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Long-term stability of GaAs-based pseudomorphic transistor heterostructures with InGaAs channel

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Abstract. Variation of the electrophysical and structural parameters of GaAs-based pseudomorphic transistor heterostructures with an InGaAs channel during more than eleven-year storage in natural conditions have been investigated. It was found that the values of the electrophysical parameters remained within specified limits (taking into account measurement errors) after 11 years of storage. The structural properties (thickness and composition of the InGaAs channel) of pseudomorphic heterostructures have undergone significant changes associated with the InGaAs channel layer broadening due to atomic diffusion.

Keywords: pseudomorphic transistors, PHEMT heterostructures, parameter stability

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Сохраняемость параметров псевдоморфных гетероструктур с InGaAs-каналом на подложке GaAs

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Аннотация. Исследованы изменения электрофизических и структурных параметров транзисторных псевдоморфных гетероструктур с InGaAs-каналом на подложке GaAs при естественном хранении в течение более одиннадцати лет. Обнаружено, что электрофизические параметры псевдоморфных транзисторных гетероструктур оставались в заданных пределах (с учетом погрешности измерения) спустя одиннадцать лет хранения. Структурные свойства (толщина и состав InGaAs-канала) псевдоморфных гетероструктур претерпели существенные изменения, связанные с размытием InGaAs-канала вследствие диффузии.

Ключевые слова: псевдоморфные транзисторы, PHEMT гетероструктуры, сохраняемость параметров

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Introduction

Manufactured electronic semiconductor devices such as diodes and transistors are typically examined with a reliability testing. One of the issues that may lead to the device's inoperability is an ageing failure – a failure the probability of which increases due to accumulated deterioration over a calendar time [1]. Ageing failure may arise from the material degradation due to internal processes and (or) environmental impact. Gradual change in parameters of the heterostructure the device is made of may result in the device failure.

In the present work, changes in the inner characteristics of the pseudomorphic high electron mobility transistor (pHEMT) heterostructures on GaAs substrates were investigated. Devices based on the pHEMT heterostructures include low-noise preamplifiers and output power amplifiers, as well as low-noise transistors. Studies of the parameter stability during long-term storage of transistor heterostructures are necessary to establish the failure mechanism, especially those resulting from a smooth change in the values of one or more parameters of the heterostructure. Defining the failure mechanism and ensuring the stability of semiconductor devices during long-term storage and operation had been a subject of research in the XX century and remains relevant to this day [2, 3]. A study on the parameter stability of the metamorphic HEMT heterostructures stored in normal conditions can be found elsewhere [4].

The pHEMT structures selected for the current research were pseudomorphic heterostructures with high electron mobility in the Ga-In-Al-As material system. The conventional pHEMT heterostructure design consists of GaAs buffer layer, undoped $In_xGa_{1-x}As$ channel with a thickness of (12–15) nm and In molar fraction $x = (0.16–0.18)$, AlGaAs barrier layer and GaAs top contact layer. Donor (one or two) AlGaAs layers, barrier AlGaAs layers and contact layers are doped with Si atoms (n-type conductivity).

Studied transistor structures were grown on 3″ semi-insulating (100) gallium arsenide substrates by molecular beam epitaxy (MBE) using a semi-industrial Riber MBE 49 setup. The growth of the pHEMT heterostructures was carried out using two epitaxy processes with 5 wafers loaded in each growth procedure. Another test structure was fabricated, designed especially for the Hall-effect measurements of carrier concentration and mobility. The only distinction from the standard structure was the thickness of the upper contact layer. Thus, the overall number of investigated heterostructures was 10 standard pHEMT structures used for non-destructive contactless measurements, and one modified pHEMT structure, that was diced into 10 samples to conduct the Hall measurements.

In order to determine a list of parameters monitored during stability tests, it is necessary to define the failure criteria and the possible consequences of reaching failures and/or critical states during storage. The functional purpose of the HEMT transistor heterostructures is to provide the high carrier mobility while maintaining the carrier concentration values in a given range. Therefore, the observed characteristics of the HEMT structures included electrophysical parameters: concentration and mobility of the main charge carriers and sheet resistance of the InGaAs transistor channel. Structural parameters (InGaAs channel composition and thickness) were also investigated.

Materials and Methods

The studies were carried out according to the developed test program using certified measuring instruments. The overall duration of the studies exceeded 11 years. Test samples put in individual plastic containers were stored indoors under normal climatic conditions that are defined in

GOST 20.57.406-81 [5] by the following values of climatic parameters: air temperature in the range of 15–35 °C; relative air humidity in the range of 45–80 %; atmospheric pressure in the range of 84–106 kPa (630–800 mmHg).

