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Terahertz wave generation from epitaxial low-temperature-grown InGaAs films on InP (100) and (411)A substrates

G. B. Galiev[1], E. A. Klimov[1], A. N. Klochkov[1], S. S. Pushkarev[1], K. A. Kuznetsov[2], V. V. Kornienko[2], G. Kh. Kitaeva[2] and O. S. Kolentsova[3]

[1] Institute of Ultrahigh Frequency Semiconductor Electronics, RAS, 117105, Moscow, Russia
[2] M.V. Lomonosov Moscow State University, Faculty of Physics, 119991 Moscow, Russia
[3] National Research Nuclear University MEPhI, 115409 Moscow, Russia

Abstract. The low-temperature growth (LTG) of the InGaAs layers on InP substrates with crystallographic orientations (100) and (411)A by means of molecular beam epitaxy is reported. The surface morphology and crystalline structural quality of the structures were shown to depend strongly on the InP substrate orientation and arsenic beam overpressure during epitaxial growth. The THz wave generation by the samples under the femtosecond laser excitation was investigated by the terahertz time-domain spectroscopy. It is found that the THz wave generation is 3 times more effective in the case of (411)A InP substrates as compared to the (100) substrates.

Introduction

The photoconductive antennas on basis of LTG III-V semiconductors are promising devices for GHz- and THz-wave detection and generation. The LTG-GaAs is a well-studied material frequently used for photoconductive detectors [1]. The LTG-GaAs is characterized by low nonequilibrium carrier lifetime (< 1 ps), high carrier mobility and low dark current [2]. These properties follow from the high density of point defects due to LTG at 150–300 °C. Photoexcited charge carriers are trapped by these defects, and therefore their lifetime is ultra-low. The relatively large band-gap (1.4 eV) of GaAs restricts the set of appropriate laser sources capable to excite carriers in the antennas. This stimulated the search of semiconducting materials having the advantages of LTG-GaAs but with smaller band-gap allowing the absorption of the radiation from more convenient lasers for optic communications (1.3 and 1.55 μm) instead of Ti-sapphire laser with a wavelength ~0.8 μm.

The LTG-InGaAs layers are widely investigated in the last years due to small band-gap (0.7 eV) and carrier lifetime. Unfortunately this material possess the substantial electron density and undesirable intrinsic conductivity. It stimulated the wide investigation of the methods to modify its properties: the ion bombardment (Br and other atoms) [3], doping by impurities (Fe, Be) [4,5] or the introduction of the periodic ErAs nanolayers [6]. In this work we investigate the effect of nonsingular (411)A InP substrate on the LTG-InGaAs layers properties. In the case of (411)A substrate the incorporation of the doping impurities from molecular beam into the lattice sites of III and V elements during growth as well as the formation of point defects can be controlled by the arsenic overpressure. So the properties of the LTG-InGaAs layers can be varied more readily for the nonsingular substrates.

1. Sample growth

The LTG-$In_{0.53}Ga_{0.47}As$ films of 1.2 μm thickness were obtained by molecular-beam epitaxy on semi-insulating substrates InP with the surface crystallographic orientations (100) and (411)A. In what follows, the samples on (100) substrates are indicated by the O letter, and the samples on (411)A substrates are indicated by the A letter. In order to maintain the identical growth conditions (a growth temperature T_g and a ratio of flows of V and III elements γ), the holder contained two different substrates and LT-InGaAs films were formed on both ones simultaneously. Samples 1 and 2 were formed at $\gamma \sim 29$, and samples 3 and 4 were formed at $\gamma \sim 90$. The samples 1 and 3 were undoped, samples 2 and 4 were doped by silicon. Growth temperature was equal to 200 °C for all samples. Grown samples were annealed in a growth chamber in As_4 flow at 500 °C for 1 hour.

2. Experimental results

The results of the atomic force microscopy analysis of the surface morphology are presented in table 1. The surfaces of the LTG-InGaAs layers grown with $\gamma \sim 29$ have a relatively smooth surface with individual pits, but growth with $\gamma \sim 90$ resulted in a complicated granular surface relief. It is notable that high temperature anneal does not influence the surface roughness of (100) samples and considerably increases that of the (411)A samples.

Table 1. Root mean square surface roughness R_q (nm) of the samples

Substrate orientation	(100)		(411)A	
Sample	1	3	1	3
After anneal	3.7	16.3	9.0	14.3
Before anneal	3.9	15.9	5.7	7.3

The THz temporal waveforms of the electric field generated by the grown samples and by the free substrates InP (100) and (411)A were measured by the terahertz time-domain spectroscopy (TDS) scheme. The pump was realized by a mode-locked Er^+ laser producing optical pulses of 100 fs duration and 1.56 μm wavelength at a repetition rate of 70 MHz. THz radiation pulses were detected with a commercial LT-InGaAs/InAlAs THz antenna at room temperature. The results for the samples after anneal are shown in Fig. 1.

