ԵՐԵՎԱՆԻ ՊԵՏԱԿԱՆ ՀԱՄԱԼՍԱՐԱՆ

ՀԱՅԱՍՏԱՆԻ ՀԱՆՐԱՊԵՏՈՒԹՅԱՆ ԳԻՏՈՒԹՅՈՒՆՆԵՐԻ ԱԶԳԱՅԻՆ ԱԿԱԴԵՄԻԱ

ԿԻՍԱՀԱՂՈՐԴՉԱՅԻՆ ՄԻԿՐՈ- ԵՎ ՆԱՆՈԷԼԵԿՏՐՈՆԻԿԱ

ՏԱՍԵՐՈՐԴ ՄԻՋԱԶԳԱՅԻՆ ԳԻՏԱԺՈՂՈՎԻ ՆՅՈՒԹԵՐ
ԵՐԵՎԱՆ, 11-13 ՍԵՊՏԵՄԲԵՐԻ

SEMICONDUCTOR MICRO- AND NANOELECTRONICS

PROCEEDINGS OF THE TENTH INTERNATIONAL CONFERENCE
YEREVAN, ARMENIA, SEPTEMBER 11-13

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Temperature ^{0}C	Intensity W/cm^2	λ_m μm	Photoresponse A
85	0.000382	8.09	3.17E-05
170	0.002472	6.54	0.00016
255	0.009124	5.49	0.00037
297.5	0.01411	5.24	0.000513
340	0.023977	4.73	0.000609

Table 1

4. Conclusion

p-InSb-n-CdTe heterojunctions have been fabricated by a simple low-temperature technology based on pulsed laser deposition (which eliminates the process of implantation, diffusion annealing). Photodiodes based on p-InSb-n-CdTe heterojunctions show good photoresponse and can serve as perspective detectors in the near and mid-infrared wavelength range

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NANOSTRUCTURES GROWTH FEATURES IN $Ga_{1-x-y}In_xAl_yN$ QUASITERNARY MATERIAL SYSTEM

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1. Introduction

The most promising from the point of view of designing new materials and devices with unique properties is at present elaboration of technologies for creation of novel semiconductor nanostructures and study of their physical properties. Steadily increasing interest towards specifically semiconductor nanostructures is caused primarily by the existence of a wide spectrum of possibilities to control the properties of semiconductors. It is known that crucial changes in their properties may be achieved by varying the composition of semiconductor solid solutions, changing the concentration and type of impurities, changing external conditions and so on. Constraints of motion of charge carriers in one or more directions leading to the dimensional quantization phenomenon open additional possibilities of efficient control of properties of nanostructure-based devices by means of changing their sizes [1–4]. Modified density of states of quantum dots (QD), nanowires, and combined QD-nanopit structures leads to essential improvement of the working optoelectronic parameters of semiconductor devices, such as lasers, photodetectors, etc. Obviously, the electronic properties of QDs depend on dot structure and the mechanism of their formation. Such nanostructures can be fabricated by nanolithography or by the self-organization method (Stranski–Krastanov mode), which is at present the most frequently employed technique. Relaxation of elastic (deformation) strain as a principle of nucleation is the basic mechanism of formation of nanostructures in semiconductor materials such as Si, Ge, III–V compounds, etc.

GaN, InN, AlN and their ternaries and quaternaries alloys are considered as one of the important semiconductors. There are fabricated lighting and displayed application on the base of those materials. Particularly, GaInN alloys have recently attracted much attention as potential materials for fabrication of blue and green light emitted diodes (LEDs), as well as for violet and blue injection lasers. Since the band gap of GaInN can be varied from 2.0 to 3.5 eV by increasing GaN concentration, the potential operating wavelengths cover nearly the entire visible spectra range [5-8]. GaN is a promising material for use it in high-speed field effect transistors, high-temperature electronic devices, UV or blue light emitters, detectors and gas sensors [9]. It is known that InN has lowest effective mass and small band gap among all III-nitride semiconductors, which can allow to suggest that it can be used in light emitting devices and high speed electronic devices as well. In particular, by controlling indium composition, InN-related compounds, including $In_xGa_{1-x}N$ and $In_xAl_{1-x}N$, have been used for band-gap engineering, which have extended the emission of nitride-based light-emitting diodes from the UV to near infrared regions. InN also can be used in tandem solar cells and thermophotovoltaic systems [9]. In addition, the sufficient lattice mismatch between GaN/AlN, GaN/InN and InN/AlN equals to 3%, 10% and 12% respectively, allows considering those materials as very attractive also for nanostructures engineering in Stranski–Krastanov growth mode.

