BUILDING TECHNOLOGIES PROGRAM
LIGHTING RESEARCH AND DEVELOPMENT

2006 PROJECT PORTFOLIO: SOLID STATE LIGHTING

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

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2006 Project Portfolio:
Solid State Lighting

The U.S. Department of Energy (DOE) partners with industry, universities, and national laboratories to accelerate improvements in solid state lighting (SSL) technology. These collaborative, cost-shared efforts focus on developing an energy-efficient, full spectrum, white light source for general illumination. DOE supports SSL research in six key areas: quantum efficiency, longevity, stability and control, packaging, infrastructure, and cost reduction.

The *2006 Project Portfolio: Solid State Lighting* provides an overview of SSL projects currently funded by DOE, and those completed from 2003 through 2005. Each profile includes a brief technical description, as well as information about project partners, funding, and research period. The *Portfolio* is a living document and will be updated periodically.

Projects are organized throughout the *Portfolio* in alphabetical order by technology, funding source, and then performing organization.

Prepared by
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APPENDIX A:
COMPLETED SOLID STATE LIGHTING PROJECTS

Low-Cost Blue/UV LEDs with Very High Photon Conversion and Extraction Efficiency for White Lighting

Investigating Organization
Boston University

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Funding Source
Building Technologies Program/NETL

Award
DOE Share: $959,993
Contractor Share: $242,700

Contract Period
10/1/04 - 9/30/06

Technology
Light Emitting Diodes

Project Summary

This project is studying a unique approach to growing GaN-based LEDs on thick textured GaN quasi-substrates, using Hydride Vapor Phase Epitaxy (HVPE) instead of more costly Metal-Organic Chemical Vapor Deposition (MOCVD). It is anticipated that the work will demonstrate vastly improved device efficiencies. This is due to the substantial reduction in defect densities normally associated with nitride devices grown on materials of differing lattice constants, such as sapphire. In addition to exploring the potential for large increases in internal quantum efficiency due to the defect density reduction, significant increases in external quantum efficiencies are also possible due to the reduction in natural wave guiding that generally occurs at material interfaces. This imaginative work will address a number of issues plaguing the performance of nitride systems and may enable future breakthroughs in device efficiency and light management.

The experimental effort will be accompanied by theoretical and numerical effort with the goal of improving device understanding, gaining physical insight, and optimizing design parameters via numerical simulation in parallel with experiments. Software tools will be developed, and commercialized, with the goal of allowing fast, efficient LED design; reducing iteration cycles; and reducing time to market. The end result of this project will be a protype with near-UV-blue LED devices with textured surfaces and a minimum efficiency of 50 Lumens per Watt. A commercialization-ready numerical simulation tool that models light extraction from randomly microtextured surfaces will also be provided.

Nanostructured High-Performance Ultraviolet and Blue LEDs

Investigating Organization
Brown University

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Subcontractor
Yale University

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $900,000
Contractor Share: $229,033

Contract Period
9/23/03 - 9/30/06

Technology
Light Emitting Diodes

Project Summary

By improving silicon wafers or media that produce light, the project integrates nano-structured active materials into synthetically grown crystals to increase light emissions. The project also combines novel optical, chemical, and physical methods to enhance photons, which increase efficiency.

In this project, nanomaterial science is synergized with fundamental optical physics concepts pertaining to light-matter interaction. The goal is to develop a new class of high-performance light emitting diodes in the blue and near ultraviolet for solid state lighting applications, covering the spectral regime of approximately 370-480 nm. The overall mission is to implement novel, highly adaptable device concepts that enable flexible use, and match the broad spectrum of requirements posed by contemporary solid state lighting approaches. The light emitters will be based on nanostructured gallium nitride and related semiconductors, which are encased by engineered nano-optical photonic confinement structures. The researchers aim to reach the goal of a highly wall-plug-efficient, high-power optical device (> 100 lm/W) by concentrating on two specific, highly interrelated elements within the LED.

First, a nanostructured active media will be created to enhance the internal radiative efficiency by using advanced concepts in epitaxial growth for synthesizing quantum dots and quantum wires. The design principles involve the enhancement of the radiative cross section, acquired from microscopic principles, by the combined interplay of electronic confinement, strain, and piezoelectric polarization fields. The researchers' goal is to reach unity internal efficiency in the active medium. Furthermore, the nanostructured media will provide a designated electronic environment that will maximize the capture of electrically injected carriers into the quantum confined radiative centers.

Second, the research will focus on the design and fabrication of advanced subwavelength optical confinement structures. These structures will encase the nanostructured active medium for enhancing the spontaneous and stimulated emission by enhancing light-matter interaction at a fundamental level and for efficiently extracting and distributing the photons for delivery into specific geometrical radiation patterns by design.

The nano-optical resonator concepts use recent work by the principal investigators with planar resonant cavity LEDs to develop efficient mesoscopic optical confinement structures in three dimensions. Such mesoscopic optical concepts merge optical near field physics with subwavelength diffractive elements. These devices exploit a large index of refraction contrasts that are provided by new approaches to microcavity fabrication in the GaN/AlN system, while providing electrical access with heterostructure engineering concepts, such as those based on tunnel junctions.

Development of Advanced LED Phosphors by Spray-Based Processes for Solid State Lighting Applications

Investigating Organization
Cabot Superior MicroPowders

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Subcontractor
Sandia National Laboratories (SNL)

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,500,000
Contractor Share: $1,562,008

Contract Period
10/1/04 - 9/30/07

Technology
Light Emitting Diodes

Project Summary

Fluorescent lamps that convert deep UV light produced in low pressure plasma discharges into broad spectrum white light characteristically achieve high conversion efficiencies. Quantum mechanical considerations associated with the relative closeness of frequency (and energy) between blue LEDs and white light currently prevent SSL from achieving the same high conversion efficiencies. This project seeks to overcome this efficiency hurdle by using a unique combination of phosphor activators, hosts, and novel spray-based synthesis techniques. The Cabot Superior MicroPowders/SNL team expects to demonstrate 60% external quantum efficiency, about twice what the very best devices deliver today. Thus, without any increase in internal quantum efficiency, devices that would exceed 80 LPW could be built using this approach.

The goal of the project is to develop luminescent materials using aerosol processes for making improved LED devices for solid state lighting applications. This will be accomplished by selecting suitable phosphor materials that are generated by liquid or gas to particle conversion in micron to submicron ranges (0.1 – 1 micron) with defined spherical morphology and various particle size distributions, coated or uncoated, and applying them by appropriate mixing with or without extra layer components such as glass particles into thin phosphor layers to create more optically efficient LED devices.

High temperature, gas-phase processing methods, including spray-based methods (such as Spray Pyrolysis) have largely been unexplored as an alternative production method for phosphor powders but have the potential for enhanced control of particle size, particle size distribution and morphology, combined with in-situ thermal treatment to achieve highly crystalline structures to achieve high quantum efficiency without the need for milling. In addition, the formation of coated particles is also possible with spray pyrolysis and could impart oxidation or hydrolytic resistance, as well as encapsulation for optimization of layer structures. In this work, we propose to explore spray-based routes as alternatives to solid state and solution methods for the production of phosphor particles for blue-to-white and UV-to-white LED applications to specifically address the phosphor particle needs described above.

Phosphor-Free Solid State Lighting Sources

Investigating Organization
Cermet Inc.

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Subcontractor
Georgia Tech

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $3,840,370
Contractor Share: $971,239

Contract Period
10/1/03 - 11/30/06

Technology
Light Emitting Diodes

Project Summary

Cermet's work focuses on growing conventional materials on novel substrates that possess unique physical properties with less internal strain. This process has the potential to increase efficiency; have emissions that can be adjusted by carefully applying potentials across the substrate; and can be made to behave like a phosphor, absorbing photons of one color and emitting new ones that are of a different color.

The goal of Cermet's effort is to implement large-area zinc oxide fluorescent substrate technology and state-of-the-art, lattice-matched nitride epitaxy technology to address substrate, epitaxy, and device limitations in the high growth area of solid state lighting. Cermet, in collaboration with researchers at Georgia Institute of Technology, will bring several technological innovations to the marketplace, including the following:

1. Truly lattice matched, low defect density (as low as 104 cm2) nitride emitter structures resulting in significantly reduced non-radiative recombination centers. This goal will be achieved by combining molecular beam epitaxy (MBE) and metallorganic chemical vapor deposition (MOCVD) with a ZnO substrate that is lattice matched to nitride LEDs in the wavelength range of 330 to 420 nm. Shorter wavelength designs are also possible using strain compensated layer growth.

2. White light emission via a self-fluorescing mechanism in the ZnO substrate. This will be accomplished by doping the ZnO substrates to yield emission in the vision spectrum. Optical pumping of the substrate will be achieved with the integrated nitride emitter.

3. Ability to adjust the color content of the white light. This will be achieved by adjusting the doping concentration of the substrate.

Project Results, Year 1: In the first year of a three-year program, the following results have been achieved. Bulk ZnO: Cermet has demonstrated large diameter doped ZnO crystals. The optical properties of these crystals are excellent, with greater than 80% transmission over the visible spectrum for a wafer thickness of 300 microns. The excellent structural properties and defect densities present in the bulk ZnO is unchanged with the addition of up to 1019 cm-3 dopants. Epitaxy: Although not a goal of the first year of the program, initial MBE and MOCVD InGaN films have been grown on ZnO substrates. Both techniques have yielded epitaxy with excellent structural properties and very low etch pit densities. In year two, devices will be fabricated that incorporate this low defect density epitaxy capability.

Small-Area Array-Based LED Luminaire Design

Investigating Organization
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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,651,867
Contractor Share: $610,947

Contract Period
1/10/05 - 1/9/08

Technology
Light Emitting Diodes

Project Summary

Cree Inc. Santa Barbara Technology Center (SBTC) is designing and developing a compact light emitting diode (LED) based luminaire that will enable the replacement of a significant portion of the current incandescent market. Specifically, the program will develop a BR/PAR-style integrated reflector luminaire suitable for low-cost insertion into existing commercial and residential lighting fixtures.

Since performance alone will not be the sole metric determining eventual wide acceptance of LED-based lighting into commercial markets, Cree will utilize a rapidly growing foundation of commercial LED and LED package manufacturing experience to ensure cost effective, manufacturable solutions are implemented in an integrated luminaire suitable for high-efficiency, drop-in replacement of existing incandescent light sources.

High-Efficiency LED Lamp for Solid State Lighting

Investigating Organization
Cree Santa Barbara Technology Center

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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,419,584
Contractor Share: $473,194

Contract Period
10/01/03 – 12/31/06

Technology
Light Emitting Diodes

Project Summary

Cree SBTC is working to develop LED chip and package technology that will enable high-efficiency, cost-effective LED lamps for solid state lighting. Although the energy efficiency of state-of-the-art LED technology now exceeds that of conventional incandescent lamps, significant improvements in the cost performance – measured in dollars per kiloLumen – are crucial to realizing substantial energy savings from solid state lighting in the near future. The objective of the program is to demonstrate the potential for solid state lamps to become available at a fraction of today's cost by substantially increasing the operating current density and energy efficiency of the white LEDs used as the lamp "filaments," compared to white LEDs available today.

In this research, Cree will leverage its highly efficient Gallium Indium Nitride on Silicon Carbide (GaInN/SiC) emitter technology, and its low thermal resistance surface mount packaging technology. The program goals will be achieved by combining innovative approaches in (a) GaInN-based materials technology, (b) LED device fabrication, and (c) solid state lamp packaging. GaN-based materials and LED chip design will be optimized to enable very high current density operation of LEDs. Advanced chip designs and fabrication techniques will be developed with improved energy efficiency by reducing the optical and electrical losses that typically occur. Packaging technology will be developed that allows an increase in the power dissipation from a given footprint and makes more efficient use of the light emitted from the LED chips. Together, the improvements will allow the delivery of a lot more light per LED chip unit area, thus driving down the overall lamp cost.

So far, work under the program has increased the quantum efficiency of a 0.9 x 0.9 mm2 blue LED chip to 35% (after packaging) when operated at a drive current of 350 mA. With the addition of a phosphor, this translates into a white LED with an efficacy of nearly 60 lumens per watt. At 700 mA, or twice the current density, blue LED quantum efficiency of 28% and white LED efficacy of 43 lumens per watt have been demonstrated.

Novel Approaches to High-Efficiency III-V Nitride Heterostructure Emitters for Next-Generation Lighting Applications

Investigating Organization
Georgia Tech Research Corporation

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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $428,632
Contractor Share: $152,097

Contract Period
10/1/03 - 1/31/07

Technology
Light Emitting Diodes

Project Summary

Georgia Tech Research Corporation is working to produce new knowledge of the roles various materials have on LED properties and efficiencies and a more detailed understanding of the fundamental chemical process behind light production. The university's goal is to assimilate new information that enables the possibility of developing more efficient green LEDs that could, in turn, produce a new LED device capable of complete color-spectrum white light.

The Georgia Tech research program will develop technologies for the growth and fabrication of high-quality green light-emitting devices in the wide-bandgap III-V nitride InAlGaN materials system. The group's research will include four components. Part One will make use of advanced equipment for the metal organic chemical vapor deposition (MOCVD) growth of III-nitride films and the characterization of these materials. Part Two focuses on the development of innovative growth technologies for high-quality green light-emitting diodes. Part Three will involve the study of strain effects and piezoelectric and polarization effects upon the LED performance. Part Four will focus on the design, fabrication, and testing of nitride LEDs.

Tasks 1 and 2: We have been studying the growth and characteristics of our standard blue LED structures which are based on growth condition optimizations for the GaN-based LED structures that were developed in the first year of this program. These LED performance characteristics are used for a reference for comparison purposes with green LED performance characteristics that are currently under study. The device structure consists of an n-type GaN:Si cladding layer, InGaN/GaN MQW, p-type AlGaN:Mg electron blocking layer, p-type GaN:Mg cladding layer, and GaN:Mg p-contact layer (from sapphire substrate to top).

Tasks 3 and 4: We have developed a 1-dimensional mode for the diode active region incorporating the piezoelectric and polarization fields in order to examine the influence of LED performance on the quantum-well and barrier alloy compositions and thicknesses. For measurement of device output and I-V characteristics, we have performed wafer-level quick-test mapping as well as measurement of fully processed devices (unpackaged die form). For device fabrication, the mesa is defined and n-type and p-type contacts are formed by employing Ni/Au and Ti/Al/Ti/Au metal scheme, respectively. The devices being fabricated exhibited bright 300K electroluminescence of ~406nm and the typical power (on-wafer probing) is ~1.2mW for a 200´200µm2 device. The Vf of the devices was as low as ~2.84V.

SCALING UP: KiloLumen Solid State Lighting Exceeding 100 LPO via Remote Phosphor

Investigating Organization
Light Prescriptions Innovators, LLC

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Subcontractor
OSRAM Opto Semiconductors, OSRAM Opto Semiconductors, Inc.
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Lawrence Berkeley National Laboratory- Lighting Research Group
Fisk University- Conservative Optical Logic Gates
LPI Precision Optics LTD.
L&L Optical Services
Northeast Photosciences

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,156,644
Contractor Share: $291,829

Contract Period
1/15/05 - 6/15/06

Technology
Light Emitting Diodes

Project Summary

Light Prescriptions Innovators, LLC (LPI) of Irvine, California, a nonimaging optics R&D company with wide experience in LED lighting optical design, proposes to team with LED chip-making giant OSRAM Opto Semiconductors, Lawrence Berkeley National Laboratory, University of California, Merced, and Fisk University, in a collaborative project applying for DOE funding. The project objective is to apply new technologies to fabricate a prototype that can prove that mass-produced high-flux LED modules can compete with fluorescent, incandescent and halogen lighting in efficacy, flux, and cost/watt.

LPI and OSRAM plan to break through the limits formerly holding back makers of LEDs (Light Emitting Diodes) seeking to create general illumination sources using white Solid-State Lighting (SSL). The most popular method being used today is by coating a blue LED with a phosphor coating. When the blue light hits the phosphor, it glows white.

Some of the drawbacks with this method are that the LED heats up and can damage the longevity of the phosphor conversion and, therefore, the life of the LED. Also, the efficiency of the LED suffers because half of the phosphor's omni directional emission goes back toward the LED chip. Much of this light gets trapped in the LED package and is reabsorbed by the chip, causing it to heat up even more than it did by the initial blue light production.

