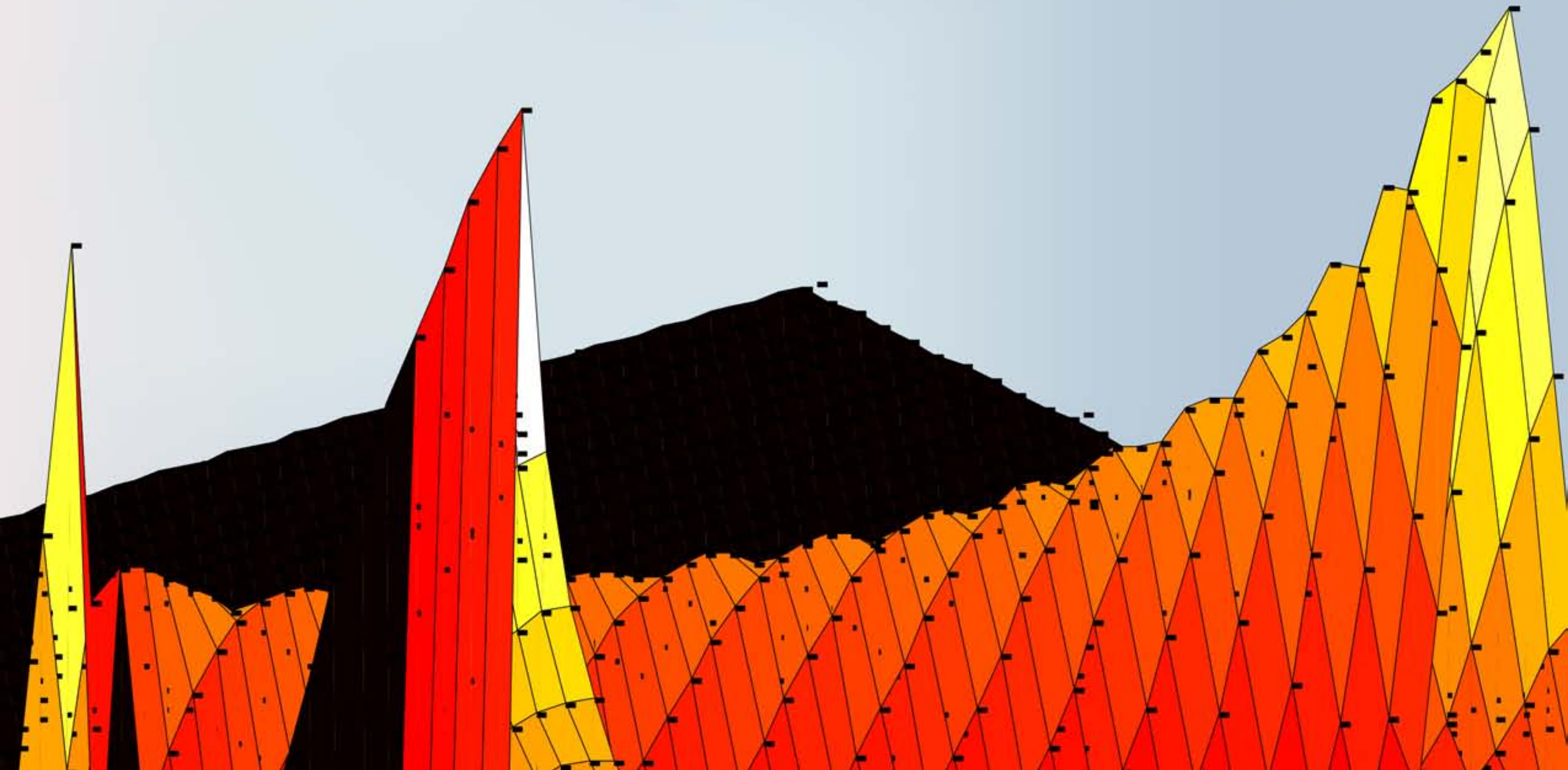
BOSE EINSTEIN CONDENSATION OF EXCITONS AND POLARITONS



Sunipa Som

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Bose Einstein Condensation of Excitons and Polaritons

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PREFACE

The possibility of Bose Einstein condensation (BEC) of excitons in semiconductors has been an interesting topic for many years. BEC is the macroscopic occupation of the lowest energy quantum state of a system of bosons. This state of matter is very difficult to observe but it is a notable example of quantum mechanics on a macroscopic scale. First the concept of Bose condensation was given by Satyendra Nath Bose and Albert Einstein in 1924. After seventy years, BEC was demonstrated for the first time in a dilute gas of rubidium atoms in 1995.

