Preface

This book has been initially prepared as a special edition of Physica Status Solidi, published as a festschrift in honor of Marc Ilegems, on the occasion of his retirement. The editors however considered that the topic was important enough to deserve a publication per se. Let me therefore state in a few words why should this volume be of interest for a large audience, and then rephrase briefly what were the achievements of Marc Ilegems that deserved to see his name associated to such a book. I will then summarize the different chapters so the the reader may have a proper overview of the content of this book.

The idea of going from a standard semiconductor laser to a vertical surface emitting system appeared at the end of the 80th (the so-called VCSEL – Vertical Cavity Surface Emitting Laser). Interesting preliminary work was accomplished by the group of Franz Karl Reinhart at Ecole Polytechnique Fédérale, in Lausanne. The idea is in fact quite simple and resides in the very high gain achievable in semiconductor active layers together with the possibility to grow monolithic distributed Bragg reflectors exhibiting reflectivities very close to 100%. It was then possible to imagine, and later indeed realize, semiconductor lasers with a very small thickness for the active layer.

What was not planned at the beginning of such a process was that the coupling between light and matter would be strong enough to bring the whole system in the strong coupling regime. It is only with the seminal work of Claude Weisbuch, during a stay in Japan, that he realized a very simple reflectivity experiment allowing him to evidence, for the first time, the existence of a strong coupling regime in a VCSEL structure, that we now call microcavities because the first aim of the system is not to make a laser. The strong coupling between excitons in a quantum well and the confined photon modes in the optical cavity, gives rise to a new quasiparticle, called polariton, that is built from half an exciton plus half a photon.

The interest on the physics of polaritons as constantly been rising since then because of the numerous and very specific properties that these new quasiparticles show. In fact, such properties come from the double nature of polaritons, bearing some resemblance to photons, and therefore behaving as bosons, as well as remembering that they are made up with electrons and holes, and therefore being able to interact. The result is that we have true bosons in the low-density limit, with an effective mass of the order of 10^{-5} times the mass of an electron. At the same

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time, these quasi bosons may interact through their electronic constituents, possibly opening the route towards real life devices. They also have a very strangely shaped dispersion relation, which allows non-linear parametric effects to occur.

In the process between the discovery of microcavity polaritons, the understanding of their complex physical properties, and the possible applications, the collaboration between the group of Claude Weisbuch, and the group of Marc Ilegems has been essential. The two teams have worked together towards first the realization of very high quality microcavities, and second the realization of clear-cut experiments allowing a very precise understanding of the properties of microcavity polaritons.

The present book aims at describing the latest advances in the physics of microcavity polaritons. It will be, I hope, useful for students and researchers in the field, allowing them to understand the basic properties of polaritons that make them so attractive and interesting.

This book is then organized in the following way.

In Chapter 1 "*Introduction*" Vincenzo Savona provides a tutorial presentation of the basics of the field and overviews what has already been published on the subject, but needs to be recalled here for sake of completeness of the volume. Indeed, some of the students interested in microcavities might not have studied these early developments.

In Chapter 2, entitled "*MBE Growth of High Finesse Microcavities*", Ursula Oesterle, Ross Stanley, and Romuald Houdré describe the growth process that has allowed them to obtain very high finesse microcavities, Such microcavities can consist of hundreds of different layers and can be several microns thick, with the absolute thickness of each layer and the smoothness of each interface having an impact on the optical quality of the structure.

In Chapter 3, entitled "*Early Stages of Continuous Wave Experiments on Cavity Polaritons*", Romuald Houdré presents a description of the basics of cavity-polariton physics. He describes several key experiments that he has been realizing and highlights the historical context of such experiments performed on cavity-polariton during the period 1992–2000. In particular, the angle resolved emission properties are described in great detail.