There is a further inefficiency in the conventional set-up, one that is also suffered by single-color LEDs. That is, if you try to gang several adjacent LEDs to act as a single light source, the great heat load is difficult to remove. This, in turn, prevents the higher currents possible with one chip alone.

What is proposed by the LPI/OSRAM team is to optically unite a number of separate, top-emitting OSRAM ThinGaN blue LEDs, using LPI's patent pending “combiner” optics that feed an exit aperture coated with phosphor. This avoids the separated chips heating each other. Also, the phosphor is far removed from the source of the heat that can reduce its efficiency, or even damage it. Further, part of the white light that tries to go back to the source will be recycled by special optics, which increases efficacy and alleviates overheating of the LED chip. The result is that the chip can now be driven harder and generate more light. A side benefit is that the proposed optics homogenizes the light, so that variations of phosphor brightness and color are minimized, in the case of flux reductions, or even a total failure, of an LED in the array.

An Efficient LED System-in-Module for General Lighting Applications

Investigating Organization
Philips Electronics North America Corporation

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Subcontractor
Philips Lighting's Corporate Calibration and Standards Lab

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,567,276
Contractor Share: $1,044,851

Contract Period
1/15/05 - 1/15/08

Technology
Light Emitting Diodes

Project Summary

Philips Lighting - Lighting Electronics NA, together with Philips Semiconductors and the Philips Corporate Calibration and Standards Lab, propose to develop multi-colored LED sources in which a single integrated package, containing multiple high power LED die, serves as a self-contained lamp module generating feedback-controlled light of user-selectable color and intensity. In addition to the LED die, the package will include first-stage optics for color mixing, optical and thermal feedback sensors, structures for thermal management, and drive and control electronics. The LED die will be close together to promote color mixing and to provide a compact source so that the package will deliver about as many lumens as current luminaires of the same exit surface area. The user will supply, via an intuitive interface, a control signal to specify lamp color and intensity. The user will not have to understand the intricacies of feedback control systems in order to use the resulting lighting system. The proposed system will be equipped to accept wireless links to remote controls and/or remote sensor signals (such as those from daylight sensors). We refer to this integrated LED multi-chip source system as an LED system-in-module (LED-SIM) and believe, based on our extensive manufacturing and commercial experience in lighting, that such an integrated system is critical for early market acceptance. Developing this technology will require capabilities in optics, thermal management, electronics, silicon integration and system architecture. We expect the LED-SIM modular approach (and the general principles that will be derived) to provide a direct path to lamp systems useful in the majority of commercial lighting applications and some residential applications. However, for the purpose of this project, we limit the carrier to be LED-SIMs intended specifically for general lighting applications (non-accent), equivalent to reflector PAR (flood) systems and recessed CFL systems. The project is organized in three phases. Two of these are stages of increasing integration, and the last is to build the resulting LED-SIM into a flood lamp demonstrator. In the first phase, experimental RGBA white-light LED-SIMs will be designed and built with integrated LEDs, sensors, drive and control electronics, first stage optics, and thermal management. The electronics will be integrated in modules (e.g., controller, driver, memory chips, passive components, and user interface electronics). Minimization of lamp size is not a priority in this phase. The goal is to make a self-contained lamp module generating feedback-controlled light of user-selectable color and intensity, and requiring only line voltage input power and a signal defining the light color and intensity. In the second phase, building on the first phase, the LED-SIM design will be finalized, by integrating the electronic functional blocks fully, incorporating optimized thermal management designs and incorporating improved optics. The size of the module will be minimized. A general output from this phase is a methodology for designing LED-SIMs that will be useable for various applications. In the third phase, a prototype lamp system, sized to retrofit a PAR38 lamp, will be made, based on the LED-SIMs. The ultimate deliverable and the result of the third phase is a flood lamp with an intuitive user interface for color and intensity selection.

Relevant results achieved so far include: 1) An LED light source containing individually packaged LEDs and electronics designed using existing components. The light maintains corrects for variations in LED spectrum using temperature feedforward and intensity feedback. Intensity of each color of LEDs is measured independently with a Y-filtered photodiode. 2) An LED light source composed of 16 closely spaced LED die, with a reflector to shape the beam to that of a flood light. There is no integrated control system.

Ultrahigh-Efficiency Microcavity Photonic Crystal LEDs

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,200,000

Contract Period
9/1/04 - 9/30/06

Technology
Light Emitting Diodes

Project Summary

This is a two-year project that will leverage work already supported under a FY03 EE Science Initiative (EESI) award. Researchers at Sandia National Laboratories will design, fabricate, and test 400 nm – 460 nm InGaN microcavity photonic crystal light emitting diodes (PX-LEDs). Enhanced light extraction will be achieved through the use of a planar cavity based on a conducting GaN/AlGaN epitaxial distributed Bragg reflector (DBR) in conjunction with a two-dimensional photonic lattice. Photonic lattices, which are two-dimensional photonic crystals, can improve the efficiency through two mechanisms: improvement of the radiative efficiency and improvement of the extraction efficiency. Both of these mechanisms require a significant overlap between the high index LED semiconductor material and the photonic lattice. The difficulty of etching GaN places rather severe limitations on the achievable etch depth (< 600 nm) for nanoscale features. The planar microcavity mitigates this difficulty by reducing the effective thickness of the PX-LED, allowing us to maximize the overlap between emission modes and the photonic lattice. Although this work will capitalize on previous work at Sandia on GaN/AlGaN DBRs, some development work will be required to produce doped DBRs with low resistivity for efficient current injection.

The fabrication of photonic lattices in GaN is expected to be particularly challenging compared to other material systems due to the fact that GaN is a very difficult material to etch. Although we have already demonstrated 200 nm diameter holes with depths of about 150 nm, further process development will be required to achieve deeper etches and smaller diameter holes where additional LED improvements are expected. New nanolithography techniques, masking materials and etch processes will be developed to fabricate nanoscale photonic lattice features over large areas. E-beam and nano-imprint lithography, combined with inductively coupled plasma dry etching, will be used to fabricate the two-dimensional photonic lattice. We will employ semi-vectorial finite-difference time-domain numerical techniques to determine the electromagnetic modes available within a given microcavity photonic crystal design and use this to calculate the effect on LED performance. Development of the theoretical model will be closely monitored by comparison to experimentally measured results throughout this program. This hybrid approach using a planar microcavity and a two-dimensional photonic lattice will allow us to produce InGaN LEDs with dramatically improved efficiency. This project has the goal of doubling the external quantum efficiency of InGaN LEDs.

Improved InGaN Epitaxy Yield by Precise Temperature Measurement

Investigating Organization
Sandia National Laboratories

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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $350,000

Contract Period
10/1/04 - 9/30/06

Technology
Light Emitting Diodes

Project Summary

This project will address the production of efficient green LEDs, which are currently the least efficient of the primary colors. This work will advance IR and UV-violet pyrometry to include real-time corrections for surface emissivity. Increasing wafer yield would dramatically reduce high brightness LED costs and accelerate the commercial manufacturing of inexpensive white light LEDs with very high color quality.

This work will draw upon and extend previous research that developed emissivity correcting pyrometers (ECP) based on the high-temperature GaN opacity near 400 nm and the sapphire opacity in the mid-IR (MIR) near 7.5 microns. Both will be tested and developed in order to see which system performs best in a production class environment. Extensive modifications, testing, and improvements are necessary in order for these pyrometers to become useful and practical in a production class, multiwafer reactor environment. The work to be done at SNL is as follows:

Task 1. UVV-ECP Development
This task extends development of an ultraviolet-violet emissivity-correcting pyrometer (UVV-ECP) installed and tested on the Sandia single-wafer research reactor. This approach relies on the opacity of the GaN epilayer at wavelengths above the bandgap. The very weak thermal emission signal near 400 nm requires a number of substantial modifications to the typical pyrometer design. The payoff has been the first true surface temperature measurements during GaN and InGaN MOCVD. All other techniques have

directly or indirectly measured the temperature of the wafer holder, which is never equal to the actual wafer temperature. Measurement of the true surface temperature will result in better control of the desired InGaN composition and, therefore, better control of the emission wavelength. This will, therefore, result in higher yield of the epitaxial process, and lower cost of the final LED product. However, in order to make a true cost impact, the UVV-ECP method must be demonstrated on production class, multiwafer MOCVD systems.

Task 1.1. Design and installation of 1st generation UVV-ECP on multiwafer InGaN MOCVD reactor.

Task 1.2. Evaluate performance of UVV-ECP for controlling InGaN temperature/ emission wavelength.

Task 1.3. Explore and develop sensitivity improvements for 2nd generation UVV-ECP.

The major milestone for this Task 1 is: UVV-ECP temperature noise (rms) <0.4 degrees at temperature of 750 ± 5 C at 1 Hz bandwidth and 3 wafer average.

Task 2. MIR-ECP Development
Another attractive spectral region for pyrometry is in the mid-infrared (MIR) beyond 7 microns, where sapphire is opaque. Other problems arise in the infrared, including absorption radiation by the gas-phase growth precursor (NH3 and metal-organics). l ~ 7.5 microns has been identified as the optimum detection wavelength, where the gases are transparent and the substrate is opaque.

Task 2.1. Develop prototype MIR-ECP for Sandia single wafer research reactor.

Task 2.2. Design and install MIR-ECP on multiwafer InGaN MOCVD reactor.

Task 2.3. Evaluate performance of MIR-ECP for controlling InGaN temperature/ emission wavelength. The major milestone for Task 2 is: MIR-ECP temperature noise (rms) <0.3 degrees over 700-800 ºC range at 1Hz bandwidth and 3 wafer average.

Development of White-Light Emitting Active Layers in Nitride-Based Heterostructures for Phosphorless Solid State Lighting

Investigating Organization
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Subcontractor
OSRAM Sylvania

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $955,656
Contractor Share: $245,273

Contract Period
10/1/04 - 9/30/07

Technology
Light Emitting Diodes

Project Summary

Building upon earlier work supported by DOE at the University of California at San Diego, researchers are using novel, combustion-produced activators to stimulate photonic emissions for otherwise non-radiative relaxation pathways. Early demonstrations of this important concept will be done on thin films using a laser ablation technique, but the potential to use the approach in the design of a practical LED heterostructure will also be explored. This work could have a dramatic impact on traditional nitride devices by substantially improving internal quantum efficiencies by as much as 30%, with virtually no added manufacturing complexity or cost.

This new effort is a collaboration between UC San Diego (PI: Prof. J. McKittrick) and OSRAM SYLVANIA (Dr. K. Mishra). The main objective is to develop a new LED architecture using thin films of nitride-based luminescent semiconductor alloys of GaN, AlN, and InN, and suitably chosen activator ions to produce white light. The activator ions will consist of one or two types of ions that, together and with band edge emission from the alloy, will yield a superposition of emission spectra from the individual activator ions and lead to a white-light emitter with high efficacy and color rendering index. These activator ions are presumed to be excited by energy transfer from the electron-hole (e-h) pairs generated in the semiconducting dies. Such a thin film can be used as an active layer in designing double heterojunctions for solid-state lighting applications. Research activities are planned to demonstrate that such an alloy can be designed by adjusting the alloy composition and activator ions, that nonradiative energy transfer from the e-h pairs to the activator ions would occur efficiently (Phase I), that thin films of such an alloy would retain the efficacy in powder form (Phase II), and that a chemical reaction route can be found to grow a thin film of this alloy epitaxially on a p- or n-type material (Phase III). The last step is critical for integrating this technology, when successfully developed, to the existing manufacturing processes of nitride-based LED systems.

ZnO PN Junctions for Highly Efficient, Low-Cost Light Emitting Diodes

Investigating Organization
University of Florida

Principal Investigator(s)
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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $914,537
Contractor Share: $228,635

Contract Period
10/30/04 - 10/30/07

Technology
Light Emitting Diodes

Project Summary

This project aims to demonstrate a viable method of synthesizing novel II-VI compound semiconductors based on Zn with Mg (and other) metallic dopants. Intended to demonstrate much better materials properties, such as increased p-type concentrations and mobility, enhanced heterojunction constructs, and other effects thought to increase internal quantum efficiency, this project will determine if indeed such a system is a practical alternative to the defect-prone III-V system (currently manufactured, but of limited efficacy). Traditionally, these materials were thought to be too brittle and too easily contaminated by environmental constituents, such as water, to be of value as LEDs. The researchers are working to overcome these limitations using unique alloying technologies.

The overall objective of this research will be formation of light-emitting ZnO-based pn junctions. The focus will be on three issues most pertinent to realizing a ZnO-based solid state lighting technology, namely: 1) achieving high p-type carrier concentrations in epitaxial (Zn,Mg)O thin films; 2) realizing band edge emission from a ZnO-based pn homojunction; and 3) achieving band edge emission for ZnO-based pn heterojunctions that are designed to yield efficient light emission. Related objectives include understanding the doping behavior of phosphors and nitrogen in ZnO and ZnMgO, identifying the potential and limitations of ZnO pn junction LED performance, and achieving electroluminescence in polycrystalline ZnO-based pn junctions fabricated on glass.

Innovative Development of Next-Generation and Energy-Efficient Solid State Light Sources for General Illumination

Investigating Organization
Georgia Tech Research Corporation

Principal Investigator(s)
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Subcontractor
None

Funding Source
EE Science Initiative

Award
DOE Share: $500,000
Contractor Share: $125,000

Contract Period
10/1/03 - 6/30/06

Technology
Light Emitting Diodes

Project Summary

GaN and InGaN, the base materials for light emitting diodes in the blue and UV parts of the spectrum, were grown on ZnO substrates using MOCVD. These materials are currently being characterized via several techniques, including X-ray diffraction, secondary ion mass spectroscopy, and etch pit density in conjunction with atomic force microscopy. Baseline GaN was already measured with respect to defect density, which was 3-5x108 cm-2. In situ substrate removal has not yet been successful. Other alternative substrates (e.g, NdGaO3) will be tested over the coming year, and we expect to obtain defect densities of the materials grown on ZnO shortly. In addition, progress has been made on reducing the 1100 C process temperature through the use of alternative nitrogen sources such as an atomic nitrogen plasma or dimethylhydrazine to replace ammonia. Reduction of the process temperature allows use of many other alternative substrates.

Phosphors were made from SrS and SrGa2S4 activated with Eu. We expect to have similar materials using Ce as the active material over the coming year. The SrS and SrGa2S4 doped with Eu were made into nanoparticles that enhanced their emission efficiency. The emission measured by photoluminescence peaked at 616nm (orange/red). Light emitting diodes were fabricated using metal-organic chemical vapor deposition of GaN and InGaN multiple quantum wells. These diodes were optimized for emission at

400nm. A second round of diodes has already been fabricated, one year ahead of schedule, with dual wavelength emissions at 418nm and 481nm. These diodes are being incorporated as pump sources with the phosphors mentioned above (SrS:Eu,Ce and SrGa2S4:Eu,Ce as nanoparticles) for measurement of equivalent lumen output. We anticipate measuring the lumen output of the integrated dual wavelength LED driving the phosphors before the new year.

Development of UV-LED Phosphor Coatings for High-Efficiency Solid State Lighting

Investigating Organization
University of Georgia Research Foundation

Principal Investigator(s)
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Subcontractor
GE Global Research

Funding Source
EE Science Initiative

Award
DOE Share: $418,049
Contractor Share: $104,533

Contract Period
1/23/04 - 12/31/05

Technology
Light Emitting Diodes

Project Summary

The objective of the work is to develop highly efficient solid state lighting sources based on UV-LED + phosphor combinations. The methods used are focused on improving the phosphor coating conversion efficiency in UV-LEDs, where the fundamental quenching mechanisms for phosphor coatings will be determined and quantified.

To increase the efficacy of white light devices, new phosphors for UV-LED excitation have been developed at GE during the last six years. However, the extreme conditions (compared to standard fluorescent lamps) in UV-LED-based devices, such as elevated temperatures and incident light intensities, can lead to luminescence losses. The goal of the program is to find the origin of the losses and quantify the loss parameters in terms of quenching temperature, ionization threshold, and saturation flux. These parameters will then be used to establish design rules for the solid state devices that will operate within a parameter space that is defined by high efficacy, good color rendering, and high lumen maintenance.

