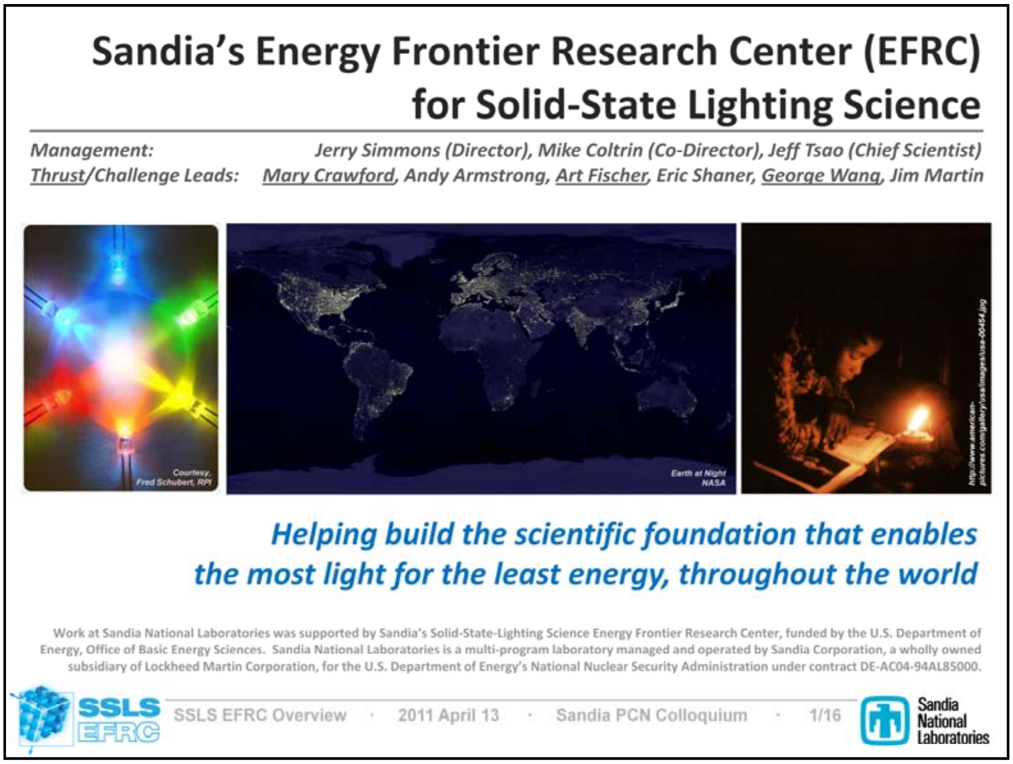
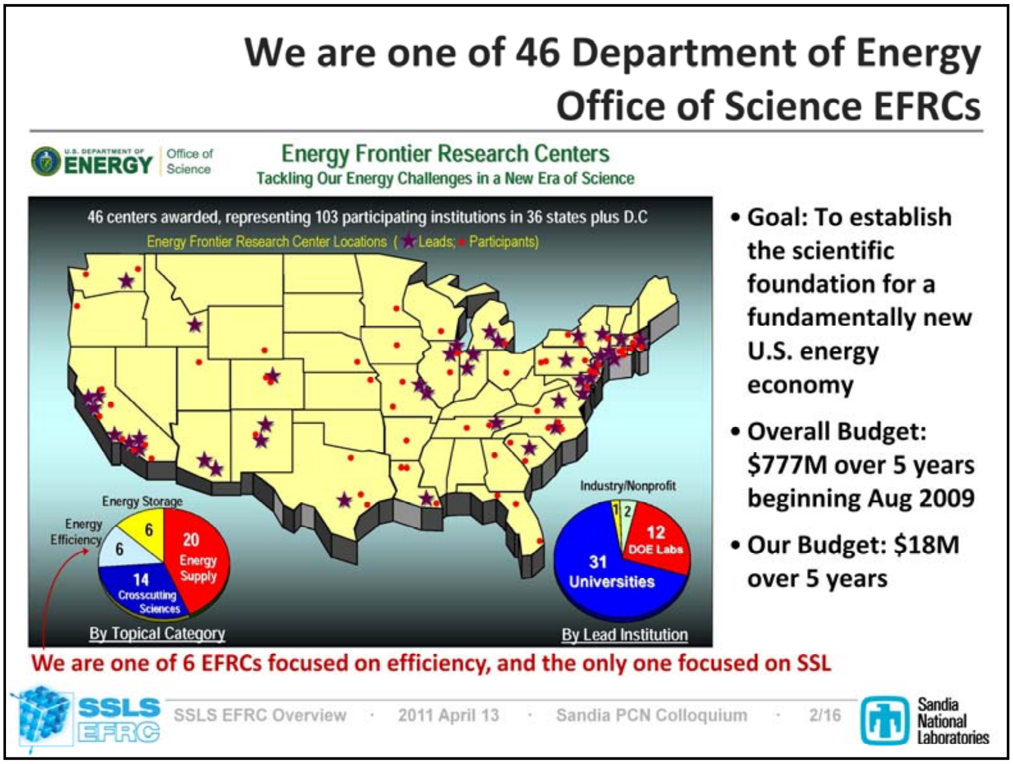
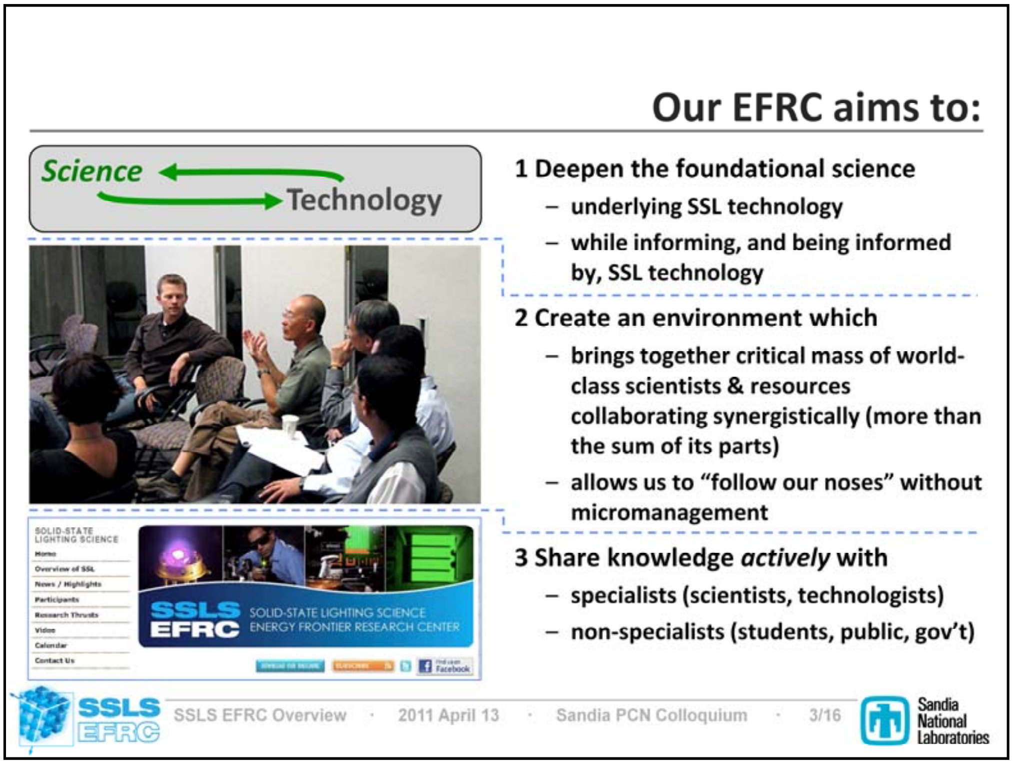



- HELLO. Good afternoon. It's a pleasure to be here today, and thank-you, Jianyu and Blythe, for the invitation.
- TODAY'S TALK. Today, I'd like to give you an overview of Sandia's Energy Frontier Research Center for Solid-State Lighting Science. I've divided the overview into three parts. First, I'll start with some general comments about how we're funded and organized. Second, I'll say a few words about solid-state lighting technology. Solid state lighting, as most of you know, is simply the use of solid-state sources, like these light-emitting diodes, to produce white light for general illumination. Finally, I'll give an overview of how we are helping build the scientific foundation that might in the long-term enable major improvements to solid-state lighting, and ultimately to enable the most light for the least energy, throughout the world.
- LIMITATIONS. I'm afraid there isn't time to be exhaustive, nor for a lot of technical detail, but if you have questions or ideas, I encourage you to talk to Jerry Simmons (our EFRC Director), Mike Coltrin (our EFRC co-director), myself, or our thrust and challenge leads – Mary Crawford, Andy Armstrong, Art Fischer, Eric Shaner, George Wang, and Jim Martin.

