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Characterization of GaN nanostructures by electron field and photo-field emission

V. Litovchenko, A. Evtukh*, A. Grygoriev

V. Lashkaryov Institute of Semiconductor Physics, 41 Nauki ave., 03028 Kyiv, Ukraine

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ABSTRACT

The electron field and photo-field emission from GaN nanostructures has been analyzed in this review. In order to explain the obtained experimental results, a model was proposed taking into account the change in carrier concentration distribution in the main and the satellite valley during the emission process. The lowering of work function (due to the increased number of carriers in the satellite valley) can explain the decrease in the Fowler-Nordheim plot slope. It was shown that the energy difference between the main and satellite valley in GaN was decreased in the case of quantum confinement, thus increasing the probability of electron transition from Γ to X valley at same electric fields.

Investigations of electron photo-field emission demonstrated that the Fowler–Nordheim plots of the emission current have different slopes for nonilluminated and illuminated devices. A model based on the electron emission from valleys having different specific electron affinities is proposed to explain the experimental results. In the absence of illumination the emission takes place only from the lower valley. Upon UV illumination and presence of a high electric field at the emitter tip, the upper valley of the conduction band appears to be occupied by electrons generated at the valence band.

1. Introduction

Wide bandgap semiconductors, such as GaN, are very promising for novel applications in optoelectronics, solid-state and vacuum nanoelectronic devices. Tremendous progress both in the science and engineering of group-III nitrides and devices based on them has been made [1].

The large bandgap of group-III nitrides and the chemical and thermal stability allow new applications. Important are also the positive characteristics such as high saturation drift velocity of electrons of nearly 3×10^7 cm/s [2] and extremely high breakdown field strengths of $(3–5) \times 10^6$ V/cm [3]. Furthermore, these materials find application for various sensor concepts because of their large piezoelectric coefficients and robustness in harsh environments [4–7].

One of the most amazing properties of III-nitride semiconductors, particularly the family of direct-bandgap semiconductors, is light emission in response to excitation mainly by means of electrical injection of minority carriers or optical and electrical beam excitation, the discovery of which revolutionized the field of optoelectronics. Specifically, light emission induced by electrical injection of minority carriers, which is termed electroluminescence (EL), has seen the most practical applications. The direct bandgap nitride semiconductors, ranging from about 0.8–6.2 eV, are ideally suited for a large variety of detectors, especially in the ultraviolet (UV) range as there are currently no serious semiconductor-based competing technologies. A large absorption coefficient (a result of the direct bandgap) and the ability to detect the UV- and solar-blind regions of the spectrum make them very attractive detector candidates.

New vacuum nanoelectronic devices can help to overcome the frequency and power limitations of solid state devices [8,9]. Field emission based vacuum micro-nano-devices (e.g. miniaturized tubes) are promising for amplification and generation of high frequency electromagnetic waves [8,10,11]. In such devices, electron transport is performed through vacuum without scattering, as is in case of solid state components, therefore setting up the basis for attaining ultrahigh frequency operation. Efficient electron field emission cathodes are here of major importance. New developments in field emitter arrays (FEAs) are therefore discussed and experimentally investigated. FEAs with high current densities are considered as promising sources of cold electrons in miniature tubes for millimeter-wave generation.

Functional field emitter based on nitride materials shows new effects, which can be used for miniaturized vacuum devices, as well

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* Corresponding author.
E-mail address: anatoliy.evtukh@gmail.com (A. Evtukh).

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as new sensors. They open the possibility for density modulation of the electron beam with a gate electrode or photo-modulation instead of velocity modulation after electron emission in the vacuum tube. The advantages obtained by pre-bunching the beam are high efficiency and significant reduction in the required RF interaction length in the tube, thereby simplifying beam transport magnetics and reducing the weight. Devices with high-power and high- efficiency can be obtained [12,13].

Currently one-dimensional and three-dimensional nanoscale materials are under focus due to their unique electronic, optical and magnetic properties, as well as potential applications in constructing novel nanodevices [14,15].

Gallium nitride (GaN), as a wide-bandgap semiconductor, has attracted a lot of attention as a material for electron field emission (EFE) devices [16]. It has strong chemical and mechanical stability, high melting point (2600 K), and low electron affinity of 2.7–3.3 eV [17–21]. Moreover, FE cathodes based on GaN have longer lifetimes than based on Si or other conventional semiconductors.

There are many researches on FE from GaN films [18,22] and pyramid arrays [23]. It was reported that the pyramid or rough-surface GaN increased the field enhancement factor (β), lowering the applied voltage for the electron emission. Thus, further enhancement of EFE characteristics is expected by the one-dimensional (1D) GaN structures. Various GaN nanowires and nanorods were fabricated and their field emission properties were investigated [24–28]. In recent years many attempts have been made to synthesize one-dimensional and three-dimensional GaN morphologies. Up to now, one-dimensional and quasi-one-dimensional GaN nanorods [15], nanowires [29], nanotubes [30], nanoribbons [31], nanobelts [32] and prismatic rods and cone nanowires [27] have been synthesized. There are also some reports about three-dimensional GaN nanostructures [33–35].