In addition to standard emission and photoexcitation measurements, the efficacy of the material is being studied as a function of temperature. These studies will be complemented by time-resolved measurements using pulsed LEDs or laser sources with nsec resolution, and will lead to a determination of the quenching temperature. In order to identify the quenching mechanism, a unique method called thermally stimulated luminescence excitation spectroscopy will be used. This method has been developed for the characterization of phosphor materials. To study saturation processes, the phosphor materials are exposed to high intensity laser radiation. Finally, blends of phosphors will be studied to monitor and evaluate the importance of energy transfer and migration within the phosphor blend.

A set of relevant parameters has been established based on transient luminescence measurements as well as investigations on the presence (quenching temperature) and origin (ionization/ level crossing) of thermal quenching. These parameters will now be used to establish design rules. This information will aid designers in developing LED packages that will minimize or even eliminate many of the phosphor quenching pathways. These rules will allow for optimization of the phosphor composition and the geometry of the LED-phosphor combination with respect to the LED emission characteristics. Thus, the LED package can be readily adapted to take full and immediate advantage of the rapidly advancing UV-LED technology.

An Advanced Nanophosphor Technology for General Illumination (Phase I)

Investigating Organization
Boston Applied Technology

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
6/27/05 - 3/26/06

Technology
Light Emitting Diodes

Project Summary

Conventional phosphors are in micrometer scale, light scattering at grain boundaries is strong and decreases light output. Conventional phosphors obtained by solid state sintering method has lower concentration quenching threshold due to non-uniform doping. The cost of the conventional sol-gel method to produce nano-phosphors is too high, due to low solubility of metal alkoxides. The salted sol-gel method (SSG) can prepare nano-phosphors in sizes from tens to hundreds of nanometers that are smaller than the light wavelength and can reduce scattering. SSG can improve uniformity of doping and lift the concentration quenching threshold. SSG is capable for massive production at low cost. We plan to make high energy-efficient nanophosphors, such as conventional YAG:Ce, and novel R2O3:Ce.

Efficient phosphors for lighting applications have been a long standing goal for researchers. The nano-phosphors generated over the contract period will greatly improve the energy efficiency for varies of lighting sources. They will be the next generation of phosphors. The SSG technology will also generate a broad impact on nano-particle fabrication. Its potential application will not be limited.

A Novel Growth Technique for Large Diameter AlN Single Crystals (Phase I)

Investigating Organization
Fairfield Crystal Technology, LLC

Principal Investigator(s)
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Subcontractor
Suny at Stony Brook, under the direction of Professor Michael Dudley

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,586

Contract Period
6/27/05 - 3/26/06

Technology
Light Emitting Diodes

Project Summary

III-V nitride-based high brightness UV and visible LEDs are of a great interest for general illumination, but the light output efficiencies of current high brightness LEDs are still inadequate. A key material issue preventing achieving higher light output efficiency in LEDs is the poor crystalline quality of the nitride epilayers resulted from lattice-mismatched substrates. AlN single crystal is the best substrate material, apart from GaN, that is suitable for III-V nitride epitaxy, particularly for UV LED epilayers with high Al contents. Fairfield Crystal Technology proposes to use a novel physical vapor transport technique to grow large diameter, high-quality AlN bulk single crystals. These AlN single crystals can be used as substrates for growth of high-quality nitride LED epilayers. In this proposed Phase I effort, a novel physical vapor transport technique for AlN single crystal growth will be studied extensively. The focus of the study is to understand the effect of the growth setups used for the physical vapor transport growth on the quality of AlN crystal boules.

High-Efficiency Nanocomposite White Light Phosphors (Phase II)

Investigating Organization
Nanosys, Inc.

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,414

Contract Period
8/1/05 - 8/1/06

Technology
Light Emitting Diodes

Project Summary

The objective of the proposed program is the development of a revolutionary and innovative down-converting system based on engineered nanocomposite materials that will dramatically improve the overall cost, performance and efficiency of solid-state white light. This is more than a new phosphor, but rather a complete down-converting system that will impact all aspects of SSWL. The proposed technology has the potential to produce solid-state white light exceed the best traditional fluorescent and incandescent bulbs, with color rendering of greater than 80, color temperature of 4,000K, and luminous efficiency of greater than 200 lm/W while at a cost of less than $1/klm.

Manufacturing Process for Novel State Lighting Phosphors (Phase I)

Investigating Organization
PhosphorTech Corporation

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,997

Contract Period
6/27/05 - 3/26/06

Technology
Light Emitting Diodes

Project Summary

Solid state lighting (SSL) is rapidly gaining momentum as a highly energy-efficient replacement technology for traditional lamps. However, current solid state LED devices still suffer from low efficiencies partly due to optical mismatch between the LED and phosphor materials. PhosphorTech has developed a new class of high index material with superior optical performance to the current state of the art. These patent-pending phosphors were optically designed to maximize LED light outcoupling through careful control of their optical properties (such as, refractive index, scattering, absorption, luminescence efficiency, etc.). During the Phase I project, PhosphorTech proposes to demonstrate the feasibility of large-scale production of these new phosphor materials. The Phase II goal will be to mass produce these materials at the levels demanded by the future SSL market.

Sliding Mode Pulsed Current IC Drivers for High Brightness Light Emitting Diodes (Phase I)

Investigating Organization
SynDiTec, Inc.

Principal Investigator(s)
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Subcontractor
Northeastern University

Funding Source
Small Business Technology Transfer, Phase I

Award
DOE Share: $99,994

Contract Period
6/27/05 - 3/26/06

Technology
Light Emitting Diodes

Project Summary

The goal of this project is to derive models to state space the dynamic behavior of High Brightness - LED (HB-LED) arrays through hysteretic pulse current averaging techniques.

To date, we have:

1. Synthesized mathematical models and derived algorithms for pulse current averaging control.

2. Modeled and simulated the new hysteretic controller for HB-LEDs. Unusual to hysteretic control, the new SynDiTec "pulsed current averaged" controllers restrict the amount that a duty ratio in a DC-DC converter can increase each switching time cycle.

3. Simulated the SynDiTec actual controllers for a boost converter using two separate software packages. Using these simulations, we have created: time domain simulations, phase plane analysis, and sensitivity simulations to model uncertainties.

4. Developed a system block diagram with pin connections for a next generation driver IC primarily designed for driving white LEDs.

5. Built a prototype of the LED driver IC with FPGA and have experimentally verified that the pulsed current averaging algorithms work effectively.

Overall, we demonstrated that the SynDiTec pulse current averaging hysteretic control works to drive HB LED's. Further, the method is simple, low cost, and feasible for driving HB LED's. Some other advantages of this method appear to be:

- Inherent pulse-by-pulse current limiting, making the power converter nearly immune to damage from overload.
- No external compensation needed.
- Fast response of the inductor current.

The SynDiTec controller with unique rate limiter is able to stabilize and control the LED current in the boost converter configuration and stabilizes to approximately 20mA, while the boost inductor current remains in DCM with peak value of 120mA. On the other hand, if traditional hysteretic control is used without the SynDiTec rate limiter, the controller does not work. That is, although the LED current stabilizes around 20mA, the inductor current never reaches steady state, and eventually ramps to theoretically infinity. Thus, the SynDiTec controller appears to maintain the simplicity of hysteretic control, but because of the unique algorithm, is applicable to HB LED systems that previously could not be directly applied with traditional hysteretic control.

Novel Low-Cost Technology for Solid State Lighting (Phase II)

Investigating Organization
Technologies and Devices International

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
7/14/04 - 7/13/06

Technology
Light Emitting Diodes

Project Summary

The main technical objective of this program is to demonstrate an alternative cost-effective epitaxial technology for fabrication of GaN-based light emitting devices for white lighting applications and to investigate these novel light-emitting semiconductor structures.

1. Investigate GaN-based materials produced by novel epitaxial technology for LED applications, including high conductivity p-type GaN and AlGaN materials and light emitting materials with increased quantum efficiency of radiative recombination.

2. Reduce defect density and impurity background concentration in light emitting epitaxial structures to improved lifetime and operation stability of the devices.

3. Develop low defect lattice matched substrate materials for high-efficiency GaN-based LED structures. GaN and AlGaN templates will be developed and tested for LED fabrication.

For group III nitride semiconductors, HVPE technology is known to be a low-cost method for the fabrication of thick quasi-bulk GaN materials. Phase I demonstrated feasibility of this technical approach for fabrication of GaN and AlGaN templates (composite substrates) for GaN-based light emitting devices and producing white light emitting structures.

In Phase II, TDI will focus on the development of cost-effective manufacturing technology for Al(In)GaN-based structures and improvement efficiency of violet, UV, and white LED lamps. The target brightness of white LEDs is 100 lm/W.

GaN-on-sapphire, AlN-on-sapphire, and AlGaN-on-sapphire template substrates for blue LEDs have been fabricated by HVPE technology and characterized. Crystal structure, optical, and electrical properties of grown materials are measured. Dislocation densities are estimated using results of X-ray material characterization. P-type Mg- and Zn-doped single- and multi-layer GaN and AlGaN structures have been grown by HVPE technology. The structures are under investigation.

Development of cost-effective epitaxial technology for high-efficient white LEDs will speed up penetration of solid-state lighting into the illumination market and improve LED performance. It is anticiapted that as a result of this Phase II SBIR program, high-efficiency high brightness GaN-based light emitting devices will be demonstrated using novel cost effective epitaxial technology. Novel substrate materials for advanced GaN-based devices will be developed and tested. Defect density in the structures will be decreased leading to better device performance. Efficiency of radiation recombination in GaN-based materials will be increased and carrier injection efficiency into light emitting regions of LED structures will be improved.

GaN, AlGaN, and AlN layers and multi-layer structures are grown employing multi-wafer growth equipment developed at TDI. Sapphire wafers used as substrate materials. The growth performed in temperature range from 1000 to 1100^{o}C. Magnesium, zinc, and silane are used for doping. The gas flow rates are varied to control GaN (AlGaN) growth rates in the range form of 0.2 to 3.0 mm/min. The layers and the structures are characterized by X-ray diffraction, optical and scanning electron microscopy, atomic force microscopy, photoluminescence, UV transmission, and capacitance-voltage (C-V) measurements.

Thin Film Packaging Solutions for High-Efficiency OLED Lighting Products

Investigating Organization
Dow Corning Corporation

Principal Investigator(s)
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Subcontractor
Philips Lighting

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,414,300
Contractor Share: $2,348,673

Contract Period
12/1/04 - 11/30/07

Technology
Organic Light Emitting Diodes

Project Summary

Dow Corning seeks to demonstrate thin film packaging solutions that are based on Silicon Carbide hermetic coatings. When these coatings are applied to glass and plastic support OLED lighting devices, they will provide longer life with greater efficiency at lower costs than are currently available.

Full realization of the potential benefits of this work requires investment and progress in component technologies for OLED lighting. The work of Dow Corning and their partner addresses a number of the key technology challenges with the objective to integrate the advances into a fully operational device. Dow first will examine and identify low-cost alternatives to the expansive display quality glass substrates used to make OLED devices today. Second, they will develop thin film device protection technology to prevent degradation by air-borne moisture. Third, they will refine the light emitting architecture to fully exploit the energy-efficient promise of OLED technology. And, finally, they will combine these advances to produce working prototypes for specialty lighting applications as a step toward realizing the full potential of this technology for general illumination purposes.

The work will be completed in three phases, each a year in duration.

High-Efficiency, Illumination Quality White OLEDs for Lighting

Investigating Organization
General Electric Global Research

Principal Investigator(s)
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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,860,883
Contractor Share: $1,226,093

Contract Period
1/4/05 - 12/31/07

Technology
Organic Light Emitting Diodes

Project Summary

GE is developing a novel organic device design and corresponding materials set that will directly result in white OLEDs capable of producing >45 LPW by the end of the program. To achieve the program goal, the team will expand the existing library of materials and designs, and develop the necessary processing expertise to produce OLED devices in which all of the spin-state and charge transport pathways are tightly controlled to convert 100% of the injected charge into a light suitable for use in a white light source.

In the first year of the program, GE developed several routes to the fabrication of multilayer devices. In addition, GE developed new chemistries for polymer materials and emissive dopants. By combining these chemistries and multilayer technology, with the new device architecture, a polymer OLED with >10% EQE was built, and the fundamental feasability of the device concept demonstrated.

Material and Device Designs for Practical Organic Lighting

Investigating Organization
Los Alamos National Laboratory

Principal Investigator(s)
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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,018,369

Contract Period
9/15/04 - 9/30/07

Technology
Organic Light Emitting Diodes

Project Summary

This project will combine theoretical and experimental approaches to methodically address key material challenges for OLED use in general illumination applications. The project will systematically advance the physical and chemical understanding of how materials-related phenomena can be altered to make very high efficiency, low voltage, stable, inexpensive, and reliable devices. The fundamental knowledge gained from this work will contribute to product development.

To establish high efficiency, low-voltage, stable materials for practical, organic light emitting diode based general illumination applications, it is necessary to simultaneously ensure that: essentially all electrons and holes injected into the structure form excitons; the excitons recombine radiatively with high probability; the minimum drive voltage is required to establish a given current density in the device; and the material and device are stable under continuous operation. We will apply a tightly knit theory/fabrication/ measurement approach to understand and optimize four essential material and device elements necessary for satisfying these requirements: 1) charge injection, 2) carrier mobility, 3) organic/organic heterojunctions, and 4) exciton processes. Because of the many material and device options available, we will develop general methods of achieving the device requirements in these four areas.

Novel Organic Molecules for High-Efficiency Blue Organic ElectroLuminescence

Investigating Organization
Pacific Northwest National Laboratory

Principal Investigator(s)
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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,400,000

Contract Period
10/1/04 - 9/30/07

Technology
Organic Light Emitting Diodes

Project Summary

This project explores using-state-of-the-art phosphorescent organic light emitters to dramatically increase the power efficiency of blue organic light emitting devices by incorporating them in novel, electron-transporting host layers. Blue is thought by many to be the color that limits the efficacy of white OLED devices, as well as full-color organic light emitting displays. Typically, organic phosphors are doped into a conductive host matrix and emission results from energy transfer from the host to the triplet state of the phosphor. Development of efficient blue OLEDs based on this technology has been particularly challenging because the host material must exhibit triplet level emission of 450 nm without sacrificing charge transporting properties. Current host materials do not meet these requirements because there is a tradeoff between increasing the bandgap of the material and decreasing the p-aromatic system, which adversely affects charge transport properties. Deeper blue phosphors have only been demonstrated in insulating, wide bandgap host materials with charge transport occurring via hopping between adjacent dopant molecules. This leads to high voltage and, therefore, less efficient devices.

An alternative route for achieving blue shifted emission energies is to replace the nitrogen heteroatoms with phosphorus. For example, aromatic diphosphine oxides are stable compounds that exhibit electroluminescence in the ultraviolet spectral region (335 nm for one example already tested) while extended electronic states in the phosphorus

atom give rise to good electron transport at low voltages. Thus, it is possible to widen the bandgap without eliminating the aromatic backbone of the molecule, which makes these materials excellent hosts for high-efficiency blue phosphors, as well as longer wavelength OLEDs.

Novel Low-Cost Organic Vapor Jet Printing of Striped High-Efficiency Phosphorescent OLEDs for White Lighting

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
Princeton University

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,400,000
Contractor Share: $1,600,000

Contract Period
10/1/04 - 9/30/07

Technology
Organic Light Emitting Diodes

Project Summary

In this program, Universal Display Corporation and Princeton University propose to integrate three innovative concepts to meet the DOE's Solid State Lighting (SSL) goals: 1) high-efficiency phosphorescent organic light emitting device (PHOLED™) technology; 2) a white lighting design that is based on a series of red, green, and blue OLED stripes; and 3) the use of a novel cost-effective, high-rate, mask-less deposition process called organic vapor jet printing (OVJP).

Our PHOLED technology offers up to four-times higher power efficiency than other OLED approaches for general lighting. In this program, we intend to combine continued advances in this PHOLED technology with an innovative striped RGB lighting design to demonstrate a high-efficiency, white lighting source.