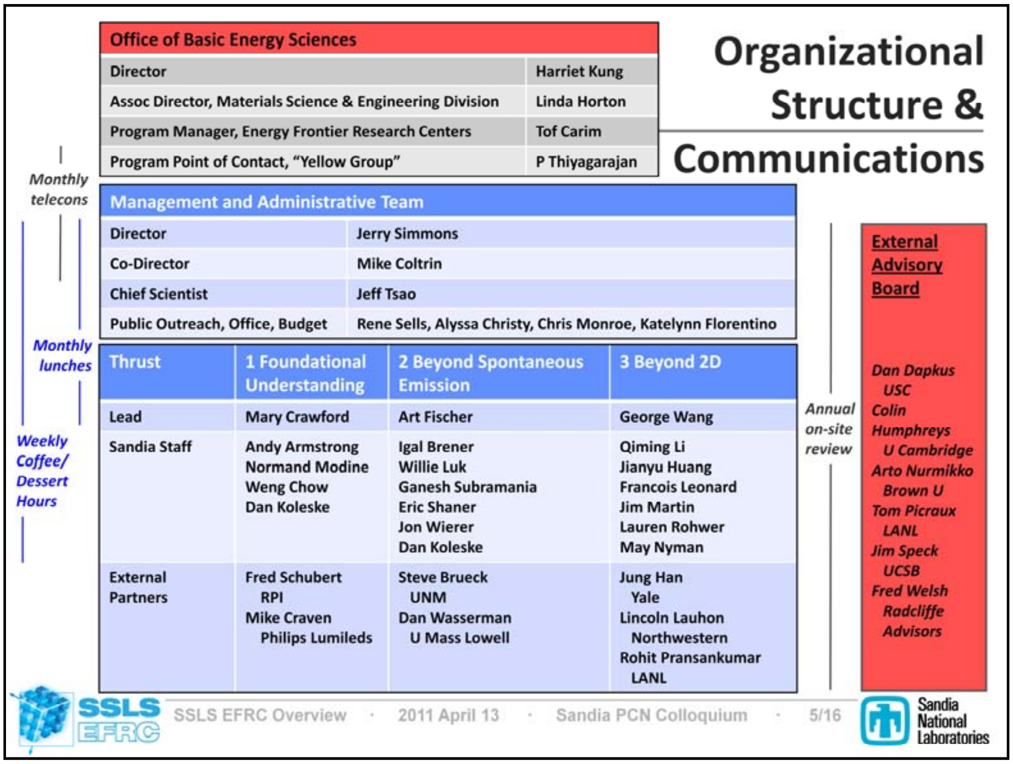



- EFRC SIZE AND BUDGETS. To put our EFRC in context, we are part of a huge Department of Energy Office of Science program, in which there are 46 EFRCs, whose overall goal is to establish the scientific foundation for a fundamentally new U.S. energy economy. Its overall budget is anticipated to be $777M over the 5 years that began about a year and a half ago, in August 2009.
- ENERGY EFFICIENCY EFRCs. Of these 46 EFRCs, most, 20 of them, are focused on energy supply. Another 6 are focused on energy storage and another 6 on energy efficiency. Of the 6 focused on energy efficiency, ours is the only one focused on solid-state lighting, although a few other EFRCs (like the ones at UC Santa Barbara and the University of Southern California) also have some work in solid-state lighting.
- OUR BUDGET. The budget for our EFRC is similar to most of the others: $18M over 5 years, or $3.6M/year.

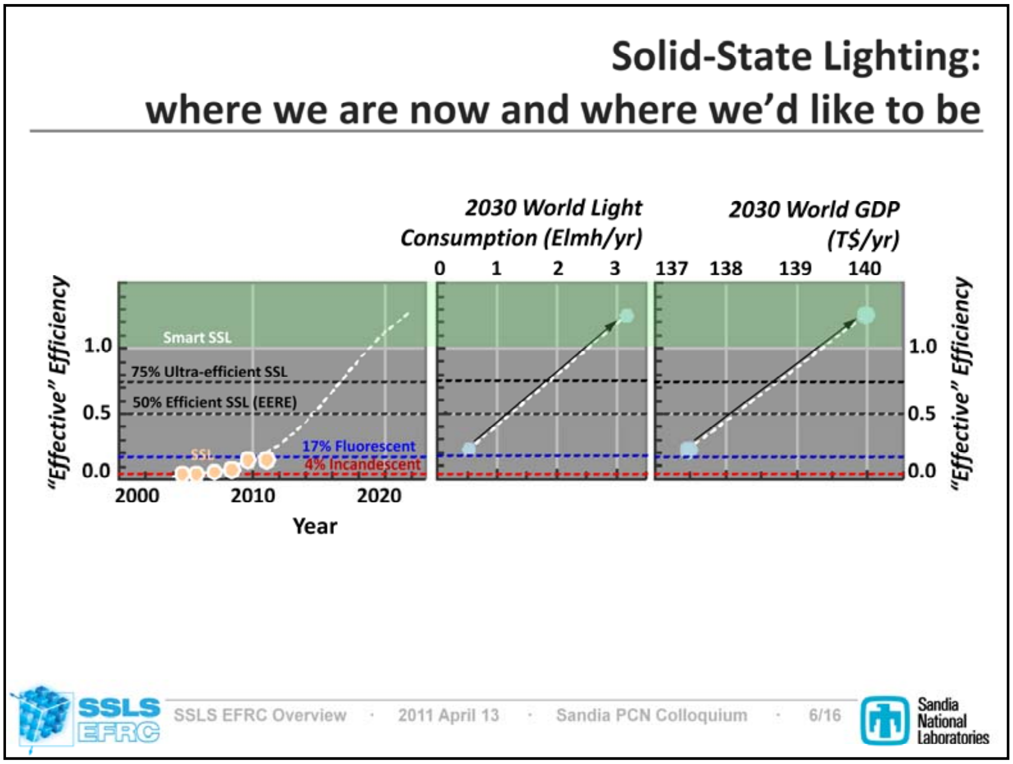



- ENVIRONMENT. Now, \$3.6M/yr means that our EFRC is big enough that we can have as one of our aims to create an environment which brings together a large and critical mass of scientists and resources collaborating synergistically, so that we can become more than just the sum of our parts. In fact, as some of you know, we have a pretty nice weekly coffee/dessert hour for informal discussions and brainstorming, whose intent in large part is to uncover synergies. Also, a 5 year life span is long enough that we have the luxury of following our noses and taking bigger risks without worrying too much about milestone micromanagement. Our weekly coffee/dessert hours are a vehicle for uncovering opportunities for collaborative synergy but, as I think our staff can attest, not for creating rigid milestones.
- SCIENCE. Within this environment, our primary aim is to deepen the foundational science underlying solid-state lighting. And, by saying the words "underlying solid-state lighting," that of course means that our science isn't being done in a vacuum. Although the science is central to our EFRC, we pay attention to informing, and being informed by, solid-state lighting technology. That's easy to do here at Sandia, of course, because, apart from the EFRC, we also have programs aimed squarely at advancing the technology, many of them staffed by EFRC scientists.
- KNOWLEDGE SHARING. Finally, let me just mention another aim of our EFRC, which is to actively share its knowledge, not just with specialists, with whom all researchers do, but also with non-specialists. If you google SSLS EFRC, our website comes up at the top, and it has a wealth of information: a basic overview of solid-state lighting; news about papers that have just been published; and audios and videos of lectures that our staff have given. Thanks to Mike Coltrin and Alyssa Christy, we're even on Facebook, if you'd like to friend us, and on Twitter, if you'd like to follow us.

