**7th FRAMEWORK PROGRAMME - Marie Curie Actions - *People***

**International Research Staff Exchange Scheme**

**POLALAS: Novel photonic nanostructures for polariton lasers**

**Project Number 230811**

**Publishable Summary of Final Report**

**Introduction**

The POLALAS project was concerned with theoretical and experimental research on exciton-polariton phenomena in photonic microstructures that are designed to exhibit novel or enhanced device functionality, including through the use of confinement of the excitations in two or three-dimensions. Exciton-polaritons currently represent one of the most topical and exciting areas of physics and the ability to confine and control them spatially opens up new opportunities in fundamental research and device applications. The project was carried out by a consortium comprising Durham University (UDUR), Universita Degli Studi di Roma Tor Vergata (UR), the Centre of Physical Sciences and Technology (FTMC) in Vilnius, and the Ioffe Physico-Technical Institute of the Russian Academy of Sciences (PTI) in St Petersburg.

Exciton-polaritons (or simply polaritons for brevity) are part-light, part-matter quasiparticles which obey bosonic statistics. As such, they can form a Bose-Einstein condensate, and do so at relatively high temperatures due to their extremely light effective mass. They can also exhibit a number of fascinating physical effects, including superfluidity, superradiance and quantum entanglement. However, as well as being of great fundamental interest, polaritons have considerable potential for the realization of a new generation of optoelectronic devices exploiting collective quantum effects at room temperature. Future polariton devices can be expected to include polariton lasers, optical logic gates, polarization modulators, spin-memory elements and quantum information devices. For the development of such technology an interdisciplinary approach is essential, including the involvement of specialists in fundamental and applied semiconductor physics, photonics, quantum optics, crystal growth, nanotechnology and device fabrication.

**Work carried out, main results and their impact**

Access to state of the art fabrication facilities is essential to provide samples for experimental research on semiconductor nanostructures and PTI was the fabrication centre for the POLALAS project and could call on a range of techniques from molecular beam epitaxy (MBE) to advanced lithography. PTI grew micropillar and nanowire structures for experimental studies that were carried out both in-house and at FTMC. A particularly significant development in the nanoscale growth work, which is attracting substantial interest from other researchers, was the use of a catalytic technique for growing nanowires.

For many years the application of THz radiation in spectroscopy, sensors and imaging was held back by a lack of satisfactory THz sources. While a number of new sources have now emerged, there is still a considerable interest in device developments that could provide increased efficiency and power, compactness, tuneability and coherence. During the project, we investigated THz emission from optically excited, structured semiconductor surfaces and also as a result of quantum transitions in polariton devices. Significant advances have been made on both themes.

A new type of THz emitter based on a modified polariton laser has been proposed in collaborative work between PTI, UDUR and UR, and is expected to make possible a relatively efficient source of coherent THz radiation. In a specially designed polariton laser structure, terahertz photons can be created by quantum transitions between the upper and lower polariton branches. Such transitions are normally forbidden but can be made allowed by mixing the upper polariton state with one of the exciton excited states using an electric field or compositionally graded quantum wells. Furthermore, the transitions are stimulated in the polariton laser regime.

Also, FTMC and PTI have studied THz emission from nanostructured semiconductor surfaces and found that GaP and other III-V crystals with chemically etched holes of nanometer size, when photoexcited by femtosecond laser pulses, emit two orders of magnitude more powerful THz pulses when the holes are filled with a metal such as Cu or Ag. Such structures are a type of wire metamaterial, and it is thought that the large enhancement of emitted THz power is caused by the resonant behavior of the metallic nanorods, which serve as an antenna array for THz waves that are generated inside the semiconductor due to the optical rectification of the laser pulses.

We reported the first experimental observation of Tamm plasmon-polaritons (TPPs), an optical excitation formed at the interface between a metal film and a multilayered dielectric mirror. Furthermore, we have shown that the coupling of TPPs to polaritons in a microcavity could form the basis of a novel approach to achieving the lateral localization of polaritons in planar microcavites. Hence localization and channeling of exciton-polaritons in chosen regions of the plane of a microcavity can be achieved by the deposition of patterned metallic films on the surface of the structure, and could provide an alternative to microdiscs and microspheres in some applications. However, particularly novel is the proposal of UDUR, PTI and UR that the technique could be used to produce polariton-based, all-optical integrated circuits since polaritons can carry information encoded in their vector polarization, and channels defined by surface metallization can be used to control their propagation and interaction. Our numerical modelling has shown that the propagation of signals can be suitably controlled and has also demonstrated the potential for functional circuits.

Visits by PTI scientists to UR have resulted in important new work on the fundamental properties of exciton-polariton condensates. Studies undertaken have included the theoretical analysis of polariton-polariton interactions and Bose-Einstein condensates of exciton-polaritons. With regard to the consideration of new cavities, UDUR has studied in detail the polariton mode structure of semiconductor submicron spheres and shown that the strong coupling of excitons to a single cavity mode is achievable.

Research on the device properties of polariton lasers concentrated on collaboration with a group at the Ecole Polytechnique Federale de Lausanne (EPFL) in the design of electrically pumped gallium nitride-based polariton lasers. Two types of pumping have been considered in the modelling: non-resonant optical pumping by an electrically driven light emitting diode and direct electrical pumping when free charges are injected directly into the laser resonator. The versatile device simulator TiberCad, developed by workers at UR, has also been adapted to model such lasers by including an appropriate combination of real-space simulations of the charge carrier dynamics and the reciprocal-space simulation of the exciton-polariton dynamics.

**Potential impact**

The project was concerned with the next generation of devices beyond current polariton-based lasers and light emitting diodes by making use of the fundamental properties of exciton-polaritons, and as such the research and its outcomes will be of interest to a wide academic and industrial audience, while at the same time helping to keep Europe’s world lead in the field.

In recent decades, social development has been strongly correlated with technological progress in the areas of information storage, transfer and processing. The development of compact, low-cost, low-energy all-optical integrated circuits and related devices would give a further boost to technological progress, and a reduction in the cost of communication systems will make them affordable for the people in the developing world and thus help in integrating the more remote areas of the globe into the universal communication space. There are of course also benefits for everybody from the contributions made to the fight against climate change.

**Further information**

Further information on the project, the research carried out and the associated publications can be found at the project web pages <http://www.dur.ac.uk/polalas/>.

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