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Review on the Polariton Dynamics

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Abstract: In this review the recent research developments and their challenges in the field of polariton dynamics have been discussed. A set of experimental and theoretical research works in this field have been reviewed. Experimental and theoretical methodologies have been explained to see the polariton dynamics. Several physical phenomena exhibited by exciton–polariton, like polariton lasing, Bose-Einstein Condensation (BEC), quantized vortices, super fluidity, superconductor have been discussed. The results on the kinetics of exciton polariton condensate in the presence of disorder, study on the light propagation in a strongly correlated medium, nonlinear effect in spin relaxation of cavity polariton and polariton emission in linear regime also have been analyzed. BEC of polaritons in thermal equilibrium, collective dynamics, amplitude mode dynamics of polariton condensate and polaritons in organic system have been explained. The research on BEC of polaritons already gave reach physics throughout the past decade but many of the advances have yet to find their way to come into the reality. This review explores the way that might be giving some solution of these problems.

Keywords: Bose-Einstein condensation, Dynamics of Polaritons, exciton-polariton, Review on polariton.

1. Introduction

In nature, bosons and fermions are two types of particles depending on their spin. Bosons have integer spin and fermions have half integer spin. Fermions obey the Pauli Exclusion Principle and as a result cannot simultaneously occupy the same quantum state. Bosons do not obey the Pauli Exclusion Principle and when average separation of bosons become comparable to thermal de Broglie wavelength then a Bose-Einstein Condensate (BEC) can be formed. The BEC occurs at high temperature for bosons with a light effective mass because we know that the de Broglie wavelength $\lambda_D = \sqrt{\frac{2\pi\hbar^2}{mk_BT}}$ is inversely proportional to the square root of the temperature and particle mass.

BEC is the macroscopic occupation of the lowest energy quantum state of a system of bosons. First the concept of Bose condensation was given by Satyendra Nath Bose in 1924. This concept appeared in a paper of S. N. Bose [1] which was about a new derivation of photon statistic and Planck distribution. In the same year Albert Einstein [2] gave the theoretical description of BEC for a homogeneous system of identical particles. First time the existence of BEC was proved experimentally in a dilute gas of rubidium atoms in 1995 [3, 4].

Exciton–polaritons (or polaritons for short) are, bosonic quasiparticles, produced as a result of the coupling between excitons and the electromagnetic field. Polaritons, consist of an emplacement of a cavity photon and an exciton, exist inside a semiconductor micro cavities. Polaritons have bosonic nature and very light effective mass, typically of the order of 10^{-4} times of the bare electron mass. Therefore above the critical density the polaritons form a condensate. The polaritons are inherently non-equilibrium in nature because of the short lifetime of polaritons. But many features of the polaritons are similar with the features that we can expect for the equilibrium BEC. These natures of polariton make it an interesting topic not only from a fundamental point of view but also from its potential practical application in future quantum technological devices. Polariton condensates form a two-dimensional structure rather than three dimensional. This two-dimensional structure allows the investigation on Berezinskii_Kosterlitz_Thouless (BKT) transition. It is a phase transition in a two-dimensional model from bound vortex-antivortex pairs at low temperature to unpaired vortices and anti-vortices at some critical temperature. The polaritons non equilibrium nature initiates new physics about macroscopically coherent systems.

BEC of excitons were predicted in the early 1960s, by the scientists of reference [5, 6]. Lots of experimental and theoretical works have been done in this field [7-11]. Now a day's polariton appears as a new candidate for the investigation on BEC. To investigate the BEC, the advantages of polaritons over excitons are two. First, the effective mass of polariton is four orders of magnitude lighter than the effective mass of exciton. Therefore, the critical temperature for reaching the polariton BEC is four orders of magnitude higher than the exciton BEC, at the same particle density. Second, in spite of unavoidable crystal disorder and defects a phase coherent wave function emits from the polariton in space through its photonic component. Inside crystal excitons could be easily localized within a fluctuating potential, which resist excitons to form a BEC. Cavity polaritons seem to be much more suitable than excitons for observation of bosonic effects because they are much less sensitive to structural imperfections of real structures. The short life time of polaritons due to first photon leakage from microcavity is the disadvantage of polaritons. The system becomes non-equilibrium because in most of the cases, polaritons' life times are shorter than their cooling time. However, excitonic component is increased in the lower polaritons when the cavity-photon resonance detuned higher than that of the quantum wells (QW) excitons. The lower polaritons have long lifetime, short cooling time and show thermalization behaviour. It is difficult to study about the standard BEC of physics by using polaritons due to non-equilibrium properties of polaritons, but it is possible to study a non-equilibrium open system contains of highly degenerate interacting bosons. From the polaritonic system it is possible to get direct experimental measurement of the quantum statistical behaviour of the condensate which is not possible in the case of atomic BEC or superfluid Helium 4. The quantum nature of the polariton condensate can be easily studied by using various quantum optical measurements on the leakage of photon field.

