Title
Efficiency Improvement of Nitride-Based Solid State Light Emitting Materials -- CRADA Final Report

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CRADA Final Report
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1. Parties: Lumileds Lighting , LBNL and UC Berkeley

2. Title of the Project: Efficiency Improvement of Nitride-Based Solid State Light Emitting Materials

3. Summary of the specific research and project accomplishments:
(Were the goals of the CRADA achieved? Include relevant information but do not include proprietary or protected CRADA information.)

The development of In_xGa_{1-x} N/GaN thin film growth by Molecular Beam Epitaxy has opened a new route towards energy efficient solid-state lighting. Blue and green LED's became available that can be used to match the whole color spectrum of visible light with the potential to match the eye response curve. Moreover, the efficiency of such devices largely exceeds that of incandescent light sources (tungsten filaments) and even competes favorably with lighting by fluorescent lamps (see Figure 1).

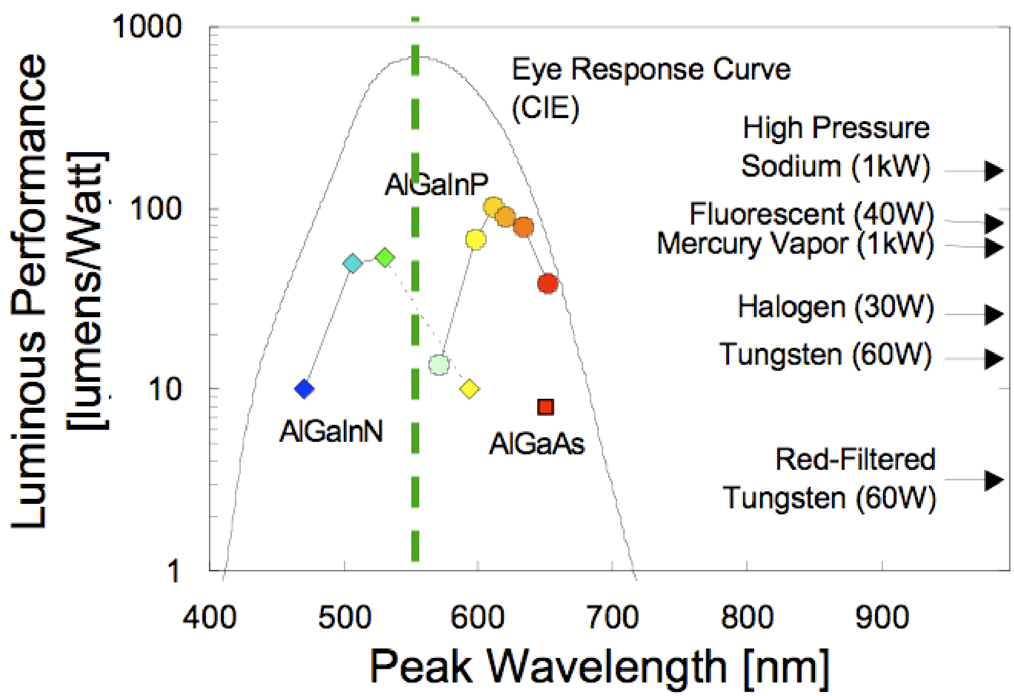

Figure1: Luminous performance of different light sources and their relation to the eye response curve. Colored data points indicate the performance of solid-state light emitting diodes (LED's). Blue and green LED's are fabricated from In_xGa_{1-x} N/GaN thin films with $x \leq 0.2$

It is, however, also seen in Figure 1 that it is essential to improve on the luminous performance of green LED's in order to mimic the eye response curve. This lack of sufficiently efficient green LED's relates to particularities of the $In_xGa_{1-x}N$ materials system. This ternary alloy system is polar and large strain is generated during a lattice mismatched thin film growth because of the significantly different lattice parameters between GaN and InN and common substrates such as sapphire. Moreover, it is challenging to incorporate indium into GaN at typical growth temperatures because a miscibility gap exists that can be modified by strain effects. As a result a large parameter space needs exploration to optimize the growth of In_xGa_{1-x} N and to date it is unclear what the detailed physical processes are that affect device efficiencies. In particular, an inhomogeneous distribution indium in GaN modifies the device performance in an unpredictable manner. As a result technology is pushed forward on a trial and error basis in particular in Asian countries such as Japan and Korea, which dominate the market and it is desirable to strengthen the competitiveness of the US industry.

This CRADA was initiated to help Lumileds Lighting / USA boosting the performance of their green LED's. The tasks address the distribution of the indium atoms in the active area of their blue and green LED's and its relation to internal and external quantum efficiencies. Procedures to measure the indium distribution with near atomic resolution were developed and applied to test samples and devices that were provided by Lumilids. Further, the optical performance of the device materials was probed by photoluminescence, electroluminescence and time resolved optical measurements. Overall, the programs objective is to provide a physical basis for the development of a simulation program that helps making predictions to improve the growth processes such that the device efficiency can be increased to about 20 %.