Mobility and concentration of the main charge carriers were determined by the method relying on the Hall effect in Van der Pau geometry using the HMS-3000 (Ecopia, Korea) experimental setup with the measurement error of ± 8 %. The measurement technique was based on GOST 25948-83 [6].

The sheet resistance was examined at 16 points on the wafer by the eddy-current method using the LEI 1510A SA non-contact resistance measurement setup by Lehighton Electronics. The measurement error of the obtained sheet resistance values was ± 4 %. A range of the sheet resistance values over the wafer area was calculated as the difference between the maximum and minimum values reduced to the mean value, expressed in percentages.

The photoluminescence (PL) maximum wavelength was determined by measuring the PL spectrum in the center of the heterostructure wafer. The distribution of the maximum wavelength and intensity was determined using the photoluminescence mapping. The RPM Sigma (Accent Optical Technologies) setup with an automatic loader was used for carrying out the PL measurements. The excitation source of the PL was a semiconductor injection laser operating in continuous wave with the wavelength of 788 nm and the output power up to 45 mW. The PL wavelength measurement error is ± 0.6 nm when using a 300 g/mm diffraction grating. The peak wavelength and intensity distribution is calculated as the root-mean-square deviation expressed in percentages using the software provided with the experimental setup.

The crystalline parameters of the channel layer were also analyzed using the X-ray diffractometer DRON-8, Bourevestnik.

Results and Discussion

Changes in electrophysical parameters

The pHEMT heterostructure parameters affecting the transistor performance the most are the concentration and mobility of charge carriers in the InGaAs channel. Fig. 1 shows the results of Hall concentration and mobility measurements in test samples.

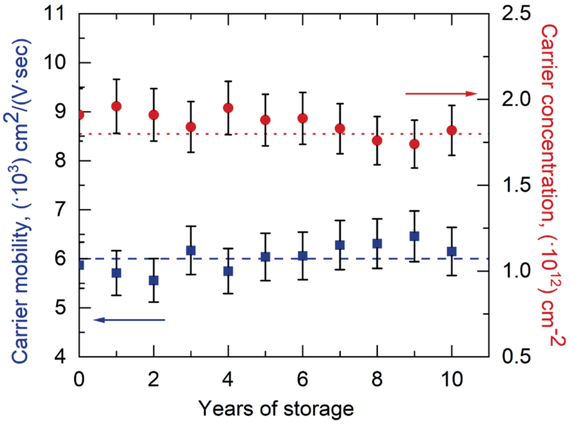

Fig. 1. The dependencies of main carrier concentration and mobility on storage time. The dotted line represents the established lower limit for carrier concentration (1.8·10^{12} cm^{-2}), the dashed line – the lower limit for carrier mobility (6.0·10^3 cm^{2}V^{-1}sec^{-1})

During the development of pHEMT heterostructures, critical values for the carrier concentration and mobility in the InGaAs channel were determined. The concentration of the main charge carriers should be at least 1.8·10^{12} cm^{-2}, the mobility of charge carriers – at least 6.0·10^3 cm^{2}V^{-1}sec^{-1} (with a measurement error of 8%), and the deviation of both concentration and mobility values across the wafer should not exceed 10%.

As shown in Fig. 1, the charge carrier concentration gradually decreases over time and approaches the minimum permissible value. The greatest decrease in concentration was 8.4% with the lowest obtained concentration value of 1.74·10^{12} cm^{-2}. The carrier mobility was gradually growing with a maximum increase of 11.9%.

The simultaneous decrease in electron concentration and increase in electron mobility with longer storage lifetime of the heterostructures might be associated with a variation of structural parameters (composition and thickness) in the InGaAs channel. Due to indium interdiffusion, once abrupt barrier-to-channel heterointerfaces became smoothed over time and the thickness of the InGaAs channel increased, while the average InAs composition decreased. Increased thickness of the InGaAs channel had also led to a decrease in the electron concentration, since the same number of carriers (electrons) became distributed over the layer of larger thickness.

According to the results of the sheet resistance measurements in pHEMT heterostructures during ten years of storage, it is possible to estimate the degree of uniformity of the electrophysical parameters distribution over the wafer. As observed from the investigation, the non-uniformity (or a spread of values) of the sheet resistance over the pHEMT wafer did not decrease much over time and had been in the range from 0.7 to 2.8 % during the studies.