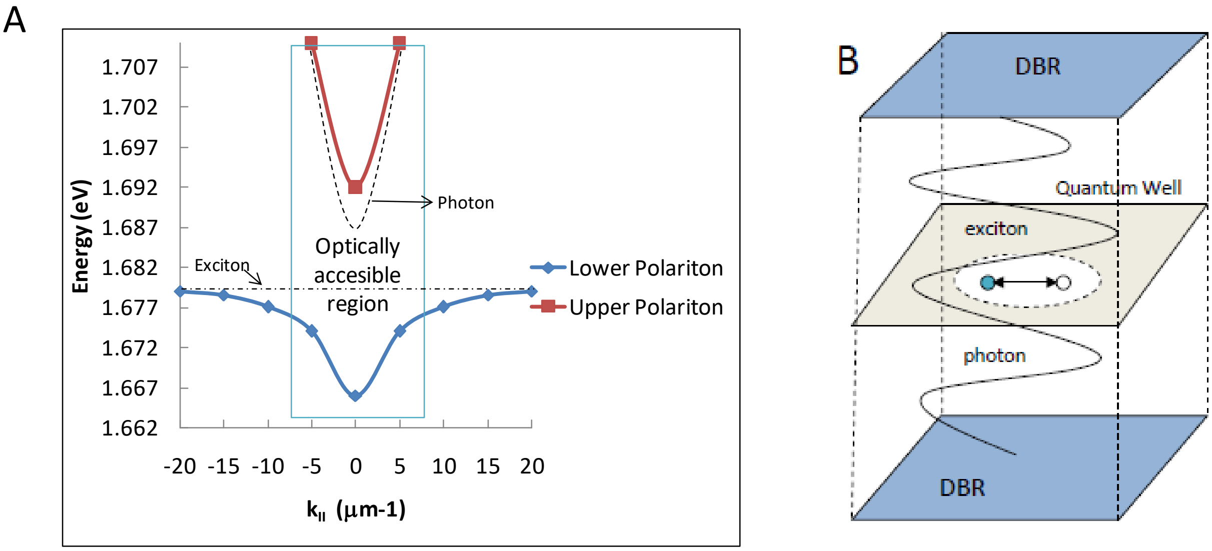
Theoretically, the relaxation and condensation behaviour of polariton can be studied by solving the Boltzmann transport equation and Gross Pitaveski equation. Generally, in an experiment, polaritons are excited by an external source, usually by a laser, and then a population of polariton is produced. These polaritons cool down and a condensate is formed. In another method a hot polariton cloud is produced which is mostly contains the lower polaritons. Then these lower polaritons scatter from the crystal and lose their energy by the emission of phonons.

In this article, the recent progress on experimental and theoretical studies of polariton dynamics has been reviewed and several physical phenomena exhibited by exciton–polariton condensates have been discussed.

2. Experimental and theoretical methodology

2.1 Experimental methodology

From the measurement viewpoint the micro cavity polariton is the best system to get polariton BEC. A microcavity is a resonator with two distributed Bragged Reflectors (DBR) at resonance with excitons in QW. Within typical material systems, to get BEC of polaritons, the optimal conditions for microcavity are (1) strong exciton-phonon interaction means it requires both large QW exciton oscillator strength and large overlap of the photon field and the QWs; (2) small exciton Bohr radius i.e. large exciton binding energy means high exciton saturation density; (3) high quality cavity i.e. long lifetime of cavity photon and polariton; (4) large polariton-phonon and polariton-polariton scattering cross sections means efficient polariton thermalization.



excitation scheme represented in the energy and momentum vector (k$_{II}$) plane. (B) Microcavity polariton

Microcavity polaritons created by strong coupling of photons with excitons. A short cavity with multiple narrow QW placed at the antinodes of the cavity field is generally preferred to get maximum exciton-photon interaction [12]. Within a microcavity system some parameters should be adjusted during the experiments. These are detuning of the uncoupled cavity resonance relative to the QW excitons, temperature of the host lattice and the density of polaritons. The quality of direct band gap semiconductor depends on fabrication technology. For both QW and microcavity system the best fabrication quality has been achieved by molecular beam epitaxial growth of $Al_xGa_{1-x}As$ based samples. Nowadays experimentalists are using wide band gap materials with small lattice constant. The exciton binding energy and oscillator strength are large enough within this materials and polariton laser may survive for the temperatures over 300 K. In this case the polariton laser can operate at visible to ultraviolet region. But these types of materials suffer crystal defects and higher concentration of impurities. The basic properties of polariton system can be characterized by reflection or transmission measurement using a weak light source. In a typical experiment within a microcavity system, polaritons are created by a laser pump pulse and then they relax under some appropriate conditions and accumulated in the ground state of the LP branch before they completely decay [8]. Pumping should be incoherent to study about the spontaneous phase transition so that there are no phase relation exists between the pump light and the condensate. Figure 1 A represents energy vs. momentum vector relation of upper and lower polaritons and optically accessible region. Figure 1 (B) represents microcavity polariton.

2.2 Theoretical methodology

Polaritons condensation kinetics involves creation, relaxation and decay processes since polariton has lifetime of 1 to 100 ps. The semi classical Boltzman transport equation can be used to describe the kinetics of polaritons [9]. The Boltzmann transport equation is given by

$$\frac{\partial Q}{\partial t}+\left(\vec{\upsilon}\cdot\overrightarrow{\nabla_r}Q+\vec{F}\cdot\frac{1}{\hbar}\overrightarrow{\nabla_k}Q\right)_{drift\,\&\,force}=\left(\frac{\partial Q}{\partial t}\right)_{\text{collision+interaction}} \tag{1}$$

The Boltzmann equation describes the particle's occupation number $Q(\vec{r},\vec{k},t)$ as a function of radius $\vec{r}$, momentum $\hbar\vec{k}$ and time t. with υ is the velocity, $\vec{F}$ is the force and ∇_r and ∇_k are the nabla operators in r and k space respectively. The terms on the left hand side are often referred to as the drift terms, and the term on the right hand side is known as collision and interaction term. The collision and interactions terms are polariton-phonon scattering and polariton-polariton scattering.

$$\left(\frac{\partial Q}{\partial t}\right)_{coll+\text{int}}=\left(\frac{\partial Q}{\partial t}\right)_{\text{Polarion-Phonon}}+\left(\frac{\partial Q}{\partial t}\right)_{Polariton-polariton} \tag{2}$$

