InAlAs/InGaAs/InP heterostructures for microwave photodiodes grown by molecular beam epitaxy

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Abstract. Pre-epitaxial (001)InP substrate cleaning, growth of In₀.₅₂Al₀.₄₈As/In₀.₅₃Ga₀.₄₇As heterostructures lattice-matched to InP substrate by molecular beam epitaxy technique and manufacturing processes of microwave photodiodes with Schottky barrier are developed in this work.

1. Introduction
In microwave photonics systems, the powerful and high-speed photodetectors, capable to generate an output electrical signal with amplitude of about 1 V at frequencies of 10-100 GHz are required [13]. Different designs of powerful high frequency photodiodes for optical fiber communication and microwave photonics systems have been proposed in literature [4]. In our work the photodiode with Schottky barrier based on the InAlAs/InGaAs/InP heterostructure was selected for implementation because of the following advantages:

• Schottky barrier contact covers all photosensitive area that reduces the series resistance in comparison with that in the traditional photodiode with an annular contact with a hole in the middle for incoming radiation;
• Schottky barrier height of metal/InAlAs contact is high that reduces dark current of the photodiode;
• metal acts as a mirror for the radiation incoming through the substrate that considerably increases the absorption in the photodiodes;
• beam contact inductance can be adjusted to increase the maximum frequency of the photodiodes.

In present paper we focused on growth of InAlAs/InGaAs/InP heterostructure. To test heterostructures photodiodes have been manufactured and studied.

2. Experiment
The InAlAs/InGaAs heterostructures were grown on semi-insulating (001)InP substrates by molecular beam epiaxy (MBE) in Riber-32P and Compact-21T MBE multi-chamber systems equipped with solid-state molecular sources. Molecular flux of arsenic and metals (In, Ga, Al) was measured using an ionization gauge that was placed in front of sample during measurements. The substrate temperature was controlled by a single-wavelength infrared pyrometer. The growth process was in-situ monitored by reflection high-energy electron diffraction (RHEED) technique. The ex-situ evaluation of the heterostructures quality was performed by the atomic force microscopy (AFM) using a Solver P-47H (NT MDT) microscope with a vertical resolution about 0.5 Å, double-crystal X-ray diffraction and photoluminescence (PL) techniques. The values of concentration and mobility in layers of
heterostructures were determined from the Hall effect measurement at magnetic field being \( B = 0.2 \, \text{T} \) by the Van der Pauw method at a temperatures 77 K and 300 K. Ohmic contacts to the samples were obtained by the high-voltage discharge of indium foil imposed on a sample. For the fabrication of photodiodes, mesa isolation was performed by using \( \text{BCl}_3 \) plasma reactive ion etching and \( \text{SiO}_2 \) layer was deposited by plasma deposition to protect the surface and reduce leakage current. \( \text{Au/Ge/Au/Ni} \) metal stack was deposited by electron-beam evaporator for ohmic contact with thermal annealing at 385°C in hydrogen ambient. For forming Shottky barrier \( \text{Ti/Au} \) (20/200 nm) metal stack was deposited on the HCl etched InAlAs surface. From the measured current–voltage (I–V) curves, the Schottky barrier height, the ideality factor, and the reverse saturation current were obtained.

3. Experimental results and discussion

3.1. Cleaning of InP substrates

Epi-ready InP substrates were cleaned by annealing in a high vacuum chamber in order to remove the oxide layer and form atomically clean surface. First, the substrate was annealed at a temperature of 200-250°C below the temperature of noncongruent evaporation of InP being 325°C in a special MBE chamber separated by a vacuum gate of the growth chamber. Volatiles and water were removed from the substrate surface without contamination of the growth chamber. The subsequent high-temperature annealing happened in growth chamber. Then oxide layer was removed at a temperature above the congruent evaporation temperature under the arsenic flux with beam equivalent pressure (BEP) \( \text{F}_{\text{As}} = 5 \cdot 10^{-5} \, \text{Torr} \) in order to prevent formation of In droplets. At a temperature of 350°C (2×3) surface reconstruction was formed. At a temperature of 450°C (2×6) reconstruction appeared. To the best of our knowledge, this reconstruction is reported for the first time. We assume that it is caused by the replacement of the phosphorus atoms of arsenic atoms. With further increase in temperature (2×6) reconstruction faded, while (4×2) reconstruction appeared at 540°C (see Figure 1) indicating the evaporation of elements of the group V (P and As). Note that (2×8) surface reconstruction was observed earlier under a phosphorus flux in the same temperature range [5]. The emergence of (4×2) reconstruction, increasing the intensity of the fractional stripes, decrease in the background intensity indicates the evaporation of the oxide layer [6]. During cooling of clean surface (2×4) reconstruction was observed. Annealing was accompanied by the desorption of phosphorus atoms which partially replaced by arsenic atoms [7–9]. This process led to the formation of InAs islands with height and lateral size of about 0.84–1.16 nm (2-3 monolayers) and 100 nm, correspondingly. Heterostructures were grown on substrates annealed at 540°C.

3.2. Growth of InAlAs and InGaAs layers

To establish growth conditions of \( \text{In}_x\text{Al}_{1-x}\text{As} \) (\( x_{\text{In}} \) close to 0.52) and \( \text{In}_y\text{Ga}_{1-y}\text{As} \) (\( y_{\text{In}} \) close to 0.53) layers lattice-matched with InP the substrate temperature and arsenic flux (BEP) varied between 460-580°C and \( (1-10) \cdot 10^{-5} \, \text{Torr} \), accordingly. Two methods were used to control the molecular flux ratio of metals and arsenic coming to the surface growth.