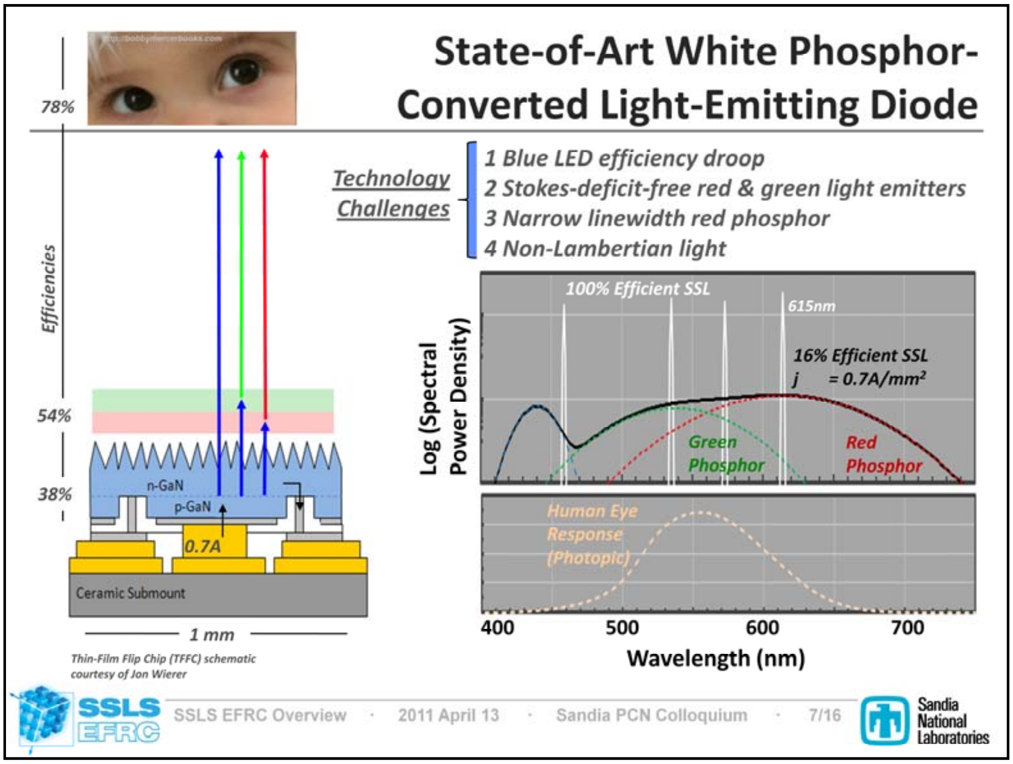

- PEOPLE. Now, I said our EFRC was large enough to have critical mass. Here I show a list of people involved in some way or another in our EFRC. 33 Sandians and 20 non-Sandians scattered across various institutions: Northwestern, Yale, U Mass, UC Merced, Philips Lumileds, UNM, Los Alamos, RPI. I can't name all of the individual names, but, all together, our EFRC "touches" over 50 researchers. And, at Sandia, we make of course heavy use of three big facilities: the Integrated Materials Research Laboratory (IMRL), the Center for Integrated Nanotechnologies (CINT), and the Microsystems Engineering Sciences and Applications Complex (MESA).



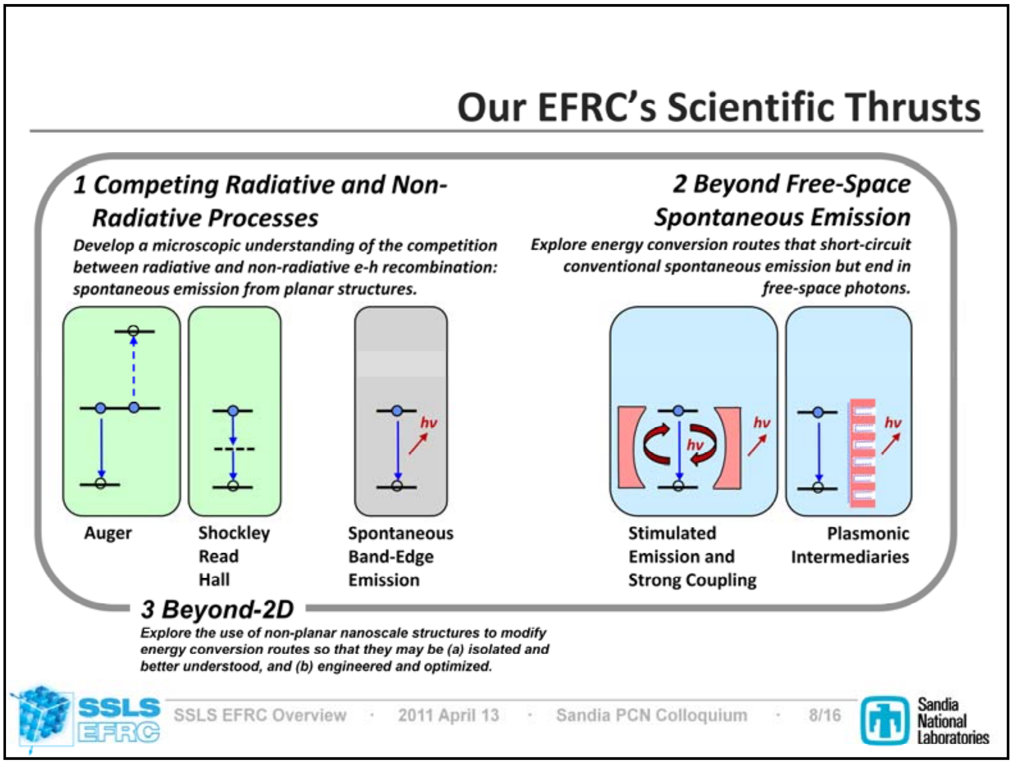

- STRUCTURE. Because we are relatively large, we do have an organizational structure. I won't go into it in detail, but we have all of the pieces you'd expect. Our sponsor is of course the Office of Basic Energy Sciences. We have a management and administrative team. We have our scientific staff. And we have an external advisory board.
- COMMUNICATIONS. All of these pieces communicate informally and formally at various intervals. Annual on-site reviews with our external advisory board – in fact these are coming up towards the end of this summer. Monthly telecons with the Office of Basic Energy Sciences. Monthly lunches with our management team and the thrust leaders, in fact we're having one today. And, perhaps most importantly, the weekly coffee/dessert hours I had mentioned earlier, for informal discussions, brainstorming and uncovering opportunities for collaborative synergy.



