**Introduction**

Semiconductor microcavities (MC), which typically consist of a *GaAs* layer with Bragg mirrors on the top and bottom, have been the subject of intense research more than a decade, since the first experimental evidence of strong coupling between the excitations of an electronic system located in the cavity and the confined photons . This strong coupling is typically realized by embedding a quantum well (QW) in the center of the MC. If the QW exhibits a pronounced exciton transition whose energy is nearly resonant with that of the confined photon, and when both bare exciton and empty cavity linewidths are small enough, a strong exciton-photon coupling is manifest by the appearance of two lines on the reflection spectra. The so called Rabi splitting between these two modes is controlled by the cavity and the QW exciton properties .

In fact, much of the physics of light-matter interaction was first studied in the field of atomic physics, where a Rabi splitting was manifest for a single atom confined in a metallic cavity . The simplest model for the interaction of a radiation field with atoms is the Jaynes-Cummings model which treats the case of a single two-level atom interacting with a single-mode radiation field, using the dipole and rotating wave approximations. When the photon energy matches the energy difference between the excited and ground states of the atom, the lowest excited states of the system are no longer degenerate. The new eigenstates of the system are thus superpositions of the uncoupled system states with an energy difference given by the Rabi frequency.

The solid state analog was first discussed by Hopfield , who showed that momentum conservation in bulk semiconductors constrains an exciton to couple only to a photon with the same wavevector. If the damping is weak enough, the new eigenstates are mixed photon-exciton modes, named exciton-polaritons. In contrast to the two-level atom case, the exciton-photon coupling strength is constant, for a given semiconductor, and does not depend on the exciton density. The use of MCs with embedded QW enables to easily control and enlarge the exciton-photon coupling strength. The polaritonic splitting, determined by the exciton oscillator strength, is about two-times larger for the 2D system compared the bulk semiconductor case, which facilitates the easy attainment of the strong coupling regime in such a system. The spectroscopic and dynamic properties of polaritons resulting from the basic resonances of the QW have been extensively studied. For planar MCs with embedded QWs, the photon-exciton interactions lead to crystal momentum conservation, resulting in a well defined polariton dispersion in this plane.

Thin dielectric structure growth technology has undergone a rapid development thougout the last two-decades, facilitating the creation of ever more elaborate structures for the investigation of light-matter interactions, in which the coupling strength is easily amplified and controlled. Such systems are typically comprised of commonly used alloy semiconductors such as *GaAs*, *AlAs* and *Alx Ga*1*−x As*. The first experiments that examined the spontaneous emission amplification in QW via light trapping were conducted by Yamamoto, where a change in the emission has been detected for high finesse semiconductor MCs. The strong coupling of QW excitons with the MC trapped photons was first shown experimentally by Weisbuch, which is in fact the first demonstration of a MC polariton. In this system the Rabi splitting is proportional to the excitonic oscillator strength. As the lowest energy excitons in the QW (the heavy and light hole excitons) are those with the strongest oscillator strength, the strong coupling regime can be easily reached. Thus the spectroscopic and dynamic properties of such MC polaritons have been extensively investigated.

In quantum structures comprised of *GaAs/Alx Ga*1*−x As* QWs, the ground state of the electronic system is de- termined by the carriers populating the conduction band resulting from the structure modulation doping. This doping can be attained through several growth techniques, of which we concentrate in the *δ*-doping scheme where a monoatomic layer of dopants is placed during the structure growth in the cladding regions of the QW. In such a structure, the QW conduction band electrons can be described as a two-dimensional electron gas (2DEG). The prop- erties of such a gas can be probed through various experimental techniques, such as optical spectra measurements

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and transform measurements based on the quantum Hall effect. The first approach enables the investigation of the entire spectrum of the gas, in contrast with the transport measurements which provide a glimpse only to the Fermi energy edge states of the electronic system. The spectroscopic measurements, conducted at low temperatures and under applied magnetic field, exhibit multi-particle phenomena stemming from electron-electron and electron-hole interactions in the presence of the 2DEG.