Polariton-phonon scattering term is given by [9]

$$\begin{aligned}\left(\frac{\partial Q_{\vec{k}}}{\partial t}\right)_{polariton-phonon}&=-\frac{2\pi}{\hbar}\sum_{\vec{p}}\left|M_{x-ph}(\vec{p}-\vec{k})\right|^2\{[Q_{\vec{k}}(1+q^{ph}_{\vec{k}-\vec{p}})(1+Q_{\vec{p}})-(1+Q_{\vec{k}})q^{ph}_{\vec{k}-\vec{p}}Q_{\vec{p}}]\\&\times\delta(E_{\vec{k}}-E_{\vec{p}}-\hbar\omega_{\vec{k}-\vec{p}})+[Q_{\vec{k}}q^{ph}_{\vec{p}-\vec{k}}(1+Q_{\vec{p}})-(1+Q_{\vec{k}})(1+q^{ph}_{\vec{p}-\vec{k}})Q_{\vec{p}}]\\&\times\delta(E_{\vec{k}}-E_{\vec{p}}+\hbar\omega_{\vec{p}-\vec{k}})\}-Q_{\vec{k}}/\tau_{opt}\end{aligned} \tag{3}$$

Where $E_{\vec{k}}=\hbar^2k^2/2M_x$, $E_{\vec{p}}=\hbar^2p^2/2M_x$ and $\hbar\omega_{\vec{p}-\vec{k}}=\hbar v_s\left|\vec{p}-\vec{k}\right|$ are the polariton energy in wavevector $\vec{k}$ state, polariton energy in wavevector $\vec{p}$ state and phonon energy, respectively. $Q_{\vec{k}}$, $Q_{\vec{p}}$ and $n^{ph}_{\vec{p}-\vec{k}}=1/[\exp(\hbar\omega_{\vec{p}-\vec{k}}/k_BT_b)-1]$ are the polariton occupation number in $\vec{k}$ state, polariton occupation number in $\vec{p}$ state and phonon occupation number, respectively. $M_{x-ph}\left(\vec{p}-\vec{k}\right)$ is the matrix element of the polariton-phonon deformation potential interaction, and τ_{opt} is the radiative lifetime of polariton. The polariton-phonon coupling is given by $\left|M_{x-ph}(\vec{p}-\vec{k})\right|^2 = \hbar D^2 \left|\vec{p}-\vec{k}\right| / (2V\rho v_s)$, where D is the deformation potential energy, V is the crystal volume, ρ is the crystal density, v_s is the longitudinal acoustic sound velocity, M_x is the polariton mass and δ is the Dirac distribution. The first term in the square brackets on the right-hand side of equation (3) is due to the Stokes scattering and the second term is for anti-Stokes scattering of polaritons.

Polariton-polariton scattering term is given by [10, 11]

$$\left(\frac{dQ_{\vec{k}}}{dt}\right)_{polariton-polariton} d^3\vec{k} = \frac{2\pi}{\hbar}\cdot\frac{V^2}{(2\pi)^6}\int d^3\vec{k}\ d^3\vec{p}\ d^3\vec{p}_2\ d^3\vec{k}_2\ M^2_{matrix}$$
$$\times\{Q_{\vec{p}}Q_{\vec{p}_2}(1+Q_{\vec{k}})(1+Q_{\vec{k}_2})\}\delta(\vec{p}+\vec{p}_2-\vec{k}-\vec{k}_2)$$
$$\times\delta(E_{\vec{p}}+E_{\vec{p}_2}-E_{\vec{k}}-E_{\vec{k}_2}) \tag{4}$$

Where $E_{\vec{k}} = \hbar^2 k^2 / 2M_x$, $E_{\vec{p}} = \hbar^2 p^2 / 2M_x$, $E_{\vec{p}_2} = \hbar^2 p_2{}^2 / 2M_x$ and $E_{\vec{k}_2} = \hbar^2 k_2{}^2 / 2M_x$ are the polariton energy in wavevector $\vec{k}$ state, $\vec{p}$ state, $\vec{p}_2$ state, and $\vec{k}_2$ state, respectively. $Q_{\vec{k}}$, $Q_{\vec{p}}$, $Q_{\vec{p}_2}$ and $Q_{\vec{k}_2}$ are the polariton occupation number in $\vec{k}$ state, $\vec{p}$ state, $\vec{p}_2$ state, and $\vec{k}_2$ state, respectively. $M_{matrix} = \frac{4\pi\hbar^2 a_1}{M_x V}$ is the matrix element with a_1 the scattering length.

Here $e_{\vec{k}_2} = e_{\vec{p}} + e_{\vec{p}_2} - e_{\vec{k}}$ or $\vec{k}_2 = \sqrt{\vec{p}^2 + \vec{p}_2^2 - \vec{k}^2}$.

But in the above case the condensation threshold of the random phase approximation of the Boltzmann equation is no longer valid. Then quantum kinetics is the appropriate tool for that. A condensed polariton system is quasi equilibrium when polaritons life time is longer than its relaxation time. In this case the static properties of polariton can be described by the Gross-Pitaevskii equation. The time dependent Gross-Pitaevskii equation is given by [12]

$$i\hbar\frac{\partial\Psi(r,t)}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + V(r) + g\left|\Psi(r,t)\right|^2\right)\Psi(r,t) \tag{5}$$

Where $\Psi(r,t)$ is the wave function, m is the mass, V(r) is the interaction potential and g is the intensity of atomic interaction. Time independent Gross-Pitaevskii equation is

$$\mu\Psi(r) = \left(-\frac{\hbar^2}{2m}\nabla^2 + V(r) + g\left|\Psi(r,t)\right|^2\right)\Psi(r,t) \tag{6}$$

Here μ is the chemical potential. The number of particles is related to the wavefunction by

$$N = \int \left|\Psi(r)\right|^2 d^3 r \qquad (7)$$

It is possible to see the structure of a BEC in various external potentials by solving the time independent Gross-Pitaevskii equation. From the time dependent Gross-Pitaevskii equation we can find the dynamics of BEC. It is used to find the collective modes of a trapped gas.