In Chapter 4, entitled "*Exciton-Polaritons and Nanoscale Cavities in Photonic Crystals*", Lucio Claudio Andreani, Dario Gerace, and Mario Agio give an overview of recent theoretical work on exciton-light coupling in waveguide-embedded photonic crystals is reviewed. The following issues are discussed: (1) a quantum-mechanical formulation of the interaction between photonic modes and quantum-well excitons, leading to a description of photonic crystal polaritons; (2) calculations of variable-angle reflectance spectra, which show that radiative polaritons can be excited by an optical beam incident on the slab surface; (3) a description of nanoscale cavities with extremely high Q-factors and low mode volumes in photonic crystal slabs; (4) a quantum-mechanical model of the interaction between confined nanocavity modes and single quantum-dot transitions, leading again to a strong-coupling regime of light-matter interaction.

In Chapter 5 entitled "*Parametric Amplification and Polariton Liquids in Semiconductor Microcavities*", Jeremy J. Baumberg and Pavlos G. Lagoudakis provide a description of parametric amplification in semiconductor microcavities as an example in which nonlinear optical interactions produced by the exchange interaction of excitons become so large that multiple scattering of polaritons becomes important. They review time-resolved observations of the polariton interactions in a number of different geometries including pumping at either the magic angle, or the bottom of the polariton trap. Situations in which the polariton dispersion is multiply occupied by large populations give rise to *k*-dependent energy shifts, modifying the dispersion dynamically, a situation termed by them *"the strongly-interacting polariton liquid."*

In Chapter 6, called "*Quantum Fluid Effects and Parametric Instabilities in Microcavities*", Cristiano Ciuti and Iacopo Carusotto present a description of the nonequilibrium properties of a microcavity polariton fluid, injected by a nearly-resonant continuous wave pump laser. In the first part, they point out the interplay between the peculiar dispersion of the Bogoliubov-like polariton excitations and the onset of polariton parametric instabilities. They show how collective excitation spectra having no counterpart in equilibrium systems can be observed by tuning the excitation angle and frequency. In the second part, the impact of these collective excitations on the in-plane propagation of the polariton fluid is explained. The authors show that the resonant Rayleigh scattering induced by artificial or natural defects is a very sensitive tool allowing to evidence fascinating effects such as polariton superfluidity or polariton Cherenkov effect.

In Chapter 7, named "*Non-Linear Dynamical Effects in Semiconductor Microcavities*", Jean-Louis Staehli, Stefan Kundermann, Michele Saba, Cristiano Ciuti, Augustin Baas, Thierry Guillet, and Benoit Deveaud describe an investigation of the parametric amplification and its coherent control in a semiconductor microcavity. The time and angle resolved pump and probe experiments show that several picoseconds after pumping the polaritons are still coherent and parametric scattering is still going on. The experimental data concerning the time integrated measurements are in qualitative agreement with the numerical data obtained from a relatively simple theoretical model based on three polarization components, pump, probe, and idler. The dynamics of parametric amplification is also studied in real time, the measurements reveal that stimulation may be considerably delayed with respect to the arrival of pump and probe.

In Chapter 8, entitled "*Polariton Correlation in Microcavities Produced by Parametric Scattering*", Wolfgang Langbein describes the measurements of the spontaneous and self-stimulated parametric emission from a semiconductor microcavity after resonant pulsed excitation. The emission of the lower polariton branch is resolved in two-dimensional momentum space, using either time-resolved or spectrally resolved detection. The polariton-polariton scattering dynamics is generally in good agreement with the theory using the nonlinearity due to the excitonic part and the dispersion due to the photonic part of the polariton. The peculiar figure-8 shaped distribution in momentum space of the final states of the parametric scattering is observed. Renormalization of the dispersion due to the bound biexciton state is found to influence the final state distribution. Using two pump directions the shape of the final state distribution can be changed to a peanut or oval for the mixed parametric processes. In this dual pump configuration, he finds that polaritons in two distinct idler-modes interfere if, and only if, they share the same signal-mode, showing the existence of polariton pair correlations that store the "which-way" information.