In order to investigate the interactions between the electronic resonances of the QW and the MC photonic mode as a function of the their energetic difference, a quantum structure has to constructed where the energy of one of the two can be altered in a controllable and constant fashion. To this end, the MC structure is constructed of layers with variable width along the diameter of the sample wafer. The end result of this approach is that the exciton energy can be treated as constant compared to that of the MC photon mode. Through illumination of a specific location along the sample the system can be brought to a interaction state where the photon mode energy equals that of the electronic resonance. The achieved coupling is typically described by two models. The first is the coupled oscillator model, in which each one of the interacting resonances is described by a simple quantum oscillator. Here, the coupling Hamiltonian of the exciton and photon with a specific coupling strength can be diagonalized in order to obtain the polariton energy spectum. A convenient form for the representation of the polaritonic excitation mode are the anti-crossing diagrams, which plot the polariron energy as a function of the energetic difference between the excitons and the photon, *δ*. Away from the resonance region of the system (*|δ| »* 0), the polariton energies equal the energies of the uncoupled exciton and photon, while close to the resonance (*δ ≈* 0) these energies deviate from those of the exciton and amount to the Rabi splitting of the system. An alternative method for the description of this coupled system is the linear dispersion model (LDM), where the transfer matrix formalism is employed. Here, the refractive index of the QW is described by an effective refractive index where the exciton is modeled by an Lorentzian oscillator.

Recently, several experimental studies have been conducted that examine the interaction of a 2DEG, introduced inside the QW through various doping mechanisms, with the MC photon. These studies have shown that in a doped QW placed inside a MC with high 2DEG concentrations (*ne ≥* 0*.*9 *×* 1011 *cm−*2 ), where the system is devoid of excitons, there are still traces of strong interaction between the trapped photonic mode and various electronic resonances of the QW. This finding confronts the accepted view that the disappearance of well excitons leads to the destruction of the polaritonic modes. As an explanation for this phenomenon, it was conjectured that the source of the observed polaritonic lines are unbound electron-hole pairs with Fermi wavevector. The coherence between these pairs, dictated by the observed strong interaction, was assumed to originate from the strong interaction itself. For the verification of this proposition, a thorough experimental study was conducted including the measurement of the reflection and photoluminescence spectra such structures in the presence of 2DEG, with and without the application of external magnetic field. The introduction of the magnetic field facilitates in the separation of the interaction of the photonic mode with the 2DEG electrons and with the well excitations. The obtained experimental results were backed by theoretical calculations including the the dispersion relations of the studied QWs, the optical susceptibility of these wells and finally the phenomenological dipole moments. In order to calculate the reflection spectra the transfer matrix method was employed. The obtained experimental results were then fitted using the proposed experimental models in order to extract various experimental parameters.

In this thesis we present a theoretical study of the electronic and optical properties of MCs with a single embedded QW in the cavity region and introduced 2DEG. Here we propose a new modeling approach of such structures based on basic physical considerations, which stands in contrast to the accepted convention of fitting phenomenological models to experimental measurement results.

We start the analysis in chapter by discussing the electronic properties of bulk semiconductors and quantum structures based on them. We start by presenting the most general formulation of the crystal Hamiltonian which is then simplified using the the Bloch formalism. In order to solve the appropriate Schrödinger equation, we resort to the semi-empirical **k** *·* **p** approach where only part of the conduction and valence subbands of the crystal are contributing, while all others are introduced as perturbations to the Hamiltonian. In order to describe the subband behavior of inhomogeneous quantum structures, we use the envelope function approximation for the description of the crystal Bloch function, and employ the Zinc-Blende model for the description of the bulk semiconductor. For the computational complexity simplification, we reformulate the problem using the two-band approximation, described by a 4 *×* 4 Hamiltonian matrix and the semi-empirical Luttinger parameters, which is further simplified by a diagonalization scheme which bring the problem down to a 2 *×* 2 Hamiltonian formulation. In this model, the conduction subbands are obtained using the effective mass approximation, where a parabolic dispersion relation is assumed. The solution the of the resulting coupled equations system for each value of the wave vector is obtained

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through the use of a transfer matrix formulation of the finite difference method computational scheme. The end result of this approach is a set of envelope functions and eigenenergies for each of the conduction and valence subbands, calculated for a wide diapason of wavevector values. These envelope functions are are subsequently used to calculate the matrix elements of the momentum in the dipole approximation, thereby providing the selection rules for the energetic intersubband transitions of the structure. In order to consider the influence of external electrons on the electronic properties of the QW, we add the proposed calculation scheme an electrostatic calculation in the form of an iterative Poisson problem solution together with the Schrödinger problem at hand. This iterative approach introduces the influence of the presence of the additional carriers through the subsequent alteration of the conduction and valence bands energetic profiles. In addition, through this quantitative presentation we introduce quantitatively the concept of the 2DEG, which plays a major role in all considered quantum structures throughout this thesis.