Changes in structural parameters

The wavelength of PL maximum (λ_{PL}) is determined by the composition and thickness of the InGaAs channel. Therefore, the λ_{PL} deviation from its initial value would indicate a change in the channel thickness and composition, that could happen over time. For the investigated pHEMT structures the value of λ_{PL} should lie within the range of (982–986) nm. In this case, the structural parameters of the InGaAs channel parameters should be in the range of following values: (12–15) nm for thickness and (0.16–0.18) rel. units for InAs molar fraction.

Experimental results of the PL maximum wavelength measurements averaged for ten test structures are shown in Fig. 2. Figure shows that λ_{PL} had monotonically decreased over the storage time and gone beyond the lower limit of permissible values at an average of 5 years of storage (taking into account the measurement error). The photoluminescence measurement data justifies the assumption of heterointerface smoothing and InGaAs channel broadening, since the total amount of indium in the channel remains unchanged after the end of growth.

The uniformity of structural parameters values (thickness and composition of the InGaAs channel) is examined by determining the variation of PL maximum' wavelength and intensity over the wafer area (in the form of standard deviation). The deviation of PL wavelength should not exceed 0.2 %, and the deviation of PL peak intensity should be less than 10%. According to the experiment, the PL maximum wavelength had varied in the range of (0.06–0.15) % of its initial value and its distribution practically did not change with time. At the same time, the variation of the photoluminescence intensity decreased significantly from (6.6–9.8) % immediately after the heterostructure growth to (1.2–3.6) % after 10 years of storage. This change was nearly monotone in nature, as can be observed from Fig. 3.

Indium molar fraction in the InGaAs channel of manufactured transistor heterostructures immediately after growth was 0.165 rel.units. To determine the In molar fraction in the channel

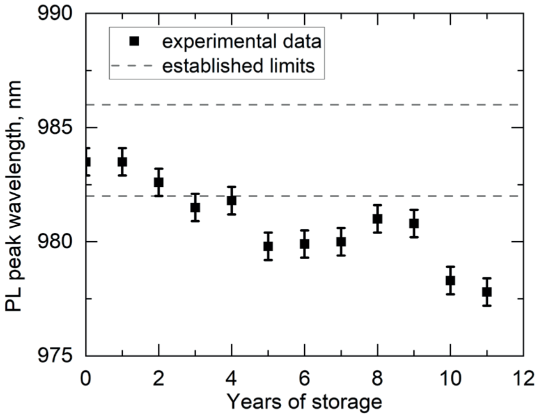

Fig. 2. The dependence of the average λ_{PL} on storage time for the PHEMT heterostructures with InGaAs-channel. The range of required λ_{PL} values (982–986) nm is depicted using dotted lines

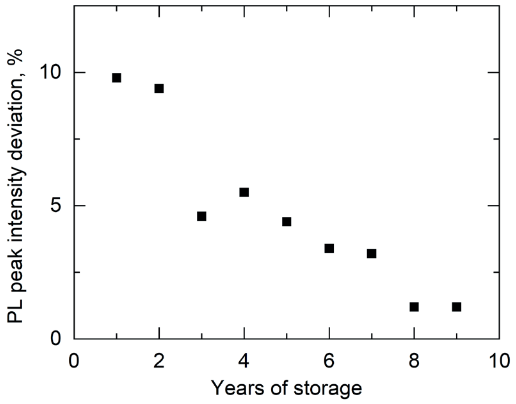

Fig. 3. The dependence of PL peak intensity standard deviation on storage time for one of the test PHEMT heterostructures with InGaAs-channel

after long-term storage, X-ray diffraction measurements of two pHEMT samples – one from each growth process – were performed. The X-ray rocking curves of both structures practically coincide, and the calculated indium molar fraction of both structures is (0.140 ± 0.005) rel. units, which is significantly less than the minimum permissible value of 0.16 rel. units.

Conclusion

During long-term storage of pHEMT transistor heterostructures for more than eleven years, the values of their electrophysical parameters have slightly changed, although remained within the specified limits (taking into account the measurement error) still after eleven years of storage. A decrease in the carrier concentration with a simultaneous increase in the carrier mobility is associated with an alteration of the InGaAs channel structural parameters (composition and thickness). Due to atomic diffusion, the thickness of the InGaAs channel increased, and the InAs molar fraction decreased from 0.165 to 0.140 rel. units (as obtained by X-ray diffraction measurements). This effect was also evident from a decrease in the PL peak wavelength.

Transistor parameter studies were carried out according to the developed testing program using certified measuring instruments to ensure the uniformity of measurements during prolonged research.

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