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Technology and characterization of p-i-n photodetectors with DQW (In, Ga)(As, N)/GaAs active region

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Double quantum well (DQW) (In, Ga)(As, N)/GaAs p-i-n photodetectors, grown by solid source molecular beam epitaxy using a radio-frequency plasma source for nitrogen with absorption for wavelengths above 870 nm have been investigated. The active region of the photodetectors contained two very thin absorption layers: 10.5 nm Ga(As, N) (structure #DP02) or 4 nm (In, Ga)(As, N) (#DP03). In spite of this, photodetectors exhibited high sensitivity (0.0525 A/W for 980 nm) for wavelength greater than the absorption edge of GaAs (870 nm). The dark current of photodetectors did not exceed 0.1 μA.

Keywords: p-i-n photodetector, diluted nitrides, (In, Ga)(As, N), GaAs-based photodetectors, double quantum well (DQW) heterostructures.

1. Introduction

One of the most promising solutions to revolutionize fiber optic long distance communication is the development of a new class of semiconductors known as diluted nitrides. Diluted nitrides such as (In, Ga)(As, N) have recently emerged as an attractive material for optoelectronic devices in the near infrared [1] and can be grown directly on gallium arsenide. This allows one to utilize well-established processing techniques and components, including high-reflectivity distributed Bragg reflectors (DBR) already available in GaAs/AlGaAs-based devices. Small content of nitrogen atoms in GaAs-based components has attracted considerable attention due to the high potential of the technique in many device applications. Large band bowing parameter of diluted nitrides gives a redshift in the absorption at low nitrogen concentrations. For photodetectors there is a possibility of extending the range of detectable wavelengths beyond the GaAs cut-off at 870 nm [1–3]. Unfortunately, (In, Ga)(As, N) compounds suffer from deterioration of structural, optical and electrical properties with increasing nitrogen fraction in the semiconductor alloys [4–9].

2. Fabrication of the devices

The (In, Ga)(As, N)/GaAs DQW p-i-n photodetector structures were grown by solid source molecular beam epitaxy. A radio frequency (RF) plasma source was used for the nitrogen atoms supply. A schematic design of the MBE system is shown in Fig. 1. The RF source is installed in a small UHV chamber, which is separated from the growth chamber by an UHV gate valve. This allows us to operate the nitrogen source long before the growth of the (In, Ga)(As, N) and therefore to reach well controlled steady-state operation conditions for the N containing layers. This configuration makes it possible to exchange parameters of the plasma source without affecting the UHV in the growth chamber. Details of the MBE system used can be found in [10].

The p-i-n photodetector structures were grown on 100 oriented n-doped GaAs substrates. Both types of the structures: #DP02 and #DP03 contain two undoped quantum wells embedded in the undoped active region. The #DP02 structures contain two about 10.5 nm $GaAs_{0.99}N_{0.01}$ quantum wells surrounded by GaAs barrier/cladding layers. A precise description of the cross-section of #DP02 structure is given in Tab. 1. The (In, Ga)(As, N)/(In, Ga)(As, N)/GaAs DQW p-i-n photodetector structures #DP03 contain two 4 nm (In, Ga)(As, N) quantum wells surrounded by (In, Ga)(As, N) undoped barrier and GaAs undoped cladding layers. For growing (In, Ga)(As, N)/(In, Ga)(As, N) DQW/barrier heterostructure the modulation growing procedure has been used. It allowed growing QW and barrier layers, which vary in