Exciton is an electrically neutral quasiparticle. Due to the Coulomb force, an electron and a hole are attracted to each other and form a bound state known as an exciton. It can transport energy without transporting charge. Exciton exists in insulators, semiconductors, and some liquids. These quasiparticles are the natural candidates for observing the BEC due to its boson nature and its light-effective mass.

Exciton–polaritons (or polaritons for short) are bosonic quasiparticles produced as a result of the coupling between excitons and the electromagnetic field. When a cavity photon and an exciton are superimposed, a polariton is formed that exists inside semiconductor microcavities. Due to its bosonic nature and very light effective mass, typically of the order of 10-4 times of the bare electron mass, above a critical density, the polaritons macroscopically occupy its lowest quantum state and form a condensate. The polaritons have a very short lifetime and due to this, it is inherently non-equilibrium in nature. However, many features of the polaritons are similar to 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.

The research on the BEC of excitons and polaritons is very important for the field of quantum information processing. BEC can be used to make quantum computers and is useful as a quantum simulator. BEC of excitons and polariton is a rapidly developing field of solid-state physics that motivated me to write this book.

This book offers an overview of the BEC of excitons and BEC of polaritons. It contains the history of BEC (Chap. 1), fundamentals of excitons (Chap. 2), fundamentals of polaritons (Chap. 3), BEC of excitons (Chap. 4), and BEC of polaritons (Chap. 5). The origin of excitons, relaxation and thermalization behaviour of Excitons have been discussed in Chapter 2. Chapter 3 contains information about the origin of polaritons, special condensate features like polariton lasing, super-fluidity, and quantized vortices. Experimental techniques, theoretical modeling, recent developments, and application of BEC of excitons and polaritons have been discussed in Chapters 4 and 5, respectively.

This book puts together the fundamentals of excitons and polaritons, all the advances, recent research works, discoveries, and applications on the BEC of excitons and polaritons. It also gives a brief outlook on future work. I believe that its straight-forward content will make it accessible and interesting to a broad readership, ranging from students, research fellows, lecturers, and engineering professionals in the interdisciplinary domains of semiconductor physics, nanotechnology, photonics, materials science, and quantum physics.

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Every book is a project that takes a long time and is the result of hard work, passion, and cooperation from other people. Therefore, I would like to express my gratitude to all the people who helped and encouraged me to write this book.

I am grateful to the publishing team of Bentham Science and specially Mrs. Fariya Zulfiqar (Manager of Publication) for their continuous encouragement, support, and patience.

Similarly, I am grateful to Prof. Heinrich Stolz, University of Rostock, Germany who supervised me for a few years and helped me gain interest and knowledge in the field of exciton, and polariton Physics. I am also grateful to my former co-workers at the University of Rostock, Germany, specially Dr. Frank Kieseling and Dr. Rico Scwratze for their useful discussions.

Special thanks to Prof. Ram Kripal, University of Allahabad, India for his continuous encouragement. I also would like thank to my colleagues at the Nehru Gram Bharati University, Prayagraj, India.

Similarly, I am grateful to all the researchers and authors in the field of exciton polariton Physics whose works helped me to get a lot of information and write this book.

Last but not least, I am grateful for the continuous support and encouragement from my family.

CHAPTER 1

Introduction

Abstract: Bose Einstein Condensate (BEC) is the fifth state of matter in condensed matter physics. It is the most impressive example of quantum behaviour on a macroscopic scale but the most difficult state to observe. When low-density boson gas is cooled to a temperature nearly absolute zero, then BEC is formed. In this condition, the bosons have almost no free energy to move relative to each other. They clump together, come into the lowest quantum state, and behave as a single atom. Then microscopic quantum mechanical phenomena work on a macroscopic scale. This chapter summarizes the history and the developments regarding BEC with a brief discussion of the key scientists in this field. In the next section, the summary of the all chapters is given.

Keywords: Bose Einstein Condensate, History of Bose Einstein Condensation, Exciton, Polariton.

HISTORY OF BOSE EINSTEIN CONDENSATION

In nature, there are two types of particles, bosons and fermions, depending on their spin. The particle with integer spin is known as Boson. Bosons occupy the same quantum state because Bosons do not obey the Pauli Exclusion Principle. Whereas a particle with half-integer spin is known as a fermion. Fermions obey the Pauli Exclusion Principle and as a result, they cannot simultaneously occupy the same quantum state. Bosons can form BEC when their average separation becomes comparable to their thermal de Broglie wavelength. We know that the de Broglie wavelength $\lambda_D = \sqrt{\dfrac{2\pi\hbar^2}{mk_BT}}$ is inversely proportional to the square root of the temperature and particle mass. Therefore, the BEC of bosons is formed at a high temperature with light effective mass.

