PREFACE

Special issue on microcavities

Guest Editors

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Light is absorbed by promoting electrons between quantum states. Our control of this key optoelectronic interaction has improved radically in recent years as we become smarter about finding ways to affect this fundamental process.

For decades, researchers concentrated on improving optical properties through changing the properties of the electronic states, by choosing appropriate atoms, molecules or solids, and by growing crystals of a perfection not found in nature. Huge developments in material science saw the introduction of many optically special materials, such as compound semiconductors and their nanostructures.

Recently we have found new ways to manipulate the light–matter interaction by modifying the *photonic* components, for instance by enhancing the optical field with feedback in cavities. This second 'knob' on the light–matter interaction manipulates the optical density of states. Besides simply enhancing the interaction by locally amplifying the electromagnetic fields, the modified optical density of states produced by photonic structuring allows emission and absorption rates to be enhanced or suppressed, now known as the Purcell effect.

Atom-filled optical cavities exhibit many of these interesting phenomena. But it was not until the advent of high-quality semiconductor epitaxy that transitions with sufficient oscillator strength and a narrow-enough linewidth could be produced to uncover a third approach to modifying the light–matter interaction. A simple offshoot of the technology development of vertical-cavity semiconductor lasers, the combination of high-reflectivity semiconductor mirrors and narrow strong absorption lines of semiconductor quantum wells, opens a new regime.

This 'strong-coupling' regime emerges when the time it takes a photon to be emitted and pass once around the cavity to be then reabsorbed (known as the inverse 'Rabi' frequency) becomes less than the time for the photon to leak out of the cavity or for the electronic transition to lose its phase coherence. In 1991 the first such semiconductor structure showed the resulting Rabi splitting, with electron and photon states being mixed together by the optical interaction into polaritons (Weisbuch *et al* 1992 *Phys. Rev. Lett.* **69** 3314).

Why do polaritons in semiconductors give us so many new properties, many of which are explored in this special issue? They are the third knob to tweak on the light–matter box because the mixing revises the underlying quantum states; polaritons then have different properties to electron–hole pairs. Instead of merely working on reshaping the wavefunctions of the electrons, we use the electric-dipole coupling to mix in some photon component and alter the way that optical energy couples in and out of the material. Polaritons have one of the biggest spatial wavefunctions that we know how to make, they possess boson symmetry, and weigh very little compared to electrons.

But it is not really their individual properties that make them of such importance, it is their interactions. It took another decade after the first polaritons were seen in semiconductor microcavities before it was found that the interaction between polaritons was orders of magnitude stronger than between electron–hole pairs (Baumberg 2001 *Physics World* **15** (3) 37 and Savvidis *et al* 2000 *Phys. Rev. Lett.* **84** 1547). The key revelation in understanding polaritons has been their dispersion relation, which is completely distorted compared to that of the electron–hole pairs (Houdre *et al* 1994 *Phys. Rev. Lett.* **73** 2043). Of course polaritons exist in bulk materials (Hopfield 1958 *Phys. Rev.* **112** 155) but the shape of the dispersion there is again different and not favourable for many of the polariton interactions that are reported throughout this issue. In semiconductor microcavities, the new dispersion relations take the form of an energy 'trap' in momentum space. As in golf, polaritons tend to collect either at the bottom of the trap or around its edges.

Through an intense concentration of research, both theoretical and experimental, over the past three years much has become clearer about how polaritons behave, including suggestions about how they can be made to work for us in producing hitherto inaccessible physical phenomena of technological interest. Thus, it is timely to collect many of the excellent contributions together into a special issue in which much of this science can be treated in the depth it deserves. We can divide the contributions into those that promise new sorts of strongly-coupled microcavity devices; those which explore how polaritons are formed, how they scatter, and how they decay; and those which identify more of the unusual polariton properties (particularly at the bottom of the dispersion relation). This latter topic reopens the question of whether Bose–Einstein (or in this case, polariton) condensation is possible or has been seen in these unusual structures. This field then crosses a number of important research areas including micro-lasers, lasing without inversion, condensation and superfluidity, new spin properties, ultrafast optical nonlinearities and quantum optics.