Our study addresses all proposed aspects successfully. Carrier localization, lifetime and recombination as well as the strain-induced generation of electric fields were characterized and modeled [1, 2]. Band gap parameters and their relation to the indium distribution [3] were characterized and modeled. Electron microscopy was developed as a unique tool to measure the formation of indium clusters on a nanometer length scale [4,5] and it was demonstrated that strain induced atom column displacements can reliably be determined in any materials system with a precision that approaches 2 pm. The relation between the local indium composition x and the strain induced lattice constant c(x) in fully strained InxGa1_xN quantum wells was found to be: $c(x) = 0.5185 + \alpha x$ with $\alpha = 0.111$ nm. It was concluded that the local indium concentration in the final product can be modulated by growth procedures in a predictable manner to favorably affect external quantum efficiencies that approached target values and that internal quantum efficiencies exceeded them.

4. Deliverables:

Deliverable Achieved	Party (LBNL, Participant, Both)	Delivered to Other Party?
Model for carrier separation, Model indium distribution	LBNL/UCB	Lumileds
Variation of MOCVD growth parameters to alter in distribution/ fields	Lumileds	LBNL/UCB
Model for recombination / LED efficiency / improved green LED efficiency	UCB / Lumileds	Lumileds

5. Identify publications or presentations at conferences directly related to the CRADA?

[1] Luminescence energy and carrier lifetime in InGaN/GaN quantum wells as a function of applied biaxial strain, N. A. Shapiro, H. Feick,W. Hong, M. Cich, R. Armitage, and E. R. Weber, J. Appl. Phys. 94, 2003, 4520
[2] Inhomogeneities and piezoelectric fields in InGaN quantum wells, William D. Hong, PhD Theses, Berkeley, Materials Sciences and Engineering, Spring 2007
[3] Local Indium Segregation and Band Gap Fluctuations in High Efficiency Green Light Emitting InGaN/GaN Diodes, J.R. Jinschek, R. Erni, N. F. Gardner, A. Y. Kim, C. Kisielowski, Solid State Comm. 137, 230 - 34, 2006
[4] Measurement of the indium segregation in InGaN based LEDs with single atom sensitivity, Joerg R. Jinschek, Christian Kisielowski, Dirk Van Dyck, Philippe Geuens Proceedings SPIE International Symposium on Optical Science and Technolgy, 3.-8. August 2003, San Diego/CA, Convention Center, SPIE 5187, 2004, 54
[5] Time, energy, and spatially resolved TEM investigations of defects in InGaN", J.R. Jinschek, C. Kisielowski, Physica B, vol.376-377, 2006, pp. 536-9
[6] Distortion and Segregation in a Dislocation Core Region at Atomic Resolution, X. Xu, S.P. Beckman, P. Specht, E.R. Weber, D.C. Chrzan, R. P. Erni, I. Arslan, N. Browning, A. Bleloch, C. Kisielowski, PRL **95,** 145501 (2005)

6. List of Subject Inventions and software developed under the CRADA:
(Please provide identifying numbers or other information.)

A software procedure was further developed to allow for local indium concentration measurements by extracting atom column positions with a precision that approaches 2 pm. The method was shown to be suitable to extract displacement fields from atomic resolution images of any crystalline materials system.

7. A final abstract suitable for public release:
(Very brief description of the project and accomplishments without inclusion of any proprietary information or protected CRADA information.)

In this CRADA the intimate link between the indium distribution in the GaN / $In_xGa_{1-x}N$ / GaN quantum well structures with $x \leq 0.2$ and the efficiency of green LED's was investigated. A method to measure the indium distribution with near atomic resolution was developed and applied to understand how growth parameters affect the indium distribution and thereby device performance. Models to predict the effect of an inhomogeneous indium distribution on external device efficiency were developed. As a result it became possible to grow green LED's of improved efficiency.

8. Benefits to DOE, LBNL, Participant and/or the U.S. economy.

The development of a solid-state lighting technology can have a major impact on the global energy consumption. In the US alone about 20 % of electricity is used for lighting. Solid-state lighting could reduce this value to only 5% at reduced costs and save 15 % of the electricity in use. The current market leaders developing this technology are located in Asian countries (Korea, Japan). This CRADA aimed at strengthening the US based company Lumileds by helping to understand physical processes that affect device performance, which is crucial in the competition for market shares.

9. Financial Contributions to the CRADA:

DOE Funding to LBNL	$ 375 000 was estimated
Participant Funding to LBNL	$90,000
Participant In-Kind Contribution Value	$ 450 000
Total of all Contributions	$ 915 000

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