With the consolidation of the model for the calculation of the electronic properties of the considered structures, we turn in chapters and to deal with their various optical properties. To this end, we present in these chapters approximate models for the calculation of various optical parameters, including the optical susceptibility, absorption and the spontaneous emission of these structures. For the sake of simplicity, we confine ourselves to a semi- classical discussion of the semiconductor, where the charge carriers are described quantum mechanically while the electromagnetic (EM) field description is classical in nature. We start by performing a second quantization of the full system Hamiltonian without the presence of the EM field, thereby introducing the concept of the hole. The EM field is subsequently added to the Hamiltonian under the dipole approximation. For the attainment of the macroscopic optical parameters of the system such as the optical susceptibility, we are required to first obtain the microscopic polarization. To this end, we turn to the solution of the Heisenberg equation for the suitable quantum operator, with the use of the full Hamiltonian of the system containing the light-matter interaction terms. The microscopic polarization equation is coupled with similar equations for the charge carrier densities quantum operators, which leads to the creation of system of three coupled equations typically termed the Bloch semiconductor equations. The solutions of this system of equations is the main focus of theoretical discussion presented in these chapter, which is performed in several stages. In chapter we ignore to Coulombic interaction present between the various charge carriers in the system, together with assumed equilibrium conditions between them and simple phenomenological description of the carrier scattering process in the crystal. In chapter we reincorporate the Coulombic interaction, which leads to a self dependent series of equations treated in a approximate fashion using the Hartree-Fock approach with the Hamiltonian first order deduction. As in chapter , an equilibrium conditions are assumed for the charge carriers and a naive phenomenological model for the carrier scattering is employed. In addition to these considerations, in this chapter we introduce the the carrier screening effect through the classical Lindhard model of the crystal dielectric function. The addition of the Coulombic interaction to the model leads to the appearance of the bandgap renormalization effect, the magnitude of which is strongly dependent on the concentration of the introduced charge carriers in the system. Both approaches presented in these chapters, provide us with the spectra of the electrical susceptibility, absorption, refractive index and the spontaneous emission for a single bare QW.

Using the introduced models, we next perform full calculation of the optical properties of quantum structures considered in this thesis, in particular of two variations of single bare *GaAs/Alx Ga*1*−x As* QWs, the first devoid of external charge carriers in the well area and the latter with a 2DEG introduced through a *δ*-doping in the cladding area. For these two structures we compare the absorption and spontaneous emission spectra calculated using the two theoretical models elaborated above and to the classical Elliot model. For the doped structures, we also consider the influence of the 2DEG concentration on the spectral properties of the structure, performing the calculations for various ambient temperatures, namely *T* = 2*K* and *T* = 77*K* . From the calculation results for the two structures, we easily observe the clear influence of the Coulombic interaction on the absorption and spontaneous emission spectra, through the appearance of clear characteristic resonative lines suitable to excitonic coupling observed in such structures. Identification of the observed interactions becomes possible by performing calculations of the electronic subbands of the considered structures using the results of chapter . These line, which clearly appear in the first structures and also for low concentrations of the 2DEG in the second one, gradually dissipate with the rise of the carrier concentration as a direct consequence of the electronic screening effect. In addition, the excitonic lines undergo an energetic shift towards high energies as a result of the effective bandgap renormalization and the filling of the state space by the additional free charge carriers. Another classical effect, exhibited in the comparison of the emission spectra, is the Burstein-Moss splitting which leads to the separation of the maxima of the absorption and spontaneous emission spectra with the rise of the 2DEG concentration inside

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the QW. The experimentally observed asymmetric spontaneous emission spectral lineshape is observed for high gas concentrations, typical for such structures measured at low temperatures.