3. Theoretical and experimental works and challenges

Several theoretical and experimental works have been done in this field [13-15]. The effect of molecular stokes shift on polariton dynamics has been explained in one recent work [16]. The authors of the study [17] reported the clear spectroscopic signatures and relaxation dynamics of excited vibration-polaritons formed from the cavity-coupled NO band of nitroprusside. For this work the researchers used two-dimensional infrared and filtered pump–probe spectroscopy. The researchers of reference [18] investigated the exciton-polariton dynamics modulated by exciton-photon detuning in a ZnO microwire. The authors of this work claimed that both the fast and slow decay rates of the exciton-polaritons are faster than that of the free excitons due to the strong coupling between excitons and photons in a microcavity. The entropy of polariton states has been studied by the authors of reference [19]. They reported that due to the significant contribution of entropy to the free energy, spectroscopy does not correctly order the free energy of the excited states. According to their free energy the reordered states are useful to understand decoherence and to predict the potential of polariton states for reactivity.

To see the cavity molecular dynamics of polaritons, the researchers of reference [20] studied numerically the linear and non linear response of liquid carbon dioxide, under vibrational strong coupling condition. The effect of multiple cavity modes on polariton relaxation has been studied by the authors of reference [21]. They concluded that more realistic cavity description needed for better understanding of modification of molecular properties by cavities. Depolarization of optically confined semiconductor's exciton-polariton condensates, polarization pinning and the optical orientation have been investigated by the authors of reference [22]. In reference [23] the polariton dynamics in feedback-coupled cavities has been studied. The authors of this study reported that a feedback cavity approach breaks the harmonic-oscillator restriction.

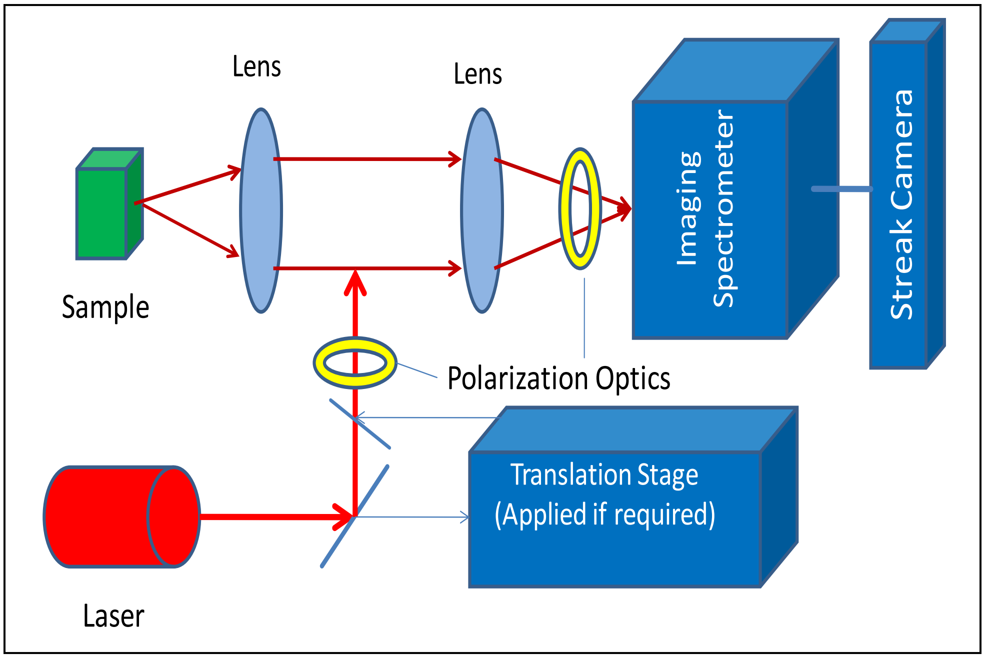


Figure 2: Experimental set up for excitation and detection of polaritons in semiconductor nanostructures.

Nowadays different behaviors of polaritons are being investigated by the several researchers in this field like polariton lasing, BEC, super fluidity, quantized vortices, superconductor, etc. Figure 2 represents one experimental set up for the excitation and detection process of polaritons.

