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AlGaAs/GaAs heterojunction phototransistor with Zn delta-doped base region

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The paper presents the technology and characterisation of *n-p-n* AlGaAs/GaAs heterojunction phototransistor (HPT) with a thin (50 nm) Zn delta-doped GaAs base region. Such a construction of the HPT transistor was applied to obtain higher current gain and lower power consumption. The electrical and optical properties of the HPT transistor were examined using electrochemical capacitance-voltage (*EC-V*) measurements, photovoltage, photocurrent and micro-Raman spectroscopies. The measured and simulated *I-U* characteristics as well as results of time response measurements are also presented and discussed. All investigations were carried out without a base bias ("floating base").

Keywords: heterojunction phototransistor, Zn delta-doped GaAs, EC-V measurements, photovoltage spectroscopy, micro-Raman spectroscopy.

1. Experiment

Heterojunction bipolar transistors (HBTs), based on GaAs technology, are widely used in the optoelectronic-integrated circuit (OEIC) [1, 2]. The work presents investigations of the heterojunction phototransistor (HPT) grown by atmospheric pressure metalorganic vapour phase epitaxy (AP MOVPE) on a (100)-oriented, tellurium-doped *n*-GaAs substrate. TMGa, TMAl, AsH_3 and DEZn were used as the growth and dopant precursors. High purity hydrogen was employed as a carrier gas. Different temperatures were applied during the growth process: 670°C (Si-doped GaAs collector), 650°C (Zn delta-doped GaAs base) and 700°C (Si-doped AlGaAs emitter). The higher growth temperature of an AlGaAs layer improves its structural quality. In the case of Zn delta-doped GaAs, the lower process temperature and a delta-doping procedure without a post-delta-doping purge step guarantee a high hole sheet concentration ($\sim 10^{13}$ cm^{-2}) inside the base region [3]. Ohmic contacts AuGeNi, using

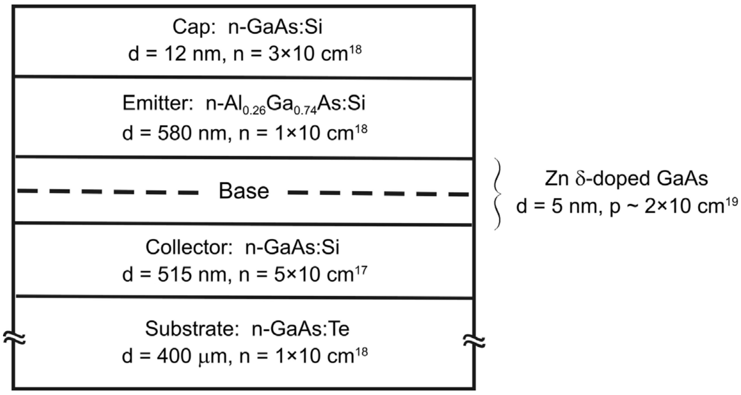

Fig. 1. Scheme of the layer structure used for HPT.

standard vacuum evaporation, were deposed on the top n^+-GaAs "cap" layer and the *n*-GaAs substrate. The top contact was ring shaped with a window for incident light. The emitter and base regions were formed using wet chemical MESA etching ($\Phi \sim 100$ μm). A scheme of the layer structure used for HPT is shown in Fig. 1.

2. Results and discussion

The carrier distribution across the HPT structure under investigation was measured using Bio-Rad PN 4300 electrochemical capacitance-voltage (*EC-V*) profiler, at a frequency of 0.3 kHz. The Bio-Rad system is equipped with the attachment for photovoltage spectroscopy (PVS), so that it is possible to analyse the composition of the emitter AlGaAs layer during *EC-V* measurements. The obtained *EC-V* profile and PVS spectrum of the AlGaAs emitter are presented in Fig. 2. Aluminium content in AlGaAs layer, estimated from PVS spectrum, was 26%, which corresponds to the band