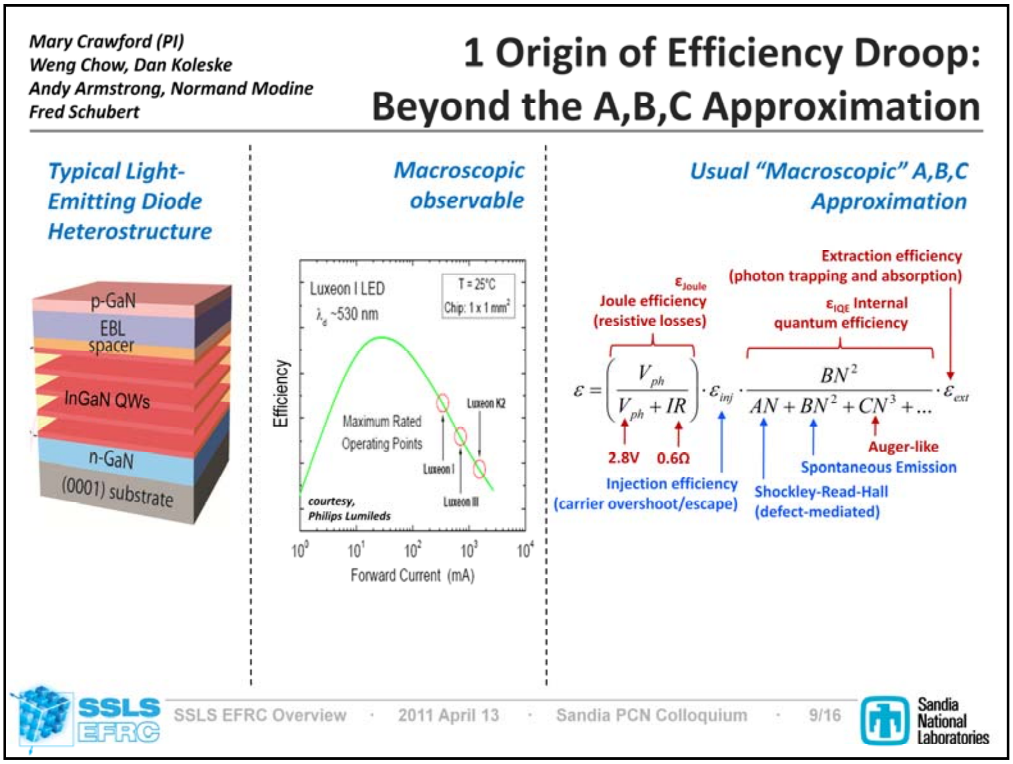

- SOLID-STATE LIGHTING TECHNOLOGY. OK, so that's a snapshot of how we're funded and organized. In this next third of my talk, let me say a few words about solid-state lighting technology, the technology on which we hope our foundational science can have long-term impact. In particular, let me say a few words about where the technology is now, and where we'd like it to be in the future.
- BEATING TRADITIONAL. Here at the left I show the evolution of the efficiency of solid-state lighting technology. The tan filled circles correspond to commercial solid-state lighting that you could buy over the past 6 years or so. The horizontal red and blue lines correspond to the efficiencies of incandescent and fluorescent lamps. You can see that the efficiency of solid-state lighting has been increasing steadily, and will soon be higher than the efficiencies of both incandescent and fluorescent lamps. Coupled with cost decreases that we also can anticipate, there is a widespread sense of inevitability in the community that we will soon see the beginning of a massive worldwide transition from traditional to solid-state lighting. However, just because solid-state lighting will become dominant *doesn't* mean there won't be more to be done, any more than when semiconductor transistors became dominant over vacuum tubes a few decades ago it didn't mean that there wasn't more to be done with semiconductor transistors.
- GOING WAY BEYOND TRADITIONAL. After all, beating incandescent and fluorescent lighting just means getting to efficiencies of 20-30% or so, so there is a lot of room for improvement beyond this. EERE has as its goal 50% efficiency, our group at Sandia has talked extensively about the possibility of 70% or higher ultra-efficiencies. And many groups in the world, particularly the group at the Smart Lighting Engineering Research Center at RPI, have talked about smart lighting, in which more efficient use is made of lighting through networked, digital systems composed of sensors, controls, and, of course, solid-state lighting. If lights are only on when you need them, the "effective" efficiency of lighting could be even greater than unity, as I've drawn in a sort of cartoonish way here.
- CONSEQUENCES. So you can see there is plenty of room for improvement, even after solid-state lighting has "beaten" incandescent and fluorescent lighting. One possible consequence of this of course is a decrease in energy consumption for lighting. In the early years of solid-state lighting research, this is the consequence that most of us focused on. But, as many of you know, our group at Sandia has gone on record more recently as saying that it is also very possible that as the effective efficiency of lighting goes up and as the effective cost of light goes down, light may become much more affordable, particularly for the developing world, and so world light consumption might actually go up. In fact, if you use trends from the past to project to the year 2030, you end up with something that looks like this: light consumption in 2030 with solid-state lighting might be more than a factor 3 higher than it would have been without solid-state lighting. And, because light is a factor of productivity, world GDP with solid-state lighting might be as much as $2T/yr larger than it would have been without solid-state lighting.
- STAKES ARE HIGH. So the economic stakes are potentially very high for continuing to push efficiencies ever higher and higher.



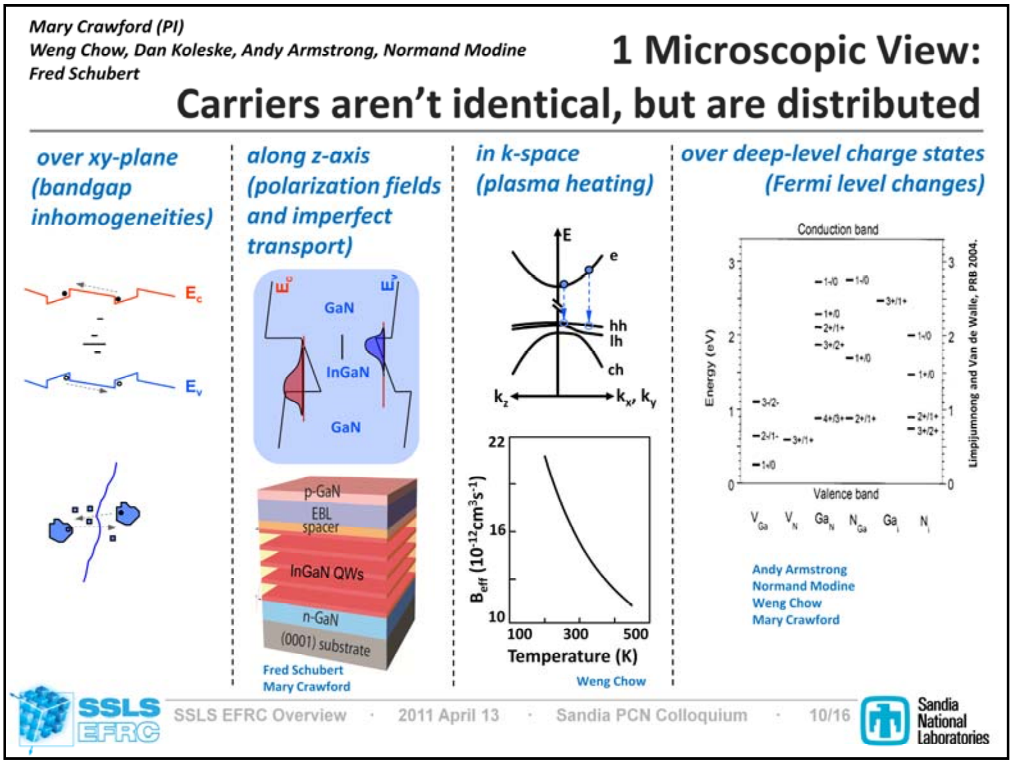

- CHALLENGES. OK, so what are some of the challenges associated with getting to higher and higher efficiencies?
- STATE-OF-ART SSL LAMP. To see what these are, here on the left I show the anatomy of a state-of-the-art white solid-state lamp. This particular one is a so-called thin-film flip-chip design pioneered by Philips Lumileds. The lamp is basically a blue LED, 1-square-mm in size, driven with 0.7A of current, and coated with green and red phosphors. Some of the blue light leaks through the phosphors. But some is absorbed by the phosphors and is re-emitted as green and red light. The combination of blue, green and red gives a warm-white light that is very pleasing to the human eye and which renders fairly faithfully colors of objects in the environment around us.
- EFFICIENCY. So why is this lamp only 15-20% efficient? Well, we can see why by looking at the three sub-efficiencies associated with the lamp.
- BLUE LED EFFICIENCY. The first sub-efficiency is that of the blue LED. It's only about 38%. In fact, late last year, Nichia reported a blue LED wall plug efficiency of 81%, so why isn't this efficiency 81%? Well, the reason is that Nichia's 81% efficiency can only be achieved at a very low injection current of 25 mA into a mm2 chip. If you drive the chip harder, then there is a phenomenon called efficiency droop that kicks in to decrease efficiency. To defray the cost of the chip, however, you would like to drive the chip harder, at least at 700 mA into a mm2 chip, and ideally even harder. At these injection currents efficiencies aren't so high. So one of the most important technology challenges right now in solid-state lighting is to eliminate blue LED efficiency droop, so you can maintain 81% efficiency at high drive currents.
- PHOSPHOR & PACKAGE EFFICIENCY. The second sub-efficiency is that of the phosphor and package. It's only about 54%. Some of that is because the phosphors don't have perfect quantum efficiency: one blue photon in isn't exactly one red or green photon out. But these are improving, leaving the more fundamental loss: the so-called Stokes deficit, the quantum deficit associated with converting a blue photon into a red or green photon. So another important technology challenge is to eliminate the Stokes deficit, perhaps by eliminating phosphors entirely and going to red and green semiconductor light emitters.
- SPECTRAL EFFICIENCY. The third sub-efficiency is the match between the spectrum of white light and the human eye sensitivity. Because of the particular characteristics of the phosphors that are used now, this efficiency is currently about 78%. To see this, here on the right I show the spectrum of a state-of-the-art white solid-state lamp in black. There is a narrow blue LED peak, and then two broad green and red phosphor peaks. I've also drawn the spectrum of a hypothetical 100%-efficient four-color RYGB source that gives the best combination of color rendering quality and match to the human eye response. You can see that the red phosphor emits too far into the deep red, where the human eye isn't as sensitive. So a final important technology challenge is to narrow the red phosphor emission and to center it around 615 nm, which is the position of the red line in this perfect RYGB source.
- SMART LIGHTING. Finally, I just want to mention one last challenge, which is related to the smart lighting idea that I mentioned in the last viewgraph. The ability to place light where you want it, and to not place it where you don't want it, would benefit from directional light sources, rather than the Lambertian light sources that we currently have. So in the long run it would be good to have device architectures that give directional, non-Lambertian light.
- SUMMARY. So, to recap, these are four important technology challenges. First, eliminate blue LED efficiency droop. Second, develop Stokes-deficit-free red and green light emitters. Third, narrow the red phosphor linewidth while centering it at 615 nm. And fourth, to get away from Lambertian light.



