15th International Conference on the Physics of Light-Matter Coupling in Nanostructures (PLMCN2014)

A conference report for the UKNC by Tim Puchtler, University of Cambridge

Introduction

The International Conference on the Physics of Light-Matter Coupling in Nanostructures (PLMCN) is an annual conference which began in 2000, focusing on all aspects of light-matter interactions in semiconductors and nano-photonics. Whilst the scope may at first seem relatively niche, given that larger conferences on wider aspects of nanostructures and semiconductors are readily found, the topics covered were relatively wide ranging; topics from polaritons and indirect excitons would be followed by optically assisted superconductivity and quantum computing, from spintronics to metamaterials. As such, there was an interesting mix of high-level discussion of a specific topic, to introducing concepts core to a study to a wider audience who would be initially unfamiliar with it. Indeed, my own oral presentation on the fabrication of gallium nitride (GaN) microdisk cavities was among only a few presentations on works which used nitride materials.

The conference was held in the Montpellier, France, with an attendance of approximately 200 delegates. Presentations were held over 5 days with no parallel sessions, consisting of 2 'plenary' talks, 15 invited talks, 73 contributed talks and approximately 80 poster presentations. One afternoon was left for a social activity consisting of a trip to the medieval town of Aigues Mortes, followed by a dinner in a picturesque vineyard.

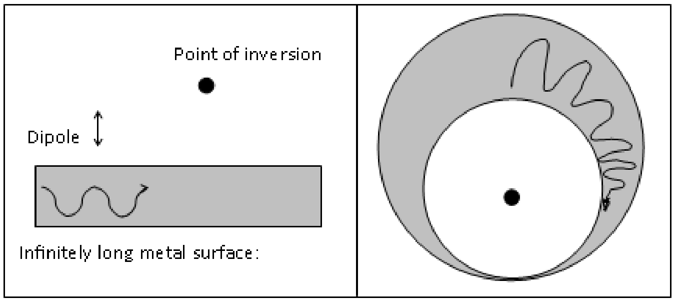
Whilst the topics were wide ranging, I will attempt to categorize them as best I can to give highlights of the reports below, from the perspective of someone working in the Nitrides.

Talk highlights

Metamaterials:

Metamaterials are those which use sub-wavelength structure to alter optical effects in ways which conventional materials cannot. This often requires the careful tailoring of surface plasmons in metals or an electromagnetic band-gap (e.g. photonic crystal) in semiconductors.

The conference began with one of the most fascinating talks, given by Prof. Sir John Pendry concerning theoretical methods for design of metamaterials systems which allow light to be focused into regions much smaller than are conventionally allowed. The technique here was 'Transformation optics'; at such small scale we are unable to use normal ray models to solve optical interactions. Instead we must go back to Maxwell's equations. But to avoid some of the heavy computations involved, we can take a system well understood and perform a transform on the entire local geometry to work out the implications of a new shape. An infinitely long metal plane near a dipole would contain a wave propagating to infinity, so performing an inversion transform could, for example, create a circle in which the field tends to a point which it never reaches. Therefore creation of this shape



forms an antenna which can be used to harvest (collect at high intensity) light. Such an approach allows us to consider a desired path of light, and view the metamaterial as a distortion of the space in which it travels (Indeed, the equations used are much like a refractive index analogy to the consideration of curved spacetime and gravity).

Whilst this approach was not employed in this talk, a similar structure was reported on by V. Balykin with the aims of demonstrating Giant Optical Nonlinearity. A 'nanoparticle with a nanohole' was created which acts exactly as described in Pendry's talk: a 'split-hole resonator' (SHR) which acts as a nano-antenna for an extremely wide wavelength range (UV – IR). Such a structure allows highly efficient heat removal, whilst maintaining the high peak power of collection associated with surface plasmon resonances and a 'lightning rod' effect.

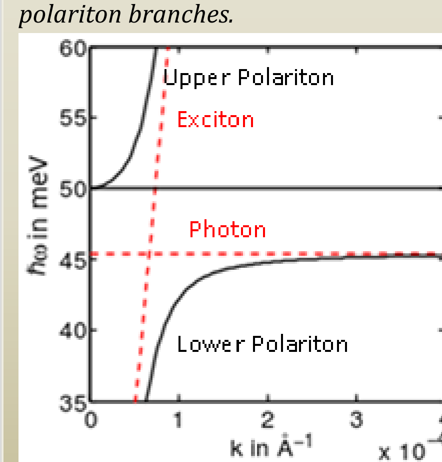
Theoretical descriptions of the manner in which similar surface plasmons interact were also given by G. Weick, who presented on a honeycomb structure of nanoparticles. Such a structure can create a band structure with Dirac-like states, similar to that of graphene. By moving the positions of the nanoparticles in the Brillouin zone, it is possible to tailor this dispersion to create a bad gap, and therefore engineer graphene-like structures from nanoparticles alone. It seems to me that this may be a more robust system potentially, as the oft-cited amazing properties of graphene rely on a lack of surface bonding which is very difficult to avoid when creating devices. This is not the case with these surface-plasmon based nanoparticles, although positioning on large scales may be difficult.