In this paper, the continuum elasticity model is applied to quantitatively investigate the growth features and nucleation mechanism of QDs, nanopits, and cooperative QDs–nanopits structures in GaInAlN quasiternary systems.

2. Calculation of total energy of cooperative QD-nanopit structures in GaInAlN material system

At the description of the competing nucleation mechanism, we assume that the surface has only discrete orientations and that only one angle needs to be considered [10], so GaInAlN-based QDs and nanopits have a shape as it is schematically presented in Fig.1.

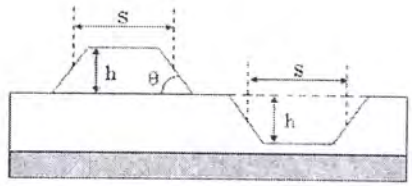

Fig. 1. Schematic view of the QD-nanopit structure's cross section.

The total free energy to form either a dot or a pit is $E = E_S + E_R$, where E_S and E_R are the change in surface free energy and the reduction of the strain energy by elastic relaxation, respectively. Minimizing the total free energy [10] with respect to

shape for fixed volume gives $s \cdot t \cdot h \times cot\theta$, where s, t, h and θ are the length, width, height (depth) and contact angle, as in Fig.1, the energy is equal to

$$E = 4\Gamma V^{2/3} Tan^{1/3}\theta - 6cV Tan\theta , \qquad (1)$$

where $\Gamma = \gamma_e Csc\theta - \gamma_s Cot\theta$. For the crystals with a cubic symmetry $\gamma_s = \frac{1}{2}\cdot\varepsilon^2(C_{11}+C_{44})d_{wet}$, $c = \sigma_b^2\frac{(1-\nu)}{2\pi\mu}$, $\sigma_b = \varepsilon(C_{11}+C_{44})$. Here γ_s and γ_e are the surface free energy per unit area for the normal orientation and the beveled edge, respectively, $\varepsilon = \frac{\Delta a}{a}$ is the lattice mismatch ratio (strain) and d_{wet} is the wetting layer thickness. The value for γ_e can be found from Young equation $\gamma_{sl} = \gamma_s - \gamma_e Cos\theta$ [11], where for Stranski–Krastanov growth mode $\gamma_{sl} = 0$ is the surface free energy corresponding to the solid-liquid interface, $\nu = \frac{\lambda}{2(\lambda+\mu)}$ is the Poisson ratio, μ, λ and C_{ij} are the shear (Lame coefficients) and the elastic modulus of the substrate. Taking into account also dependence of the wetting layer thickness versus strain, the expression for the total energy can be written as

$$E = 4\left(\gamma_e Csc\theta - \frac{1}{2}\varepsilon^2(C_{11}+C_{44})a\cdot e^{-35.84\varepsilon}Cot\theta\right)V^{2/3}Tan^{1/3}\theta - 3\varepsilon^2(C_{11}+C_{44})^2\cdot\frac{(1-\nu)}{\pi\mu}\cdot V Tan\theta . \qquad (2)$$

In order to obtain analytical expression for the strain (deformation) dependence of wetting layer thickness in the case of the GaInAlN quasiternary system, we performed mathematical approximation of experimental data. Approximation curves are presented in Fig. 2. We used in our calculations the following expressions for d_{wet} : in monolayers (ML): (i) if the deformation strain is positive, then $d_{wet} = 0.05\varepsilon^{-3/2}$ at $\varepsilon > 0.03$ [12] and $d_{wet} = 24.181e^{-31.034\varepsilon}$ at $0 < \varepsilon < 0.03$ (accuracy of approximation $R^2 = 0.9635$), (ii) if the deformation strain is negative, then $d_{wet} = 0.15|\varepsilon|^{-3/2}$ at $|\varepsilon| > 0.035$ [12] and $d_{wet} = 45.162e^{-23.03|\varepsilon|}$ at $0 < |\varepsilon| < 0.035$ (accuracy of approximation $R^2 = 0.9934$).

Dependence of the GaInAlN strain-induced dots and pits total energy versus volume, calculated at $\gamma_e = 10.15\cdot10^{-5}$ J/cm^2, $\mu = 30.34\cdot10^4$ J/cm^3, $C_{11} = 272.3\cdot10^3$ J/cm^3, $C_{44} = 130.3\cdot10^3$ J/cm^3, $\nu = 0.361$ and $\theta = 0.785$ (45°), is presented in Fig. 3(a) at different values of strain.