The first idea of BEC appeared in a paper about a new derivation of photon statistics and Plank distribution [1] which was written by Satyendra Nath Bose in 1924. In his paper, he derived Plank's quantum radiation law in a new way where he derived it on the basis of quantum statistics' but not on the basis of classical Mechanics. Then he sent this paper to Albert Einstein. Einstein was impressed by his work, he translated this paper into German language and submitted it in the Journal, Zeitschrift fur Physik in the name of Satyendra Nath Bose which was published in 1924. After that, Einstein extended this idea in the case of matter in two papers. He [2] gave the theoretical description of BEC for a homogeneous system of identical

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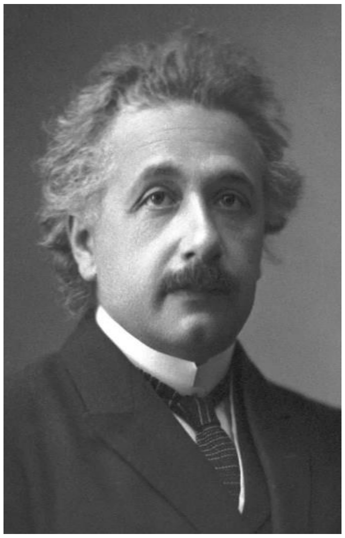
particles in 1925. In this theoretical description, he speculated that because of atoms condensed in its lowest energy state, the phase transition takes place in case of non-interacting atomic gas and it is the result of quantum statistical effect. From the results of Satyendra Nath Bose and Albert Einstein works, an idea of Bose Einstein statistics came out that describes the statistical distribution of Bosons. Boson particles include photons and atoms like helium-4.

After a long time, there was no noticeable work done on that. Then in 1937, it had been discovered that helium II is a superfluid. In January 1938, this work was published by a Soviet Physicist, Pyotr Kapitsa and also by Canadian Scientists John F Allen and Don Misener at the University of Toronto. Helium was first invented by Kammerlingh Onnes in 1908.

Satyendra Nath Bose

Satyendra Nath Bose was born on 1st January 1894 and died on 4th February 1974. He was an Indian theoretical physicist and mathematician. He is well known for his work on Bose Einstein condensate. In the early 1920, he gave the theoretical description of BEC. In 1954, he was awarded the Padma Vibhushan by the Government of India. He was also a Fellow of the Royal Society.

Albert Einstein



Albert Einstein, was born on March 14, 1879, Ulm, Württemberg, Germany and died on April 18, 1955, Princeton, New Jersey, U.S. He is well known for developing the special and general theories of relativity and in 1921 he won the Nobel Prize in physics for the explanation of the photoelectric effect. His mass energy equivalence relation $E=mc^2$, is the world's most popular equation.

Kammerlingh Onnes

CHAPTER 2

Fundamentals of Excitons

Abstract: An electron and an electron hole are attracted to each other by electrostatic Coulomb force and combine. This bound state of electron-hole pair is known as an exciton. It can carry energy without transferring net electric charge because it is an electrically neutral quasi-particle. Excitons exist in semiconductors, insulators and some liquids. Frenkel exciton and Wannier-Mott exciton are the two types of excitons. In this section, the origin of excitons, types of excitons, and the relaxation and thermalization behavior of excitons with some research results have been discussed.

Keywords: Auger decay, Exciton phonon scattering, Exciton exciton scattering, Origin of excitons, Relaxation behavior of excitons, Thermalization behavior of excitons.

THE ORIGIN OF EXCITONS

In 1931, Yakov Frenkel first proposed the concept of excitons. He said that without transferring the charge, this excited state can move in a particle-like fashion across the lattice [1, 2].

By using the band theory, it is possible to describe the creation of exciton. At zero temperature, a pure semiconductor has no free charge carriers. Therefore, all the energy levels in the conduction bands are completely vacant and all the energy levels in the valence bands are completely filled with electrons. Excitons can be built in two ways in case of direct band gap semiconductor: the first one is when a semiconductor absorbs a photon that has sufficient energy to give rise to an electron from the valence band to the excitonic bound state but its energy is less than the band gap energy. The second one is when a semiconductor absorbs a photon that has energy equal to the band gap energy or more than this. In this case, an electron from the valence band goes to the conduction band. Then free holes and electrons are created in the valence band and conduction band, respectively. These free holes and electrons bind with each other and produce exciton. Therefore to produce a free electron and hole within a direct band gap semiconductor, the least energy requirement is the band gap energy (Fig. **2.1**).

