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Applications of functionally graded materials in optoelectronic devices

MATEUSZ WOŚKO, BOGDAN PASZKIEWICZ, TOMASZ PIASECKI, ADAM SZYSZKA, REGINA PASZKIEWICZ, MAREK TŁACZAŁA

Faculty of Microelectronics and Photonic, Wrocław University of Technology,
ul. Janiszewskiego 11/17, 50-372 Wrocław, Poland

Up to now research on functionally graded materials (FGM) was focused on their mechanical and strength properties. The paper presents a review of possible applications of A^{III}–B^{V} group materials with graded composition for optoelectronic devices, such as *p-i-n* diodes, heterojunction photodetectors and lasers. Nowadays, there are no optoelectronic devices fabricated from FGM. The theoretical simulation showed that devices with FGM active region would have superior characteristics compared with classical constructions.

Keywords: functionally graded materials (FGM), functionally graded materials, A^{III}–B^{V}, optoelectronic.

1. Introduction

Functionally graded materials (FGM) are materials in which some particular physical properties are changed with dimensions. Properties of such materials can be described by material function $f(x)$. In homogenous materials this function is constant, like in Fig. 1**a**. In the case of a junction of two different materials function $f(x)$

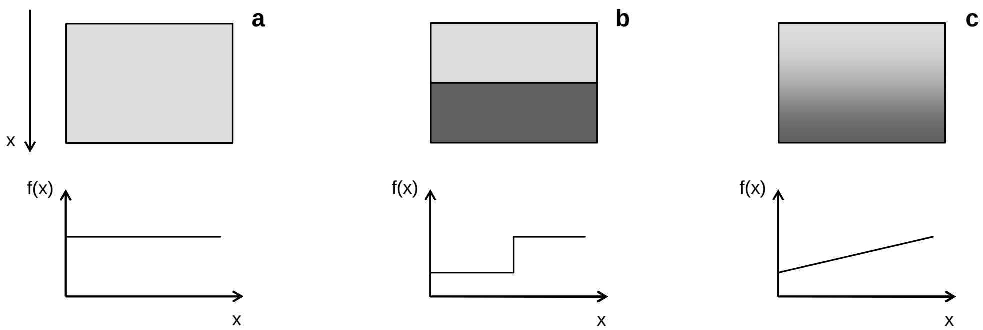

Fig. 1. Schematic representation of materials function in different structures; homogenous material (**a**), junction (**b**), FGM (**c**).

has a stair-shape (Fig. 1**b**). In FGM, this material function should be continuous or quasi-continuous. It means that particular properties change continuously or quasi -continuously along one direction, like it was shown in Fig. 1**c**. In many cases FGM could be presented as a composition of several connected thin layers.

Depending on the number of directions the proprieties changed, we can discriminate one-, two- or three-dimensional FGM, what can be mathematically described for 3-D FGM as:

$$\frac{\mathrm{d}F}{\mathrm{d}x} \neq 0, \qquad \frac{\mathrm{d}F}{\mathrm{d}y} \neq 0, \qquad \frac{\mathrm{d}F}{\mathrm{d}z} \neq 0$$

where $F(x, y, z)$ is the material function.

2. Possible applications of FGM in optoelectronics

Nowadays graded materials are widely used for antireflective layers, fibers, GRIN lenses and other passive elements made from dielectrics, also for sensors and energy applications [1]. For example, the modulation of refractive index could be obtained in such components through the change in material composition. Another possibility is to apply concept of gradation in semiconductor active devices. In semiconductors the material function can describe energetic bandgap, refractive index, carrier concentration, carrier mobility, diffusion length, built-in electric field and another properties which strong influence the parameters of optoelectronic devices.

2.1. Graded buffer layers for heteroepitaxy

Typically nitrides are grown on substrates which do not structurally and thermally fit to epitaxial layer. The structural and thermal mismatch can be up to 30%. There are several methods which could help to overcome this problem, like low-temperature multilayer, lateral epitaxial overgrowth technique or applying the structured substrates. By using graded materials, like $Al_xGa_{1-x}N$ it is possible to distribute strain in buffer layer and reduce cracking in active layer. Because the lattice and thermal expansion

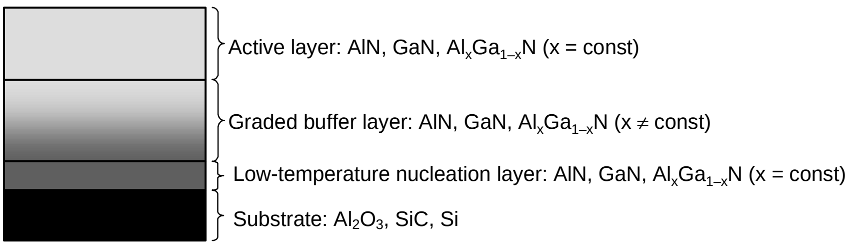

Fig. 2. Structure of heteroepitaxially grooved $A^{III}N$ compounds with graded buffer layer.

coefficient change continuously with the content of Al in GaN, thus tension is arranged softly through graded layer. The idea of graded buffer layer is shown in Fig. 2.