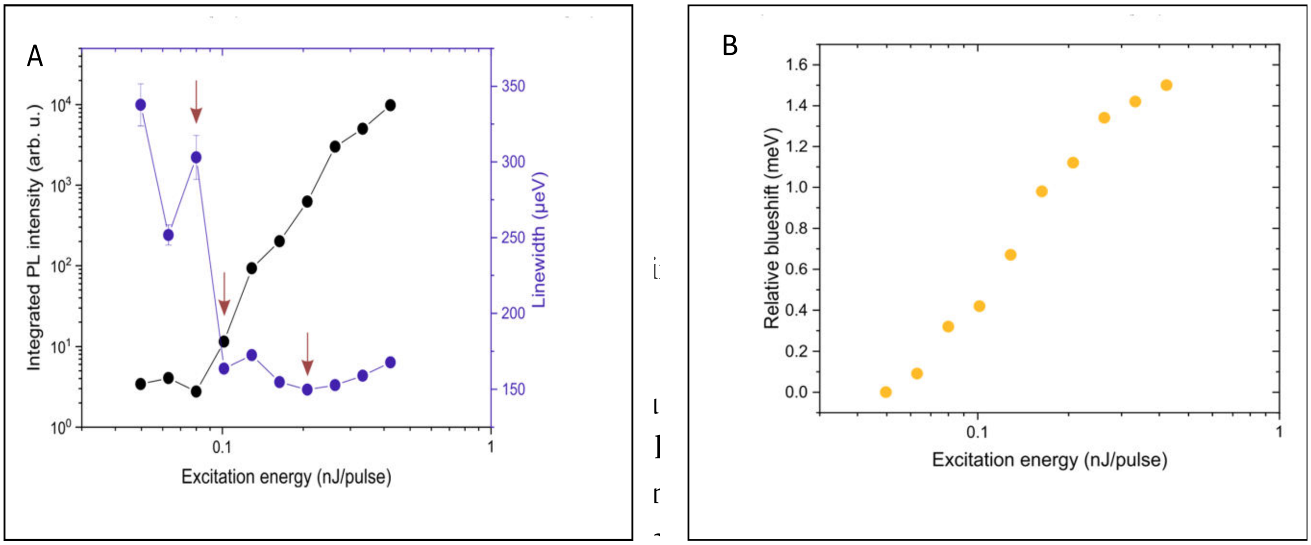
3.1 Polariton laser

The polariton laser can operate at ultralow power therefore nowadays it is drawing much attention in the laser technology. This property of polariton laser is suitable for some application like several optoelectronic devices, high-speed optical switching etc. After giving required optical pumping by spontaneous emission of photons from matter waves, the polariton laser generates laser like light. For this reason, the polariton laser can operate with very low input power. Whereas, laser produced by stimulated emission.

The authors of reference [24] analyzed the relaxation kinetics of cavity polaritons by solving the semiclassical Boltzmann equation. Especially they have studied on polariton laser and polariton superfluidity in microcavities. Polaritons go through Berezinskii Kosterlitz Thouless (BKT) phase transition towards the superfluid phase and form a local quasi-condensation, that allows polariton lasing with large band gap microcavities for the temperatures over 300 K.

Polariton laser has high fluctuation in intensity therefore low coherence and for which it is difficult to control its thermal stability especially for nanoscale devices. This is one of the difficulties of the development of polariton laser. Another most important obstacle to get polariton laser is the kinetic blocking or bottleneck effect of the relaxation of polaritons. This effect can be controlled by taking low concentration of free electrons in the system because in this case an efficient electron-polariton scattering is present [24].

Polariton lasing at room temperature has been investigated in recent work [25]. The authors of this work used dielectric microcavity containing non-polar III-nitride QW as an active media. They reported that microcavities exhibit two closely spaced lower polariton branches at room temperature. The electrically pumped inversion less polariton lasing is also observed from a bulk GaN-based microcavity diode at Room temperature, in the study [26]. The researchers of reference [27] investigated on the exciton-polariton lasing for topological defects at room temperature in an organic lattice. Figure 3 (A) represents the integrated photoluminescence intensity and line width of the topological domain boundary defect with respect to excitation energy. At the polariton condensation threshold, for the value of ≈ 0.10 nJ/pulse, line width decreases suddenly toward the resolution limit of the spectrometer indicates the buildup of phase coherence [27].



dispersions plotted for 0.08 nJ/pulse, 0.10 nJ/pulse and 0.21 nJ/pulse respectively. (B) Variation of emission energy with laser excitation power. A continuous increase of a blue shifts (emission energy), induced by phase-space filling effects, with a total shift of 1.5 meV caused by the exciton-polariton nature of the system is observed. Reprinted (adapted) with permission from [27]. Copyright 2021, American Chemical Society

Figure (B) represents the variation of emission energy with laser excitation power. The output intensity increases sharply and nonlinearly by approximately 3 orders of magnitude. By measuring the correlation function, using a Michelson interferometer, the spatial and temporal coherence have been investigated [27]. The work on ultralow threshold polariton lasing from a single GaN nanowire which was strongly coupled to a large-area dielectric microcavity has been studied by the researchers of reference [28]. The authors of reference [29] studied on exciton-polariton lasing. They reported that the polariton lasing can be obtained from a degenerate polariton condensate with non-resonant excitation by spontaneous radiative recombination. Two-dimensional topological Polariton laser has been studied in reference [30]. The researchers of reference [31] investigated on semiconductor polariton laser which is a new source of coherent light. They claimed that their results will be helpful to get the better polariton lasers and nonlinear polariton devices. The authors of the study [32] on polariton laser by electrical pumping from microcavity that contains multiple QW concluded that their result will be helpful for practical implementation of polaritonic light source and by using wide band gap materials it is possible to get polaritonic light source at room temperature. Polariton Laser in the Bardeen-Cooper-Schrieffer Regime has been studied by the researchers of reference [33].

But still it is difficult to make a real polariton laser experimentally. Theoretically, to describe the formation of the coherent state and the spin relaxation, a quantum theory should be developed. More clarification needed on scattering in microcavities. Experimentally, it is important to fabricate a cavity that produces strong coupling of exciton and light at room temperature and the study of polariton relaxation both in doped and undoped cavities. Increasing the polariton life time and improvement of mirror quality is also helpful.

3.2 BEC of Polaritons in Thermal Equilibrium

The polaritons life time within microcavity is 30 ps or less [34] due to the leakage of microcavity. At thermal equilibrium within an exciton polariton condensate the role of quantum fluctuation has been investigated by the researchers of the recent work [35]. They got a large phase window where both bosonic excitons and fermionic quasi-particles are present with strong coupling of photons. The authors of the study [36] reported about the quantum depletion in a non equilibrium exciton polariton condensate. This work suggests more work needed to understand this field deeply.

Partial thermalization has been claimed by the authors of few works [37, 38] but it is difficult to get polariton condensate at thermal equilibrium due to the short life time of polaritons. The authors of reference [39] have suggested a solution to solve this problem.

They have developed a GaAs-based high-quality factor (Q) microcavity structure by molecular beam epitaxial to get polaritons of long lifetime. They mentioned that an improvement of the cavity Q by at least an order of magnitude is needed to get a polariton of long-life time. That means the increase of one order of magnitude of the number of the quarter-wavelength layers in the distributed Bragg reflectors that make up the mirrors of the cavity, is required. The detail procedure has been discussed in reference [40]. They got a polariton of lifetime 270 ps at resonance by using a microcavity structure with the value of Q is approximately 320000 and the value of cavity photon lifetime is approximately 135 ps.