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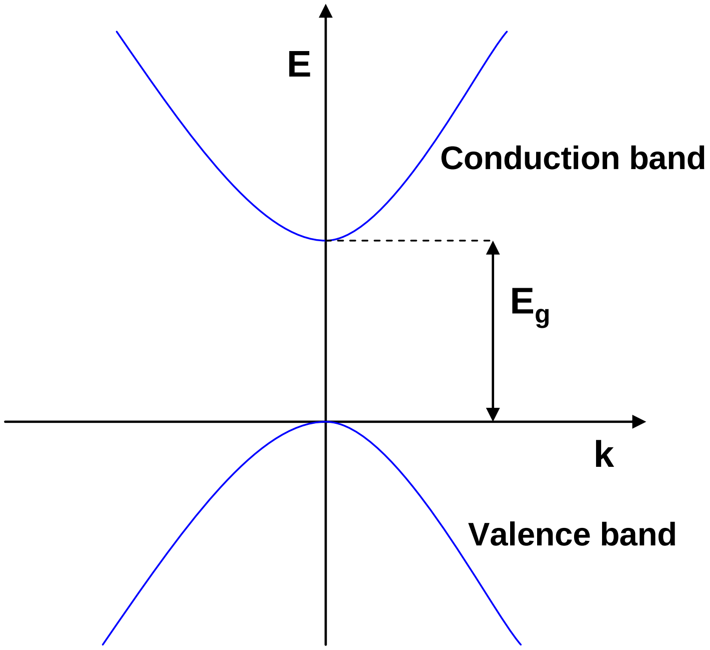

Fig. (2.1). Representation of the band structure of a direct band gap semiconductor. E_g is the band gap energy [3]. E is the energy and k is the momentum vector. Upper side band is known as a conduction band and a lower side band is known as a valence band.

The exciton's binding energy can be represented by the equation:

$$E_b = \frac{e^4 \mu_{ex}}{2\hbar^2 \varepsilon^2 n^2} \qquad n = 1, 2, 3........ \qquad \textbf{(1)}$$

Where the exciton reduced mass is μ_{ex} , the electric charge is e, and ε is the static dielectric constant. The relation between the static dielectric constant ε, the dielectric constant $\varepsilon_0 = 8.85419 \times 10^{-12}\ \mathrm{A^2 s^4 kg^{-1} m^{-3}}$ and the dielectric number of the material ε_r is $\varepsilon = 4\pi\varepsilon_0\varepsilon_r$. If the effective mass of the electron is m_e and the effective mass of the hole is m_h then the exciton reduced mass is μ_{ex} that can be written as $\mu_{ex} = m_e m_h / (m_e + m_h)$. The orthoexciton has slightly smaller binding energy than paraexciton due to the spin-orbit coupling. The Hamiltonian of the electron and the hole coupling can be represented by equation [4, 5]:

$$H = -\frac{\hbar^2\nabla_e^2}{2m_e} - \frac{\hbar^2\nabla_h^2}{2m_h} - \frac{e^2}{\varepsilon|r_e - r_h|} + \frac{\hbar^2}{2\mu_{ex}} \cdot \frac{l(l+1)}{r^2} \quad \textbf{(2)}$$

Here the position coordinate of the electron is r_e, the hole is r_h and the exciton is r. The angular momentum quantum number is *l*. The corresponding Eigen values form a series of exciton energies that can be written as:

$$E_n = E_g - \frac{\mu_{ex}\left(e^2/\varepsilon\right)^2}{2\hbar^2 n^2} + \frac{\hbar^2 k^2}{2M} + \frac{\hbar^2}{2\mu_{ex}} \cdot \frac{l(l+1)}{r^2} \quad \textbf{(3)}$$

Here the binding energy and the kinetic energy of exciton are represented by the second term and the third term, respectively. The fourth term is also an energy term of exciton that generated during the process of electron hole coupling and the creation of exciton. The band-gap energy is E_g. M is the mass of exciton.