- Measurement of BEP by an ionization vacuum gauge considering the ionization coefficient of each chemical element. Indications of the gauge at the opened and closed source shutter were measured. Calculation from these values is a BEP each material.
- Measuring the rate of growth, using the time oscillation in the intensity of RHEED strip. The growth rate of ternary alloy is determined by the total flux of metals, the flux of each metal was evaluated in growth process of binary compounds. These data were used to define the composition and thickness of the alloy layers.

According to the X-ray diffraction (XRD) data, the best structural parameters of InAlAs layers were obtained at 520-535°C for \( \text{BEP}_{\text{As}} \) of \( (1.5-2) \cdot 10^5 \, \text{Torr} \). Measured and calculated positions of (004) XRD peaks of the InAlAs layer good match. The full width at half maximum (FWHM) of double-crystal X-ray rocking curve was as low as 20”, that is very close to the value of 13” for InP substrate, as illustrated in Figure 2. The Figure 3 shows PL spectra at 77 K and 300 K from the InAlAs
layer grown at 535°C. The 77K PL spectrum comprises a single band peaked at 1.508 eV with a FWHM of 27 meV that originated from band-to-band transitions. In contrast to PL from the AlInAs layers grown at lower temperatures no impurity-related bands have been observed.

**Figure 1.** RHEED images of InP substrates annealing under the arsenic flux with BEP$_{\text{As}}$ of $5 \cdot 10^{-5}$ Torr, (2×6) reconstruction at a temperature of 450°C. Image showing the 2-by and 6-by periodicity in the [110] and [110] azimuth direction, respectively.

**Figure 2.** Calculated (1) and experimental (2) X-ray rocking curve (Cu Ka, 004 reflex) of the In$_{0.52}$Al$_{0.48}$As layer grown at a temperature 535°C and BEP$_{\text{As}}$ $1.5 \cdot 10^{-5}$ Torr.

Figure 4 demonstrates the AFM image of the InAlAs layers grown at 535°C and BEP$_{\text{As}}$ $1.5 \cdot 10^{-5}$ Torr with monoatomic steps, evidencing in a two-dimensional growth mode. The root mean square (RMS) value of the surface roughness in the $1 \times 1$ μm$^2$ area is about 0.113 nanometers.

**Figure 3.** 77 and 300 K PL spectra.

**Figure 4.** $1 \times 1$ μm$^2$ AFM image of In$_{0.52}$Al$_{0.48}$As In$_{0.52}$Ga$_{0.47}$As layer grown at a temperature layers grown at a temperature 535°C and BEP$_{\text{As}}$ 535°C and BEP$_{\text{As}}$ $1.5 \cdot 10^{-5}$ Torr. $1.5 \cdot 10^{-5}$ Torr.

Dependence of carrier concentration and mobility of In$_{0.52}$Al$_{0.48}$As layers on growth conditions has been investigated. It was found that the electron concentration decreases when the growth temperature reduces.

The following conditions were chosen for growth of In$_{0.53}$Ga$_{0.47}$As layers: a 480°C growth temperature and arsenic BEP $3 \cdot 10^{-5}$ Torr. In these conditions two-dimensional growth occurs, the RMS value is 0.5–0.7 nm, i.e. 2-3 monolayers. XRD evidences in structural uniformity of these layers.
The electron concentration and mobility at 300 K was about $1.45 \times 10^{15}$ cm$^{-3}$ and 6600 cm$^2$/V·sec, respectively. At 77 K epitaxial In$_{0.53}$Ga$_{0.47}$As layers become non-conducting.

3.3. Growth of InAlAs/InGaAs/InP heterostructure

The layer consequence for microwave photodiode heterostructure is presented in table 1.

| Layer Description | Thickness | Material Composition |
|-------------------|-----------|----------------------|
| 30 nm Protect layer | In$_{0.53}$Ga$_{0.47}$As |
| 30 nm Barrier layer | In$_{0.52}$Al$_{0.48}$As |
| 50 nm Gradient layer | InGaAlAs |
| 600-1500 nm Undoped absorbing layer, thickness depends on operating frequency | In$_{0.53}$Ga$_{0.47}$As:Si $5 \times 10^{18}$ cm$^{-3}$ |
| 50 nm Absorbing n$^+$ layer | In$_{0.52}$Al$_{0.48}$As:Si $5 \times 10^{18}$ cm$^{-3}$ |
| 300 nm Contact layer | |
| 400 µm Substrate | InP (001) |

At the growth of the InAlAs/InGaAs/InP heterostructure each layer was grown at different temperature, namely, InGaAs layers were grown at 480°C whereas InAlAs layer was grown at a temperature above 500°C. To conduct continuous process that excludes capture of undesirable background impurity in chemically active Al-containing layers and does not overheat InGaAs layers, growth of InAlAs layer was divided into several stages. Growth started at 480°C, and then the temperature was gradually raised to about 530°C, finally the temperature was lowered to 480°C. This approach allows to grow heterostructure in a two-dimensional growth mode with RMS lesser 0.3 nm.

Microwave photodiodes with a various diameters of 200, 150, 100, 75 and 50 µm of Shottky contact have been fabricated. Devices showed typical diode $I$-$V$ characteristics. For 50 µm photodiodes the Schottky barrier height 0.787 eV, the ideality-factor 1.07 and the reverse current less $2 \times 10^{-9}$ A was obtained.

4. Conclusion

The technology of pre-epitaxial vacuum cleaning of (001) InP substrates and MBE growth of multilayer heterostructures for microwave photodiode were considered. Optimum conditions for growth of InAlAs/InGaAs heterostructures were established. The suitability of heterostructure for manufacturing of photodiodes was demonstrated.

This work was supported by the RFBR grants nos.14-29-08124.

5. References

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