We have included a review article by Quatropanni and co-workers, which discusses theoretical aspects of the nonlinear optical properties of semiconductor microcavities in the strong exciton–photon coupling regime, which was planned to appear as a separate paper in *Semiconductor Science and Technology*, but which was considered more appropriate to be incorporated in this issue. A theoretical description of coherent nonlinearities in semiconductor microcavities is given by Savasta *et al*, who show that the strong energy dependence of the two exciton states damping is crucial to explain the dependence of the experimentally reported results on Rabi splitting and detuning. Stimulated polariton scattering, arising from the bosonic character of polaritons, is described by Skolnick's group, who also emphasize the role of the unusual dispersion of the lower polariton branch to allow much of the new physics in semiconductor microcavities. Non-linear effects in semiconductor microcavities, which include stimulated polariton scattering, parametric oscillation, spin dynamics, and the possibilities of a polariton condensate, are discussed by Baumberg *et al*. The suppression of the relaxation bottleneck on the lower polariton branch and the stimulation of the emission in II–VI based microcavities is demonstrated by Dang and collaborators, who also probe the coherent dynamics along the lower polariton branch by means of angle-resolved four wave mixing experiments. The possibility to observe parametric polariton amplification at room temperature is discussed by Deveaud's team, who demonstrate that this could be achieved in cavities, in which quantum wells with a large exciton binding energy are embedded, such as in GaN-based cavities. The effects induced by a two-dimensional electron gas on the interaction between the electromagnetic field and the excitons in a semiconductor microcavity are discussed by Cohen *et al*, who show that the presence of the electron gas is responsible for an efficient interaction between electrons and polaritons. The modification of the optical mode spectrum in microcavities, by introducing lateral photon confinement, is demonstrated by Bayer and collaborators, who show the possibility of tailoring elastic polariton pair-scattering and a suppression of the spontaneous emission for quantum dots embedded in such cavities. The optical properties of biexcitons in microcavities are reviewed by Langbein *et al*, who perform a detailed investigation of the polariton–biexciton transition and study the biexciton binding energy and dephasing in a microcavity at low temperature. A detailed experimental study of linear and circular polarization dynamics in secondary emission of microcavities in the strong coupling regime is presented by Amand's group, who show that it is possible to manipulate the polariton spin and alignment within the optical dephasing time. The spin dynamics under non-resonant excitation is presented by Viña's co-workers, who demonstrate that the polarization of the emission is controlled by the detuning of the cavity and the exciton modes, leading to crossed-polarized emission after circularly-polarized excitation at negative detunings. The enhancement of the resonant Raman scattering using semiconductor planar microcavities is described by Fainstein and Jusserand, who also propose a novel phonon microcavity structure and demonstrate the existence of acoustical phonon confined modes in these structures. Exciton–polariton lasing and its relation with the formation of a macroscopic coherence, associated with a Bose–Einstein phase transition, is reviewed by Yamamoto *et al*. A calculation of the phase diagram of a weakly interacting polariton gas in a microcavity is given by Kavokin and collaborators, who also describe the possible condensation of polaritons using a quantum kinetic formalism. The quantum mechanical nature of the light field in semiconductor microcavities is revealed by the teams of Gibbs and Koch, who describe entanglement effects in the probe reflectivity of a microcavity system and squeezing in the incoherent emission. Normal-mode coupling in photonic crystals is demonstrated by Ishihara's group, who present experimental evidence of the strong coupling regime, detuning schemes, and anticrossing behaviour in absorption and photoluminescence investigations. Characteristic features of organic semiconductor microcavities, the similarities and differences between inorganic and organic cavities operating within the strong coupling regime and the identification of novel features of the organic systems that can be exploited in new structures are discussed by Bradley *et al*, who also present prospects for inorganic/organic hybrid materials that may form the seed of a new paradigm in optoelectronic devices. A theoretical analysis of resonant acousto-optic Stark effects for microcavity polaritons is presented by Ivanov and Littlewood, who also discuss possible applications of this effect for optical modulation and switching.

Hopefully, as well as providing a new resource, this issue will stimulate imaginative exploitation of this emerging field.