By the emission of photons, excitons make them visible. The excited excitons can come to the ground state by releasing the energy [3]:

$$h\nu = E_g - E_b + E_k \quad \textbf{(4)}$$

This process is known as the radiative recombination. The radiative recombination is also possible by the emission of phonon and photon together, with energy:

$$h\nu = E_g - E_b + E_k \pm E_p \quad \textbf{(5)}$$

Here the energy of the phonon is E_p and the exciton kinetic energy is E_k. The "+" sign is used for anti-stokes scattering process and "-" sign is used for stokes scattering process. According to the momentum conservation, two types of processes are possible: one is phonon-assisted transitions $k = k_{photon} + k_{phonon}$ and another is direct transitions $k = k_{photon}$.

The exciton’s fine structure is generated by the coupling of spins by the exchange interaction. The hole and electron have either antiparallel or parallel spins. An exciton’s property depends on momentum (k-vector) in periodic lattices.

CHAPTER 3

Fundamentals of Polaritons

Abstract: Polariton is a bosonic quasiparticle. When an electromagnetic wave strongly interacts with the dipole active transition of the medium, then polariton is formed [1]. In other words, when light scatters and goes through any interrelated resonance, then the polaritons can be formed. In this chapter, the history of polariton, category of polaritons, their constituents, and light-matter interaction have been explained. Special condensate behaviour of polaritons like polariton lasing, superfluidity, and quantized vortices are also explained.

Keywords: Building block of polaritons, History of polaritons, Light-matter coupling, Polariton laser, Superfluidity, Quantized vortices.

THE ORIGIN OF POLARITONS

The coupling between a photon and a polar excitation in a substance is known as polariton (Fig. **3.1 A**). Polaritons are of different types. They are phonon polaritons, exciton, Intersubband polaritons, Surface Plasmon polaritons, Bragg polaritons, Plexcitons, Magnon polaritons, pi-tons, and Cavity polaritons.

- **Phonon polariton:** When the coupling of an infrared photon and an optical phonon takes place, then the Phonon polariton is formed.
- **Exciton polariton:** When the interaction of exciton with visible light takes place, then the exciton polariton is formed [2].
- **Intersubband polariton:** The intersubband polariton is formed due to the coupling of an intersubband excitation with an infrared or terahertz photon.
- **Surface Plasmon polaritons:** When the Surface Plasmons interact with light, then the surface Plasmon polaritons are formed.
- **Bragg polaritons:** When the coupling of bulk excitons and Bragg photon modes takes place, then the Bragg polariton is formed. It is also known as Braggoritons [3].
- **Plexcitons:** The Plexcitons are formed due to the coupling of plasmons and excitons [4].
- **Magnon polaritons:** When magnons interact with light, then the magnon polaritons are formed.
- **Pi-tons:** When interchanging charge or spin variations interact with light, then the pi-tons are formed. This is completely dissimilar from magnon or exciton polariton.

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- **Cavity polaritons:** Within a semiconductor microcavity, both the exciton and photon have a 2D character. When these excitons and photons interact, the cavity polaritons are formed.

Scientist Tonks and Langmuir first observed the oscillation in ionized gasses in 1929 [5]. Then in the early 1950, the classical theory of electromagnetic waves in the ionic crystal near optical phonon frequency was proposed by Tolpygo [6, 7] in 1950 in a Soviet scientific literature. First, they called it a light exciton which was recommended by the Scientist Pekar. The name polariton was first suggested by the Scientist Hopfield which was accepted later. The combined states of electromagnetic waves and phonons in ionic crystals are called the phonon polariton. Dispersion relation of the phonon polariton was obtained by Tolpygo in 1950 [6, 7] and Huang in 1951 [8, 9]. Later on, a study on quantum theory of electromagnetic waves near excitonic resonance and polariton was conducted by Scientists Fano in 1956, Hopfield in 1958 and Agranovich in 1959. In 1952, Scientists Pines and Bohm published their work on collective interaction. In 1955, Scientists Frohlich and Pelzer described Plasmons within silver. Then in 1962, Scientists Ritchie and Eldridge published their experimental work on released photons from the irradiated metal foils. In 1968, the Scientist Otto published a paper on surface Plasmon-polaritons [10]. In 2016, the superfluidity of polaritons at room temperature was noticed by using an organic microcavity with stable Frenkel exciton-polaritons by Giovanni Lerario *et al*. [11]. The invention of a new three-photon bound state has been reported by some scientists[12, 13] in 2018. In the advancement of quantum computers, these new three-photons related to polaritons could be helpful.