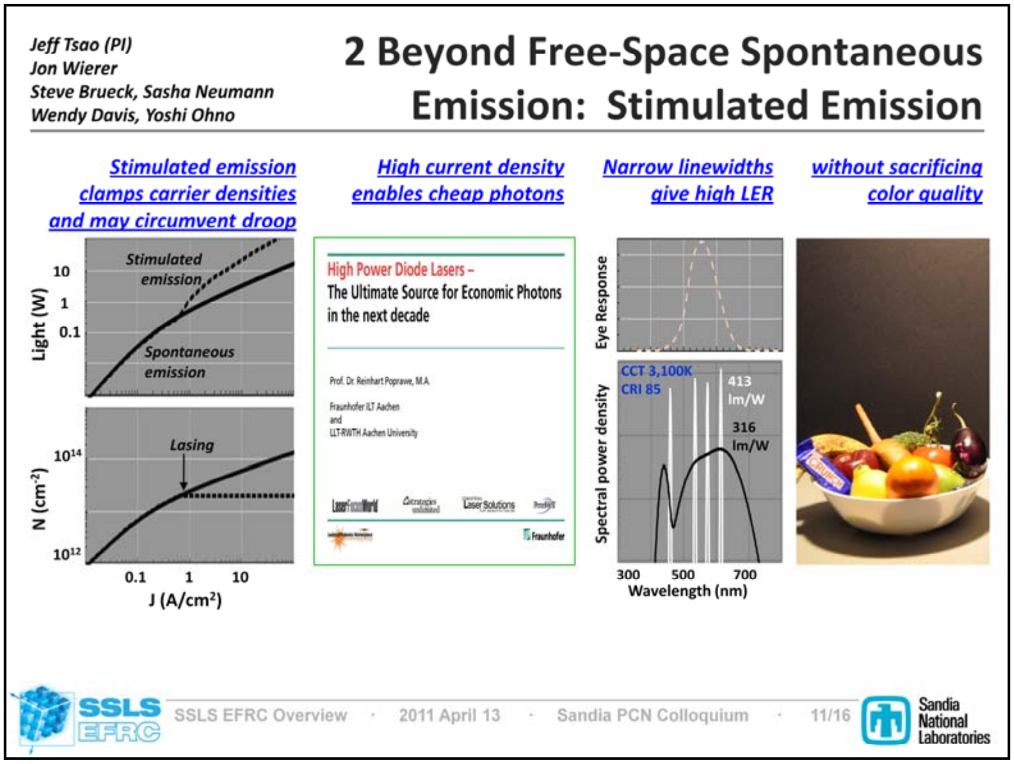

- OUR EFRC. That brings us to our EFRC, which is aimed at exploring foundational science that could in the longer term lead to solutions to these technology challenges. I want to emphasize the longer term, though. We are by and large not looking at short-term incremental "fixes" to these challenges, fixes that industry is investing tons of money looking at. On the one hand, we therefore run the risk of being made obsolete: industry could easily solve these challenges without our foundational science. On the other hand, insights that we help generate may accelerate solutions or even enable novel solutions that aren't even being considered right now. Moreover, the foundational science that we develop could in the long run easily have a broader sphere of applicability beyond solid-state lighting.
- PLAN. So what I'd like to do in the remaining third of this talk is to describe some of the scientific work that is going on in our EFRC, and you will see that it runs the gamut from long term to even longer term. I'll basically run through 6 challenge areas drawn from our three scientific thrusts.
- THRUST 1. Our first thrust is "Competing Radiative and Non-radiative Processes," in which we aim to develop a microscopic understanding of the competition between radiative and non-radiative e-h recombination where the structures are conventional planar structures and the radiative recombination is via conventional spontaneous band-edge emission. Some of the competing non-radiative recombination mechanisms might be, as illustrated here, Auger recombination or Shockley-Read-Hall recombination from point defects.
- THRUST 2. Our second thrust is "Beyond Free-Space Spontaneous Emission," in which we aim to explore energy conversion routes that short-circuit the conventional spontaneous emission being studied in Thrust 1, but nevertheless ultimately end in free-space photons. For example, routes by which electron-hole pairs interact with resonant photons in a cavity, resulting in stimulated emission or even strongly coupled exciton-photon polaritons. Or, for example, routes by which electron-hole pairs interact with plasmons and then are subsequently diffracted out into free space. Moreover, these new energy conversion routes, by altering the competition between radiative and non-radiative processes being studied in Thrust 1, can be a means of elucidating that competition.
- THRUST 3. Our third thrust is "Beyond-2D," in which we aim to explore the use of non-planar nanoscale structures to modify energy conversion routes so that they may be (a) isolated and better understood, and (b) engineered and optimized. These routes could be the free-space spontaneous emission studied in Thrust 1 or the "beyond free-space spontaneous emission" energy conversion routes studied in Thrust 2.
- SYNERGIES. You can see from this description of our Thrusts that there is plenty of room for synergy. I wouldn't say we are yet taking full advantage of these possible synergies, but we are looking forward to more and more synergies in the years to come.
- PLAN. OK, so now let me run through our challenge areas.



