Microcavities and Photonic Crystals:

a historical perspective on the development of concepts

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For a large part, microcavities and photonic crystals aim at controlling the interaction of light and matter in semiconductors.

The topic of light-matter interaction in semiconductors has itself long triggered a huge effort both due to its importance in the fundamental understanding of these solids and in the many applications that depend on it. On the former aspect, we can cite the photoconductivity property, light emission capability and various electro-optic and non-linear effects. On the latter aspect, we recall such large-scale applications as light detectors, LED's and lasers, photovoltaic generators, displays, etc.

It has been recognized since long that the fundamental optical properties are intimately linked to features originating in the symmetry and dimensionality of the electronic system: the first models of absorption edge of semiconductor and insulators relied on free Bloch electrons in the one-electron model. Soon after, Frenkel, Peierls and Wannier developed the exciton concept, as it appeared that the translational invariance of the crystal required that the photoexcited electronic species preserve the crystal symmetry.

To complicate (or simplify) the description of the system, one has to consider the complete system of electronic (excitons) and electromagnetic (photons) states. Then, one can have situations, at low enough temperatures and concentrations, where both types of excitations interact coherently giving rise to coupled-mode excitations, the excitonic polaritons, pioneered by Pekar and Hopfield in the late fifties. Absorption phenomena are sharply changed in the polariton picture as they are due to polariton scattering and not to the light-matter interaction. Photoluminsecence becomes a second-order process due to the propagation of polaritons and their escape at the semiconductor-air interface. Already in the fifties (Toyozawa, Hopfield), it was pointed out that a relaxation bottleneck due to diminishing density of states (DOS) was playing a major role in the luminescence of such species, as otherwise relaxation towards the zero-energy ground state would prevent any luminescence.

Of course, these considerations were further developed with the advent of lower dimensionality semiconductor structures. The first breakthrough came with the advent of quantum wells (QWs). The vastly improved light-matter interaction over 3 D "bulk" semiconductors relies at first-order in the freezing of one degree of freedom in such structures, yielding more spectrally concentrated optical features such as absorption and gain for free carriers. This was well shown by the progress in semiconductor lasers due to the use of QW active layers, and from the increased exciton binding energy, allowing exciton effects at room temperature, therefore larger electro-optic and nonlinear effects.

A major surprise in QW luminescence is the dominance of free exciton species over bound excitons, at variance with bulk materials, and also of the higher quantum efficiency of QW materials. This was only understood in the late 80'ies (Deveaud) as due to the symmetry breaking between 2D exciton states and 3D photon states, which makes luminescence allowed at first order, and therefore much more efficient than in the bulk (the effect had been predicted by Agranovitch and Dubovskii in 1966).

In view of the successes of QWs, large efforts were devoted since the mid-eighties to the fabrication and evaluation of lower dimensionality systems such as quantum wires (QWRs) and quantum dots (QDs), in order to freeze more degrees of freedom, and therefore reach sharper optical features in the spectrum of such structured solids as determined by the density of states. The interplay between electronic and photonic dimensionalities for QWRs and QDs again introduces specific modifications of the lifetime against bulk material However, quantum dots, with their atom-like discrete energy levels, suffer from the difficulty of fabricating such minute structures with small enough size fluctuations.

It is only in the 80'ies that it was recognized that another way exists to modify the light-matter interaction in solids, although it was recognized long ago for atoms: it is that based on the control of photon modes. For atoms in cavities it opened the field of cavity quantum electrodynamics (cavity QED). For solids, it can be achieved either through microcavities or photonic crystals.

The first era in the field (end of 80'ies-beginning 90'ies) dealt with the control of the directionality of spontaneous emission in the "weak" coupling regime between semiconductor excitations and cavity. There was also a search for modification of the lifetime through the Purcell effect but the use of planar cavities and/or of broad emission lines prevented the observation of a large effect.

The observation in 1992 of cavity polaritons (CPs) due to the "strong" coupling regime between 2D excitons and photons led to a variety of novel phenomena, such as disorder averaging, ultrafast resonant emission, 2D Rayleigh scattering, and spectacular nonlinear effects. The novelty of the system comes from the fact that CPs have a finite ground state, with very remarkable features, as these quasi-particles behave like photons (light mass) or like excitons (interactions with one another, with phonons, with disorder). Unfortunately, like their 3D counterparts, CPs experience a relaxation bottleneck due to the diminishing DOS when reaching photon-like (i.e. light mass) states. This forbids so far the applications of the strong-coupling in the real-world (i.e. room-temperature and electrically-injected devices), and also direct observations of fundamental phenomena such as spontaneous Bose condensation.

On the other hand, major advances have been made in the past few years in the weak-coupling regime, with resonant-cavity LEDs being now marketed. Next generation devices will include full 3D control of photon modes, through micropillars or photonic-crystal based structures. The latter should allow ultimate control of photon modes, with applications in quantum and integrated optics.