Building Blocks for Polariton Formation

Exciton in Semiconductors

When an electron couples with a hole by coulomb interaction then a bosonic quasiparticle exciton is formed. An excited electron comes to the conduction band from the valence band and produces a hole. Then, this electron and hole bind together and make the exciton. Electron's energy can be described as:

$$E_e(k) = E_g + \frac{\hbar^2 k^2}{2m_{e\_eff}} \tag{1}$$

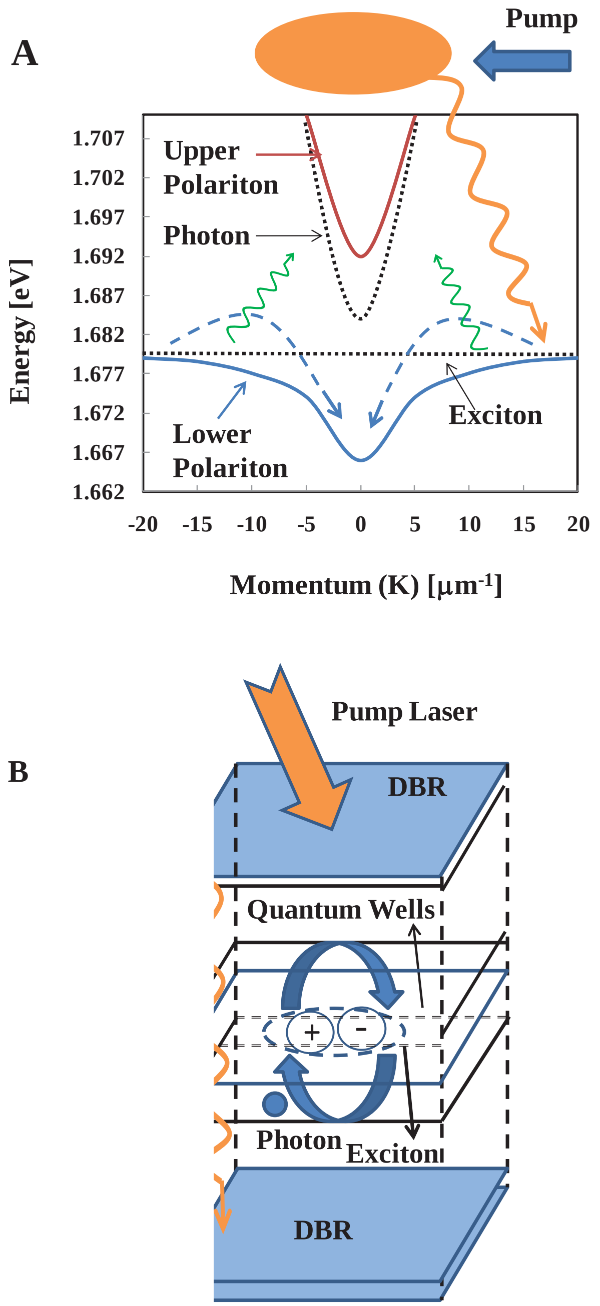

Fig. (3.1). (A) Upper polariton branch, lower polariton branch and polaritons optical excitation scheme represented in the energy and momentum vector (k) plane. Here, hot electron-hole pairs are injected into the microcavity by laser pumping. Excitons are produced and strongly interact with the

CHAPTER 4

Bose Einstein Condensation of Excitons

Abstract: The research on the Bose Einstein Condensation (BEC) of polaritons is of increasing importance due to its many technological applications. Several experimental and theoretical methods have been applied for the investigation on the BEC of excitons. Different experimental procedures and theoretical methods have been discussed in this chapter. Current research progress in this field and the applications of the BEC are also explained.

Keywords: Boltzmann transport equation, Developments of the Bose Einstein Condensation of excitons, Experimental procedures to get Bose Einstein Condensation of excitons, Technological applications of the Bose Einstein Condensation of excitons.

EXPERIMENTAL TECHNIQUES TO GET BEC

Early Experiments

Spectral Analysis Experiment

Till now, many experimental methods have been applied by different researchers to get the BEC of excitons. One of them is the spectral analysis experiment. This is the first experiment which shows the ability to get exciton BEC in Cu_2O [1, 2]. In that experiment, after excitation, a thin shape of excitons like a pancake is created that were not trapped and able to outflow from the surface. For excitation, a green laser is used that was absorbed within 5 mm of the surface. But at high density, exciton stays at the point of formation for a few nanoseconds. The orthoexciton phonon assisted luminescence spectrum could be well fitted by the Bose Einstein distribution:

$$I(E) \infty D(E) f(E) \infty E^{1/2} \frac{1}{e^{(E-\mu)/k_B T} - 1} \quad \textbf{(1)}$$

Where, E is the exciton kinetic energy, $I(E)$ is the intensity of the exciton distribution, $D(E)$ is the density of states of the excitons that is proportional to $E^{1/2}$ in three dimensions and $f(E)$ is the occupation number of the excitons that is proportional to $e^{-E/k_B T}$ at a low density.