3.3 Polariton emission in linear and nonlinear regime

The polariton emission dynamics directly depends on the polariton wave vector and exciton-photon energy detuning. When the excitonic and photonic wave functions are combined linearly it produces the wave function of polariton which crucially depends on the bare excitonic and photonic energies. Since photon like polariton has a very small mass, approximately 10^{-4} of the mass of the electron therefore it has very small density of states. Consequently, the probability of scattering of polariton by phonon is very low.

Polariton emission in linear and nonlinear regime has been studied in reference [41-45]. The researchers of the study [45] reported that they have seen the energy blue shift of polariton condensate. They concluded that the energy blue shift arises due to the intermolecular energy change. The authors of reference [46] investigated the dynamics of polariton emission in linear regime. In the linear regime three types of spectra were observed first is the upper polariton branch, second is the lower polariton branch and third is the uncoupled (with photon) bound exciton. The linear regime disappears with increasing pump power (excitation density threshold). To overcome this difficulty and to study on the polariton dynamics in the linear regime, the excitation density has to be taken to below of its threshold value. Below the threshold, the relaxation directly depends upon the phonon scattering, which is not efficient to dissipate its linear regime.

The authors of reference [47] investigated the microscopic description of exciton-polaritons in micro cavities. They reported that the effect of particle exchange on the Rabi coupling is much smaller than as expected in the standard treatment of previous research works. In their opinion previous works overestimate the effect of Pauli exclusion on Rabi coupling it means that they neglect the light induced modification of the size of the exciton. The nonlinear effects in spin relaxation of cavity polaritons have been studied theoretically by the authors of reference [48]. Under the condition of pumping, it has been seen that the spin relaxation time as well as the polarization of the dynamics of polariton is proportional to the detuning between the excitons and cavity mode energies.

The positive detuning shows that the curve between upper (UP) and lower polariton (LP) is parabolic. Typically, it means that the bottom of photonic band lies above the excitonic band. Conversely, if the bottom of excitonic band lies below than the photonic band then the non parabolic curve generates.

Due to the variation of effective masses of the polaritons, a bottleneck region arises in the lower polariton branch. This reduces the polariton energy relaxation, occurred by acoustic phonon scattering. There are two ways to remove this difficulty. One is, using doped samples with free carriers and another is, using strong pumping regime for which the polariton concentration will be high enough and polariton-polariton scattering will be efficient.

3.4 Collective dynamics of polariton condensate

If the particle collapse with common phase it shows collective quantum behavior such as interference, quantized vortices and super fluidity. The behavior of super fluid motion of polaritons is different from BEC because BEC is only observed for dilute atomic gasses at small temperature in the range of μk.

The collective dynamics of polariton condensate in a semiconductor micro cavity has been studied in reference [49]. The manifestation of this paper was the coherent light matter wave packet, which creates the features of super fluid. Velocity of the super fluid is observed as 1% of the speed of light. The authors of this paper reported that if the size of wave packet is equal to the size of obstacle, it split into two fluids. The authors of the study [50] investigated on the collective dynamics of a polariton condensate within a semiconductor microcavity. The researchers of this work claimed that they observed diffusion less motion of polariton condensate. In reference [51] the authors studied on collective pairing of resonantly coupled microcavity polaritons. The authors of this work concluded that a molecular super fluid phase exist with regular polaritons super fluid phase. The collective Polaritons condensates with a synthetic gauge field have been studied by the authors of reference [52]. Within a trapped polaritons condensate, the dispersion of the collective polaritons has been measured in this work. They have measured the characteristic spin textures in an interacting spinor condensate of exciton polaritons by calculating inter and intra-spin polariton interaction constants. The researchers of reference [53] observed collective oscillations within a round box trap with low-energy and low-momenta of an exciton-polariton condensate.

Many difficulties were observed by the researchers to study about the collective dynamics of polaritons. First, polaritons life time is very short, few picoseconds in the cavity (~ 4 ps). It creates hinders to detect their dynamics and spatial non homogeneities provided by the defects. Further to detect of their movement in the cavity some difficulty arises due to the production of stray light from the resonant component. Finally, to block a stray light from laser, a confocal set up is used in some experiments. Complexities were also observed due to the production of free electrons and holes as well as excitons simultaneously. It may have been controlled by the varying of lattice temperature and population of photo excited carriers.

3.5 Amplitude mode dynamics of polariton condensates

Superconductors and cold atomic gasses are very good examples of amplitude modes of polaritons. In amplitude modes the density of condensed and non-condensed particles are fluctuates. The authors of reference [54] have published the study on amplitude mode dynamics of polariton condensates. They have used Dicke model to do this work. Upper polaritons and lower polaritons have been formed due to strong coupling of excitons and photons in semiconductor micro cavity. It is possible to construct BEC states of polaritons as well as coherent light emission by the pumping in semiconductor micro cavity. Outside the micro cavity the coupling of polariton with electromagnetic radiation may be coherently controlled by external pumping. With the excitation of phase mode, the collective behavior of micro cavity polariton arises such as super fluidity and vortex dynamics. The amplitude mode of upper polaritons branch has been considered in the paper [54] which directly depends upon the resonant excitation of the system.

The researchers of reference [55] observed the amplitude mode in a microcavity polariton condensate which was driven by intrinsic quantum fluctuation. In this work the authors mentioned that the amplitude mode is not stable due to two reasons first, there is an attractive interaction between amplitudes modes and second, there is scattering between amplitude modes and phase mode. Due to the instabilities of amplitude modes, an inhomogeneous condensate is formed. When only the upper polaritons are pumped then the instability due to wave mixing does not occur but the instability arises due to the attractive interactions. In this case a condensate actually Bose supernova is produced for cold atomic gasses.

