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Some technology aspects for quantum enestor through $A^{III}B^{V}$ multicomponent nanoepitaxy

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Abstract. For the first time, it has been considered some quantum enestor technology aspects concerning the integration approach for Si-CMOS and site-controlled InGaN/GaN quantum dots, which provides the possibility to realize single photon sources (SPS)/single photon detector (SPD) for quantum processing based on $A^{III}B^{V}$ direct bandgap multicomponent heterogeneous nanostructures and their light energy storing capability, by an analogy with the photosynthetic process in plants.

Keywords: III-nitrides, LED, solid solutions, $A^{III}B^{V}$, energy storage.

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1. Introduction

50 years ago in 1963-1966, technology of LEDs and LDs based on multicomponent alloys InGaAsP [1] was developed. This multicomponent approach gives a new additional technological freedom in bandgap engineering, crystal lattice and thermal expansion coefficient matching, especially for quantum wells and dots in III-nitrides (III-N) nanostructures, which is very important for integration design.

Coherent light accumulation during photosynthesis is a prime example of quantum effects in biology. It led to the emergence of a field termed “quantum biology” [2].

The enestors (energy storage processors of white light) [3-5] can display the solution of energy efficiency problems of diode lighting to a new level through the use of high efficiency conversion and storage of solar radiation energy in multilayer nanostructures of III-N with monolithic integration.

In this paper, we have considered heterogeneous $A^{III}B^{V}$ direct bandgap multicomponent alloys in their light accumulation possibility as an analogy of photosynthetic process in plants as well as some integration approach for Si-CMOS and site-controlled InGaN/GaN quantum dots with their possibility of single photon sources (SPS)/single photon detector (SPD) quantum processing for the enestor.

2. Quantum analogy between heterogeneous alloys and photosynthesizing systems in plants

Photosynthesis in plants has aroused enormous interest in the structure–function relations, as they can serve as blueprints for artificial light accumulation systems with quantitative estimation. Conclusive structural information is not available yet, reflecting the sample heterogeneity inherent to the natural system, nevertheless it is found that there is strong size-dependence, so size of grains is one of the critical parameters when regulating photochemical functions [6, 7].

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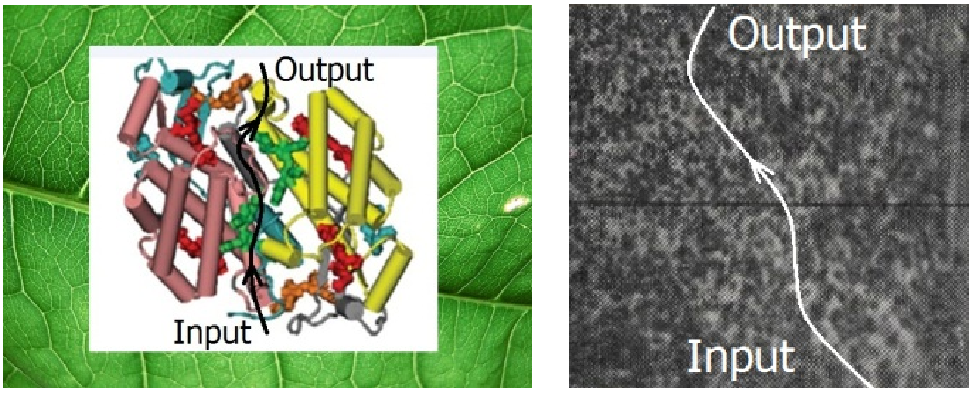

a b

Fig. 1. Analogy of plant photosynthesis process in their light collecting complexes: a) different colors arise from different chromophores (optimal quantum path – black line); b) different colors arise from heterogeneous $A^{III}B^{V}$ direct band gap multicomponent alloy nanostructures (optimal quantum path –white line).

Sunlight energy is absorbed by special molecules, like chlorophyll, that are embedded in proteins comprising the photosynthetic unit. Hundreds of these "chromospheres" (light absorbing molecules) are used to accumulate sunlight and direct the excitation energy to nature's solar cells – proteins called as reaction centers. Thus, these light-accumulating complexes compensate for the mismatch between solar irradiance and the optimal rate of reaction center operation (Fig. 1a). Heterogeneity in direct bandgap multicomponent semiconductors alloys (Fig. 1b) can have analogy of photosynthetic process in plants [2, 8].