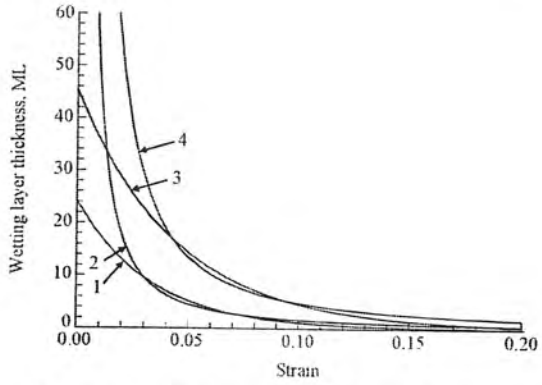

Fig. 2. Strain-dependence of the wetting layer thickness: (1) $d_{wet} = 24.181e^{-31.034\varepsilon}$ ML, $\varepsilon > 0$; (2) $d_{wet} = 0.05\varepsilon^{-3/2}$ ML, $\varepsilon > 0$; (3) $d_{wet} = 45.162e^{-23.03|\varepsilon|}$ ML, $\varepsilon < 0$; (4) $d_{wet} = 0.15|\varepsilon|^{-3/2}$ ML, $\varepsilon < 0$.

To attain a stable geometry, the island must first overcome the energy barrier E^* which occurs at volume V^*. Finding the maximum of (2), dependences of the critical energy and critical volume versus strain are presented in Figs. 3(b) and 3(c), respectively. From those figures is quite visible that both E^* and V^* strongly depend on the strain and dramatically decrease at the increasing of the strain, and at the critical strain of $\varepsilon^* = 0.039$ the sign of energy and volume is changed. We assume that at $\varepsilon < \varepsilon^*$ the mechanism of the nucleation is changed from the growth of dots to the nucleation of pits. Clearly, at small

misfit ($\varepsilon < \varepsilon^*$), the bulk nucleation mechanism dominates. However, at $\varepsilon > \varepsilon^*$, when the energy barrier becomes negative as well as a larger misfit provides a low-barrier path for the formation of dislocations, the nucleation of pits becomes energetically preferable.

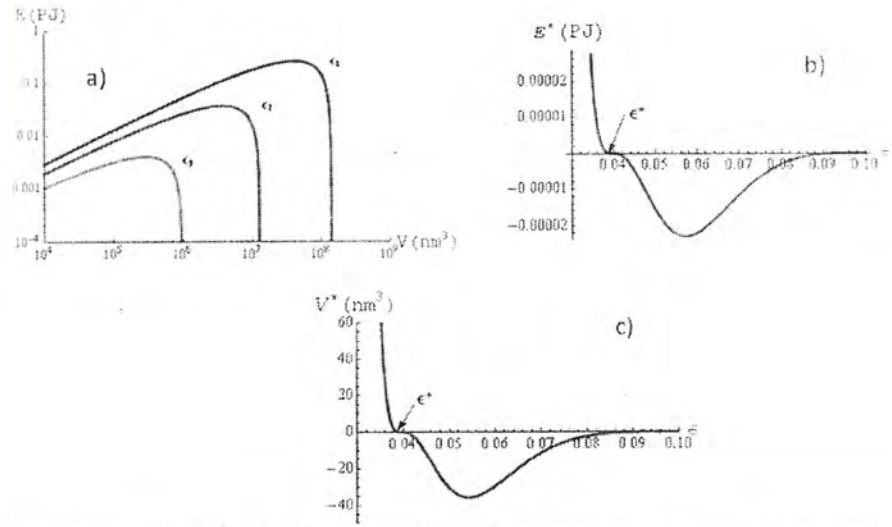

Fig. 3. (a) – dependence of the GaInAlN strain-induced islands (dots and pits) energy versus nanostructure's volume at different strain (1 – ε_1=0.02, 2 – ε_2=0.025, 3 – ε_3=0.03). Critical energy – (b) and critical volume – (c) versus strain.

3. Conclusions

Thus, the continuum elasticity model was applied to quantitatively investigate the growth features and nucleation mechanism of QDs, nanopits, and cooperative QDs–nanopits structures in GaInAlN quasiternary systems. It was shown, that nanostructures formation critical energy (E^*) and critical volume (V^*) strongly depend on the strain and dramatically decrease at the increasing of the strain. Calculations revealed that for GaInAlN material system at the critical strain of $\varepsilon^* = 0.039$ the sign of critical energy and volume is changed. We assume that at $\varepsilon < \varepsilon^*$ the mechanism of the nucleation is changed from the growth of quantum dots to the nucleation of nanopits. Obviously, at small misfit ($\varepsilon < \varepsilon^*$), the bulk nucleation mechanism dominates. However, at $\varepsilon > \varepsilon^*$, when the energy barrier becomes negative as well as a larger misfit provides a low-barrier path for the formation of dislocations, the nucleation of pits becomes energetically preferable. Presented results are very important from technological point of view and can be used at nanoengineering in GaInAlN material system.

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