In chapter we turn to the discussion of the main topic of this thesis, namely the microcavity structure. We first present the basic concepts of a classical optical resonator and discuss the implementation of such resonators through the growth of thin epitaxial layers composed of two or more types of semiconductor materials resulting in a creation of a couple of distributed Bragg reflector (DBR) mirrors with a cavity region of a target wavelength whole multiple width between the two. We present numerical methods for the calculation of transmition and reflection spectra of such structures, and in particular the classical transfer matrix method (TMM). After discussing the optical properties of these microcavities, we elaborate on the quantum interaction theory of the optical and electronic excitation in microcavities, and develop the concept of microcavity polariton. To this end, we first discuss the Jaynes-Cummings model of a two-level absorber developed in the framework of atomic physics and utilize it for the demonstration of the Rabi splitting of such a system when coupled with a single EM field mode. This simple model can be generalized to a system with multiple such absorbers, describing the interaction between the electronic resonances created inside the QW placed in the cavity region and the EM field modes of this cavity. Equivalently to the atomic theory, we show formulation of the coupled oscillator model for such a system, and thereby introduce the concept of the polariton as a coupling between the electron-hole resonance and the mode of the EM field.

In order to investigate the optical properties of a microcavity with an embedded QW in the cavity region, a way must be found to incorporate the two in a unified computational framework. To this end, we present a new approach based in the classical linear dispersion model (LDM), where the phenomenological description of the refractive index of the QW is replaced by the results of the models presented in earlier chapter. This differs from the common approach of fitting the theoretical models to experimentally extracted data, and enables us to extract the optical properties of the entire structure from the optical properties of a bare QW obtained from basic physical principles. After the introduction of the computational procedure, we apply it to a particular MC structure, which has also been previously investigated experimentally. We first present the calculated reflection spectra for of bare MC structure, and find that a linear change in the width of the epitaxially grown dielectric layers comprising the structure leads a proportional linear shift in the spectral position of the cavity mode of the trapped light. Next, we introduce the two types of QWs, discussed in chapter , inside the cavity region of this MC. For the two resulting structures, we present the calculation results of the reflection spectra obtained for various values of the broadening coefficient *δ*. From these spectra we extract the energetic locations of the reflection for all values of *δ* and thereby attain the anti-crossing curves for each structure. Along these curves a typical splitting can be seen near the interaction region between the EM field mode of the MC and the electron-hole resonances of the QW. By fitting these curves to a coupled oscillator mode a set of parameters can be extracted, which enable us to evaluate the properties of these light-matter interaction and their strength. For the structure with devoid of 2DEG in the well region, this analysis affirms these interaction to be well in the strong coupling regime.

For the second structure, with the introduced 2DEG inside the well region, we also examine the influence of the carrier concentration on the properties of these interactions. Through the comparison of the anti-crossing curves attained for each of the concentrations we observe the existence of a strong coupling between the EM field mode and the electron-hole resonances up *ne ≈* 1*×*1011 *cm−*2 . This differs from the results obtained in chapter for the bare QW, where the excitonic resonances disappear at gas concentrations above *≈* 6 *×* 1010 *cm−*2 . By comparing the observed resonance energies of this MC reflection spectra to the calculation results of the intersubband transition energies of a bare single QW, we show that they match the allowed transitions near the Fermi edge of the structure and not the Brillouin zone center. This observation is compatible to the experimental observations presented earlier, and

attests to the fact that the strong coupling between the EM field mode and the Fermi edge electron-hole resonance is cause to the appearance of the observed lines in the reflection spectra.

By fitting these anti-crossing curves to the coupled oscillator model and manual extraction of various parameters, we examine the coupling strength and the linewidths of discussed resonances. We see that while the coupling strength diminishes with the 2DEG concentration, the linewidth rises considerably, but the coupling stays well within the bounds of the strong coupling regime. Finally, by extracting the admixing parameters of various resonances from the coupled oscillator fitting results, we examine the contents of the various anti-crossing branches in the attained curves. Again, we observe the crucial part of the EM field mode of the MC in maintaining the strong coupling with the electron-hole resonance even at high 2DEG concentrations.