3.6 Kinetics of exciton polariton condensate in the presence of disorder

Polariton condensation within a semiconductor microcavity in the presence of disorder is also an interesting topic. Sometimes disorder prevents to get polariton BEC [56]. It creates dissipative

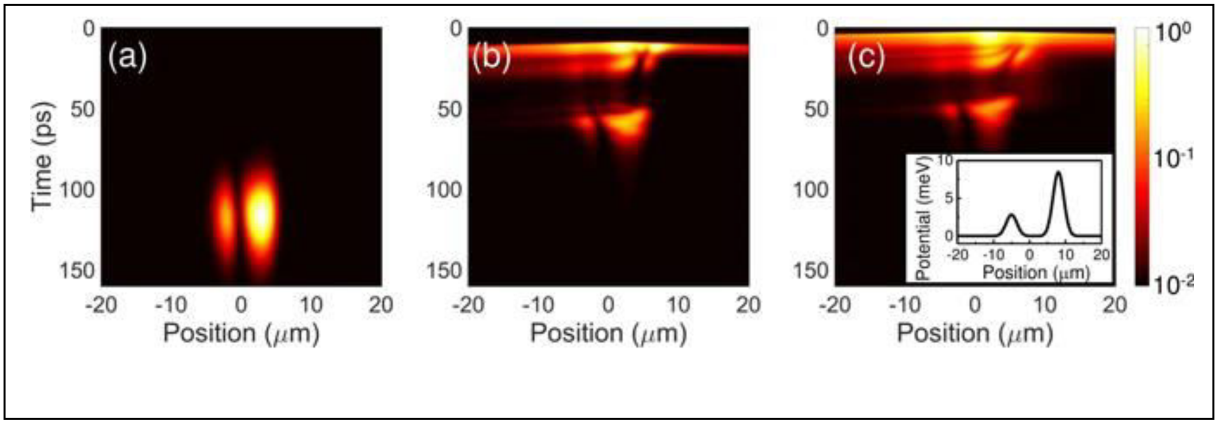


Figure 4: Simulation results with disorder potential of a time resolved propagation of polariton condensate with different pump pulse strength. (a) Pump pulse strength 1.5 P_0 (b) Pump pulse strength 8 P_0 (c) Pump pulse strength 15 P_0. To observe the first condensation pulse, pumping amplitude denoted by P_0. The disorder potential is presented in the inset of (c). Reprinted (adapted) with permission from [56].

nature of exciton polaritons. The authors of reference [56] reported that due to reflection and trapping potential, the multiple pulse polariton dynamics are observed (see figure 4). In the positive part of the space, a strong potential barrier triggers the irregular oscillations and blocks the flow. At higher pump pulse strength the simulation results show that the multiple pulses are merging into one fast polariton propagation of the polaritonic nonlinear wave in the negative direction.

Sometimes it is possible to get polariton BEC in the presence of disorder [57]. The authors of references [58-62] investigated on the exciton polariton condensate due to disorder. The authors of reference [58] solve a kinetic equation with structural disorder of the medium. They found that weak disorder accelerates the condensation as well as the thermalization in several order of magnitudes.

3.7 Study on the light propagation in a strongly correlated medium

Because of great scientific and technological significance nowadays the study on the light propagation in a strongly correlated medium is very popular and increasing interest in both atomic and solid-state physics. Still, it is unknown the effects of environmental coupling on the kinetics of single slow-light quanta. In reference [63] the authors have developed a non-perturbative theory for the quantum dynamics of a dark state polariton in BEC and they have investigated the effects of strong interactions between its spin wave component and the surrounding condensate. In the presence of strong interactions when light propagates through an atomic BEC, the Polaron quasiparticles are formed. When light couple with atom weakly then the polaron polariton arises and it supports in light propagation with spectral features. Dark state polaritons are formed due to photon dressing. From their work it has been observed that how polaritonic and polaronic quasiparticles are formed and investigation can be done by the transmission spectrum of the interacting medium. It is a powerful setup for understanding the system with light-matter coupling in the presence of strong interaction. This approach can be helpful to understand the other interaction effect in many body physics such as exciton polariton in semiconductors or interaction effect between atomic states.

The authors of reference [64] made a special potential trap along the length of a nanowire made by Al(Ga)N and from its polariton emission they investigated on the strong coupling effects. It has been mentioned that a near equilibrium, polariton BEC is formed at room temperature. In this case the researchers made a Al(Ga)N nanowire device by the dielectric microcavity with a single Al(GA)N nanowire of diameter 50 nm and length 6 μm buried in the center of a λ sized cavity. The microcavity is etched into square mesas □ $10\ \mu\text{m}$ in size with 1 μm of the $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}$ end of the nanowire exposed. The height of the potential trap is 85.7 meV over a distance of□ $3.5\ \mu\text{m}$. The single nanowire is positioned in the microcavity in such a way that □ $1\ \mu\text{m}$ of the $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}$ region is exposed from the mesa and optical excitation is provided at this end. Figure 5 (A) represents photo lumiscence intensity (measured in the normal direction) vs. energy density curve of Al(GA)N nanowire device [64]. In these emission spectra the second peak has smaller intensity than first one. In this case the authors believe that due to localization by dielectric-cavity–induced photonic disorders, the second peak corresponds to a transverse mode. Counts of polariton emission vs. time for different incident energy density plotted in figure 5 (B) for the above mentioned Al(GA)N nanowire device [64]. It is the rising part of the transient. Here the decay time decreases with increasing excitation, reflecting enhanced polariton relaxation into the $k_{□}$ □ 0 states in the GaN (trap) region of the nanowire. The authors of reference [65] observed a strong coupling of Fermi gas with light within a cavity. The set of propagation equations for the light field and atomic coherences have been solved numerically in reference [66]. The authors of this work reported that there is good agreement between experimental results and their simulation's results.