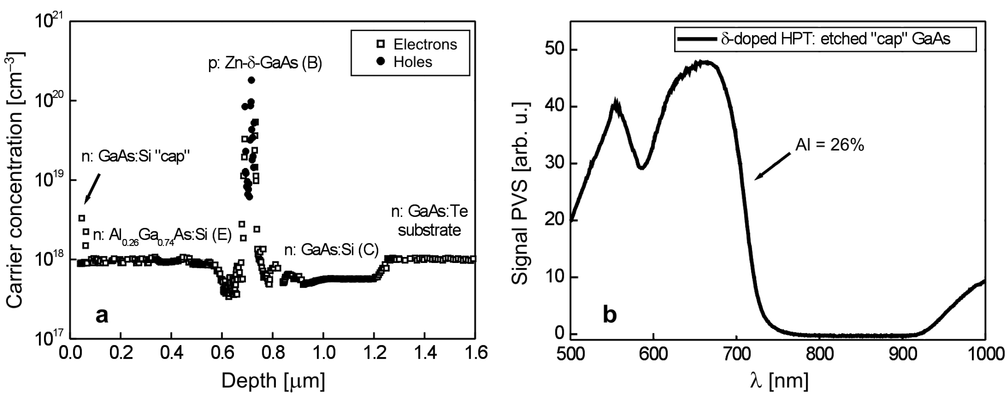

Fig. 2. *EC-V* profile of the HPT structure (**a**). PVS spectrum of the AlGaAs emitter layer (**b**).

gap value of 1.75 eV. The electron concentration inside emitter and collector layers confirmed expected values. In the case of Zn delta-doped base, precise determination of the hole concentration is very difficult, because of the two *p*-*n* junctions between a very thin *p*-type Zn-delta layer and *n*-type AlGaAs emitter and *n*-type GaAs collector.

So, to estimate the hole concentration inside the base region, micro-Raman spectroscopy on the chemically bevelled HPT sample was applied. Description of this method was reported in [4]. The obtained Zn distribution along the bevel length exhibits maximum concentration of 1.7×10^{19} cm^{-3} and dopant spreading (FWHM) of 4.7 nm (Fig. 3).

All device characteristics were measured without a base bias ("floating base"). The optically generated carriers, mainly inside the collector GaAs layer, are responsible for the HPT work. The photocurrent (PC) spectra of the HPT, measured for different

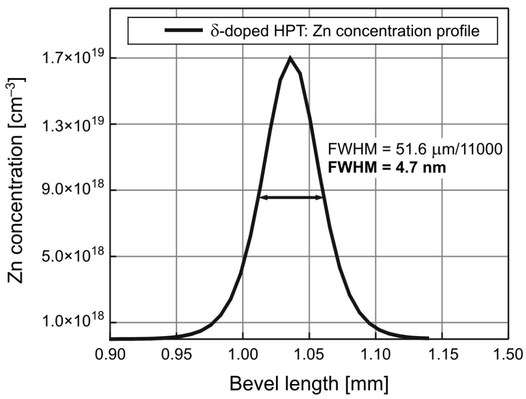

Fig. 3. Zinc distribution inside the base region estimated by micro-Raman spectroscopy.

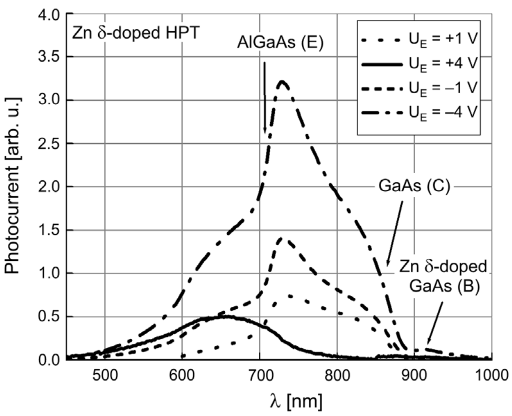

Fig. 4. PC spectra of HPT transistor.