Using this background technology, the team will focus on developing and demonstrating the novel cost-effective OVJP process to fabricate these high-efficiency white PHOLED light sources. Because this groundbreaking OVJP process is a direct printing approach that enables the OLED stripes to be printed without a shadow mask, OVJP offers very high material utilization and high throughput without the costs and wastage associated with a shadow mask (i.e., the waste of material that deposits on the shadow mask itself). As a direct printing technique, OVJP also has the potential to offer ultra-high deposition rates (> 1,000 A/sec) for any size or shaped features. As a result, we believe that this proposal will lead to the development of a cost-effective manufacturing solution to produce very high efficiency OLEDs. By comparison to more common ink-jet printing (IJP), OVJP can also produce well-defined patterns without the need to pattern the substrate with wells, and the material set is not limited by viscosity and solvent solubility.

At the completion of this three-year program, we will demonstrate a 6” x 6” white PHOLED lighting panel consisting of fine-featured R, G, and B stripes (200 – 500 um width) with an efficiency exceeding 50 lm/W using OVJP. This project will significantly accelerate DOE’s ability to meet its 2015 DOE SSL targets of 70 – 150 lm/W and less than $10 per 1,000 lumens for high CRI lighting (76-90). Coupled with a low-cost manufacturing path through OVJP, we expect that this achievement will enable DOE to achieve its 2015 performance goals by the year 2013, two years ahead of schedule.

Surface Plasmon Enhanced Phosphorescent Organic Light Emitting Diodes

Investigating Organization
University of California, Santa Barbara

Principal Investigator(s)
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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $854,860
Contractor Share: $213,382

Contract Period
10/01/04 – 1/31/08

Technology
Organic Light Emitting Diodes

Project Summary

Work by leading OLED researchers has repeatedly demonstrated that phosphorescent OLED performance is not limited to 25% of the relaxation pathways that produce photonic emissions, owing to statistical spin of excited states normally associated with singlets. Phosphorescence is routinely used in the laboratory to fabricate phosphorescent OLEDs with performance surpassing 80%. This project will explore novel radiative decay control techniques to harness the energy of triplet states that are chemically and quantum-mechanically different, but functionally similar to currently accepted phosphorescent methods. The three-year project will systematically explore blending of chromophores and different plasmon structures to achieve better efficiencies via enhanced triplet annihilation and utilization.

Novel Materials for High-Efficiency White Phosphorescent OLEDs

Investigating Organization
University of Southern California

Principal Investigator(s)
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Subcontractors
Princeton University
Universal Display Corp.

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,350,000
Contractor Share: $494,068

Contract Period
10/1/04 - 9/30/07

Technology
Organic Light Emitting Diodes

Project Summary

This project involves a materials synthesis effort, in which large families of materials will be generated, intended for use in each of the different parts of the OLED. Each of the materials will be prepared with a specific device concept in mind, which involves resonant injection of carriers into the emissive layer. The materials to be prepared and examined here include carrier transporting/injecting materials, host materials for the doped emissive layer, and phosphorescent dopants, in a range of colors as well as broadband emitters. All of these materials will be extensively screened for chemical and thermal stability before being incorporated into OLEDs. OLED testing will be done in both monochromatic and white OLED structures. Many of the materials being prepared in this program will be useful in a range of different OLED structures and could be adopted by other research groups and programs to enhance the efficiency and stability of their devices.

The device architecture used in this program will rely on several specific design criteria to achieve high efficiency and long lifetime. The use of phosphorescent dopants will be necessary in any OLED structure to meet the DOE's performance goals. The emissive materials are all phosphorescent complexes, which have demonstrated long device lifetimes and high efficiencies in monochromatic devices, which are expected to carry over to properly designed white devices. The weak link in these materials is the blue phosphorescent dopant. These materials will be specifically targeted, and have a sound strategy to solve the blue reliability problems. In addition to designing the optimal monochromatic and broadband phosphors for the devices, a controlled energetic alignment for the devices will be relied upon, which will minimize drive voltage and increase the exciton formation efficiency. The carrier-injecting materials will be chosen to match the HOMO and LUMO levels in the emissive dopant exactly, such that the carriers are injected into the phosphorescent dopant in a resonant process. The phosphor will be doped into a wide gap host material, which will prevent host-carrier interactions, keeping the carriers and excitons exclusively localized on the phosphors.

The tasks for the three-year-term are laid out below. Work has begun on tasks 1, 2, and 3. Candidate material is in hand and the process of optimizing synthetic procedures and carrying out initial testing will begin soon.

Task 1: Energy graded carrier injectors
The goal of this task is to prepare a range of thermally and oxidatively stable materials, with roughly 100 mV separating the oxidation potentials of each pair of injectors. This set of materials will allow for selection of the best material for resonant hole injection for any given dopant. In order to accomplish resonant injection into the emissive layer (EML) the HOMO level of the hole transporter immediately adjacent to the EML will need to be aligned with the HOMO of the dopant. The goal of this task is to design, prepare, and test a series of materials that will be both thermally and reductively stable, and that have reduction potentials, spaced roughly 100 mV intervals. This set of materials will allow us to select the best material for resonant electron injection for any given dopant.

Task 2: Wide gap host materials
The host material for these resonant injection WOLEDs must be a stable benign matrix. Both holes and electrons will be carried by the dopant, thus the host matrix must have a wide carrier gap, with the host LUMO above the LUMO of the dopants and the HOMO of the host below the HOMO of the dopant. In addition to having a wide carrier gap (with appropriately placed orbital energies), the host matrix must have a high triplet energy, to prevent dopant quenching by the host. Several different types of materials will be examined as hosts. Materials will be screened by thermal and electrochemical methods, and promising candidates tested in OLED structures (both blue and white emitting devices).

Task 3: Deep blue emitters
Several new organometallic complexes will be investigated as deep blue emitters in blue and white OLEDs. The initial focus will be on Ir complexes with 6-member metallocyclic rings and phenyl substituted cyclometallated pyrazole ligands. A range of different ligands and metals will be surveyed for the optimal blue dopants. Blue dopants will be tested for electrochemical and thermal stability, as well as OLED tests for efficiency and reliability.

Task 4: Monochrome high-efficiency green, yellow, red emitters

In order to make high-quality WOLEDs by triply doping of the EML, we need not only highly efficient and stable blue emitting materials, but also have stable and efficient green, yellow, orange, and red emitting dopants as well. We will develop a family of such emitters, well-matched for energy absorption from the blue emissive materials. A prerequisite for incorporating these materials into WOLEDs is that they have both high-efficiency and device lifetime in monochromatic devices. Thus, these materials will be initially screened in monochromatic OLEDs and then the best materials will be incorporated into WOLEDs.

Enhancing Charge Injection and Device Integrity in Organic OLEDs (Phase II)

Investigating Organization
Agiltron Inc.

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,942

Contract Period
8/1/05 - 8/1/06

Technology
Organic Light Emitting Diodes

Project Summary

Agiltron is developing an innovative, low-cost anode surface modification technology for OLEDs, designed to significantly increase device efficiency and improve device stability and lifetime as well. Researchers have developed stable, high-yield, high hole transporting molecules that can cross-link to form ultrathin coatings. These coatings will be used to modify the surface of the indium tin oxide (ITO) anode of the OLED to enhance the injection of holes into the active area and increase device stability. Significantly, and in parallel, Agiltron is also developing a low-cost mist deposition approach for OLED fabrication that is scalable into a continuous mass production manufacturing technique. In this Phase II, we are continuing our development efforts that were begun in Phase I, where the feasibility was demonstrated through a continuous optimization and scale-up of air-stable and cross-linkable HTL materials synthesis and development of low-cost, large-scale mist deposition processes for polymer OLED fabrication. Agiltron's hole transport materials have been evaluated with promising results in a real device environment by GE's Solid State Lighting Group. The test results show Agiltron materials are more robust at high brightness conditions than current industry standard PEDOT, which indicates that more stable devices and longer device lifetimes can be expected. Agiltron's approach represents an unparalleled opportunity to contribute to the OLED performance target goal of 100 lumens per watt and a lifetime of 50,000 hours, and the cost target goal of $3.00 per 1000 lumens.

New Stable Cathode Materials for OLEDs (Phase II)

Investigating Organization
International Technology Exchange

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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,824

Contract Period
7/14/04 - 7/13/06

Technology
Organic Light Emitting Diodes

Project Summary

Many of the cathode materials currently in use in Organic Light Emitting Diodes (OLEDs), both for display and general lighting applications, are highly reactive metals, such as Mg, Li and Ca, and alloys, which are unstable and prone to oxidation. This complicates manufacturing and requires complex encapsulation techniques. It has led to reduced lifetimes of the devices. There is a need to develop cathode materials that have low work function for efficient electron injection, can be coated over large areas with a robust deposition process, and possess a higher degree of environmental stability against oxidation than cathode materials currently in use. This project will develop a new class of nanostructured amorphous carbon cathode coatings that satisfies those criteria. The materials can be coated on a variety of substrates, as thin films using plasma enhance chemical vapor deposition (PECVD), allow tailoring of the work function over a wide range and are dense to resist the penetration of both oxygen and water. During Phase I, the first examples of this new class of cathode coatings were produced that demonstrated the principle. OLED devices incorporating the nanocomposite films as cathodes were made and tested, and areas for optimization of the composition and deposition conditions were identified. During the first year of the two-year Phase II project, a specially designed PECVD tool has been constructed for the deposition of nanocomposite cathode films. In the second year, deposition conditions are being optimized to provide films with varying and controllable work function and efficient electron injection into the organic emitter layer. The films will be analyzed with TEM, X-ray and photoelectron

spectroscopy to determine structure and work function, and tested as cathodes in OLED devices.

Solid state lighting based on OLED devices have the potential to provide highly energy-efficient general lighting. This could effect very substantial energy savings, as much as 10% of the nation's total energy use by some estimates. This technology represents an industry of the future where the U.S. still maintains a technological lead, substantially due to the efficacy of the DOE-funded program. The coatings developed under this Phase II project will become an important enabling technology to realize the potential of OLED-based general lighting. Other applications include OLEDs for displays, particularly displays on flexible substrates.

Zinc-Oxide Based Light Emitting Diodes (Phase II)

Investigating Organization
Materials Modification, Inc.

Principal Investigator(s)
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Subcontractor
General Atomics Display Systems, San Diego, CA

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
8/1/05 - 7/1/07

Technology
Organic Light Emitting Diodes

Project Summary

Indium Tin oxide, currently used as the transparent conducting oxide electrode in OLED construction, is very expensive. It is desirable to lower the cost and resistivity of the electrode material and increase its optical transmissivity. In order to improve the cost and efficiency of OLEDs for solid state lighting, this project is studying alternate transparent conducting oxide materials. In the Phase I effort, selectively doped conducting oxides were deposited on polished glass substrates. Transparent films with low resistivity (<20 ohms/sq) and optical transparency (>85%) were obtained. In the Phase II effort, these conducting oxides will be deposited on flexible substrates for fabrication of green-colored exit signs. The signs will be developed to meet ENERGY STAR® requirements.

High-Efficiency White Mesh Phosphorescent OLEDs (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
Princeton University, under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $98,894

Contract Period
6/27/05 - 3/26/06

Technology
Organic Light Emitting Diodes

Project Summary

Universal Display Corporation (UDC), in collaboration with Professor Mark Thompson from the University of Southern California (USC) and Professor Stephen Forrest from Princeton University, propose to improve the efficiency of white phosphorescent OLEDs (PHOLED™) using novel emissive region doping profiles that further enhance the light outcoupling efficiency and the carrier recombination efficiency of PHOLEDs by 30% over that of conventional uniformly doped PHOLEDs.

Varying and optimizing the doping profile within the emissive layer may improve the recombination efficiency in PHOLEDs, and hence increase the external quantum efficiency (EQE). In addition, the novel structures, such as mesh layers, that we are investigating in this program, could also improve the outcoupling efficiency by aligning the molecular transition dipole moments parallel to the substrate, which would then further increase the EQE.

At the end of this Phase I, we hope to demonstrate a white PHOLED having >30 lm/W at 800 nits, with correlated color temperature between 2,800 K and 6,000K, and color rendering >75.

Transparent, Highly Efficient White OLEDs for Lighting Applications (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
Princeton University

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
9/1/05 - 8/31/06

Technology
Organic Light Emitting Diodes

Project Summary

In Phase II of this SBIR, UDC and Princeton University will demonstrate high-power-efficiency white transparent OLED (TOLED) lighting panels. The team will continue to develop white TOLEDs focusing on maximizing efficiency and transparency through less absorbing organic and conducting oxide layers. In addition, the team will optimize monolithically encapsulated TOLEDs.

The reason for implementing monolithic thin film encapsulation is to reduce the optical loss at the OLED-to-air interface. UDC will demonstrate the potential for stacking TOLED/OLED and TOLED/TOLED together to create high luminous intensity lighting panels or transparent lighting panels. All of these activities are working toward realizing a 20% increase in optical outcoupling. We believe that Phase I results have clearly demonstrated that the approach of using a TOLED within an optical reflector has the potential to achieve enhanced optical outcoupling for white light sources. Specific technical issues identified during Phase I included that the efficiency of the TOLED device could be increased through better engineered cathodes, and that further development of the overall design of the TOLED within the reflector cavity is required to fully assess the potential for using white TOLEDs for general illumination.

Specifically, the key objectives of Phase II are:

1. Demonstrate improved TOLED device performance by using IZO (replacing ITO) as the transparent conducting oxide in the transparent cathode.

2. Demonstrate a combined efficiency transparency product by improved TOLED layer designs.

3. Implement a monolithic thin film TOLED encapsulation to enhance light extraction.

4. Optimize the thickness of all the layers in the TOLED to maximize light output by microcavity modeling.

5. Demonstrate high luminous output stacked TOLED/OLED or TOLED/OLED with appropriate index-matching gel/adhesive.

6. Stimulate, design, and fabricate a TOLED/OLED with a parabolic dish reflector lamp.

7. Fabricate deliverable: a 6x6 white TOLED lighting prototype CRI>75, CIE coordinates similar to that of a blackbody radiator at a color temperature between 2,500 K and 6,000 K, and power efficiency > 25 lm/W at lighting luminance levels of 1,000 cd/m^2.

Low-Voltage, High-Efficiency White Phosphorescent OLEDs for Lighting Applications (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
Princeton University under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
8/1/05 - 8/1/06

Technology
Organic Light Emitting Diodes

Project Summary

The approach taken in this project is to combine novel low-voltage dopants, world record efficient phosphorescent OLED emission layers, and a stacked PHOLED architecture, to demonstrate a high-power efficiency >50 lm/W organic light source.

In Phase I, the goals were met and a white PHOLED, based on red, green, and blue phosphorescent emitters, was demonstrated to have a world record power efficiency of 20 lm/W at a luminance of 800 cd/m2. This device was reported at the 2004 Society for Information Display conference in Seattle, Washington. The overall excellent performance was accomplished without the use of outcoupling enhancement, so there remains significant potential to increase the power efficiency of low voltage PHOLEDs by a factor of more than 1.5.

In Phase II, UDC, Princeton University, and USC are further exploring new materials and device architectures that will be used by UDC in the fabrication of high-efficiency prototype lighting panels. The anticipated benefits of this work will be to demonstrate a new path for highly efficient white light sources by introducing a new dimension to the device design, such as high power, thereby significantly reducing the size of the substrate necessary for devices to produce optical power (>800 lumens) for room lighting.

The stacked PHOLED (SOLED™) is based on red, green, and blue (R-G-B) or white sub-pixel elements that are vertically stacked on top of each other versus sub-pixel elements that are laterally spaced. This is possible because these sub-pixels employ transparent p- and n-doped organic layers enabling R, G, or B light to be emitted coaxially through the contacts, the adjacent sub-pixels, and the substrate. The area of the device can easily be halved if two PHOLEDs are stacked, and hence the substrate cost savings and device manufacturability would both significantly improve by a factor of at least two, and improvements would scale with the number of PHOLEDs stacked on each other.

At the end of Phase II, we will deliver a 6"X6" prototype lighting panel based on low-voltage, high-power-density PHOLED lighting sources that are >25 lm/W efficient, have CRI >75, and CIE coordinates similar to that of a blackbody radiator at a temperature between 2,500 K and 6,000 K.

Novel Light Extraction Enhancements for White Phosphorescent OLEDs (Phase II)

Investigating Organization
Universal Display Corporation

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Subcontractor
Princeton University under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
7/1/05 - 6/30/06

Technology
Organic Light Emitting Diodes

Project Summary

The goal of this project is to realize an innovative approach to low-cost solid-state white light sources by applying two novel outcoupling schemes to our high-efficiency phosphorescent OLEDs (PHOLED™) to achieve power efficiencies >60 lm/W.