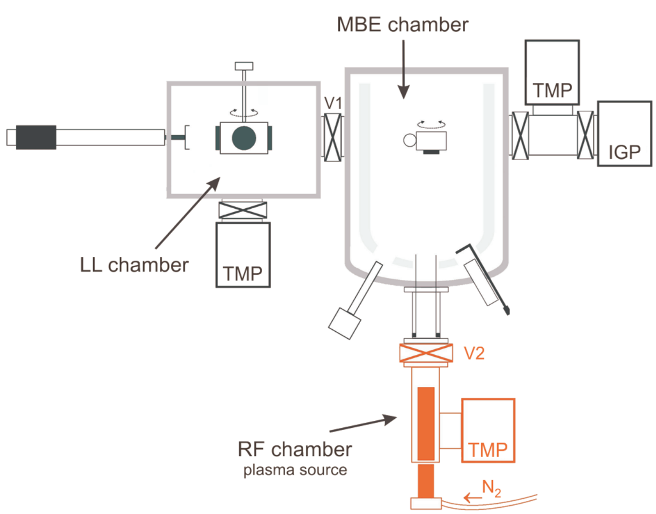

Fig. 1. Schematic cross-section of the RF MBE used for the growth of (In, Ga)(As, N)/GaAs DQW p-i-n photodetectors.

T a b l e 1. Structure of the # DP02 Ga(As, N)/GaAs DQW p-i-n photodetector.

Layer/material	Layer thickness	Doping concentration
Surface – GaAs:Si	450 μm	$N_d = 7\times10^{18}$ cm^{-3}
Buffer – GaAs:Si	500 nm	$N_d = 6\times10^{18}$ cm^{-3}
Cladding layer – GaAs	200 nm	undoped active region
Quantum well I – Ga(As, N)	10.5 nm	
Barrier – GaAs	15 nm	
Quantum well II – Ga(As, N)	10.5 nm	
Cladding layer – GaAs	200 nm	
Contact layer – GaAs:C	100 nm	$N_a = 2\times10^{19}$ cm^{-3}

T a b l e 2. Structure of the # DP03 (In, Ga)(As, N)/(In, Ga)(As, N)/GaAs DQW p-i-n photodetector.

Layer/material	Layer thickness	Doping concentration
Surface – GaAs:Si	450 μm	$N_d = 7\times10^{18}$ cm^{-3}
Buffer – GaAs:Si	500 nm	$N_d = 6\times10^{18}$ cm^{-3}
Cladding layer GaAs	200 nm	undoped active region
Barrier I – (In, Ga)(As, N)	12.5 nm	
Quantum well I – (In, Ga)(As, N)	4 nm	
Barrier II – (In, Ga)(As, N)	19 nm	
Quantum well II – (In, Ga)(As, N)	4 nm	
Barrier III – (In, Ga)(As, N)	12.5 nm	
Cladding layer GaAs	200 nm	
Contact layer – GaAs:C	100 nm	$N_a = 2\times10^{19}$ cm^{-3}

composition, in stable growing conditions. A description of #DP03 structure can be found in Tab. 2. The #DP02 and #DP03 p-i-n photodetector structures, which vary in active regions, should be characterized by different sensitivity and absorption edge. In the case of the #DP03 structure the band-gap of the quaternary alloys quantum wells is smaller than in the case of the QW of #DP02 structure. By this reason for the #DP03 structure the spectral sensitivity should be higher for wavelengths longer than 870 nm and the absorption edge should be shifted towards longer wavelengths in comparison with #DP02 p-i-n structure.

The growth parameters of the epitaxial structures were optimized also using room temperature photoluminescence (PL). For #DP02 the nitrogen concentration in the Ga(As, N) layer is 1%. For structure #DP03 with (In, Ga)(As, N) QWs, which contains about 35% In and 4% N, the maximum of PL reaches 1440 nm, Fig. 2. The growth temperatures of (In, Ga)(As, N) QW layers or/and barriers were reduced from 595 °C to 490 °C and 410 °C for #DP02 and #DP03 structures, respectively.

To fabricate p-i-n photodetector devices two standard UV photolithography processes were used to defined circular 200 μm mesa structures. Mesas were obtained by wet chemical etching using a H_3PO_4:H_2O_2:H_2O solution. Using another

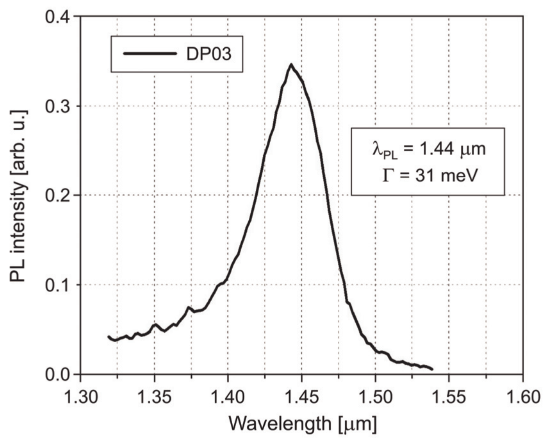

Fig. 2. PL spectra of #DP03 structure.