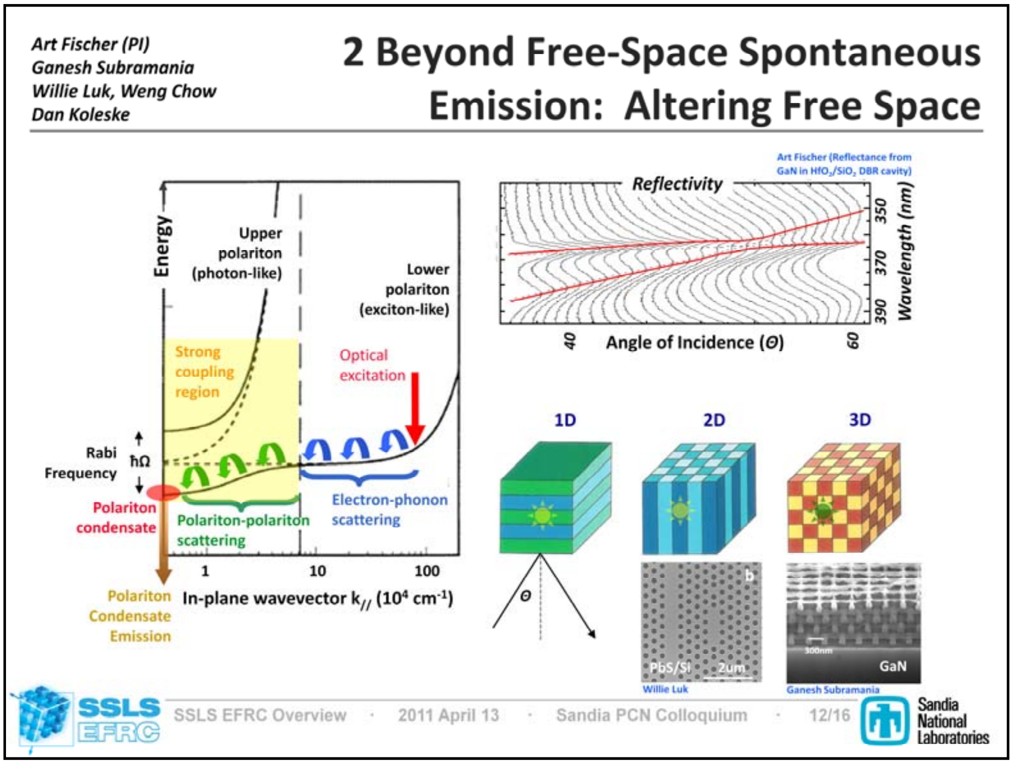

- EFFICIENCY DROOP. Let's start with Thrust 1, led by Mary Crawford. Within this Thrust, the dominant challenge has been to unravel the origin of the efficiency droop that I had mentioned earlier.
- HETEROSTRUCTURE. To see what we mean by efficiency droop, here on the left I show a typical light-emitting diode heterostructure, with a bunch of InGaN quantum wells sandwiched between n-GaN and p-GaN. You inject electrons from the bottom and holes from the top, and hope that the electrons and holes collect in the quantum wells and recombine radiatively.
- DROOP. Instead, what you find experimentally is illustrated in the middle. As you increase the electron and hole injection, power conversion efficiency first goes up, then peaks and droops. In other words, the fraction of power out that is spontaneous emission increases at low currents, then decreases at high currents.
- A,B,C MODEL. So why is this? Well, power conversion efficiency is the product of a number of terms, including a Joule inefficiency associated with resistive losses and injection inefficiency associated with carrier overshoot and escape. These are certainly important, and Fred Schubert at RPI, who is part of our EFRC, has been studying in great depth the injection inefficiency. But the heart of efficiency droop is the internal quantum efficiency, and the usual way of treating this is within the so-called A,B,C approximation. Basically, you treat all the carriers in this device as identical, and lump them all into a single carrier density, N. Then you write the carrier recombination rate as a polynomial in that carrier density. There's a first-order non-radiative term associated with defects; there's a second-order radiative term associated with spontaneous emission; and there are possible third-order or higher-order non-radiative terms associated with Auger or other processes.
- SHORTCOMINGS. In fact, no one has yet figured out how to explain efficiency droop with physically reasonable and constant values of the three A,B,C coefficients, despite a tremendous amount of work over the past several years.



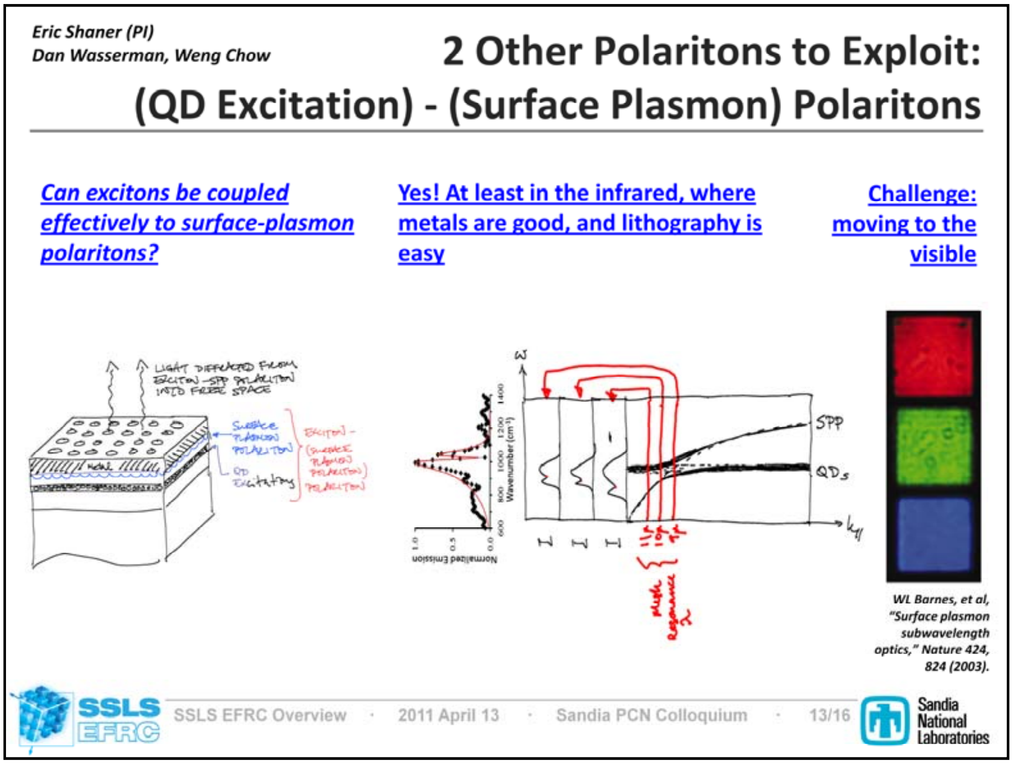

- OUR VIEW. Our view, gradually forming, is that the reason it's been hard to explain is fundamental. If you take a microscopic view of the carriers, they aren't all identical. Instead, they are distributed in a number of different ways over a number of different "spaces," so to speak.
- XY PLANE. For example, in the x-y plane, looking down on a structure, there may be lateral variations in bandgap, due to compositional or quantum well thickness non-uniformities. Carriers can get localized in smaller bandgap regions, protected from defects, then spill out at higher carrier densities and become unprotected from defects.
- Z AXIS. Along the z-direction, polarization fields can cause electrons and holes to move to opposite sides of a quantum well, altering virtually every recombination process, radiative or non-radiative. Spontaneous emission will be slower, because of the reduced spatial overlap between electron and hole wave functions. But defect-mediated non-radiative recombination might also be slower. If your point defect happens to be spatially located to the hole-rich side of this quantum well, then hole capture might be fast, but electron capture, which you need to complete the recombination process, might be slow. Then, on the much larger spatial scale associated with the heterostructure itself, Fred Schubert and Mary Crawford have shown that imperfect transport can also cause electrons and holes to occupy the different quantum wells along the heterostructure differently, and this will also cause variations in the overall recombination rate.
- K-SPACE. In k-space, electrons and holes are not always at zone center, but, especially at high carrier densities, can begin to fill their bands. Because these bands have different curvatures, they will be filled differently, again altering recombination rates. Indeed, Weng Chow has taken this into account quantitatively, and has shown that the effective B coefficient for spontaneous emission decreases as you increase the temperature of the electrons and holes and as the bands fill.
- CHARGE STATES. Finally, point defects often have multiple charge states, with different energies, different occupancies depending on the Fermi level, and different cross-sections for electron or hole capture. One can imagine situations in which, as carrier densities increase, different charge states become occupied, and therefore the rates at which electrons and holes get captured change. Indeed, Normand Modine, Andy Armstrong, Weng Chow and Mary Crawford are beginning to take this into account quantitatively, and have shown that point-defect-mediated recombination can sometimes appear to be highly nonlinear.
- BOTTOM LINE. So our thinking is that one *needs* to take a microscopic view of the carriers if one is going to treat correctly the competition between radiative and non-radiative processes, and if one is going to develop a quantitative understanding of efficiency droop.