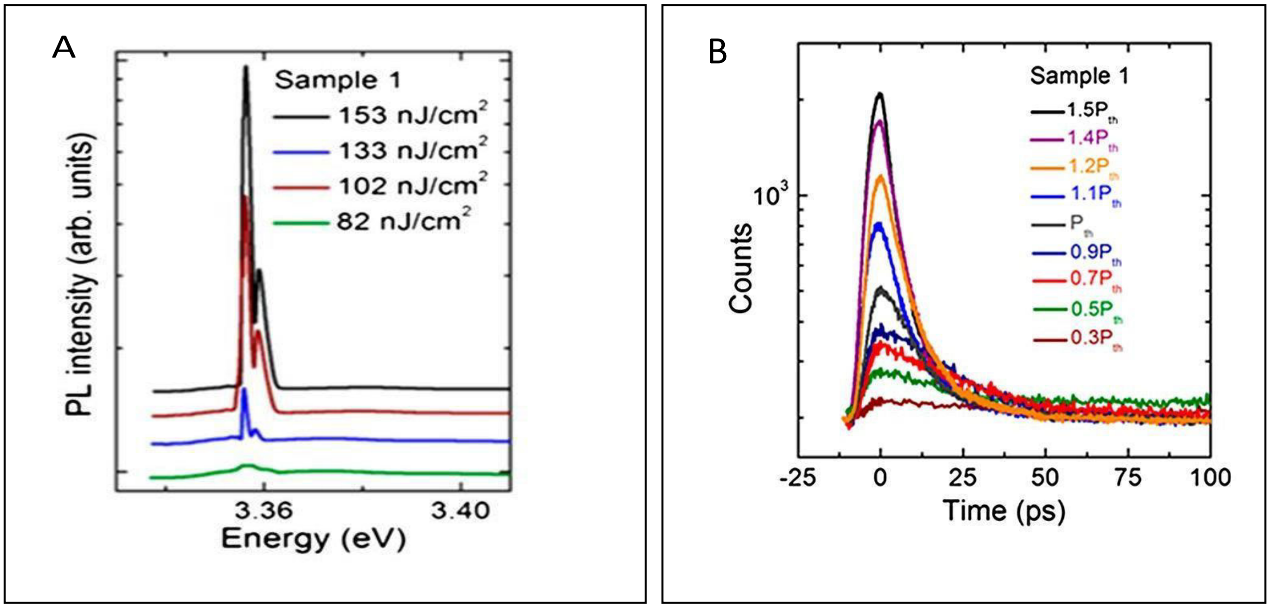


Figure 5: (A) Photo lumiscence intensity (measured in the normal direction) vs. energy density curve of Al(GA)N nanowire device. (B) Transient polariton emission measured as a function of incident energy density of the Al(GA)N nanowire device. Reprinted (adapted) with permission from [64].

3.8 Polariton in organic system:

this work they have explained a structure of strongly coupled two microcavities. One microcavity contains an organic semiconductor whereas another microcavity contains a series of weakly coupled inorganic QWs. They reported that a delocalized polariton state is created by optical hybridization between the optical modes of the two cavities. Their work gives a new idea to create highly efficient polariton devices. In one recent review paper [60] the BEC of exciton polariton in organic microcavities has been reviewed. The researchers of reference [68] reported that due to strong light matter coupling a new quantum state, organic cavity polariton is formed. It has been claimed that using time resolved microscopy this organic exciton polaritons induce long-range transport over several microns. In this case the propagation velocity of polaritons is surprisingly lower than the expected. This work may be helpful to design the future organic electronic devices. Organic exciton–polariton condensate in a lattice at room temperature has been studied by the researchers of reference [69]. They discussed about an experiment conducted on a polaritonic lattice at different conditions of surrounding. In their work Frenkel excitons are created by fluorescent proteins and the soft nature of these Frenkel excitons allows making a photonic lattice. In distinct orbital lattice modes of different symmetries the controlled loading of the coherent condensate has been explained and finally the authors explore the self localization of the condensate in a gap state. They concluded that a new organic polariton on GaAs platform may be produced, which has extensive application. The researchers of reference [27] also studied on the polariton laser in an organic lattice at room temperature. They explained the exciton-polariton lasing at room temperature for topological defects, comes from the engraved lattice structure.

4. Conclusions

Though, research on polariton dynamics already shown very reach physics but more investigation needed to get the answer of several unknown questions. The dynamics of polariton depends upon many parameters such as radiative life time of polaritons, the excitation of the system, detuning between the excitons and cavity mode energies, as well as the relaxation towards its lowest state. Nowadays one important thing is polariton laser but still it is difficult to get it in reality. More theoretical clarification needed on scattering in microcavities. It is important to fabricate a cavity that produces strong coupling of exciton and light at room temperature. Improvement of mirror quality and increasing polariton lifetime is also helpful.

Due to the short life time of polariton it is difficult to get polariton condensate at thermal equilibrium. To overcome this difficulty, one should increase the number of the quarter-wavelength layers in the distributed Bragg reflectors by at least one order of magnitude. In the case of polariton dynamics in linear regime one should take polariton density below the threshold value because over the threshold value the linear regime disappears. In the case of amplitude mode of polariton dynamics, it has been seen that it is not stable and an inhomogeneous condensate is formed. To overcome it one should pump only upper polaritons then the instability due to attractive interaction only present and BEC is formed.

The study on the light propagation in a strongly correlated medium is also a very interesting topic. More clarification needed to know the effects of environmental coupling on the kinetics of single slow-light quanta. Another important issue where more investigation needed is the polariton dynamics within a semiconductor microcavity in the presence of disorder. Because, it is not clear that the disorder effect favorable for the polariton condensation or not and sometimes it is not possible to remove the disorder. Nowadays several research works are going on the organic polaritons. Research in this field may be helpful to create highly efficient polariton devices in future.

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