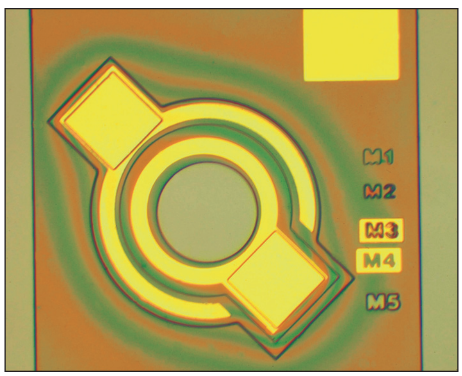

Fig. 3. Photo of the Ga(As, N)/GaAs DQW p-i-n photodetector.

two lithography processes and UHV evaporation a ring-shaped AuGe/Ni/Au contact on the n-doped layer and Pt/Ti/Pt/Au contact on the p-doped layer were deposited. Both n- and p-layer contacts were deposited on the same side of the structures to create planar p-i-n photodetector structures. Resistivities of the metal contacts were estimated to be better than $1\times10^{-6}\ \Omega cm^2$ for n-contact and $3.6\times10^{-4}\ \Omega cm^2$ for p-contact without annealing and $5\times10^{-5}\ \Omega cm^2$ after annealing.

A photograph of the Ga(As, N)/GaAs DQW p-i-n photodetector is presented in Fig. 3.

3. Device performance

Despite very thin absorbing layers of about 10.5 nm Ga(As, N) or 4 nm (In, Ga)(As, N) for structures #DP02 or #DP03, respectively, the photodetectors discussed are characterized by the absorption edge shifted towards longer wavelength, beyond absorption edge of GaAs (870 nm). The photocurrents of the p-i-n photodetectors were measured by using a setup equipped with several laser sources. The dark currents and photocurrents obtained in #DP02 and #DP03 DQW p-i-n photodetectors for different illumination wavelengths as a function of reverse bias are shown in Figs. 4 and 5. The dark current of #DP02 p-i-n photodetector does not exceed 0.01 μA in the investigated range of reverse bias. Within the same bias range the dark current of #DP03 is one order of magnitude higher. For both types of the DQW p-i-n photodetectors a ratio between the dark current and the photocurrent value varies between three and two orders of magnitude from the low to higher reverse bias.

A spectral characteristic of the (In, Ga)(As, N)/(In, Ga)(As, N)/GaAs DQW p-i-n photodetector is presented in Fig. 6. For a wavelength of about 870 nm the GaAs absorption edge is visible. The weaker photocurrent value achieved beyond this cut-off wavelength comes from absorption in very thin (In, Ga)(As, N) QWs. A halogen

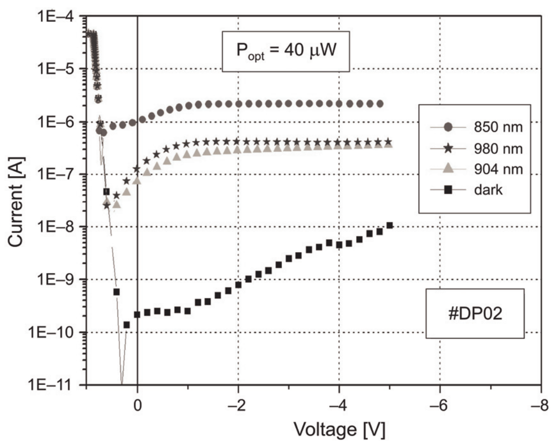

Fig. 4. Current-voltage characteristic of Ga(As, N)/GaAs DQW p-i-n photodetectors (#DP02) for different wavelengths.