Integrated LED/SC matrixes can be made using MOCVD on Si substrate with transistor microstructures [9] and InGaN/GaN defect-free nanorods with site-controlled quantum dots [10] due to heterogeneous growth.

3. Direct bandgap multicomponent heterogeneous nanostructures

Optoelectronic properties of heterogeneous structures are determined by the properties of their heterogeneity. Therefore, the spectra of recombination radiation can have very wide bandwidth. So, one can consider these solid solutions as a set of crystal areas of different composition, which can interact like a classical heterojunctions. It can be observed in BAlGaInNPAsSb direct bandgap multicomponent alloys [4, 11] when using cathodoluminescence with electron beam focused up to 1 μm on the surface of the sample at $T = 300$ K in different points spaced from each other at different distances. There can take place a strong dependence of the position and size of the bands of luminescence on the excitation level. With increasing the excitation level, the half-width of the luminescence line increases, the maximum shifts to the low-energy region, and the high-energy peak appears. With increasing the level of excitation, the high-energy peak becomes predominant.

Let us consider the features of radiation recombination in direct bandgap multicomponent solid solutions due to availability of nano-homogeneous regions of various sizes that makes quantum superposition interaction possible.

If the composition fluctuates statistically at a distance of within a few lattice parameters, we can consider solid solutions as homogeneous crystals. Generation and absorption of photons can be characterized by a corresponding change in the energy of inter-band transitions that are determined by the splitting of the discrete levels of the solid solution atoms, when they are combined in a lattice (Fig. 2).

If the size of homogeneous nanostructures is approximately 10…50 nm, their properties are determined by the energy gap between the corresponding values of the edges of the conduction band E_c and the valence band E_v of neighboring nanostructures.

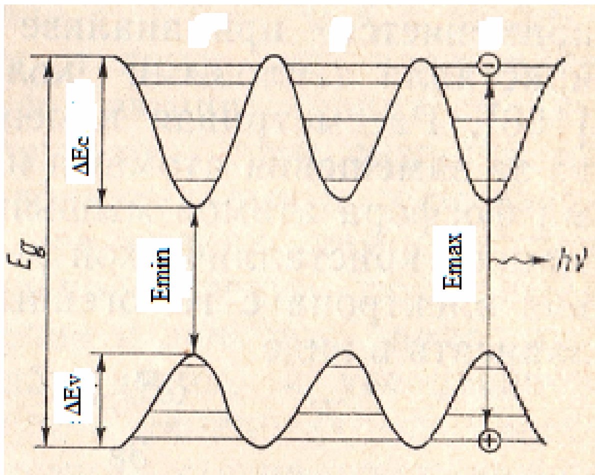

Fig. 2. Superlattice potentials of $A^{III}B^{V}$ heterogeneous alloys (E_{min} – for electron, E_{max} – for photon).