In Chapter 9, named "*Spin Dynamics of Exciton-Polaritons in Microcavities*", Ivan A. Shelykh, Alexei V. Kavokin, and Guillaume Malpuech address a complex set of optical phenomena linked to the spin dynamics of exciton-polaritons in semiconductor microcavities. Their state can be fully characterized by a so-called "pseudospin" accounting for both spin and dipole moment orientation. The pseudospin dynamics of exciton-polaritons is quite rich and complex, giving rise to non-trivial changes in polarization of light emitted by the cavity versus time, pumping energy, pumping intensity and polarization. The authors overview the essential experimental results in this field before presenting a formalism allowing to interpret the key experimental findings. The strong coupling regime leaving aside all polarization effects in VCSELs is also discussed.

In Chapter 10, entitled "*Bose–Einstein Condensation of Microcavity Polaritons*", Vincenzo Savona and Davide Sarchi first summarize the basic facts about Bose–Einstein condensation of weakly interacting systems. Then, they review the main experimental and theoretical works aimed at the realization of this intriguing phenomenon in the system of microcavity polaritons. All the experimental results until present suggest that Bose– Einstein condensation is still eluding the experimentalists' efforts. On the theoretical side, only recently polaritons have been described within a quantum field theory of an interacting Bose gas, suggesting that polariton condensation might occur at least as a consequence of polariton parametric scattering under resonant excitation.

In Chapter 11, named "*Polariton Squeezing in Microcavities*", Antonio Quattropani and Paolo Schwendimann describe the squeezed states that may be found in solids when considering solid state excitations like polaritons. Squeezing may be observed through the polariton radiation field component, whose statistics reproduces the statistics of the polaritons. The squeezing of polaritons in different semiconductor systems and excitations regimes is discussed. For a sufficiently low density of excitation, an intrinsic but very small squeezing is found for bulk as well as for quantum well and microcavity polaritons. When the density of excitation becomes larger, a large amount of squeezing of microcavity polaritons induced by polariton–polariton scattering is demonstrated both in theory and in experiment.

In Chapter 12, "*High Efficiency Planar MCLEDs*", Reto Joray, Ross P. Stanley, and Marc Ilegems extend the discussion of microcavities towards experimental and theoretical work on the optimization of the light extraction properties of light-emitting diodes. They demonstrate that such works have led to the current high efficiency microcavity LEDs but also to the high brightness LEDs based on other approaches, which are presently available on the market. An overview of the state of the art of planar semiconductor microcavity LEDs is presented.

In Chapter 13, entitled "*Progresses in III-Nitride Distributed Bragg Reflectors and Microcavities Using AlInN/GaN Materials*", Jean-François Carlin, Cristof Zellweger, Julien Dorsaz, Sylvain Nicolay, Gabriel Christmann, Eric Feltin, Raphael Butté, and

Nicolas Grandjean propose to use lattice-matched AlInN/GaN to replace the Al(Ga)N/GaN material system for III-nitride Bragg reflectors, despite the poor material quality of AlInN reported until very recently. They report an improvement of AlInN material that allowed for successful fabrication of a microcavity light emitting diode, a distributed Bragg reflector with 99.4% reflectivity and microcavities with a quality factor over 800. These results establish state-of-the-art values for III-nitrides, and announce the future importance of AlInN in GaN-based optoelectronics.

In Chapter 14, that closes this book, entitled "*Microcavities in Ecole Polytechnique Fédérale de Lausanne, Ecole Polytechnique (France) and Elsewhere: Past, Present and Future*", Claude Weisbuch and Henri Benisty present an overview of semiconductor microcavity research, with emphasis on the activities carried out at Ecole Polytechnique Fédérale de Lausanne and Ecole Polytechnique (Palaiseau, France). They give clues for the understanding of the past as well as indications for future possible developments.