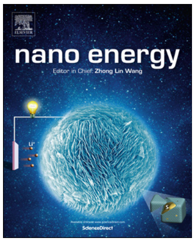
Nano Energy (2015) **13**, 140–173

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/nanoenergy



REVIEW

Performance enhancement of GaN-based light emitting diodes by the interaction with localized surface plasmons

In-Hwan Lee[a,*], Lee-Woon Jang[a], Alexander Y. Polyakov[a,b]

[a]*School of Advanced Materials Engineering and Research Center for Advanced Materials Development, Chonbuk National University, Jeonju 561-756, Republic of Korea*
[b]*National University of Science and Technology, MISiS, Moscow, Russia*

Received 5 September 2014; received in revised form 15 December 2014; accepted 30 January 2015
Available online 21 February 2015

KEYWORDS
Localized surface plasmons;
Light emitting diodes;
Metal nanoparticles;
External quantum efficiency

Abstract
The effects of localized surface plasmons (LSPs) on the enhancement of photoluminescence and electroluminescence efficiency of GaN-based light-emitting diode (LED) structures are reviewed. It is shown that the LSPs formed by metal nanoparticles (NPs) or by local thickness variations of the metal films can contribute to the enhancement of light emitted by LED structures under optical or electrical excitation. The problems of choosing a suitable metal for such LSPs in the given spectral range are discussed. Various approaches to incorporating the LSP NP films into the LED structures are analyzed. The issues specific to different spectral ranges (blue, green, UV) are described. The wavelength range for which the application of LSP particles can be useful depends on the metal used, the shape and dimensions of the particles, and on their density and distribution. Roughly, as a first order approximation, it is concluded that Ag is in general the best material for the blue spectral region, Au is best for the green region, and Al is most suitable for the UV region. It is demonstrated that core/shell Ag/SiO_2 NPs for the blue region have serious advantages in terms of stability over Ag NPs. For blue LEDs it is found that the most important factor is the suppression of the efficiency droop with increasing LED output power. For green and UV regions the most important factor is the strong influence of the non-radiative recombination channels. In addition, for the UV LEDs the increased light extraction efficiency is also an important issue. It is shown how LSP NPs can provide efficient means to combat these problems.

---

[*] Corresponding author.
E-mail address: ihlee@jbnu.ac.kr (I.-H. Lee).

http://dx.doi.org/10.1016/j.nanoen.2015.01.050
2211-2855/© 2015 Elsevier Ltd. All rights reserved.

Contents

Introduction

Surface plasmons (SPs) are collective oscillations of conducting electrons near the surface of metals. Such oscillations occur upon interaction with light and produce resonant absorption and scattering of light known as plasmon resonances. These resonances occur at specific frequencies of electromagnetic field whose frequency in the bulk, ω_p, is a function of the density of conducting electrons and their effective mass, but for electrons near the surface it depends also on the dimensions and shape of the metallic particle and the refractive index of the surrounding media (see, e.g. Refs. [1-4]). The strength of the electric field in the vicinity of SPs can be very high, which has a profound effect on absorption, scattering and spontaneous light emission of molecules, quantum wells (QWs) or quantum dots (QDs) placed in close proximity to SPs. When the dimensions of metallic particles become small this leads to the formation of another type of collective excitation called localized surface plasmons (LSPs) (Naturally, any surface irregularity, such as thickness variations induced by roughening or intentionally by lithography, will also lead to the formation of LSPs). For particles whose dimensions are small compared to the light wavelength the resonance frequency becomes a strong function of the dimensions, shape, and local environment of the nanoparticles (NP). The interference of electric field produced by several closely spaced LSP NPs can produce enormous concentration of local electric field that can strongly enhance the scattering, absorption or emission of molecules, QWs, QDs placed in the "right" location. For metallic particles whose dimensions in one direction are much longer than the wavelength the result could be effective propagation of light in this direction.

Thus, an enormous field of research and practical applications called plasmonics is opening with the adoption of metallic nanostructures (see e.g. Refs. [1-4]). The completely new phenomena related to the huge increase of molecular fluorescence or Raman scattering in the vicinity of metallic NPs, and strong improvement of quantum efficiency of photovoltaic cells owing to the LSP-related concentration of electric field, formation of microantennae and microwaveguides based on LSP NPs have been discovered and studied. These studies have resulted in practical applications of metallic nanostructure LSPs in sensors measuring locally the refractive index of the gases and liquids and thus their composition, in extraordinary increase of sensitivity of fluorescence (so-called surface enhanced fluorescence) and Raman scattering (surface enhanced Raman scattering) techniques, making it possible to detect individual molecules, to develop new characterization techniques in biology and medicine, allowing to detect and localize, e.g. cancer tumors, and in many other exciting phenomena and applications.

At the same time, great progress has been achieved in developing techniques of fabrication and assembly of metallic NPs of desired dimensions and shape. This is a vast and rapidly developing field that we would not endeavor to even partially cover within the space of the present paper. The reader is referred to several excellent recent reviews covering different aspects of the problems and providing a good introduction to the field and supplying references to important original papers [1-8].

What we will concentrate on instead will be the physical phenomena related to one particular aspect of LSPs interaction with matter, namely, LSP phenomena in semiconductor light emitting diodes (LEDs), and, even more narrowly, LSP phenomena as related to the performance of QW LEDs based on group III-Nitrides. Such LEDs have come recently to the forefront of research and development aimed at the creation of new extremely efficient solid-state light sources for the visible-UV spectral range (see e.g. [9]). The material basis of III-Nitride LEDs is constituted by solid solutions of InAlGaN and respective QWs and QDs. All these materials have direct bandgaps spanning the spectral range from near infrared (0.6 eV or 2000 nm for InN) to deep ultraviolet (DUV) (6.2 eV or 200 nm for AlN).

These solid solutions have hexagonal wurtzite structure and can be grown by a variety of methods such as metallorganic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), and hydride vapor phase epitaxy on various substrates of sapphire, SiC, Si, GaN, AlN, etc. (see e.g. Ref.