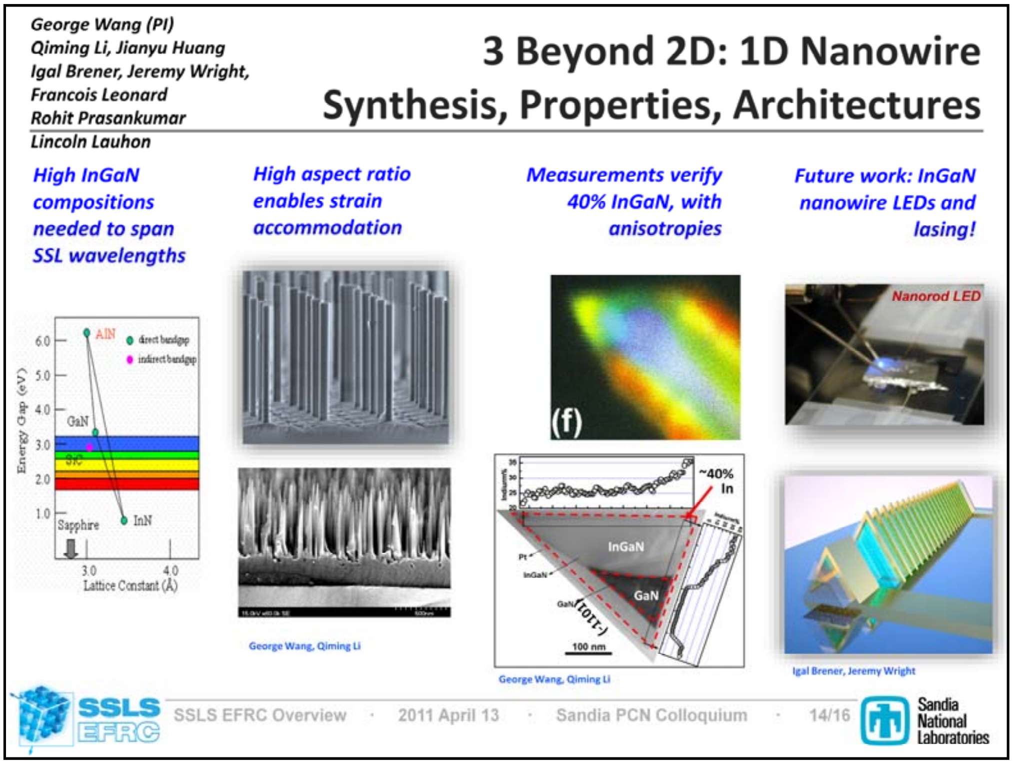

- STIMULATED EMISSION. Moving on to Thrust 2 now, one way of altering the competition between the radiative and non-radiative processes we have been talking about for Thrust 1, is to introduce another radiative process beyond free-space spontaneous emission. One such radiative process of course is stimulated emission. In other words, suppose instead of putting your heterostructure in free space, you put it in an optical cavity and make a laser. Above the lasing threshold, stimulated emission becomes dominant over spontaneous emission, and at the same time carrier densities get clamped. That means that if there is a non-radiative carrier recombination mechanism, like Auger recombination, that kicks in at high carrier densities, it might be circumvented in a laser device. Not only that, but you get spatial directionality from a laser, for free!
- PROBLEMS WITH LASERS. This sounds intriguing, but of course there are a number of potential problems. One is that lasers have the reputation of being expensive. In fact, at least in the infrared, lasers can actually be an extremely economical source of photons. Another is that lasers have very narrow linewidths. In the extreme, if you had, say, four lasers at different colors, but were missing all of the spectra in between, a big question has been: would you be able to render well the colors of objects in the environment around you?
- HUMAN FACTORS EXPERIMENT. Well, to answer this question, Jon Wierer and I just finished doing an experiment with Steve Brueck and Sasha Neumann at the University of New Mexico, and with Wendy Davis and Yoshi Ohno at NIST. We have more quantitative data, but here's the qualitative result: a photo of a bowl of fruit illuminated by a four-laser white light source. In fact, it looks like such a source actually does provide good color rendering quality, and this result opens up the possibility of using such sources for general illumination.



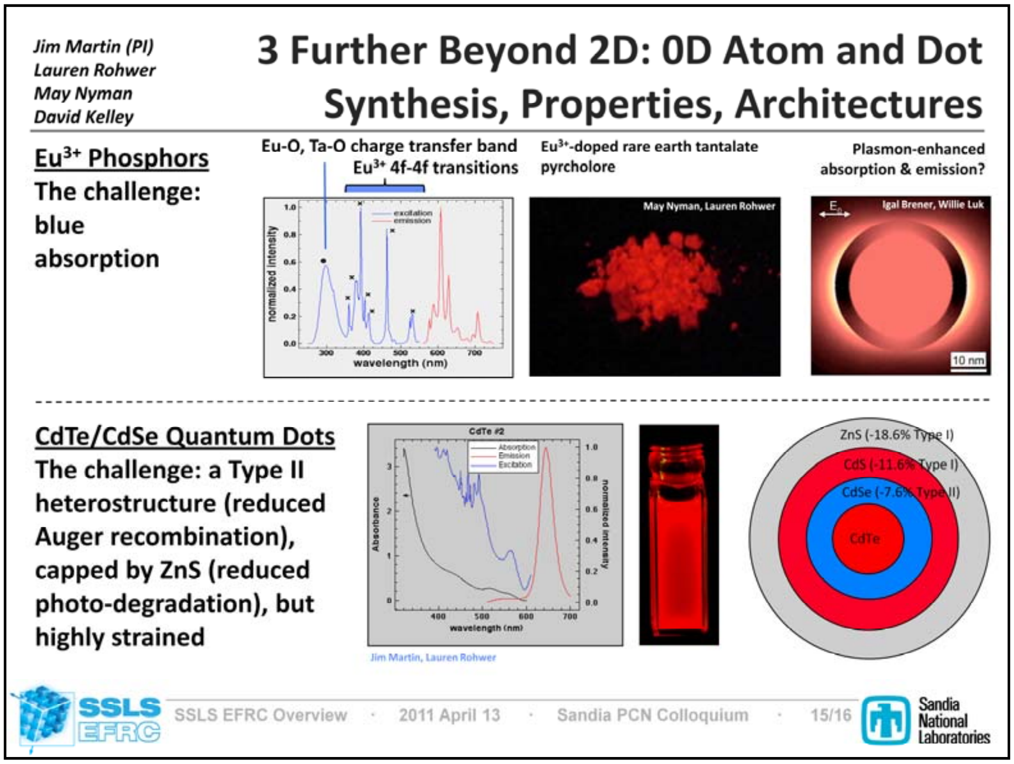

- ALTERING FREE SPACE. Now, I've just described one way of going beyond free-space spontaneous emission, which is through stimulated emission. Another way is to alter free space. In other words, to control spontaneous emission rates by texturing space into photonic crystals and thereby manipulating photonic densities of states. One can do this of course in 1D, 2D and 3D. Here's a 2D example from Willie Luk, where he has been looking at modified spontaneous emission from PbS quantum dots overlaid on top of a 2D silicon photonic crystal. Here's a 3D example from Ganesh Subramania, where he has been looking at modified spontaneous emission from a 3D GaN photonic crystal.
- SPECIAL CASE: EXCITON IN A CAVITY. Now, an important special case of a photonic crystal is when you carve out a cavity inside the photonic crystal. And a special case of this is when the resonance frequency of the cavity is a stop band of the photonic crystal, so you've basically constructed a high-Q optical cavity. Then, if you put an emitter, or an exciton, inside the cavity, and the exciton energy matches the cavity resonance, you can enter the so-called strong coupling regime. In this regime, a photon that is emitted by an exciton bounces around in the cavity until it is reabsorbed by the exciton, and the energy cycles back and forth between the exciton and the cavity photon.
- POLARITON. This strong coupling regime is interesting because you end up with a composite particle, a polariton, that is a mixture of a photon and an exciton. On a dispersion diagram like this, the upper branch of these polaritons is more photon like, and the lower branch is more exciton like. One signature of such strong coupling is this Rabi splitting, which can be probed using angle-resolved reflectance. Here's an example where Art Fischer has placed a GaN cavity in a 1D photonic crystal, and measured the position of reflectance features associated with the two polariton branches, showing the splitting.
- CONDENSATES. A next step will be to see whether one can create a gas of these polaritons, then condense them into a single-wave-function Bose-Einstein condensate. This condensate should emit light that can be measured because it does have a photon component, and the emitted light should be coherent and laser-like. So this is a possible way of getting the equivalent of lasing at low exciton densities, rather than the usual situation where you need very high exciton densities. It's also a way of getting directional, rather than Lambertian, light.