Polaritons:

The majority of talks at PLMCN were focused on forming polaritons in the InGaAs materials system. Such a system allows much cleaner formation of dislocation free QW structures than GaN materials, which can be chemically etched to form cavities, high Q-factor cavities, and QD systems grown by Stranski-Krastanov growth. Whilst the nitrides can have extremely long exciton lifetimes and oscillator strengths beneficial to polariton systems, they also have large effective masses, making formation of polaritons more difficult. As such, very few of these talks concerned GaN.

Perhaps the most interesting aspect of polaritons is the mix of being able to use optical tools to manipulate and measure

When a cavity enters the strong coupling regime, the lifetime of the photon in the cavity exceeds the exciton lifetime. Under resonant excitation the energy of the system oscillates at the Rabi frequency. Such a system can be treated as a quasi-particulate boson with energy states described by 'upper' and 'lower' polariton branches.



(Image modified from wikipedia)

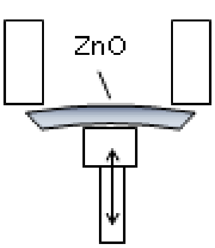
states whilst also creating strong nonlinearities from exciton-exciton interactions, allowing more novel devices to be created. The best example of a talk on this subject was given by Jacqueline Bloch regarding photonic lattices. She discussed recent work forming photonic crystal-like structures from nanopillars which could be engineered to strongly adjust polariton propagation properties analogously to electron transport in a benzene molecule. It was also possible to use the properties of polaritons generated by resonant or non-resonant excitation (pumping out of a polariton branch and allowing a cascade of relaxation to form the condensate) to alter the properties of photonic systems such as an 1D interferometer cavity (30 um across, in which path lengths are changed by the detuning magnitude of excitation), or even a structure analogous to a coulomb blockade in which a small region of dielectric connected to a source and drain was sufficiently small to create a region of only one polariton and hence single photon emission.

It was also interesting to note that polariton systems, which are normally considered in very clean systems (As), have been reproduced in wide band-gap materials such as GaN and ZnO. T. Guillet reported on a ZnO based microcavity using AlN/AlGaN and SiO_2/SiN Bragg reflectors which has exhibited polariton lasing up to 300K. Surprisingly threshold powers were only 6 times that of operation at 8K. Such a success is certainly nice to hear from the perspective of one working in these wide band-gap materials! Indeed, cavity Q was only 2600, certainly achievable in GaN, if only enough active material could be deposited with enough uniformity to achieve narrow line widths. The challenges in doing this with GaN materials was reported on by Raphael Butte, who commented not only on successful implementation of VCSEL structures and room temperature polariton diodes, but also explained the issues facing either InGaN or GaN active layers: InGaN active layers allow easier p-type doing in the GaN lattice but also feature large broadening mechanisms and hence require more material to reach sufficient gain, whereas GaN active layers can be grown ‘cleaner’, but the AlGaN lattice is difficult to p-dope. Despite this such advances in this material are remarkable.

Optomechanics

In many optical cavities, geometries are selected to allow efficient extraction of photons. Commonly pillar shapes are used to attain this. By using such a geometry, J. Claudon reported not only on a very high extraction efficiency from ‘nano-trumpets’ containing QDs (>75% extraction efficiency) and Gaussian far field emission, but by using a piezo-stack at the base of the trumpet to control mechanical oscillation strength managed to couple the QD emission and mechanical systems in the ultra-strong coupling regime (exciton-phonon coupling Rabi oscillations at the same frequency as the mechanical oscillations).

A mechanical oscillation created in piezoelectric materials induces an alternating electric field. This field may be coupled to local excitonic states in the same manner as photon coupling, and hence weak and strong coupling regimes can be created in a system with a great deal of control over field behavior.



The use of piezoelectric effects to study exciton interactions was explained in a talk by G. Jacopin, in which a ZnO nanowire was placed in a clamp allowing accurate pressures to be applied, straining the sample. By use of high spatial resolution cathodoluminescence SEM (an Attolight system with a streak camera) it was possible to map movement of exciton states along the strain field of the sample. This demonstrated that donor bound excitons can be drifted by a strain gradient in the material, and this process has been modelled as a 'hopping' process of individual excitons between donor sites mediated by the strain field.

Ultra-strong coupling:

I must confess my ignorance so far as I was previously unaware of this topic matter entirely. Whilst there were only a few talks regarding this area, it was informative to see more fundamental limits to the coupling schemes possible.

G. Scalari reported on ultra-strong coupling at THz frequencies utilizing a 2DEG with split-ring resonators to alter the material properties. Such a metamaterial allows the electron transport to be tailored, and by the use of superconductivity the Ohmic loss can be avoided. Coupling constants (Ω/ω) of 0.87 have been achieved (a current maximum reported in this type of system).