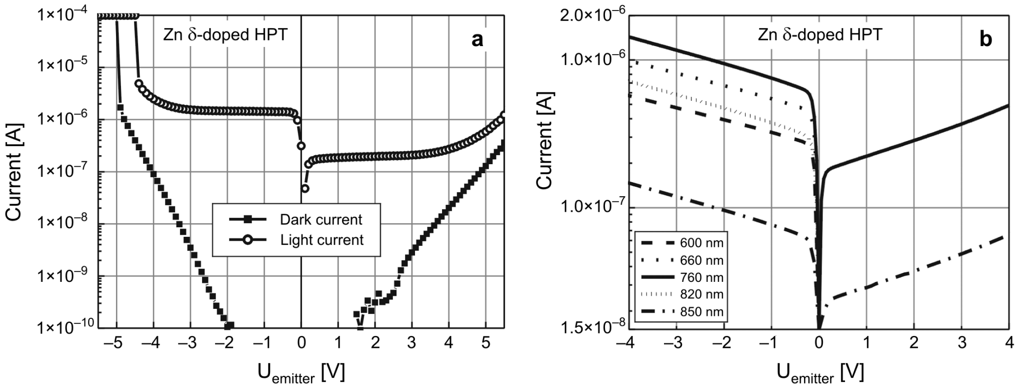

Fig. 5. Measured *I-U* characteristics of HPT (**a**). Simulated *I-U* characteristics of HPT structure (**b**).

emitter bias (+1 V, +4 V, –1 V, –4 V), are shown in Fig. 4. Halogen lamp as a light source and standard lock-in technique was applied. The spectra presented exhibit peaks corresponding to the absorption maximum of the particular HPT layers. For negative emitter voltage (normal HPT work) and lower photon energies, the absorption occurs mainly in GaAs collector and partially in Zn delta-doped GaAs base. In the case of higher photon energies and positive emitter voltage (inverse HPT work) the absorption in AlGaAs emitter is significant.

Dark and light *I-U* characteristics of the HPT transistor were measured using the calibrated source at 850 nm with optical power of 8.5 μW in fibre. The results are presented in Fig. 5**a**. The dark current is very low (tens of pA) and for negative emitter voltage rises faster with the applied voltage than in the case of positive emitter voltage because there is no energy barrier for electrons passing from AlGaAs emitter, through GaAs base to GaAs collector. Under illumination the current rises above 1 μA for normal HPT work and is nearly one order higher in comparison with the value obtained

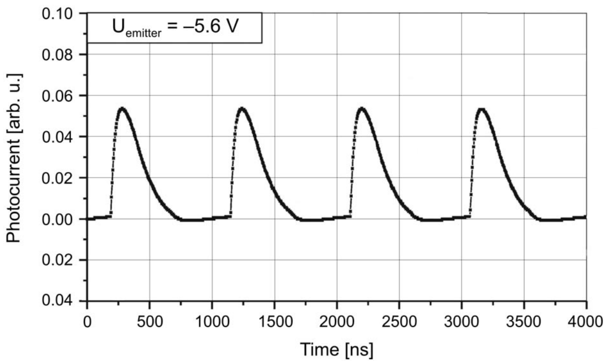

Fig. 6. Time response of the HPT for near breakdown bias voltage (–5.6 V).

for HPT inverse work. This is due to the higher energy barrier for electrons passing from GaAs collector to AlGaAs emitter for positive emitter bias. The observed breakdown above 5.5 V (for negative and positive emitter bias) was not destructive. The measured ***I-U*** characteristics are compared to results obtained from simulations of the HPT structure using SimWindows v. 1.5 program.

The simulations were performed for different incident light wavelengths with optical power of 0.5 mW/cm^2 (Fig. 5**b**). For the wavelengths of 850 and 760 nm (maximum current) the characteristics for the positive emitter voltage are included. The calculated characteristics exhibit similar ***I-U*** dependence to the measured ones. Because of the very low values of the dark current and high values of the light current for optical power above 0.5 mW/cm^2, the simulation results for the above-mentioned parameters were incorrect and they are not presented.

The time domain measurements were done by using pulse laser light source with the wavelength of 850 nm for which free carriers are generated in GaAs collector and Zn delta-doped GaAs base. The optical pulse width and period were 400 and 1000 ns, respectively. In the case of the emitter bias near breakdown voltage (5.6 V), the HPT showed fast switching with a rise time of 50 ns and a fall time of 250 ns (Fig. 6).

3. Conclusions

Technology and characterisation of the *n-p-n* GaAs/AlGaAs phototransistor with Zn delta-doped base have been presented and discussed. Electrical and optical measurements of the epitaxial HPT structure show a good agreement between the designed and the obtained parameters. The device ***I-U*** characteristics exhibit the low value of the dark current and the abrupt breakdown near 5.6 V. For this value of the bias voltage, the HPT transistor showed fast switching response with rise time of 50 ns. This is a promising feature from the point of view of application of the phototransistor presented as a fast optical switch.

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