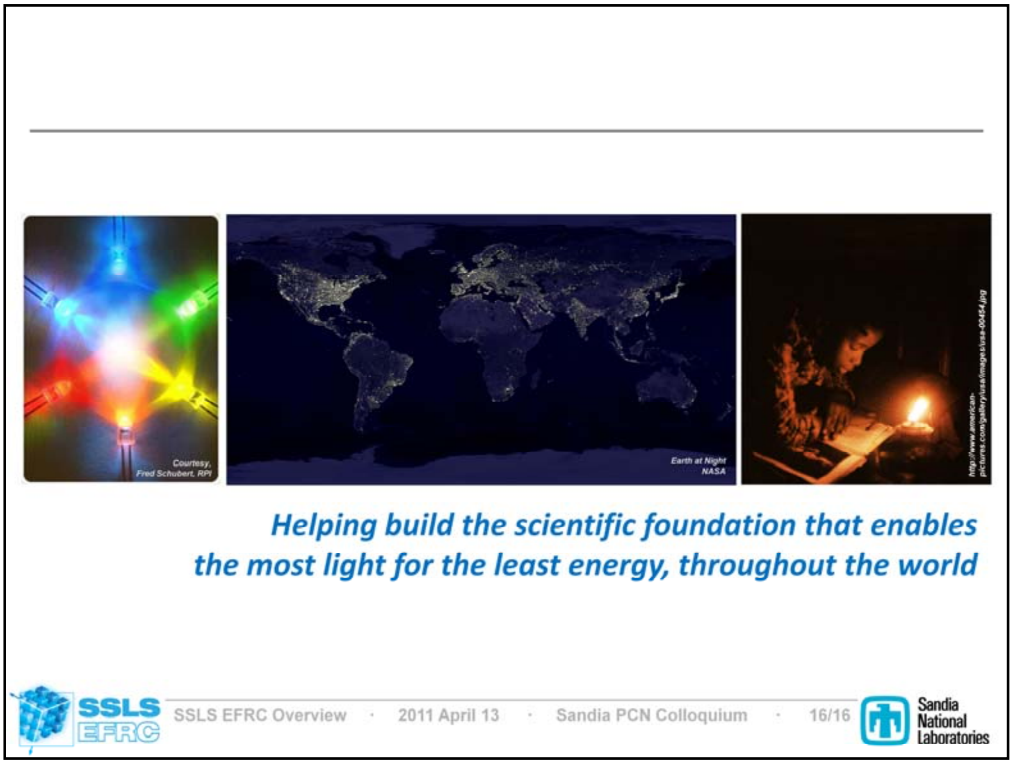

- EXCITON-SPP POLARITONS. Now, exciton-photon polaritons aren't the only kinds of polaritons that one can excite enroute to getting light out into free space. Surface plasmon polaritons are another kind. Here I show some work by Eric Shaner, Weng Chow, and Dan Wasserman at the University of Massachusetts, in which they demonstrated strong coupling between quantum dot excitations and surface plasmons.
- SCHEMATIC. A cartoon of their experiment is shown at the left. There is a layer of quantum dots, then a spacer layer, then a perforated metal. The metal supports a surface plasmon polariton – a composite particle that is part bulk plasmon part photon. The surface plasmon polariton interacts with excitations in the quantum dot through fringing fields and this interaction produces yet a higher order polariton, a composite particle that is part quantum dot excitation and part surface plasmon polariton.
- STRONG COUPLING. Just as with the exciton-photon polariton, if the coupling is strong enough, there will be a Rabi splitting between the upper and lower polariton branches that one can probe using emission spectroscopy, using the perforation spacing as a means to determine the in-plane k-vector that one is probing. In fact, they see a very pronounced splitting, which I believe represents the first observation of strong coupling of a quantum dot excitation created by direct electrical injection.
- MOVING TO THE VISIBLE. Of course, this experiment was done in the infrared, at wavelengths near 10 microns, where metals are good, and the perforation spacing is coarse so the lithography is easy. One challenge going forward will be to see what one can do in the visible. We're cautiously optimistic, since it is the red that is one of the key problems in solid-state lighting, and red of course is at the long wavelength end of the visible where metals are still not too bad, and the lithography may not be too difficult.




- BEYOND 2D. Up until now, I've talked about planar 2D structures – textured, possibly, but nonetheless planar and 2D. Going to non-planar non-2D structures can in principle alter the competition between radiative and non-radiative processes that we are interested in in Thrust 1. They can also open up new architectures for Thrust 2, in which we are trying to go beyond free-space spontaneous emission.
- NANOWIRES. Nanowires are an obvious example. Here, one of the main motivations is compositional flexibility. Right now the only efficient GaN-based light emitter is in the blue, and it is based on very low In-content InGaN. On this energy gap versus lattice constant diagram the InGaN is almost GaN, and so if it's grown on GaN there isn't much strain. If you want to get to the green, yellow and, especially, the red, you need much higher In content InGaN, and strain becomes a big problem. With nanowires, the aspect ratios are so large that strain can be accommodated much more easily. Here I show two examples of nanowires that George Wang, Qiming Li and their team have grown: the bottom example is catalyst-grown from the bottom up; the top example is etched down from the top followed by lateral regrowth.
- TONS OF WORK. Now, GaN-based nanowires are in their infancy, so right now George and his team are doing a lot of very basic experiments exploring the synthesis and properties of these nanowires. For example, Jianyu Huang has been looking at fracture mechanics, Rohit Prasankumar at Los Alamos National Lab has been looking at ultrafast carrier dynamics, Francois Leonard has been looking at electron and hole confinement, and Lincoln Lauhon of Northwestern University has been using atom probe tomography to map 3D distributions of impurities and dopants.
- 40% INGAN. Here I just wanted to show that, in fact, relatively high In content InGaN can be achieved. These are cathodoluminescence measurements in which InGaN was grown around a GaN nanowire, showing that In content as high as 40% can be achieved.
- FUTURE WORK. In future work, we'll begin to look at some nanowire-based device architectures, including nanowire LEDs and lasers, and especially nanowire lasers that Igal Brener and his post-doc Jeremy Wright have already begun working on.




- FURTHER BEYOND 2D. Going even further beyond 2D, of course, are 0D atoms and quantum dots. I had mentioned earlier that one of the technology challenges of solid-state lighting is the red phosphor, which has a wide emission linewidth that extends out into the deep red. Here, we have been looking at two ways of circumventing this problem.
- ATOMS. One way, shown at the left, is to explore a new generation of phosphors based on Eu3+. Because emission from Eu3+ is from f-shell electrons that are shielded from the lattice, the emission linewidth can be very narrow, and, just by coincidence, Eu3+ has a very strong emission line right at 615 nm, perfect for solid-state lighting. You can see the sharp red emission here from this Eu3+ doped rare earth tantalate developed by May Nyman, Lauren Rohwer and co-workers. The problem is that narrow-line red emission is not enough, you also need good absorption in the blue. However, the most intense absorption lines and bands for this particular phosphor are in the UV, so one challenge is to figure out how to engineer a host in which that intense absorption has been shifted to the blue. We don't know if this is the answer or not, but an intriguing possibility might be to use metal shells around the chromophore, which Igal Brener and Willie Luk have shown can give plasmon-enhanced absorption and emission.
- QUANTUM DOTS. Another route to a better red phosphor is through quantum dots. The near-perfect choice is CdTe/CdSe core-shell quantum dots, which have this beautiful and very efficient emission in the shallow red along with nice absorption in the blue. The main problem is photo-degradation, which eventually kills efficiency. So here I've sketched the "home-run" structure that Jim Martin, Lauren Rohwer and Dave Kelley, their collaborator at UC Merced, are trying to synthesize. It has a CdTe/CdSe core-shell, which is a type II heterostructure, so the holes are in one layer and the electrons in the other layer. This helps minimize non-radiative Auger recombination, which would be detrimental to efficiency. Then, after you've grown the CdTe/CdSe core-shell, you keep growing but switch the column II element and then the column VI element to end up with CdS and ZnS final capping layers. This ZnS layer is extremely important, because ZnS is one of the few II-VI materials known to be stable against photo-degradation. The problem, though, is there are tremendous lattice-constant mismatches. Between the CdTe core and the final ZnS cap layer the mismatch is -18.6%. So there will be very interesting challenges associated with this synthesis.




- BYE. With that, let me just say that we have in this EFRC the opportunity to make tremendous impact on a technology that will change the world in a very visible way. We are almost two years into it, and have a little more than three years left. We've done a lot of cool stuff already, but I think it's fair to say we are just getting started, and the next three years will be very very exciting. Thanks for your attention.