The Phase I goals were exceeded by fabricating white PHOLEDs with microlenses having 24 lm/W at a luminance of 1,000 cd/m2. The efficiency improvement was obtained by increasing the outcoupling efficiency by 22%. The total forward emission for devices with and without the lens arrays were measured with an integrating sphere, such that all forward-emitted light was collected in the sphere. Currently, we have made green, red, and blue-striped white 6"×6" lighting panels having a maximum efficiency of 30 lm/W, and are continuing to develop PHOLEDs that emit 500-800 lumens for room lighting.

In Phase II, UDC and Princeton University will demonstrate high-power-efficiency white PHOLED lighting panels. The team will build on their successful Phase I program to demonstrate white PHOLEDs that have improved outcoupling efficiency through the attachment of microlens arrays, in addition to incorporating OLED luminaires that increase the total PHOLED outcoupling efficiency by at least 50%.

White LED Package Efficiency and Brightness

Investigating Organization
Cree

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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,247,250

Contract Period
9/1/00 - 10/1/04

Technology
Light Emitting Diodes

Project Summary

In this completed program (October 2004), Cree SBTC and LBNL developed high-efficiency, high-radiance LED and packaging technology to push white LED brightness into the 50-60 lumens-per-watt range. At such levels, novel solid state lamps using a few LED "filaments" should be capable of replacing less energy-efficient lighting technologies. Potential benefits include lamp dimability, efficiency, consistent lifelong color, extended lamp life, and the absence of toxic materials.

By the end of the program, Cree demonstrated white lamps with output of 67 lumens at 57 lumens per watt using a single LED chip, and compact lamp prototypes with output up to 1200 lumens at >40 lumens per watt using multiple LEDs.

In this research, Cree leveraged its highly efficient Gallium Indium Nitride on Silicon Carbide (GaInN/SiC) emitter technology. Advanced chip designs and fabrication techniques were developed to increase the energy efficiency of the LED chip by reducing the optical and electrical losses that typically occur. The development process used a combination of optical modeling, device simulation, fabrication, and characterization of device prototypes to assess the impact of various design modifications on chip performance. LED chip efficiency nearly tripled over the course of the program.

In addition, novel solid state lamp package technology was developed with LBNL to ensure that light emitted from the LED chip can be used efficiently in actual lighting applications. This work included thermal and optical modeling to establish package design constraints, and the use of high-reliability materials for very long-lived LEDs. Lamp prototypes were built and evaluated to see how various materials and design geometries affected heat dissipation and light output from a compact LED source. One such demonstrator was a narrow viewing angle (±30) light source with the same optical source size as a conventional MR16 lamp. In this case, the LED lamp output 800 lumens with an efficacy of 40 lumens per watt, or roughly the same amount of light as a commercial halogen reflector lamp at more than twice the energy efficiency.

LED Substrates and New Materials

Investigating Organization
LumiLeds Lighting U.S., LLC

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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,377,000

Contract Period
9/1/01 - 12/31/03

Technology
Light Emitting Diodes

Project Summary

In a two-and-a-half year program that ended in Spring 2004, Lumileds Lighting worked with Sandia National Laboratories (SNL) to understand how and why certain physical and chemical processes affect the performance of InGaN/GaN compound semiconductor LEDs. The project had three research areas: 1) the study of performance impacts caused by different kinds of material dislocations and defects and ways to reduce these for LED structures grown on sapphire substrates; 2) the direct measurement of various physical properties of different semiconductor layers during reactor growth; and 3) the feasibility of using semiconductor nanoparticles for the efficient conversion of blue or ultraviolet light to broad spectrum, high-quality, white light.

In the first area, a cantilever epitaxy (CE) process developed at SNL was employed to reduce dislocation density in GaN. CE is a simplified approach to low dislocation density GaN that requires only a single substrate etch before a single GaN-based growth sequence for the full device strucure. CE has achieved low dislocation density GaN in layers only a few microns thick, and the effect of CE on high power InGaN/GaN LED performance was measured. In the second area, the team developed advanced tools and measurement techniques for use in reactors under the extreme conditions necessary to grow these compound semiconductor films. These measurements demonstrated the possibility to exert much more precise control over important physical parameters that establish the electrical and optical properties of products made in these reactors. In

particular, they demonstrated improved process control over critical temperatures at key growth steps, improving run-to-run color targeting for green LEDs by several factors. The team has also used advanced chromatographic techniques to monitor gas compositions at critical intervals. Using these methods, the quality and uniformity of the films can be improved dramatically.

In the third area, the researchers investigated the use of sophisticated, tiny semiconductor structures (nanoparticles, or "quantum dots") to convert the monochrome emission characteristic of inorganic compound semiconductor LEDs to more useful broadband emissions, such as white light. The team produced samples to determine their performance attributes and achieved record high quantum efficiencies for certain quantum dot materials. It also investigated means for incorporating the quantum dots into thin films that can be applied to high power LED chips to produce white LED lamps based solely on semiconductors. The team identified several challenges that need to be overcome before devices like these can eventually may be made on a commercial scale, providing an important step forward in DOE's quest of vastly increased efficiency in LEDs.

Development of Photonic-Crystal LEDs for Solid State Lighting

Investigating Organization
Lumileds and Sandia National Laboratory

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Subcontractor
University of New Mexico

Funding Source
EE Science Initiative

Award
DOE Share: $500,000

Contract Period
9/1/03 - 9/1/05

Technology
Light Emitting Diodes

Project Summary

Sandia National Laboratories, working together with Lumileds Lighting, a major U.S. manufacturer of high power LEDs, and the University of New Mexico, are developing photonic lattices for improving the efficiency of blue LEDs based on indium gallium nitride (InGaN) emissive layers. Photonic crystals have the potential to couple substantially more of the light internally generated within the active layers of an LED into external, usable radiation than is possible with simple planar surfaces. The light output from planar surfaces is limited by a classical optical effect known as total internal reflection, which allows only a small fraction of the internally generated light to escape from the high refractive-index LED materials. Photonic crystals, with periods comparable to the optical wavelength within the LED, employ diffractive effects to couple out light that is otherwise unavailable, enhancing the overall efficiency of the LED an important step toward realizing commercial lighting applications. The photonic lattices being developed in this project are two-dimensional photonic crystals. These photonic crystals can improve the efficiency of LEDs through two different mechanisms: improvement of the radiative efficiency of the device and improvement of the extraction efficiency. Extensive process development is being performed to fabricate the extremely fine, nano-scale features necessary for the production of a photonic crystal using electron beam, nano-imprint, and interferometric lithography. Detailed theoretical calculations are also being performed to design photonic lattices for improved LED efficiency. Characterization of photonic lattices with emissive layers is being done on processed wafers in order to confirm theoretical calculations and provide design guidelines. Finally,

complete LEDs are being fabricated using various photonic lattice designs and the emission efficiency is being determined. The project has a goal of doubling the external quantum efficiency of InGaN LEDs.

Sandia National Laboratories' Joel Wendt has developed an optimized process for the electron beam patterning of photonic crystals onto GaN LEDs. This process is dependent on the details of the photonic lattice being patterned, as well as the mask material being used. The process was developed by exposing a large variety of test patterns and characterizing the resulting patterns. A large number of photonic crystal LEDs have been successfully patterned. The patterned LEDs are either sent to Lumileds or retained at Sandia National Laboratories for etching and characterization.

Sandia National Laboratories has also been exploring the development of a nano-imprinting process to enable the rapid patterning of large areas. This type of inexpensive, large-area patterning process will be necessary for the production of LEDs using photonic lattices. Sandia is currently exploring imprinting features using commercially available resists.

Professor Steven Brueck of the University of New Mexico (UNM) has been contracted by Sandia National Laboratories to explore the development of interferometric lithography for use in the patterning of large-area photonic crystals on GaN LEDs. Interferometric lithography is the use of the interference between a small number of coherent optical beams to create small-scale periodic patterns in a single, parallel, large-area exposure. A 360-nm period pattern is used as an etch mask to fabricate photonic crystal LEDs. This pattern was written over an area (~ 2.5×2.5 cm2) much larger than that of a single LED in only a few seconds with a pair of two-beam interferometric lithography exposures. The pattern was generated at UNM on a partially fabricated III-nitride LED wafer. After completion of the fabrication, this LED yielded uniform light emission from the largest-area (1x1 mm2) III-nitride photonic crystal ever demonstrated. Efforts are currently underway to evaluate the impact of this structure on the quantum efficiency of this device, and to optimize the photonic crystal structure.

This achievement has both scientific and technological implications. Large area devices are important for verifying the extraction efficiency gains available with photonic crystals and for enabling a systematic optimization of the photonic-crystal parameters. Edge effects in small devices (10's to 100's of microns) can mask the important physics that becomes evident at larger areas. The process is very facile, allowing rapid and inexpensive changes in the pattern period, the dimensions of the pattern features, and the pattern symmetry. The interferometric lithography process creates a much larger-area pattern than was used in this experiment. UNM is already patterning an area of ~ 2.5×2.5 cm2 in a single exposure. Extension to a more highly engineered, full-wafer patterning tool, necessary for the ultimate goal of low-cost, high-volume manufacturing, is an important future direction.

Sandia National Laboratories' Ron Hadley has developed a three-dimensional semivectorial finite-difference time-domain (FDTD) computer code to evaluate the impact of the photonic crystal on the LED efficiency. He has compared the predictions of this code to actual planar LED output characteristics and achieved good agreement. This code is now being used to predict the output from a variety of photonic-crystal LED designs. The code's predictions are being benchmarked against experimental photonic-crystal LED results. The development of this code should enable the team to predict the optimum photonic crystal for use with a particular LED in a much shorter time than would be required for a purely Edisonian approach.

Novel LED Phosphor Research

Investigating Organization
University of California-San Diego

Principal Investigator(s)
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Subcontractor
None

Funding Source
EE Science Initiative

Award
DOE Share: $439,814

Contract Period
9/1/01 - 9/30/02

Technology
Light Emitting Diodes

Project Summary

There are two possible structures for a white LED. The first option is to develop an efficient white-emitting material that can replace the red-, green-, and blue-emitting materials in the classic LED heterostructure.

The second option is to embed a single composition, white-emitting material or three-phosphor blend (red, green, and blue) into the epoxy dome that surrounds the UV-emitting LED heterostructure. Existing white LEDs use a blue-emitting diode that excites a yellow-emitting phosphor embedded in the epoxy dome. The combination of blue and yellow makes a white-emitting LED.

The University of California-San Diego has discovered and developed a single composition white-emitting phosphor that is a terbium activated and cerium co-activated oxide. Cerium efficiently transfers energy to terbium, which mainly has a green emission with blue and red satellite peaks. Cerium-activated oxides have a saturated blue emission, but a long emission tail that extends into the green and red regions of the visual spectra. By enhancing the green and red emission from this phosphor using terbium, an efficient, long UV-excited white-emitting phosphor may be achieved. In addition, a tri-blend phosphor mixture has been discovered.

High-Efficiency Nitride-Based Solid State Lighting (Novel LED Structures)

Investigating Organization
University of California, Santa Barbara

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Subcontractor
Lighting Research Center at Rensselaer Polytechnic Institute

Funding Source
EE Science Initiative

Award
DOE Share: $2,995,155

Contract Period
9/15/01 - 3/31/05

Technology
Light Emitting Diodes

Project Summary

This project is focused on developing efficient white-light-emitting luminaires via a combination of novel GaN-based blue light emitting diodes (LEDs) and conventional YAG:Ce-based yellow phosphors. The blue LEDs 'pump' the yellow phosphor, and white light results from proper color mixing.

Typical (In,Al)GaN LEDs are composed of thin (< 0.1 micron) stacked layers with varying composition and doping (i.e., electrical conductivity), which are processed in a cleanroom to etch a defined mesa structure and deposit metal contacts. Unfortunately, due to the relatively high index of fraction of these materials, only a little light (< 8% per face), generated within the chip, escapes from it. Thus, a significant enhancement in light extraction (and, therefore, overall efficiency) is needed.

The novel LEDs studied in this project are termed Microcavity LEDs (MC-LEDs), whose total thickness is a fraction of a conventional LED. This reduced cavity thickness (ideally about 0.5 micron or less) causes the formation of optical modes within the structure and their accompanying directional emission from the structure. This directional emission is calculated to lead to high light extraction efficiency (> 40 %), given that we can carefully control the thickness and composition of the various device layers, which, in the case of a quantum well, are as thin as 10 nanometers. In addition, microcavity formation requires precise control of device thinning after the as-grown film has been detached from its substrate. Lastly, the electrical contacts and mirror(s) on either side of the structure need to be properly formed, both requiring significant processing optimization.

We are also developing luminaire designs that are tailored for directional emission from MC-LEDs. These luminaires must first be designed using ray-tracing and other optical modeling software, since the internal and external geometry of an ‘optimal’ luminaire design is often not inherently obvious. In addition, the placement of the yellow phosphor and the composition/refractive index of its medium must be properly chosen, since they directly affect overall luminaire efficacy. Once these factors have been considered and a prototype is constructed, we place an MC-LED in the luminaire to experimentally verify the efficiency and uniformity of light emission.

Ultraviolet LEDs for Solid State Lighting

Investigating Organization
Cermet

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Subcontractor
None

Funding Source
Small Business Innovation R&D

Award
DOE Share: $99,694

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

Two approaches are emerging as viable techniques for the production of solid state white light: visible wavelength LEDs coupled with modified phosphor compositions and UV emitters coupled with traditional, highly efficient YAG phosphors. The latter approach has the advantage of producing light with familiar color temperatures (warmth), which will greatly enhance the adoption rate of the light source by the public. However, UV (340 nm and 280 nm) semiconductor emitters with sufficient power required to stimulate YAG phosphors are not available.

The goal of this program was to develop the technology necessary to enable commercial production of high-quality (In,Al,Ga)N epitaxial materials and high-performance UV LEDs on AlN substrates for solid state lighting applications. Three major areas were targeted for a successful program through a Phase II effort: 1) development of production grade bulk AlN wafers using Cermet's Vapor Growth Process; 2) development of better quality materials, which include p- and n-type doped AlGaN and InAlGaN-based multi-quantum wells; 3) and introduction of novel LED device structures.

Project Results
In the nine-month Phase I program, Cermet and Georgia Tech's efforts focused on two of the three major technological barriers in the development of UV emitters. The first effort focuses on development of high-quality, bulk AlN crystals to eliminate dislocations,

which can be a major contributor to efficiency roll-off at high drive current densities. Bulk AlN minimizes thermal expansion cracking in high Al-content emitters. Aluminum nitride substrates are transparent in the UV portion of the spectrum, allowing through-wafer emitter designs into the deep UV. Lastly, AlN has a significant thermal conductivity, enabling effective power management of large area power (>0.5 watt) LEDs for SSL needs.

Two-inch-diameter bulk AlN was grown using Cermet's process. The materials exhibited an etch pit density of 1 x 10 5 cm-2 and X-ray peak widths as low as 76 arc seconds. Polished surfaces of 5.8 angstroms (rms) were achieved on this material. The second effort focuses on development of high n-type doping level in AlxGa1-xN alloys. Initial AlGaN layers and multiple quantum wells were grown on AlN substrates, with excellent structural results obtained.

Novel Active Layer Nanostructures for White Light Emitting Diodes (Phase I)

Investigating Organization
Dot Metrics Technologies

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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/13/04 - 4/13/05

Technology
Light Emitting Diodes

Project Summary

The most efficient solid state white lights developed to date typically use a bright blue light emitting diode, as a blue source, and, simultaneously, to optically excite an inorganic downconverter, converting a fraction of the blue light to yellow. The yellow light is mixed with the leftover blue to be perceived by the human eye as white. The energy efficiency of such a “white light emitting diode” is limited because the photonic downconversion process suffers from a fundamental energy loss (“Stokes shift”) as higher energy blue photons are converted to yellow. Also, the color uniformity in the illuminated region is not ideal, because the geometry of the blue source (a chip) is different than the source geometry of the yellow source (a layer atop the chip).