Coupling regimes: *Rabi frequency: Ω*
Excitation frequency: ω

Weak	*Strong*	*Ultra-strong*	*Deep-strong*
$\Omega << \omega$	$\Omega < \omega$	$\Omega \sim \omega$	$\Omega > \omega$

Fermi's golden rule → *Dressed states* → *Decoupling*

The normal description of cavity coupling (Jaynes Cummings model) breaks down for ultra-strong coupling; descriptions have to go beyond a first order perturbation. Beyond this, light and matter decouple as the field 'avoids' the excitonic dipole entirely (deep strong coupling).

The description of the polariton dispersion used so frequently at this conference can be shown to break down for the ultra-strong coupling regime. This was explained, a new model given, and experimental data shown to support this new model, in a talk by A. Vasanelli. The work used a similar metamaterial based on plasmonic confinement atop an InGaAs QW, in which the electrons are not confined to the semiconductor layer but show a collective resonance based on the metamaterial surface. The modified exciton dispersion then exhibits a band of disallowed energies which can be altered by the dimensions of the metasurface.

Nitrides:

Whilst my work exclusively focusses on InGaN/GaN materials, I couldn't help but get somewhat excited at the small number of talks featuring nitride systems, almost all focused on AlN/GaN structures. The plenary talk given by Prof. Arakawa was perhaps one of best summations of the range of advantages of the nitride materials and overview of some of the work he's done over the last few decades. Certainly the paper his group published earlier this year demonstrating a single-photon source operating up to 300K is a realization of the properties that make the nitrides worth developing in this area. This device was made by incorporation of a GaN QD atop an AlN pillar, allowing greater confinement laterally whilst minimizing the negative impacts of strain.

Considering the large proportion of talks focused on polaritons at the conference, it was interesting to hear from P. Bhattacharya regarding progress in III-V polariton lasers. Beyond higher confinements of nitrides allowing room temperature single photon sources, nitrides also have large exciton binding energies at room temperatures, large exciton-phonon coupling strengths and the absence of a polariton relaxation bottleneck at room temperatures. Because of this, room temperature polariton lasing has been achieved using GaN/InGaN nanowires embedded in a microcavity (horizontally or vertically). The nanobeams allow easy growth on silicon with reduced numbers of defects, a lower polarization field and the ability to grow relatively clean InGaN disks along the structure. Whilst the Q-factor of these structures is not very high compared to other materials systems (maximally ~5000), the low surface recombination velocity of the nitrides (two orders of magnitude lower than GaAs) allows polariton condensation to be seen. Electrically injected polariton emission at room temperature was also reported upon.

Other notable talks

Two talks notable for their novelty were those of H. Nguyen regarding 'Sonic black holes in polariton fields' and A. Kavokin's talk on 'Exciton mediated superconductivity'.

Nguyen explains that the transport properties of a quantum fluid is analogous to the 'river interpretation' of general relativity: the ability for a sonic wave to move 'upstream' along a flow depends on the relative motion of the fluid (curvature of spacetime), theoretically having an event horizon should the flow be significant enough. He claims to have realized this system by fabrication of a 1D cavity in which polaritons are created under resonant excitation. Whilst at low pump powers, the flow is supersonic and contains reflected components from a blockade at the centre of the cavity, higher pump powers lead to subsonic flow on the pump side of the device. The lack of reflected wave intensity was given as evidence for creation of the 'event horizon' at the blockade, although the relevance of describing the system in this way was questioned by several delegates.

A. Kavokin's talk describes a theoretical investigation into superconductivity, assessing the possibility of using excitons, rather than phonons, to create Cooper pairs. In a weak coupling regime of a semiconductor cavity, an excitonic condensate is created in which excitations of the electron cloud (described as Bogolons) create BCS pairs in a nearby metallic layer. The strength of the interaction can be finely tuned by optical excitation. The biggest challenge in such a system is the increased interaction velocity of excitons, many orders of magnitude greater than phonon velocities. Therefore the Cooper pair must be very small. However, by use of a double QW system allowing indirect excitons (electron and hole separately trapped in individual, nearby QWs) this problem can be overcome. If materials properties could be controlled accurately enough (largely a matter of very high doping levels) the room temperature superconductivity could be realized, albeit in a very small carefully created system.

Summation:

Whilst there were several talks detailing work with significant overlap to my own regarding better cavity fabrication, I believe it was really some of the more advanced physics that caught my attention: should GaN growth continue to develop in quality, these types of experiments should become possible in GaN.

Having such a perspective shows insights into the future of the GaN system, and the possibilities of where further work will someday be applicable.

There were not only talks about the materials system I have a personal interest in, but also topics I would be unlikely to encounter anywhere else. I was able to present my work to an international community, and have many interesting discussions from scientists of a variety of backgrounds. I would therefore like to give my sincere thanks to the UKNC for their contribution in funding this trip for me.

Tim Puchtler, 19/6/2014