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With $\left|\mu / k_B T\right| \sim 0.1$ stays over a wide range of densities. Therefore, the BEC gas did not cross the phase boundary but stayed near it. This is termed as Bose saturation. The absolute density of the particles is:

$$N = \int_0^\infty \frac{1}{e^{(E-\mu)/k_B T} - 1} D(E) dE \tag{2}$$

According to equation (2) at the absolute density, the spectrum fits the Bose Einstein distribution of the particles.

At each point in time by taking the ratio of the total luminescence intensity and the measured exciton cloud volume, the relative change in the density can be calculated. Then the densities from the fits have been compared to the relative change in the density. The researchers of reference [1] reported that over a wide range of densities, the variation in the density can be calculated from the fits of those agreed with the variation in the density from the intensity data within a factor of two.

Later the researchers of reference [3] investigated on the BEC of paraexcitons. In Cu_2O by applying uniaxial stress, they reduced the multiplicity of the orthoexciton ground state. It has been claimed that according to the ideal gas theory, the paraexciton density is higher than the density to obtain BEC. The emission intensity of the orthoexciton emission line is 500 times stronger than the paraexcitons emission line. Another brighter emission line also stays near it. Therefore, it is very difficult to make line shape analysis of the paraexcitons phonon assisted emission.

In these above experiments, by taking an image of a three-dimensional (3D) crystal in two dimensions (2D), the photons are collected. Then the fluorescence from the exciton gas must be united over one dimension. Therefore the difficulty arises in interpreting the three-dimensional data integrated over one dimension. To overcome this difficulty, the researchers of reference [4, 5] did their experiments with excitons, or exciton-polaritons, in two dimensions.

Transport Experiments

From the transport experiment, it is possible to know about the transport of the excitons rather than spectral signatures [6-9]. In this experiment, to get low-density exciton gas flow within a three-dimensional crystal of Cu_2O, a red laser of long-wavelength is used. Here the exciton energy nearly resonates with the photon energy of the laser. To create a very concentrated exciton cloud at the surface, a very intense pulse of green light is used. That exciton cloud excites one surface of the crystal. From the opposite side of the crystal, excitons are detected. Sometimes, a bimetal detector is used over a millimeter distance that converts the excitons into free electrons and holes. An external current is produced from these holes and free electrons. If excitons relocate through the crystal into the detector, then the signal is produced.

The researchers of reference [6-9] reported that when the green laser pulse intensity exceeded a critical threshold value, the exciton signal increased sharply on the back side of the crystal. The speed of the sound throughout the crystal and the arrival time of the pulse are similar. The author explained the excitons' motion throughout the crystal as superfluid motion when the exciton density exceeded a critical density threshold value.

But both spectral signature experiments and transport experiments have some drawbacks and because of this, any of these experiments did not show BEC. To get very high exciton density, very intense surface excitation has been used in these two experiments. In both of the cases, the exciton gas was produced very far from the equilibrium. Therefore the outflow of the phonon wind and heat flow of the excitation region should be modeled. Because of these reasons, both experiments were not so successful.

Nowadays Experiments

Experimental Procedure 1

Nowadays, experimental procedures are little different than the early experiments. In 2012, the researchers [10] studied the Bose Einstein condensation of excitons in cuprous oxide at ultra-cold temperatures. For their experiment, they used narrow-band tunable dye laser (Coherent CR599, laser dye Rhodamine 6G). The laser was pumped by a 5W green solid state laser (Verdi 5). A closed feedback loop was used to stabilize the laser power nearly 1%. A wave meter of High Finesse WS7 and resolution 60 MHz was used to measure the laser frequency and line width. In the middle of the spectrometer exit slit and the detector, a fourfold magnification optical imaging system was used to improve the spectral and spatial resolutions. A natural cuprous oxide crystal originally found in Namibia has been used for their experiment in the form of millimeter sized cubic specimens with clear-cut surfaces. They reported that the quality of that crystal is very high. It has low defect density and long paraexciton lifetime up to 1μs.

CHAPTER 5

Bose Einstein Condensation of Polaritons

Abstract: Several experimental and theoretical procedures have been used to get the Bose Einstein Condensation (BEC) of polaritons. Nowadays, the investigation of the BEC of polaritons is vastly popular and increasing attention in atomic as well as solid-state physics because it has many technological applications. In this chapter, different experimental procedures, excitation, and observation methods are explained. Recent research developments in this field and the application of the BEC also are discussed.