Recent results on InGaN LEDs have highlighted the positive effect of nanostructure on LED efficiency (O'Donnell, Martin et al. 1999). Dot Metrics Technologies and UNC Charlotte are working to incorporate multicolor nanostructured active layers into light emitting devices to achieve the same advantages with more color flexibility. In Phase I, we are formulating mixtures of various sizes of semiconductor quantum dots and integrating them into quantum dot composite structures. The color of the peak luminescence of a semiconductor quantum dot is dictated by the quantum size effect when the particle size is small compared to the Bohr-exciton radius (Brus 1984). Deposited quantum dot samples are analyzed with fluorescence microscopy and scanning probe microscopy. A preliminary LED design has been developed and LED devices are currently being fabricated in a designed experiment to determine optimum conditions for high-efficiency white light emission.

References:

Brus, L. E. (1984). "Electron-electron and electron-hole interactions in small semiconductor crystallites: The size dependence of the lowest excited electronic state." Journal of Chemical Physics 80(9): 4403-4409.

O'Donnell, K. P., R. W. Martin, et al. (1999). "Origin of luminescence from InGaN diodes." Physical Review Letters 82: 237-240.

Development of Silicon Nanocrystals as High-Efficiency White Phosphors

Investigating Organization
InnovaLight

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Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

Silicon nanocrystals produced and capped in the sub-10nm regime are efficient light emitters in the visible range due to quantum confinement effects. The specific color of emission is dictated by the size of the particle. As such, an ordered distribution of nanocrystals can be used to produce white light. This characteristic, coupled with nanocrystalline silicon's inherent stability and efficiency, makes these materials appropriate for use as phosphors with blue or near-UV high brightness light emitting diodes (HB-LEDs) in producing efficient white light for the general illumination market– a large and compelling market opportunity.

Silicon holds great promise in this application. First, silicon is capable of high efficiencies. Researchers have shown efficiencies approaching 90% from photo-excited silicon nanoparticles prior to any attempt to optimize emission. Second, the inherent stability of silicon, firmly substantiated over its 30 years as the fabric of modern day electronics, uniquely enables long lifetimes. Color stability is also achieved using a single material solution to reach all of the colors of the visible spectrum. This avoids the differential aging characteristic of other approaches that require multiple materials to do the same thing. Third, these novel materials can be tuned to achieve a high-quality white light by simply controlling the size distribution. Lastly, the surface passivation of the particles enable them to be suspended in a variety of solutions that, in turn, enable a number of efficient and well-understood, solution-based deposition schemes, such as ink jet printing. This is an important issue for manufacturability, and for successful commercialization. The combination of these advantages makes silicon a compelling option for HB-LED phosphors for white light emission.

InnovaLight has already produced unique size-controlled silicon nanocrystals with a variety of emission colors (color being a function of size). These materials have demonstrated high initial efficiencies. During the course of this grant, improvements to the photoluminescent quantum efficiency and color tunability was attempted through synthetic process control, particularly in the area of surface passivation. In addition, optimization of the color quality of white light emission was to have been conducted had high-efficiency emission been obtained.

The objective of this grant was to determine the capability of nanocrystalline silicon to function as a phosphor for use with high-brightness LED's. When this proposal was drafted, InnovaLight had demonstrated that relatively efficient photoluminescence in the visible region was obtained from colloidal silicon nanocrystals. They had also demonstrated color tunability in this material system, which offered potentially great benefits for achieving a phosphor with a high color-rendering index (CRI). Although Innovalight was successful in producing soluble silicon nanocrystals by surface derivatization, work is still being done on optimization of the surface properties of these novel materials. It is anticipated that significant improvements in efficiency could be achieved through improved surface passivation. Over the course of this project, significant improvements in passivation were achieved in that higher band-gap materials (yellow- and green-emissive silicon nanocrystals) were stabilized. In addition, proof-of-concept devices were fabricated utilizing silicon nanocrystals as phosphor materials in combination with blue-emitting high-brightness LED's. These proof-of-concept devices, although not yet optimized for optimal color-rendering, proved that white emission was possible by using silicon nanocrystal light emitters as phosphors. At the conclusion of this study, a large range of organic passivation methods had been attempted. However, all of these attempts were incapable of producing nanocrystalline silicon with higher photoluminescent quantum efficiency than unpassivated material. Although attainment of high quantum yield material remains a challenge to commercialization, Innovalight is continuing to explore new schemes to achieve high-efficiency, color-tunable silicon nanocrystal materials. Based upon discoveries made after the conclusion of the grant, it is expected that these new processes will improve the quantum efficiency of these materials to a level that is needed for the commercialization of these materials as phosphors. Continued effort will then be needed to optimize the use of these materials to achieve high CRI with conventional HB-LEDs.

General Illumination Using Dye-Doped Polymer LEDs

Investigating Organization
Intelligent Optical Systems

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Subcontractor
None

Funding Source
Small Business Innovation R&D

Award
DOE Share: $99,998

Contract Period
7/1/02 - 6/30/03

Technology
Light Emitting Diodes

Project Summary

New illumination technologies should be cost effective and have an acceptable color-rendering index (CRI). OLEDs, as broadband white light sources, are one such technology. A major advancement in the development of OLEDs has been the implementation of phosphorescent dyes as the emitting species, which has prompted large device enhancements to both monochrome and broadband OLED systems.

These advances have also created opportunities to enhance lighting efficiency by mating electro-phosphorescence with novel polymers. Intelligent Optical Systems (IOS) is pursuing this pathway, which is expected to result in easy-to-process polymer materials. These materials have exceptional properties, and are an inexpensive and efficient general illumination lighting source. This methodology will allow polymer light emitting devices (PLEDs) to obtain the outstanding efficiencies of small molecule-based devices.

IOS has successfully demonstrated a white light source for general illumination that uses the triplet emission from one or more dyes embedded in a novel polymer matrix. Using this approach, the devices maximize the conversion of charge-to-light. The methodology is unique because the polymer matrix allows the use of highly efficient phosphorescent dyes as emitters within the device architecture. The researchers expect that external device efficiencies will be greater than 4%, while maintaining excellent color rendering quality and high brightness.

In the first phase of the project, IOS demonstrated the feasibility of producing PLEDs significantly more efficient than existing fluorescent-based white devices. Future research will involve strengthening and enhancing the PLED technology by studying performance degradation issues. Material purity, device fabrication pathways, and device structural design will be researched. This research will be instrumental in improving the device fabrication capabilities, material analysis, and overall lighting knowledge needed for this technology to improve solid state lighting efficiency.

Gallium Nitride Substrates for Improved Solid State Lighting

Investigating Organization
Kyma Technologies

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Subcontractor
None

Funding Source
Small Business Innovation R&D

Award
DOE Share: $100,000

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

Device cost and limitations in GaN materials technology, manifested by the lack of a large, native-nitride substrate, currently holds back the incorporation of GaN-based devices into solid state light sources. The use of GaN substrates will address these issues by reducing the number of performance-hindering defects in devices and by achieving lower costs because of fabricating devices with higher yields. Kyma Technologies has developed a process for fabricating 50 mm GaN substrates, enabling the realization of high-efficiency blue-green and UV LEDs.

The availability of freestanding GaN substrates should significantly simplify the growth of GaN since lattice and thermal issues will no longer be relevant. Homoepitaxy growth decreases the average GaN threading dislocation density, thus improving the electrical properties of the material. The accomplishment of low-dislocation-density GaN material will increase lifetime and brightness in optoelectronic devices. Moreover, lower defect levels should also increase thermal conductivity of the GaN, which will be beneficial for device operation. Wafer cracking and/or bowing will be minimized because the coefficient of thermal expansion between the GaN epitaxial layer and the substrate will be the same.

Kyma Technologies and Georgia Tech are developing a process for production of LED device structures with low defect densities on gallium nitride substrates. The nitride MOVPE growth process is being used to grow gallium nitride epitaxial layers on this

substrate material. The program will determine the optimal growth conditions for MOCVD growth of GaN on GaN substrates. The GaN substrate has structural and thermal properties that will improve gallium nitride and AlGaN layers in the device structure. The electrical and optical characteristics and defect density of GaN epitaxial layers on GaN substrates will also be characterized.

Kyma Technologies has completed the Phase I SBIR and demonstrated the feasibility of producing LEDs on gallium nitride substrates. The Phase I development effort focused on GaN substrate characterization, demonstration of growth of GaN epitaxial films, and fabrication of a SQW LED device. The blue LEDs fabricated on gallium nitride substrates operated with a forward voltage (Vf) of 3.0 – 3.5 V at 20 mA for a LED emitting at a wavelength of 450 nm. This represented an improvement over the same device fabricated on a sapphire substrate.

Enhanced Optical Efficiency Package Incorporating Nanotechnology Based Downconverter and High Refractive Index Encapsulant for AlInGaN High Flux White LED Lamp with High Luminous Efficiency LED Phosphor Performance (Phase I)

Investigating Organization
Nanocrystals Technology

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Subcontractor
None

Funding Source
Small Business Innovation R&D

Award
DOE Share: $99,933

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

Nanocrystals Technology LP (NCT) has developed unique nanotechnology-based materials that will cost-effectively enhance performance of white LED lamps for general illumination applications. These innovations include optically non-scattering efficient downconverter Nanophosphors and high refractive index (HRI) Nanocomposites that enhance both the Package Optical Efficiency (POE) and Light Extraction Efficiency (LEE) of white LED lamp at the package level.

Today in white LEDs, blue-to-white light conversion is exclusively achieved by using YAG:Ce 3+, an efficient broad-band, yellow-green phosphor. One of the drawbacks of this system is that the mixing of blue/yellow color not only produces halo effect, but also yields inferior color rendering. Absorption process in phosphors such as YAG:Ce 3+, involve impurity states of rare-earth (RE) emission that have low absorption coefficient of about 40 cm-1 in the region of interest. The low absorption in RE systems requires larger size particles and increased scattering to enhance the net absorption. Nanocrystals has demonstrated that in nanophosphors, the absorption coefficient associated within intra-atomic states of the RE-activator is enhanced by two orders of magnitude. These nanophosphors, when optimized, would eliminate the required scattering conditions and the halo effect.

NCT has developed nanocomposites of refractive index of 1.8 . This was achieved by incorporating TiO_2 nanoparticles with proprietary coating that are dispersed uniformly to yield optically transparent nanocomposites. The HRI encapsulants were used to demonstrate >25% improvement in efficiency of green and red LEDs. Furthermore, we have incorporated YAG:Ce^{3+} bulk phosphor of refractive index 1.85 in nanocomposite encapsulant of refractive index 1.8. The matched refractive indices render the downconverter nanocomposite optically transparent. These optically transparent HRI nanocomposites containing bulk YAG-phosphor increase the efficiency of white LEDs by 40% over the current LEDs that use the same YAG-phosphor and encapsulant of refractive index of 1.5.

Projected 50% enhancement in POE due to the optically non-scattering downconverter, when combined with an additional ~40% enhancement in LEE due to HRI encapsulant, would lead to a good color-quality, high-luminous efficacy white LED lamp with ~ 95 lm/W using present AlInGaN blue LED die/chip with wall-plug-efficiency of 25%. With improved LED chip efficiency in the future, the use of HRI nanocomposites and nanophosphors will allow us to achieve luminous efficacy of 200 lm/W.

High-Efficiency Nanocomposite White Light Phosphors (Phase I)

Investigating Organization
Nanosys Incorporated

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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,891

Contract Period
7/13/04 - 4/12/05

Technology
Light Emitting Diodes

Project Summary

The objective of the proposed program is the development of a down-converting system based on engineered nanocomposite materials that will improve the overall cost, performance, and efficiency of solid state white light.

The Phase I project focuses on determining the feasibility of utilizing engineered nanocomposite down-conversion layers for white light illumination and demonstrating the potential benefits from a perfectly color-matched, non-scattering, index-matched, high quantum yield, thin-film phosphor layer technology. This project will increase our understanding of the various loss mechanisms occurring within the complete system and is directed at 1) fabricating optimum nanocomposite mixtures based on theoretical predictions; 2) demonstrating the effect of controlling index of refraction and scattering in the phosphor layer; and 3) projecting eventual performance improvements upon further materials optimization and device design in Phase II.

The proposed technology has the potential to produce solid state white light exceeding the best traditional fluorescent and incandescent bus, with rendering of greater than 80, color temperature of 4,000 K, and luminous efficiency of greater than 200 lm/W, while at a cost of less than $1/klm.

New, Efficient Nano-Phase Materials for Blue and Deep Green Light Emitting Diodes (Phase I)

Investigating Organization
Nomadics

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Subcontractor
Oklahoma State University

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/1/04 - 4/1/05

Technology
Light Emitting Diodes

Project Summary

Scientists at Nomadics have invented several nanomaterials exhibiting strong emissions in blue (435 nm) and deep green (555-585 nm). These new materials will complement, and possibly replace, the existing GaN-based and InP(As) based materials for illumination and full-color displays.

Phase I will involve the demonstration of a new type of blue emission material with a high photoluminescence quantum yield (>40%), high stability and low cost that is promising for blue LEDs. It will involve the demonstration of II-VI semiconductor nanoparticle LEDs with efficient deep grain emission (555-585 nm), low power, and high stability. Phase I will also demonstrate the concept of all-inorganic semiconductor nanoparticle LEDs with much better performance in electroluminescence efficiency, brightness, stability, and longevity than organic/inorganic nanoparticle LEDs.

The application of LEDs are ubiquitous and include indicator lights, numeric displays on consumer electronic devices, flat panel displays, general illumination, biological/ biomedical imaging and detection, and bacterial disinfection.

The goal of this project is to fabricate efficient nanoparticle LEDs with emission wavelengths in the range of 555- 585 nm. To meet the overall goal of fabricating deep green LEDs, this project will focus on the following objectives in Phase I:

1. Synthesis of silica-coated CdTe, CdSe, and CdSe/CdS solid nanoparticles with emission wavelengths in the range of 555-585 nm and photoluminescence quantum efficiency greater than 50%.

2. Demonstration of efficiency enhancement and lifetime improvement by PLD fabrication of nanoparticle/PPV LEDs in high vacuum.

3. Demonstration of high-efficiency electroluminescence and good stability from all-inorganic nanoparticle LEDs by sandwiching nanoparticle monolayers between p-type (SiC, ZnTe) and n-type (Si) semiconductor layers. All-inorganic nanoparticle LEDs should exhibit low operation power and voltage and high longevity.

4. Improvement of recipes for making blue nanoparticles with narrow-size distribution and high (40%) efficiency.

Successful accomplishment of these objectives will serve as proof-of-principle and will warrant continuation of the research into Phase II with a focus on demonstrating viable nanoparticle LEDs with external quantum efficiency of 25-30%, brightness of 2000 cd/cm2, and lifetime of 5000 hours.

At this point, we have successfully made nanoparticle with deep green emission with high efficiency and have observed electroluminescence from our nanoparticle LEDs. Light emitting diode performance is affected by the thickness of the hole and electron transport layers. By optimizing the thickness of these layers, we have successfully confined the carriers within the nanoparticle emitting layer and observed strong luminescence from the nanoparticles.

High-Extraction Luminescent Material Structures for Solid State Light Emitting Diodes (Phase I)

Investigating Organization
PhosphorTech Corporation

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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,976

Contract Period
7/1/04 - 4/1/05

Technology
Light Emitting Diodes

Project Summary

In Phase I, PhosphorTech successfully demonstrated novel high-performance fluorescent materials for next generation lighting application using solid state lamps. The novel phosphor materials and lighting devices were based on hybrid organic/inorganic systems with superior color rendering and power conversion efficiencies to the current-state-of-the art technology. These materials were fabricated using controlled solid-state synthesis techniques and were derived from existing UV-efficient phosphors that were modified to allow blue light absorption and broadband emission in the yellow-green (550-580 nm) and yellow-orange (580-610 nm) part of the visible spectrum.

Novel non-garnet materials were successfully demonstrated with luminous efficiencies exceeding those of commercial cerium-doped yttrium aluminum garnet phosphors (YAG:Ce). During Phase I, various compositions of the SrxBa(1-x)SiO4:Eu phosphor system have been successfully synthesized by solid state reactions using SrCO3, BaCO3, and SiO2 as precursors. In addition, ZnSexS(1-x):Cu phosphors were successfully produced using a copper-doped mixture of ZnS and ZnSe precursors. The organic materials used in the study were commercially available fluorescent pigments based on rhodamine and auramine molecular compounds. Using the phosphor materials with a blue LED, hybrid solid-state sources were demonstrated with luminous efficiencies exceeding those of YAG-based LEDs. Two hybrid approaches were demonstrated: (1) Blue LED using an inorganic-organic phosphor system; and (2) Blue/Red LEDs using an inorganic phosphor. Stability tests were conducted on the new hybrid materials and new lamp designs were developed to minimize thermal aging for high-power applications.