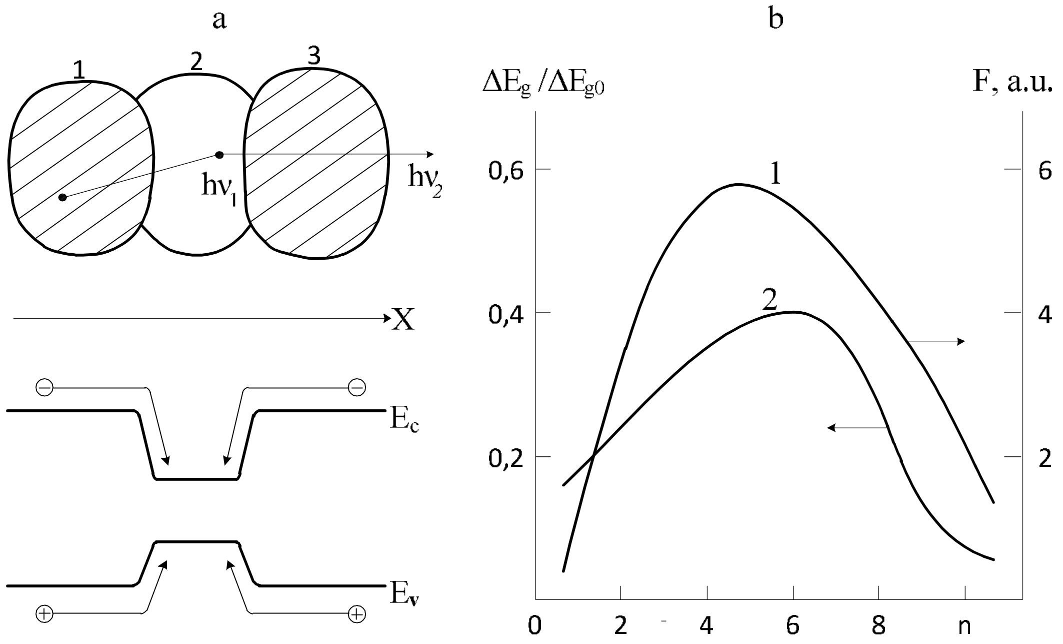

Fig. 3. a) The optical model of heterogeneous solid solution nanostructures; b) the change of the photoluminescence intensity, *F* (1), and the deviation from linearity of the bandgap, E_g/E_{g0} (2), depending on the recrystallization transition number, *n*.

Heterogeneous solid solution nanostructures (Fig. 3a) with linear dimensions equal to the mean-free path length of photons represent optically inhomogeneous media. The bandgap changes at the boundaries of heterogeneous solid solution nanostructures. So, the radiation generated in the wide bandgap region 1, can pass through the narrow band region 2 and be absorbed with subsequent generation of photons, for which the wide bandgap region 3 can be an optical window and potential barrier. In addition, there is the inter-band drift toward the narrow gap region under the action of internal field proportional to the gradient E_g.

4. SPS/SPD quantum processing for enestor

InGaN/GaN quantum dots (QDs) exhibit large exciton binding energy (>26 meV) and band offsets, making them an ideal candidate for quantum information processing at high temperatures with single-photon emission. Photon qubits are almost decoherence-free, and they can function at room temperature. In 2001, the KLM scheme (after the inventors Knill–Laflamme–Milburn) introduced a novel concept for photon-based quantum information processing, where operation of arbitrary photonic circuits is obtained just with single SPS, SPD and linear optical components [12]. It was an enhancement for this technology that led to the implementation of small algorithms in this framework. Photon losses in waveguides remain really the primary source of errors. Abundant exertion was focused on the optimization of single photon detectors and sources, too.

Photonic qubits are also promising applicants as long-distance buses for quantum communication in hybrid systems and quantum cryptography, manipulating their outstanding speed and coherence properties.

Thus, most semiconductor QDs are epitaxially grown using the self-assembled processes such as the Stranski–Krastanov growth [13], which has very limited control over the QDs' positions and dimensions, making them difficult to be employed at the device level [14, 15].

We have demonstrated novel processes for fabrication of site-controlled InGaN/GaN QDs on Si (100) (Fig. 4) [10].

It can provide SPE with electrical injection from an InGaN/GaN quantum dots in a single nanowires and make it very attractive from the viewpoint of compatibility and integration with silicon technology (Fig. 5).

5. Light storage for enestor

Some technological aspects of MOSVD-graphene-like 2D AlCN (Fig. 6) for supercapacitors and thin film batteries for quantum enestor have been developed. The *c*-sapphire substrate was treated in an ammonia vapors (horizontal reactor, EPIQUIP unit) at a temperature of 1050 °C for 20 min at the reactor pressure 20 mbar within the temperature range T = 250…1000 °C [16]. Pirolysis of TMA leads to nanocarbonization of sapphire and formation of aluminocarbonitride structures on the surface of activated sapphire. Appearance of this formation has been evidenced by the decrease of the electric resistivity magnitude by one order and its semiconductor anisotropic nature of the temperature dependence.