THz radiation signals in Fig. 1 consist of two repeating parts of approximately the same shape and amplitude. The

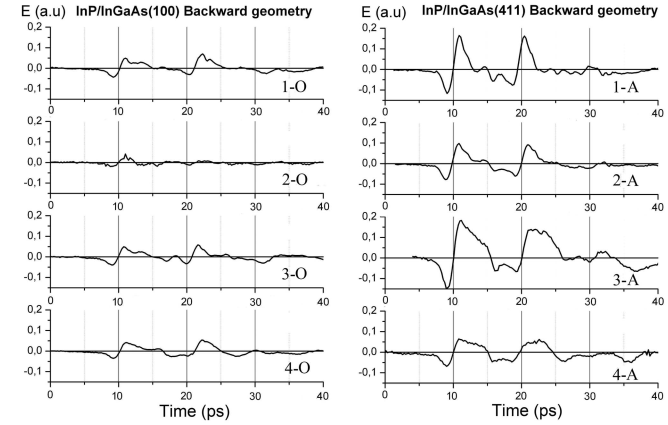

Fig. 1. Temporal waveforms of the electric field generated by LT-InGaAs layers at (100) substrates (left graph) and (411)A substrates (right graph).

second part follows the first one after 10 ps. It cannot be explained as a reflection of initially generated THz pulse from the backward surface of the InP substrate because the InP absorption coefficient in the considered terahertz range is too large (100 cm^{-1}). Moreover, the amplitude of the second pulse is not less than that of the first one. As was shown by TDS measurement of free InP substrates, THz generation from the substrates was totally negligible or in 1-2 orders less than that from the samples with LT-InGaAs films. We suggest that the latter pulse appears due to THz generation of LT-InGaAs film caused by the pump wave reflected from the backside of a 400 μm substrate.

THz wave pulses from LT-InGaAs films grown at $\gamma \sim 29$ and at $\gamma \sim 90$ have the same electric field amplitude but different shapes and consequently different frequency spectrum. Fourier transform of THz radiation pulses (see Fig. 2) yields the same frequency domain 0.1-0.5 THz for the samples 1-A and 3-A, but maximum of the THz radiation spectral density for the sample 3-A lies lower than in case of the sample 1-A (0.09 and 0.18 THz, respectively).

The Si doping of the LTG-InGaAs layers resulted in approximately twofold decrease of the generated pulses amplitude for both substrate orientations and for both As overpressures. But Si incorporation did not influence the pulse waveform and frequency spectrum.

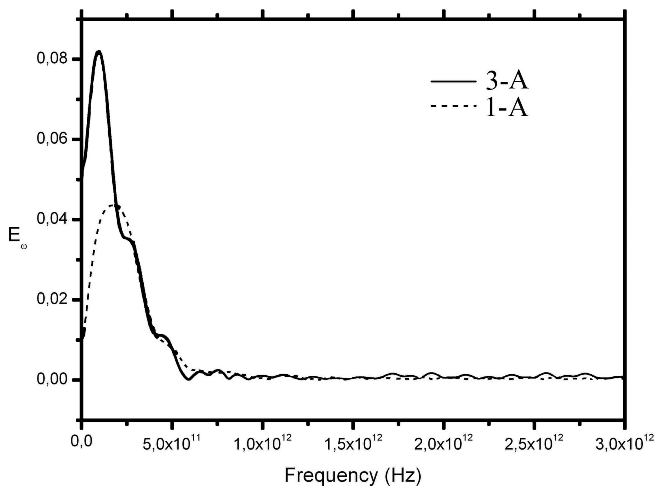

Fig. 2. Frequency waveforms of the electric field E_ω (arb. units) generated by LT-InGaAs layers on (411)A InP substrate

We want to note, that the THz radiation pulses from LT-InGaAs films grown on (411)A substrates have maximal amplitudes which are 2-3 times larger than that from LT-InGaAs films on (100) substrates. This could result in greater effectiveness of the THz wave generation by LTG-InGaAs photoconductive antennas.

Table 2. Amplitudes of the generated pulses (a.u.) for samples 1-4 and bare substrate

Substrate type	1	2	3	4	Substrate
(100)	0.07	0.05	0.06	0.06	0.01
(411)A	0.17	0.10	0.19	0.07	0.02

3. Conclusions

Using of InP (411)A substrates for the LTG-InGaAs epitaxial growth instead of InP (100) substrates is shown to cause the LT-InGaAs crystal structure modification that is essentially more effective for the THz wave generation. This phenomenon would be significant in further manufacturing of photoconducting devices for the THz wave generation and detection.

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References

[1] A. Krotkus *et al*, *J. Phys. D: Appl. Phys* **43**, 273001 (2010).
[2] M. R. Melloch *et al*, *Annual Rev. Mater. Sci.* **25**, 547 (1995).
[3] J. Mangeney *et al*, *Appl. Phys. Lett.* **97**, 161109 (2010).
[4] C. D. Wood *et al*, *Appl. Phys. Lett.* **96**, 194104 (2010).
[5] A. Takazato *et al*, *Appl. Phys. Lett.* **91**, 011102 (2007).
[6] A. Schwagmann *et al*, *Appl. Phys. Lett.* **96**, 141108 (2010).