexes of Si with point defects. The determined dissociation energy depends on the Al mole fraction and varies from 60 to 140 meV. This result is in good agreement with the point defect and complex energies that are presented in [6]. A large width of this emission peak also suggests that a complex is involved in the transition.

Comparing the emission from n-GaAs and n-$Al_xGa_{1-x}As$ layers with the emission from layers that are in contact with heavily doped layers revealed that emission lines from homojunctions were more intensive. This is related to the enhancement of the PL intensity found in a homojunction [13, 14]. Hence, the results suggest that the contact of n-GaAs with n^+-GaAs and n-$Al_xGa_{1-x}As$ with n^+-$Al_xGa_{1-x}As$ will give rise to a PL spectra intensity that is about 10 and 20 times higher, respectively.

5. Conclusions

The PL spectra for Si donor doped GaAs/$Al_xGa_{1-x}As$ structures grown for the preparation of MW and THz detectors have been identified. The PL emission lines from $Al_xGa_{1-x}As$ were a result of enhanced excitonic transitions and recombination with the C- and Si-acceptor. The broad band emission that dominates at higher temperatures is related to point defects or complexes in the material.

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MIKROBANGŲ IR TERAHERCŲ DETEKTORIAMS SKIRTŲ GaAs/AlGaAs DARINIŲ FOTOLIUMINESCENCIJOS APIBŪDINIMAS

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Santrauka

Ištirti Si donorais legiruotų $GaAs/Al_xGa_{1-x}As$ darinių, skirtų mikrobangų ir terahercų detektoriams, fotoliuminescencijos (FL) spektrai plačiame temperatūrų intervale nuo 3,6 K iki kambario temperatūros ir esant įvairiems žadinančios šviesos intensyvumams nuo 0,002 iki 6,8 W/cm². $Al_xGa_{1-x}As$ spektre nustatytos linijos, susijusios su eksitonine spinduliuote bei rekombinacija per C ir Si akceptorines priemaišas. Taip pat FL spektre matyti plati juosta, kurios ryšio energija priklauso nuo junginio sudėties x ir kinta nuo 60 iki 140 meV. Ji susieta su taškinių defektų arba kompleksų tarp Si ir taškinių defektų susidarymu. Pateiktos $Al_xGa_{1-x}As$ surištojo eksitono su akceptorine ar donorine priemaiša ryšio energijos priklausomybės nuo sudėties x ($0 < x < 0,4$). Nustatytas GaAs ir $Al_xGa_{1-x}As$ spektrinių linijų sustiprėjimas iki 20 kartų. Šis sustiprėjimas siejamas su n/n^+ sandūrų egzistavimu šiuose dariniuose.