2.2. GRINSH lasers

In conventional edge lasers applied for fiber telecommunications there are several factors which influence the quality of a device. Two most important are low threshold current and numerical aperture of light beam. It is possible to decrease the numerical aperture, but also to increase threshold current [2], through increasing the active region

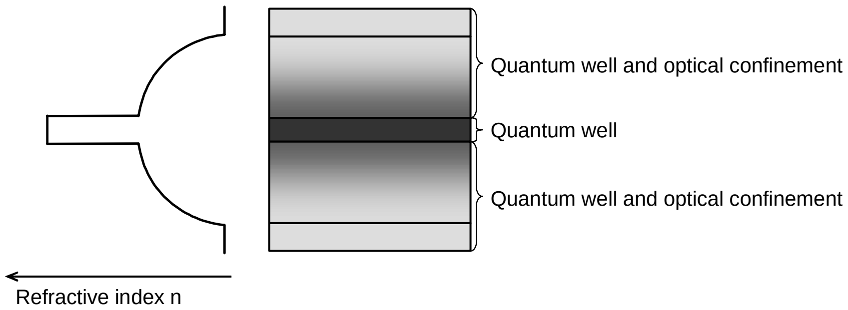

Fig. 3. Schematic GRINSCH structure.

thickness. One of the possible solutions is using graded-index separate-confinement heterostructure (GRINSCH). In such structures, shown in Fig. 3, graded material is used as a cladding layer of wave-guide and as a barrier for carriers.

2.3. High-efficient photodetectors and solar cells

The fundamental limitation of efficiency of homogenous silicon solar cells is the constant energetic band-gap width in bulk material. Because the high-energetic radiation is absorbed in a shallow layer under surface, it is necessary to form electric field in close vicinity to the surface. Generated carriers can effectively be separated in

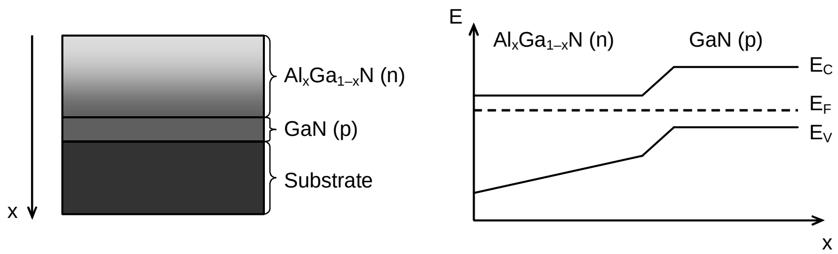

Fig. 4. Schematic structure of *p-n* photodiode with graded layer.

electric field, therefore the diffusion length of carriers should be longer than junction depth.

Another factor which decreases carrier generation efficiency is the difference of energetic band-gap and absorbed photons energy. By using materials with gradation of energetic band-gap, it is possible to match absorption edge with band-gap, what improves generation efficiency [3]. The appliance of cascade of junctions with different energetic band-gap width could be one of the solutions [4]. Another way to overcome this limitation is the use of graded material. The idea of such device is shown in Fig. 4.

2.4. Tunable photodetectors

Fundamental theory of band to band generation assumes that only photons with energy higher than energetic band-gap can create electron-hole pair. The main concept of tunable photodetectors refers to the possibility of shifting absorption edge. Another challenge in such devices is separation of generated carriers.

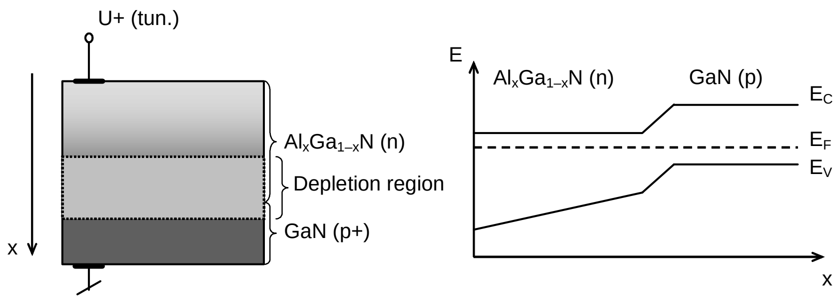

Fig. 5. Schematic structure of tunable photodetector.

Schematic concept of voltage tunable photodetector is shown in Fig. 5. By changing the voltage between *p* and *n* region, it is possible to modulate thickness of depletion region. Because only the carriers which reach depletion region can be separated, thus voltage influences the absorption edge (depletion region covers layer with different energetic band-gap).

3. Conclusions

Functionally graded materials are perspective materials for modern optoelectronic devices, such as low threshold current edge lasers (GRINSCH) and tunable photodetectors. Graded layers can be also used as buffers in heteroepitaxy of nitrides.

Development and characterization of FGM is a real challenge and needs thorough analysis. The methodology of measuring layers with graded changing properties is not well known and should be elaborated. Another problem is the interrelation between different material properties. It is difficult to change one parameter, like energetic band-gap, without influencing the others, like refractive index. Also modeling techniques of FGM should be elaborated to obtain better understanding of the properties of structures and devices fabricated from these materials.

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