Such different GaN morphologies were produced by numerous methods such as sol–gel method, simple thermal evaporation method [24,36], templates method, pulse laser ablation (PLA) [25,37,38], and chemical vapour deposition (CVD) method [36,37,28–40]. The 1D GaN structures were obtained either by NW growth or GaN etching, where etching is widely used for GaN surface roughening and nanotip formation [18,41,42].

Photoelectric field emission has attracted great interest from two points of view: drastic improvement of beam brightness due to increased emission current [43] and generation of modulated electron beams by means of photomixing. The ability to generate a high frequency modulated beam directly at the cathode, known as prebunching, through pulsed optical excitation would benefit vacuum nanoelectronics devices. A photo-assisted field emission spectroscopy method has been developed for characterization of the energy bands of wide bandgap materials used in optoelectronics, solid-state and vacuum nanoelectronic devices.

2. Intervalley carrier redistribution in nanostructured semiconductors at electron field emission

The intervalley redistribution of hot electron in semiconductor materials plays the principal role in a set of important physical effects such as Gunn oscillation effect, HEMT (High Electron Mobility Transistor) transistors, electron field emission, etc. [44–49].

However, for some perspective materials, in particular GaN, the external electric field is not enough for intervalley redistribution by conventional ways, when the bulk structures of the experimental samples is used [47], due to the scattering on rather large energy optical phonon (for GaN $E_{ph} \approx 90$ meV), large value of the electron-phonon interaction factor and, as a result, very low optical phonon lifetime $\tau_{sp} \approx 3 \times 10^{-14}$ s, whereas experimental times of the spontaneous decay gives substantially larger values $\tau_{dec} \approx 8.5 \times 10^{-14}$. That means, that even at ultra short electric pulse ($\tau_t \leq 10$ ps) [47,48], the applied electric field pulses, usually used in experiments, is less on the order the values of the presented τ_{vo}, measured with help of the optical time decay τ method or obtained by Monte Carlo theoretical calculation [46–52].

Hence, the problem appears how to obtain in GaN (and similar wide bandgap semiconductors) high energy hot electrons, with energy enough for intervalley redistribution. The mechanism of the "phonon throat" for quantum well phonons has been proposed in [44,45] for solution of this problem in relation to HEMT. The barrier for scattering of electron energy appears due to the quantization of the phonon spectra in narrow potential wells and, as a result, substantial decreasing of the electron-phonon interaction. This allows in such a way to obtain the rather high value of carriers mobility in quantum channel, and hence, high frequency HEMT transistors.

Electron field emission offers a new possibility for the study of band structure parameters, such as intervalley energy difference, electron affinity from different conduction band valleys, and intervalley free electron redistribution due to heating of carriers by external high electrical fields. The conelike shape and small size of the field emitter cathodes allow reduction in lattice overheating, which is a serious problem for devices operating at high electric fields [53–61]. Important peculiarities of the wide bandgap semiconductors are their large intervalley distance (1–2 eV or higher), as well as charge trapping and piezoelectric phenomena [55,62,63]. The conduction band nonparabolicity can also play a significant role leading to the decrease in the electron mobility. Under such circumstances, the drift mobility at high electrical fields decreases even without any carrier redistribution taking place from the central to the upper (satellite) valley [57]. At extremely high electrical fields, additional field emission mechanisms can appear, namely, the emission from charged traps in the wide forbidden gap, localized on the surface or in the bulk, and emission from the valence band. In the case of wide bandgap semiconductors, these effects can be substantially suppressed.

Several EFE measurements and simulations for quantum sized cathodes have shown possible transformation of the energy bands [54–60]. The quantum-size effect decreases considerably the intervalley energy difference for cathodes with tip radii of few nanometers [60]. The first theory of field emission from semiconductors was reported in Refs. [64,65]. It was based on degenerated carrier statistics and took into account different electron masses in semiconductor and vacuum.

Additional important features, such as complex many valley structure of the Brillouin zone, hot carrier generation, and intervalley carrier redistribution have been considered in Ref. [52]. Furthermore, the quantum mechanical tunneling process from the backside metal-semiconductor junction is an important mechanism for current transport through thin barriers. The top of the triangular barrier used in the proposed model [52] of the semiconductor-vacuum interface was additionally lowered by the image force potential.

Tunneling probability of electrons from a semiconductor into vacuum has been derived from the time independent Schrödinger equation:

$$-\frac{\hbar^2}{2m_e} \cdot \frac{d^2\Psi}{dx^2} + V(x)\Psi = E\Psi, \tag{1}$$

which can be rewritten as:

$$\frac{d^2\Psi}{dx^2} = \frac{2m_e(V-E)}{\hbar^2}\Psi, \tag{2}$$

where ħ is the normalized Planck constant, Ψ is the wave function, m_e is the effective electron mass, $V(x)$ is the potential relief on the electron path, E is the energy of electron, and x is the tunneling direction from the surface into vacuum (see inset in Fig. 1).