Future improvement of the phosphors' quantum efficiencies along with improved LED performance and luminaire designs are expected to yield luminous performance exceeding that of fluorescent lamps. Various illumination architectures will need to be evaluated and built in order to maximize the light extraction from the solid-state lamp system while maintaining high longevity at high power levels. Commercialization of some of the new non-garnet materials is currently being pursued by PhosphorTech, and at least two patent applications were filed with the U.S. Patent Office on inventions that were derived, in part, from Phase I research.

Efficient Hybrid Phosphors for Blue Solid State LEDs

Investigating Organization
PhosphorTech Corporation

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Subcontractor
None

Funding Source
Small Business Innovation R&D

Award
DOE Share: $99,984

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

PhosphorTech is pursuing the development of high performance fluorescent materials for next generation lighting application using solid state lamps. The novel phosphor materials and lighting devices will be based on hybrid organic/inorganic systems with superior color rendering and power conversion efficiencies to the current state of the art. These materials will be fabricated using controlled synthesis techniques. Existing UV-efficient silicate phosphors will be modified to allow blue light absorption and broadband emission in the yellow-green. The goal of Phase I is a white LED having a luminous efficiency of 30 lm/W (2 times that of incandescent bulbs) and a color rendering index over 80. The goal of Phase II is a white LED having a luminous efficiency > 50 lm/W and a CRI > 90.

The availability of efficient white LEDs will open up a number of exciting new application markets, such as white light sources replacing traditional incandescent and fluorescent light bulbs and efficient low-voltage backlights for portable electronics. The down-converting hybrid phosphor materials could also be used to make pixilated screens for full-color photonically driven displays (using RGB filters), and even in maintenance-free LED-based traffic lights.

Novel Low-Cost Technology for Solid State Lighting (Phase I)

Investigating Organization
Technologies and Devices International

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Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,976

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

The work of Technologies and Devices International focuses on demonstrating a novel epitaxial technology with substantially reduced process cost for fabrication group-III nitride epitaxial structures for white light emitting diodes. The technology is based on hydride vapor phase epitaxy (HVPE) of AlGaN/GaN light emitting structures.

For group-III nitride semiconductors, HVPE is known to be a low-cost method for fabrication of thick quasi-bulk GaN materials, GaN-on-sapphire, and AlN-on-sapphire templates used as substrates for device fabrication. The Phase I objective is to extend HVPE cost-effective epitaxial technology for the fabrication of white light emitting devices. Al(In)GaN-based blue ultra violet emitters fabricated by HVPE technology for lighting applications will be demonstrated.

This technology will also provide a number of technological advantages for the growth of high-efficient blue and UV light-emitting structures. General lighting devices will be fabricated by packaging the blue or UV LEDs with a white light conversion phosphor blend. Potential applications include residential general illumination, aviation, and hazard indicators.

The researchers have also designed light emitting structures and investigated material deposition HVPE technology. A novel HVPE method has grown two sets of epitaxial materials. Grown samples are under characterization. The next step will be to grow p-type AlGaN layers, and to fabricate structures for blue-UV LED dies processing and delivery of pn structures for phosphorous deposition.

High-Efficiency ZnO-Based LEDs on Conductive ZnO Substrates for General Illumination (Phase I)

Investigating Organization
ZN Technology

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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/3/04 - 4/12/05

Technology
Light Emitting Diodes

Project Summary

High-efficiency, white light LEDs will be fabricated from alloys of ZnO on conductive ZnO substrates utilizing a phosphor(s) to convert the nearly monochromatic, blue or near UV light of the LED to white light. The method for p-type doping patented by the PI along with the growth of high quality ZnO substrated in-house will enable the project to proceed rapidly. The inherent luminous efficiency of ZnO along with the ability to construct totally vertical devices due to the conductive substrate and the lower cost of the basic materials will result in increased efficiency and lower cost than the current technology.

ZnO-based LED structures will be fabricated and characterized during Phase I. Initially, a simple pn device will be made and fully characterized for electrical and electro-optic characteristics. Subsequently, a single quantum well LED will be constructed using a CdZnO alloy as the quantum well and MgZnO as the barriers. The LED structure will be fully characterized and the data used to project efficiency of an optimized LED device based on these compounds. Selection of phosphor(s) for conversion to white light and their impact on the overall efficiency will be projected.

Development of this technology will result in high efficiency, low cost, white light LEDs for general illumination. In addition, it will also result in high brightness bleu and ultra violet LEDs for application in displays, backlighting and other applications. The

technology for high efficiency diode lasers will derive from the LED technology. These lasers will have application in the high density optical storage industry (DVDs, etc.), in the printing industry, (i.e.. direct computer writing to printing plates) a in other areas requiring a highly compact, high efficiency laser source in the blue of ultra violet.

OLED Durability and Performance

Investigating Organization
General Electric Global Research

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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,951,064

Contract Period
9/1/00 - 11/15/03

Technology
Organic Light Emitting Diodes

Project Summary

GE Global Research conducted a three-year program to reduce the long-term technical risks that are keeping the lighting industry from embracing and developing OLEDs. The specific goal was a demonstration light panel that delivers white light with brightness and light quality comparable to a fluorescent source and with an efficacy better than that of an incandescent source. This required significant advances in three areas: 1) improvement in OLED energy efficiency at high brightness; 2) improvement of white light quality for illumination; and 3) the development of cost-effective, large-area fabrication techniques.

The technical effort was divided into three main technical phases designed to achieve a significant milestone at the end of each year.

In Phase I, GE developed a small area-efficient white light device. This task involved sourcing available blue polymers and using these to fabricate and evaluate device performance. One polymer was chosen for white device development. The key outcome of this phase was the first demonstration that high illumination-quality white light could be generated using OLED technology.

Phase II focused on scaling up the white device manufacturer to a device measuring 36 square inches. In order to do this, new area-scalable device designs were developed to allow the development of large area OLEDs using low cost techniques. The key outcome of this phase was the invention of a novel device design that is tolerant to manufacturing defects and scalable to a large area.

Phase III was devoted to improving the underlying OLED device efficiency and developing the technology and system optimization required to build a 2 ft. x 2 ft. demonstration panel for white-light illumination. The key outcome of this phase was a final 2 ft x 2ft OLED deliverable panel with the following “world-record” specifications:

- Color Temperature: 4000 K Efficacy: 15 Lumen/Watt
- Color Rendering: 88 CRI Light Output: 1200 Lumens

This project was successful both in meeting its technical objectives and in demonstrating to the lighting community that OLEDs are a potentially viable solid state lighting source. This is evidenced by the healthy quantity and variety of OLED lighting projects currently being funded by DOE.

Polymer OLED White Light Development Program

Investigating Organization
OSRAM Opto Semiconductors

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Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $4,650,000

Contract Period
2/5/04 - 1/31/07

Technology
Organic Light Emitting Diodes

Project Summary

OSRAM-OS is working on a 3-year project to develop, fabricate, and fully characterize a 12-inch x 20-inch OLED white light prototype for DOE. This work is being conducted at the company's OLED R&D Center in San Jose, CA. OSRAM's Materials and Device Group is currently working closely with major polymer materials suppliers to develop the polymer emissive technology needed to meet the performance milestones of this project. The Process Development Group is developing the process for fabricating the OLED white light prototype, and the Product Development Group is performing the electrical and optical characterization. This group is also developing the white lighting module including the electronic control for powering the lighting source. Finally, the lighting module will be field tested by Electric Control Systems Division within OSRAM/Sylvania.

The advanced white light prototype will be based on multiple, discrete 2-inch x 3-inch white light devices fabricated on glass substrates. Two approaches for achieving white light from the discrete devices will be pursued in parallel. In the first, the device will use a broadband light-emitting co-polymer for the generation of white light, from either a single large area emitting film, or from a number of segmented light emitting films. In the second approach, the device will use a larger array of color tri-stripes, or tri-segments, of red, green, and blue polymer emitters combined with a light diffuser to produce white light.

Currently Osram is developing, together with their materials partners, white emitting co-polymers which deliver more than 6 lm/W at 300 nits with a device half-life of more than 1000 hours. In parallel, OSRAM has been developing red, green and blue conjugated polymer solutions to be used for ink jet printing the light emitting segments. Over the next two years in order to improve efficiencies, Osram will also investigate the use of light extraction techniques and the use of molecularly dispersed triplet emitters.

In the third year of the program OSRAM-OS expects to produce a color-balanced OLED white light source with luminous efficacy of 20 lm/W at 800 nits, and achieve an operating half-life of 3,000 hours.

Enhancing Charge Injection and Device Integrity in Organic LEDs (Phase I)

Investigating Organization
Agiltron Inc.

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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/13/04 - 4/12/05

Technology
Organic Light Emitting Diodes

Project Summary

Organic lighting emitting diode (OLED) based sold state lighting is a candidate technology that offers significant gains in power efficiency, color quality, and life time at lower cost and less environmental impact than traditional incandescent and fluorescent lighting. However, current achievements in OLED devices have not yet realized the power efficiency and lifetime requirements for general lighting applications. Two important factors limiting performance are on-efficiency and non-balanced charge injection leading to poor device stability.

The goal of this program is to develop innovative, low cost OLED anode surface modification technology, which will increase device energy efficiency by 5 to10 times while also significantly improving device stability and lifetime simultaneously. OLED anode (ITO) modification using an ultra-thin cross-linked hole transporting layer is planned by means of a low-cost self assembly approach. Cross-linkable, high hole transporting molecules will be synthesized and application methods commensurate with automated processing will be developed.

Air-stable, cross-linkable, high mobility hole transporting molecules have been synthesized with a high yield. These molecules are being spin-coated on conventional ITO substrates, on which multilayer OLED structures will be fabricated. Improvements in device energy efficiency and lifetime by the novel ITO surface modification layer will be evaluated and compared with OLED devices built on bare ITO substrates and substrates coated with other ITO modification agents. The coating process will be scaled to coat large-area rigid or flexible ITO substrates under an ambient environment using low-cost automated dip-coating or roll-to-roll coating processes, which are under development.

High performance OLEDs will be extremely beneficial for solid state lighting, high brightness image displays, sign indicators, automobile displays, and wearable electronics.

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High-Performance, Silicon Nanocrystal-Enhanced Organic Light Emitting Diodes for General Lighting (Phase I)

Investigating Organization
InnovaLight

Principal Investigator(s)
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Subcontractor
University of Texas at Austin

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/15/04 – 4/15/05

Technology
Organic Light Emitting Diodes

Project Summary

Silicon nanoparticles hold great promise toward enabling highly efficient, color tunable, and cost-effective white light emitting devices capable of meeting the high standards of the general illumination market. While silicon, in its usual bulk form, does not emit light, when the particle size is reduced below five nanometers, these silicon nanoparticles can display very bright photoluminescence. Single-particle spectroscopy research has shown that quantum efficiencies approaching 100% are technically possible. Depending upon the size of the nanoparticle, this emission is tunable throughout most of the visible spectrum and into the IR. Precise variation of size and size distribution provides a simple, yet powerful, means of controlling emission quality. Also, since the emitter is the same silicon material in all cases, we do not anticipate differential aging problems that would tend to degrade emission quality over time.

The objective of this Phase I grant proposal is to develop a novel core-shell passivation scheme to stabilize silicon nanocrystal photoluminescence and, ultimately, achieve the theoretically predicted 100% quantum efficiency. InnovaLight is currently well on the way toward achieving this milestone. In Phase I, silicon nanocrystals will be treated using an innovative passivation scheme that coats them with novel inorganic shells. Two different core-shell combinations will be explored and proof-of-concept devices will be made. The resultant materials will be analyzed for both their physical and emissive properties. The goal is to have well-characterized, light emitting particles ready for device optimization work in Phase II, a project we anticipate will focus on employing the stabilized nanocrystals in novel hybrid organic light emitting devices.

Numerous other high value market opportunities exist for the proposed technology as well, including flat panel displays, specialty lighting, biological sensors, quantum dot lasers, and novel floating gate memory structures. There is much commercial value in furthering research into this fundamental scientific area.

New Stable Cathode Materials for OLEDs (Phase I)

Investigating Organization
International Technology Exchange

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,800

Contract Period
7/1/03 - 4/30/04

Technology
Organic Light Emitting Diodes

Project Summary

NAC (nanostructured amorphous carbon) materials can be made electroactive by "doping" with a wide range of elements and compounds. The materials are deposited in a vacuum using plasma-enhanced chemical vapor deposition (PECVD) with the substrate at or near room temperature. The films can be deposited on a wide range of substrates, including polymeric and other organic substrates.

NAC films are dense and can be made pinhole-free at a thickness below 1 mm. They have excellent properties as corrosion protection coatings, implying that these films are effective barriers to water and oxygen. The work function can be varied by doping with elements with different electronegativities.

During Phase I, OLEDs were fabricated with a 100 nm thick emitter layer of Alq3 and a PEDOT:PSS hole conducting layer on ITO. The top layer was an Al-doped NAC cathode layer. The performance of these OLEDs were compared with that of OLEDs made with evaporated Al metal films as cathodes. Additionally, OLEDs were made in the reverse order with the emitter layer deposited on top of the NAC cathodes and with a thin, semi-transparent Au film as anode. The results fulfilled the objective of demonstrating the proof-of-principle that NAC coatings can be used as cathode materials. The Al-NAC cathodes had a turn-on voltage of ~8V vs. ~4V for cells with evaporated Al metal cathodes.

In addition, atomic force microscopy of the NAC coatings revealed that the ~1mm coatings that were used were atomically smooth and free of pinholes.

Zinc Oxide Light Emitting Diodes (Phase I)

Investigating Organization
Materials Modification, Inc.

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/14/2004 - 4/14/05

Technology
Organic Light Emitting Diodes

Project Summary

In order to improve the cost and efficiency of OLEDS for solid state lighting, an alternate transparent conducting oxide (TCO) electrode has been proposed. This TCO will be prepared as a sputtering target and coated on glass substrates. These will be converted into fully functional OLEDS for evaluation. An alternate to ITO will provide for lower cost and potentially higher performance OLEDs, flat panel displays, electrochromic mirrors and windows, and defrosting windows.

A selectively doped TCO has been synthesized and pressed into a sputtering target. The TCO has been deposited onto a glass substrate at various sputtering conditions to obtain films of various resistivities and transmittance. The substrates will be used for the construction of OLED for testing and evaluation at Universal Display Corporation.

New Solid State Lighting Materials (Phase I+)

Investigating Organization
Maxdem

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,957 (Phase I), $749,813 (Phase II)

Contract Period
7/1/02 - 6/30/03 (Phase I), 6/1/03 – 6/1/05 (Phase II)

Technology
Organic Light Emitting Diodes

Project Summary

Maxdem is currently working to extend Phase I results to a three-color system. In addition, more economically efficient methods of synthesis of the new phosphors are being developed. In the first quarter of Phase II, new monomers and phosphors have been prepared. These will be tested in OLEDs when all three (blue, green, red) phosphors have been fully characterized.

Maxdem will work to develop white-emitting electroluminescent materials and devices. A concept to control energy flow within the emitting layer will be used to prepare and evaluate a large number of polymers and blends. Optimization of material and device structures will result in phosphors meeting solid state lighting system performance and cost requirements.

The goal is to enable broad lighting applications primarily in the commercial and military sectors. The proposed concepts may also have utility in other photonic applications, such as displays, lasers, sensors, and photovoltaic devices.

Efficient Nanotube OLEDs (Phase I)

Investigating Organization
NanoTex

Principal Investigator(s)
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Subcontractor
Lawrence Berkeley National Laboratory

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
9/22/04 - 4/12/05

Technology
Organic Light Emitting Diodes

Project Summary

Polymer, based OLED is recognized as an ideal source for area lighting application for the potential large area production and approaching the required efficiency and unit brightness, and color rendering effects. In order to achieve low cost and high efficiency, it is crucial to have an air stale cathode with efficient electron injection properties.