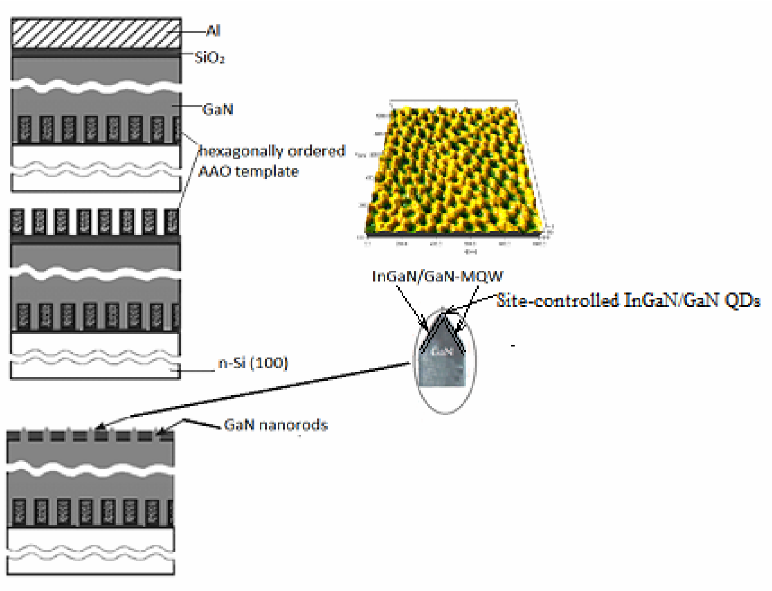

Fig. 4. Site-controlled InGaN/GaN QDs on Si (100).

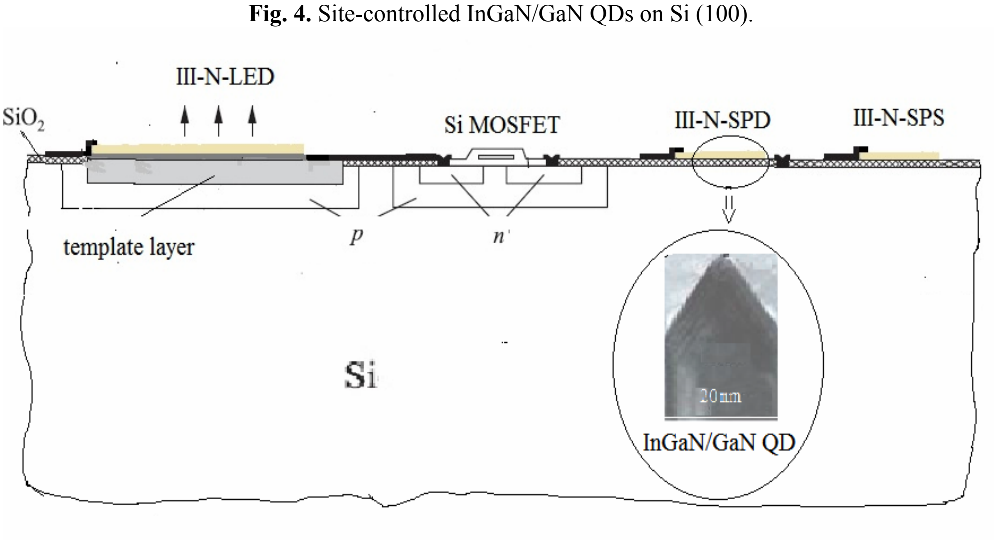

Fig. 5. Fragment of Si-CMOS and III-N QD SPS/SPD integration for enestor.

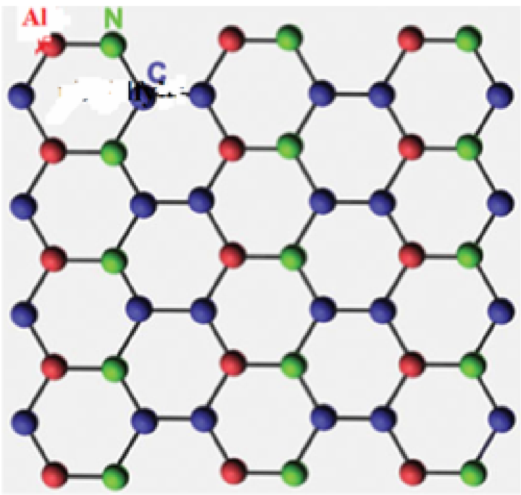

Fig. 6. MOSVD-graphene-like 2D AlCN.