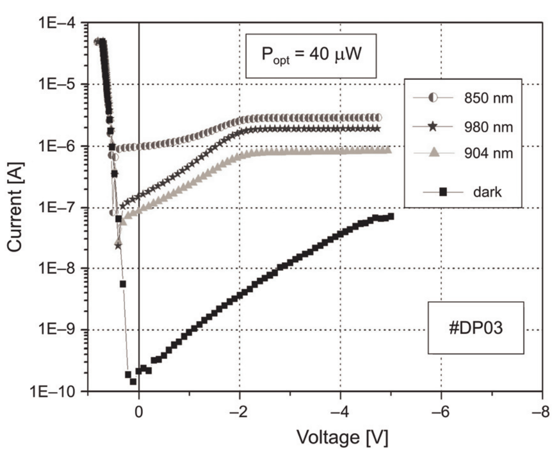

Fig. 5. Current-voltage characteristic of (In, Ga)(As, N)/(In, Ga)(As, N)/GaAs DQW p-i-n photodetectors (#DP03) for different wavelengths.

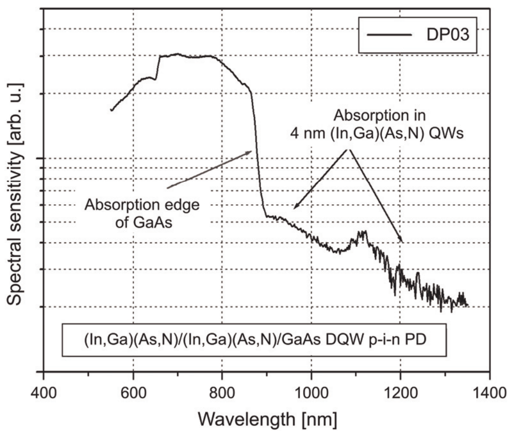

Fig. 6. Spectral characteristic of (In, Ga)(As, N)/(In, Ga)(As, N)/GaAs DQW p-i-n photodetector.

lamp with calibrated optical power was used as a source for spectral characteristic measurements.

On the basis of the measurements the sensitivity of the DQW p-i-n photodetectors for different wavelengths and optical power $P_{opt} = 40$ μW at bias $U = -3$ V was determined and is presented in Tab. 3. For wavelengths shorter than 870 nm the photodetectors are characterized by the high sensitivity because of the absorption

T a b l e 3. Sensitivity of p-i-n DQW photodetectors determined for 3 V reverse bias.

λ [nm]	#DP02 [A/W]	#DP03 [A/W]
850	0.060	0.0750
904	0.009	0.0195
980	0.012	0.0525

in GaAs. Beyond the GaAs cut-off at 870 nm the spectral sensitivity decreases. However, for wavelengths around 980 nm (see Figs. 4 and 5) and for #DP03 structure for wavelength about 1100 nm (Fig. 6), slight increments of spectral sensitivity are observed. The increase of the spectral sensitivity of p-i-n heterostructures for several longer wavelengths could be caused by resonant enhancement effect inside the device structures.

4. Conclusions

We demonstrated fabrication and properties of p-i-n photodetectors based on GaAs substrates with Ga(As, N) and (In, Ga)(As, N) DQW active region. Despite very thin absorbing layers: 10.5 nm or 4 nm for structures #DP02 or #DP03, respectively, the photodetectors exhibited high sensitivity for wavelengths longer than the absorption edge of GaAs (870 nm). The p-i-n photodetector with (In, Ga)(As, N) QWs (#DP03) exhibited sensitivity of 0.0525 A/W for 980 nm at 3 V reverse bias. The dark current of the photodetectors did not exceed 0.1 μA in the investigated range of reverse bias. As we expected the #DP03 p-i-n photodetector structures exhibit higher spectral sensitivity due to the smaller band-gap of QWs, compared to the #DP02 structure.

It seems that taking advantage of the high reflectivity GaAs/AlGaAs DBR mirrors already available on GaAs substrates, it should be possible to achieve high sensitivity and narrow spectral characteristic for resonant-cavity photodetectors with (In, Ga)(As, N) or Ga(As, N) DQW active region [11, 12].

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