Carbon nanotube (CNT) has been demonstrated as a viable electron injection material for OLED application, with the need to increase solubility and dispersion to improve performance.

In Phase I, NanoTex proposes to use purified single wall type of CNT, combined with surfactant conductive polymer, to develop a stable solvent processible cathode for OLED applications.

Polymer White Light Emitting Devices (Phase I)

Investigating Organization
Reveo

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,800

Contract Period
7/1/03 - 4/30/04

Technology
Organic Light Emitting Diodes

Project Summary

The goals of Phase I are to demonstrate the functionality of Reveo's new material technology for light-emitting electrochemical cells (LECs) with frozen p-i-n junctions, and to demonstrate the applicability of the materials to organic electroluminescent devices. Devices fabricated with the new materials will be tested for white light quality, high efficiency, high brightness, low operating voltage, and insensitivity to electrode materials and film thickness. Success developing this material may lead to improved solid-state lighting performance for general illumination.

The feasibility of the frozen junction approach was successfully demonstrated in Reveo's recent research for single color light emitting devices and showed great potential in flat panel color displays.

The characteristics of the frozen junction LECs make it possible to fabricate high efficiency, high power output and long lasting light emitting devices at low cost. Because balanced charge injection in LECs is insensitive to the band gap and ionization potentials of semiconducting polymers, frozen-junction LECs provide an approach to fabricating high quality white lights

There are three main methods that have been proposed to produce white OLED devices using polymers or organic small molecules. 1) The first one is to dope the single host emissive layer with some laser dyes that emit at different color ranges from the host material or blending two different emissive materials; 2) An alternative one is to use a microcavity structure to get two or three emissions simultaneously from one emissive layer; 3) The third one is to use a multi-layered device structure to get different color emission at the same time from different emissive layers

Since LECs utilize single layer organic materials, the first method is the most suitable for LECs to generate white light. In Phase I, organic emitting materials used in white OLEDs will be used in LECs to demonstrate the feasibility of producing white light. In phase II, organic light emitting materials will be specially designed and synthesized for LEC devices to generate high-efficiency, high-power, long-lasting, and low-cost white light.

The simplest solid electrolyte system was chosen in Phase I to prove the concept of Reveo's innovation. Commercially available poly(ethylene oxide), PEO, will be used as the ion transport material. Organic salts will be synthesized bearing vinyl polymerizable functionality. The new electrolyte system and commercially available emitters will be used to fabricate LECs with frozen p-i-n junctions. Devices will be made and tested for unipolar light emission, fast response, high brightness, low operating voltage and insensitivity to electrode materials and film thickness.

Polymer Composite Barrier System for Encapsulating LEDs (Phase I)

Investigating Organization
T/J Technologies, Inc.

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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
6/27/03 - 6/25/05

Technology
Organic Light Emitting Diodes

Project Summary

Organic light emitting devices (OLEDs) may find widespread application as replacements for fluorescent lighting, small displays, and general indoor/outdoor illumination. However, advanced packaging materials are needed to improve their lifetime and durability. This project will develop a transparent, high-barrier polymer composite system for encapsulating OLEDs. The composite materials, comprised of a high barrier polymer and highly dispersed nanoscale additives, will extend the operational lifetime of OLEDs to over 10,000 hours. Dramatic improvements in the moisture and oxygen barrier properties of transparent polymers will be achieved by tailoring the processing and microstructure of the nanocomposite systems. Phase I will produce polymer nanocomposites comprised of a high barrier polymer and a range of selected additives that can be oriented to reduce gas and vapor permeation. In addition, solution-based processing will be utilized to improve additive dispersion and the ability to orient the additive. The materials will be screened for optical clarity and moisture/oxygen transmission rates.

In this program, T/J Technologies and Michigan State University will co-develop a transparent, high barrier polymer composite system for encapsulating OLEDs. The composite materials, comprised of high barrier polymer and highly disperse nanoscale additive will extend the operational lifetime of OLEDs to >10,000 hours. Dramatic improvement in moisture and oxygen barrier properties of transparent polymers will be achieved by tailoring the processing and microstructure and nanocomposite systems.

In Phase I, polymer nanocomposites comprised of high barrier polymer and a range of selected additives that can be oriented to reduce gas and vapor permeation will be produced. Solution-based processing will be utilized to improve additive dispersion and the ability to orient the additive. The materials will be screened for optical clarity and moisture/oxygen transmission rates.

The target application for this technology is polymer based encapsulants for low cost OLEDs. It is anticipated that OLEDs will find application as replacement for fluorescent lighting, small displays, decorative lighting, glowing wallpaper and general indoor/outdoor illumination. Additional market opportunities for low cost, transparent, high impact plastics with significantly increased moisture and oxygen barrier properties include lightweight replacement of glass n structured applications, lenses, coatings for electronic packaging and flexible packaging films for food and non-food applications to replace existing metallized and laminate films.

Monomer-Excimer Phosphorescent OLEDs for General Lighting (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/02 - 6/30/03

Technology
Organic Light Emitting Diodes

Project Summary

See White Illumination Sources Using Striped Phosphorescent OLEDs (Phase I).

Novel High Performance OLED Sources (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
Princeton University
under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
6/27/03 - 6/25/05

Technology
Organic Light Emitting Diodes

Project Summary

Based on its research in phosphorescent OLED (PHOLED) technology, the project team has demonstrated OLEDs that are up to four times more power efficient than previously thought possible. In this Phase II program, Universal Display Corporation, Princeton University, and the University of Southern California are further pursuing two novel approaches to further increase the efficiency of broadband white light generation building on the successful feasibility studies of highly efficient white PHOLED technology demonstrated in our two previous DOE SBIR Phase I awards.

Novel Striped Design for White OLED Illumination Sources. Here the Team is investigating the use of PHOLEDs in a striped-pattern R-G-B configuration to demonstrate very-efficient white light generation. In this configuration, each stripe contains one of three colors, red, green and blue, or red, yellow and blue. Fabricating white OLED light sources in this manner offers a number of potential advantages and benefits. These include 1) very high power efficiency, 2) long lifetime, 3) excellent CIE and CRI, 4) full color tunability, and 5) color correction for differential aging.

Monomer-Excimer White OLED Illumination Sources While there are a number of possible approaches to produce white OLED (WOLED) lighting; USC and Princeton University recently demonstrated a novel approach using high-efficiency phosphorescent excimers. In addition to offering a power efficient approach, this approach also offers provides opportunities to reduce both the number of dopants and the number of discrete emissive layers, simplifying the device structure, the fabrication process and the resulting manufacturing costs. Our approach to reduce the number of dopants and structural heterogeneities inherent in the preceding architectures is to employ a lumophore that forms a broadly emitting state, such as an excimer or exciplex (i.e. an excited state whose wavefunction extends over two identical or dissimilar molecules, respectively).

Recently, the team has accomplished the following: New platinum functionalized random copolymers for use in solution processable white organic light emitting devices were synthesized and evaluated. A record 100% internal quantum efficiency green [CIE (0.30, 0.64)] device was fabricated. This device had EQE = 20% and a luminous efficiency = 75 cd/A at 100 cd/m2. A new record efficiency blue device has been developed. Blue [CIE (0.14, 0.21)] devices were fabricated with a luminous efficiency of 19 cd/A and an external quantum efficiency of 12% at 100cd/m2. This is a much higher efficiency than can be achieved from fluorescent emitters, and is a 60% improvement over previous blue device reports provided by UDC. Developed a model to predict the ability of an end-user to differentiate between the various colored striped lines.

In Phase II, the team will demonstrate white OLEDs with greater than 20 lm/W efficiency at 800 cd/m2, and deliver 6” x 6” prototype lighting panels, based on tiling four 3” x 3” sub-panels. This work will then be coupled with parallel development programs focusing on improving PHOLED performances through new materials development, device optimization, lifetime improvement, and novel approaches to enhance the optical extraction efficiency. The successful completion of this Phase II program will significantly accelerate the use of OLED devices as commercial sources of general illumination.

Novel Light Extraction Enhancements for White Phosphorescent OLEDs (Phase I)

Investigating Organization
Universal Display Corporation

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Subcontractor
Princeton University
under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/21/03 - 4/20/04

Technology
Organic Light Emitting Diodes

Project Summary

In Phase I, Universal Display Corporation, a developer of OLED technologies for flat panel displays, lighting and other opto-electronic applications, is working to demonstrate innovative techniques to improve OLED power efficiencies, a critical performance attribute for the general lighting industry. Universal Display and its research partners at Princeton University and the University of Southern California are developing several novel approaches for producing highly efficient white light using the Company’s phosphorescent OLED (PHOLED™) technology.

In addition to the use of this highly efficient PHOLED technology, better light extraction techniques are required to achieve the power efficiency targets of the general lighting market, as in a conventional OLED only approximately 25% of the generated photons are emitted from the device. In this program, Universal Display and Princeton University demonstrated the feasibility of using specialized designs, such as lens arrays, on an OLED device to enhance the amount of generated light that is captured or extracted from the device as useful light.

Specifically, two key objectives of Phase I were: Demonstrate and deliver a white PHOLED light source on a glass substrate, with an attached flattened lens array to provide enhanced optical extraction over a similar device without an attached lens.

Characterize the above white light sources and demonstrate > 15 lm/W at 800 nits luminance.

During Phase I of this program, the team accomplished several key goals: developed a process for producing different microlens silicon molds, demonstrated device performance characteristics that met expectations, and explored new outcoupling schemes based on models of outcoupling enhancement using aperiodic gratings.

Silicon molds for forming microlenses from poly-di-methyl-siloxane (PDMS), a thermal curable elastomer, were fabricated. The ability to control the dimensions and shape of the silicon mold is important since these factors affect the outcoupling efficiency. Our work demonstrated that we have the capability to optimize the silicon molds to further enhance the outcoupling efficiency by adjusting the period and size of the array elements.

Both sets of microlenses formed from the molds improved the outcoupling efficiency by ~22%. The improvement in efficiency was found by comparing the total forward emission from devices with and without the microlens array attached to the glass substrate. The total forward emission was found by using an integrating sphere, such that all forward emitted light was collected in the sphere. The efficiency of a white device operating at 6.3 V and 20 lm/W having CIE (0.39, 0.40) at 800 cd/m2 was improved such that the same device with microlenses operated at 6.3 V and 24 lm/W at 1000 cd/m2, which met our goals.

Novel Lower Voltage OLEDs for High-Efficiency Lighting (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
Princeton University
University of Southern California

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/03 - 4/30/04

Technology
Organic Light Emitting Diodes

Project Summary

The team led by Universal Display Corporation with their university partners at Princeton University and the University of Southern California is focusing on the development of novel, low-voltage phosphorescent light emitting structures to enable OLEDs with power efficiency >20 lm/W at a brightness of 800 cd/m2. The power efficient OLEDs will result from the development of innovative, highly conductive hole and electron transport systems in conjunction with high-efficiency triplet emitters.

Triplet emitters contain a heavy metal atom that facilitates the mixing of singlet and triplet states, allowing singlet to triplet energy transfer through intersystem crossing. This leads to highly efficient devices where 100% of the excitons can potentially produce optical emission, in contrast to only approximately 25% in conventional fluorescent devices. The high conductivity hole and electron transport systems will be achieved by selecting p- and n-type dopants along with the appropriate organic buffer layers. The resulting structure will be a p-i-n type device. The team has already identified several candidate material systems and is currently working to improve their stability.

The novel structures will also have potential use in energy-efficient, long-lived, solid state white OLED applications in general illumination, automotive, and wearable electronics. The team is already exploring two approaches for generating white light in a parallel Phase I SBIR effort. The first approach is based on a simple striped R-G-B configuration, and the second on using a phosphorescent monomer-excimer emission layer. P-i-n doping can be incorporated into both of these approaches.

The purpose of this Phase I was to demonstrate and deliver to DOE a white light phosphorescent OLED (PHOLEDä) light source, employing p- and n-type conductivity dopants, having a power efficiency close to 20 lm/W at a luminance of 800 cd/m2. The key tasks were:
Specifically, the key objectives of Phase I were:

1. Demonstrate and deliver a white PHOLED light source on a glass substrate with a drive voltage close to 3V at 800 cd/m2 luminance through the use of conductivity doped p-type and n-type transport layers.

2. Investigate the use of ion implantation to improve the efficiency of the doping process.

3. Develop organic dopants for n-type organic transport layers.

4. Characterize the above white light sources and demonstrate > 20 lm/W at 800 nits brightness for a CIE of (0.33, 0.33) and CRI > 75.

During Phase I of the pin PHOLED program, the team met the Phase I goal and developed a low voltage, 20 lm/W white PHOLED as well as explored strategies to improve device stability. These efforts led to an 6.3 V, 19.7 lm/W white device with CIE (0.39, 0.40) at 800 cd/m2, a 7.0 V, 17.1 lm/W green PHOLED with a lifetime of 35 h under an accelerated constant current drive of 40 mA/cm2, and a novel n-type dopant with reduced diffusivity.

Transparent, Highly Efficient White OLEDs for Lighting Applications (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/13/04 - 4/12/05

Technology
Organic Light Emitting Diodes

Project Summary

The objective of this work is to demonstrate the technical feasibility of increasing the optical extraction efficiency of a white OLED light source using transparent OLED (TOLED) technology.

In Phase I, optimized white transparent phosphorescent OLEDS (T-PHOLED), designed specifically for general illumination sources will be simulated. This will lead to the demonstration of an approximate 1 cm^2 white T-PHOLED light source on a glass substrate, optically coupled to an external reflector to provide a greater than 20% enhanced optical extraction over a similar conventional bottom emission device.

The objective of this work is to demonstrate the technical feasibility of increasing the optical extraction efficiency of a white OLED light source using transparent OLED (TOLED) technology.

The ultimate outcome of this work is to develop a novel energy-efficiency, long-lived, solid state white lighting source based on phosphorescent organic light-emitting device (PHOLED) technology. This novel light source may find application in diffuse lighting application in the commercial, residential, and industrial sectors. Based on novel features that include its thin, lightweight form and transparency, this product may also be used in novel architectural, automotive, and wearable electronic applications.

White Illumination Sources Using Striped Phosphorescent OLEDs (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
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Subcontractor
Princeton University
University of Southern California

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/02 - 6/30/03

Technology
Organic Light Emitting Diodes

Project Summary

Based on its research in phosphorescent OLED (PHOLED™) technology, the project team has demonstrated OLEDs that are up to four times more power efficient than previously thought possible. Under two DOE SBIR awards, Universal Display Corporation, Princeton University, and the University of Southern California pursued a novel approach to broadband white light generation based on this highly efficient PHOLED technology.

Fabricating a white OLED light source from a series of striped PHOLEDs has the potential to provide a tunable, white lighting source with the requisite performance for CIE and color rendering. So far, the team has demonstrated the feasibility of using this approach for flat-panel displays.

The aim of this Phase I study was to demonstrate a striped white light PHOLED light source. UDC has successfully completed and achieved all 3 of the goals set to demonstrate this task. We successfully fabricated 1” striped white PHOLED sources with CIE co-ordinates of (0.32, 0.39) and a CRI of 86 (15% higher than the program goal) and demonstrated a power efficiency of 5.5 Lm/W at 800 cd/m2 exceeding the program goal by 10%. Finally a preliminary study was made to determine the minimum stripe resolution necessary for a 3 color white light source to appear uniform to the eye. This work demonstrates the feasibility of the striped PHOLED color source approach to enable next generation flat panel general illumination sources.

Recently, UDC was awarded a phase II contract to continue the development of a general illumination source using PHOLEDs. In Phase II, UDC plans to demonstrate a white PHOLED light source on a glass substrate with an efficiency of 20 lm/W at a luminance of 800 cd/m2. Additionally, UDC plans the demonstration and delivery of 6” ´ 6” prototype lighting panels based on PHOLED lighting sources, based on tiling four 3” ´ 3” sub-panels. This will involve the mechanical and electrical design of the panels, with particular focus on the manner in which individual light sources are interconnected, design and fabrication of drive electronics, mask layout for the component sub-panels, along with their fabrication and characterization.

The successful completion of this Phase II work will significantly accelerate the use of PHOLED devices as commercial lighting sources. The integration of these parallel efforts with the strategies developed in this proposal will enable PHOLEDs to become a viable source of general illumination.