6. Conclusion

For the first first, it has been considered some quantum enestor technology aspects concerning integration approach for Si-CMOS and site-controlled InGaN/GaN quantum dots with their possibility to serve as single photon sources (SPS)/single photon detector (SPD) quantum processing concerning $A^{III}B^{V}$ direct bandgap multicomponent heterogeneous nanostructures in their light collecting possibility by an analogy of photosynthetic process in plants.

References

1. Sirota N., Osinsky V. Radiation of *p-n* junction based on solid solution of indium phosphate-gallium arsenide crystals. *Trudy Akademii Nauk SSSR*, *ser. fiz*. 1966. **171-172**. P. 317–319 (in Russian).

2. Scholes G.D. Quantum-coherent electronic energy transfer: Did nature think of it first? *J. Phys. Chem. Lett*. 2010. **1**, № 1. P. 2–8.
3. Osinsky V., Osinsky A., Miller R. AlInGaNAsP alloy for LED and laser applications. *LED 50-th Anniversary Symposium*. October 24-25, 2012, Urbana-Champaign, Illinois, USA.
4. Osinsky V.I., Malyshev S.A., Masol I.V., Labunov V.A., Lyahova N.N., Gorokh G.G., Blynsky V.I., Diagilev A.V. Accumulation of photocarriers in enestors based on heterogeneous multicomponent III-nitrides. NANO-2016: *Materials V Intern. Sci. Conf.* Minsk, November 22-25, 2016.
5. *Patent of Ukraine № 29568/3У/16* from 19.12.2016. Energy-accumulating processor for light.
6. Günther L.M. et al. Structure of light-harvesting aggregates in individual chlorosomes. *J. Phys. Chem. B*. 2016. **120**, No. 24. P. 5367–5376.
7. Uwada T. et al. Size-dependent optical properties of grana inside chloroplast of plant cells. *J. Phys. Chem. B*. 2017. **121**, No. 5. P. 915–922.
8. Osinsky V., Masol I., Onachenko M., Sushiy A. Decoherence of III-N low dimensional nanostructures quantum processors. *IX Vserossiyskaya konferencia "Nitrides of gallium, indium and aluminum: structures and devices"*. Moscow, 2013. P. 100–101 (in Russian).
9. Masol I., Osinsky V., Sergeev O. *Information Nanotechnology*. Kyiv: Macros, 2011.
10. Osinsky V.I., Lyahova N.N., Hlotov V.I., Sukhovyy N.O., Litvin O.S., Deminskyi P.V. Photoluminescence spectrums of GaN/InGaN MQDs on GaN nanoroads. *Uchionnye zapiski fizicheskogo fakulteta MGU.* 2014. №2. P. 142304, 1–4 (in Russian).
11. Osinsky V.I., Privalov V.I., Tikhonenko O.Ya. *Optoelectronic Structures Based on Multicomponent Semiconductors*. Minsk: Nauka i tekhnika, 1981.
12. Knill E., Laflamme R., Milburn G.J. A scheme for efficient quantum computation with linear optics. *Nature*. 2001. **409**(6816). P. 46–52.
13. Tu R.-C. et al. Ultra-high-density InGaN quantum dots grown by metalorganic chemical vapor deposition. *Jpn. J. Appl. Phys*. 2004. **43**. P. L264.
14. Strekalov D.V., Leuchs G. Nonlinear interactions and non-classical light. *Preprint arXiv:1701.01403*. 2017.
15. Zhang L. et al. Charge-tunable indium gallium nitride quantum dots. *Phys. Rev. B*. 2016. **93**. No. 8. P. 085301.
16. Osinsky V.I., Lyahova N.N., Masol I.V., Grunyanskaya V.P., Deminsky P.V., Sukhoviy N.O., Stonis V.V., Onachenko M. Nanocarbide processes in MOS epitaxy of III-nitride structures. *Optical and Quantum Electronics in Computers and Intellectual Technologies.* 2012. P.62–72.