Keywords: Application of polariton condensation, Bose Einstein Condensation of polaritons, Experimental techniques to get polariton condensation, Optical observation methods, Theoretical modeling to get polariton condensation.

EXPERIMENTAL TECHNIQUES TO GET BEC

The condensation of polariton can be obtained by reducing the temperature for the fixed particle number. Another way to get the polariton condensation is, for a particular temperature, the particle number has to be increased until the critical density for the condensation is reached. At a low concentration, excitons act as bosons but indeed excitons are made by fermionic particles. At a high concentration, excitons' fermionic behaviour comes into play. Therefore, it is difficult to get a proper density of polaritons, to obtain condensation. There are two ways to solve this problem. First, it is necessary to use the materials that have strong exciton binding energy. It will prevent the separation of the particles at high densities which is necessary for condensation. Another is to use the coupled quantum wells. In this case, it is possible to get the high exciton density before saturation effects occur because the coupling of quantum wells delocalizes the excitons.

The coupling of lower polaritons with external photons is the principle decay mechanism. This interaction can be observed directly. A photon is produced outside of the cavity when a polariton decays. By using standard optical techniques, this can be detected. The energy and in-plane wave vector should be conserved in this procedure. Other properties like angular momentum and phase coherence will also be conserved. It is possible to do the investigation on the emitted light from polaritons and also possible to know the system properties without any damage to the population. Polaritons can be created directly by pumping. In an alternate way, it is possible to stimulate electronic states at far higher energy than the polaritons.

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These excited electronic states create a carrier of gas. If it cools down, then a quasi-thermal distribution of polaritons is formed.

Excitation Methods

To generate populations of polaritons, most of the experiments have used optical methods. This is the most convenient method. By using this process, it is possible to inject carriers electrically as shown in reference [1] where the researchers have work on the electronic polariton laser. To get the desired population, one must select the optical method in case of optical injection. There are two types of pumping, one is resonant pumping and another is non-resonant pumping. By resonant pumping, it is possible for experimentalists to create polariton populations directly and manipulate the quasicondensate properties. Non resonant pumping produces a quasi-thermal population of polaritons with the storage of free carriers and excitons.

Resonant Pumping

Resonant pumping produces a model of population or quasi-condensate with desired qualities. A condensate can be produced in a mono-energetic state by using a coherent source. Two condensates can interact by using two resonant beams [1]. To produce a condensate, it is also possible to apply a resonantly inserted pulse with low density [2, 3]. Due to the presence of a quasi-thermal background of polaritons, it would be possible to blend a thermally formed condensate. In this case, cool-down time is not required to form a condensate.

Non Resonant Pumping

In the case of non-resonant pumping at short wavelengths, the reflectivity minima of the Distributed Bragg reflector (DBR) are used. Then it is possible to create free carriers in the quantum wells with good productivity.

To know the full picture of polaritons properties, non-resonant pumping is often the optimal solution. In case of low polariton concentration, discharge may be seen only from the lower states. The excitons in the quantum wells scatter many times to come into the polariton states. For this reason, it can be assumed that most of the properties of the pump like polarization and phase coherence will be lost before becoming polariton. This behavior is most favorable for the studies of condensation. Several types of excitation lasers are used for excitation, depending on the type of experiment. These are described below.

Continuous Wave (CW) Multimode Titanium Sapphire

This is a standard Z cavity multimode Ti:Sapphire laser with a triple birefringent plate filter that allows a multimode emission of a relatively large width nearly 10 GHz. The Ti:Sapphire crystal has a typical emission spectrum starting from nearly 690 nm to 1 micron. The cavity length is on the order of 60 cm according to the mode spacing that is on the range of 250 MHz. The presence of multiple modes produces noisy lasing that gives a clear mark in the polariton luminescence. The noise is adequately slow to follow the excitonic reservoir and therefore, there is a time-dependent blueshift of the polariton condensates *via* the exciton polariton collisions that enlarge the spectra notably (roughly by a factor of 5). It has been proved that a stable lasing of this laser can be obtained at 695 nm, because this wavelength is at the border region of the gain spectrum. The output power of this laser is nearly 600 mW for 5.5 W of pump power.

Continuous Wave (CW) Multimode Laser Diodes

The continuous wave multimode laser diodes are used to overcome the noisy multimode CW laser in the experiments. These diodes are not tunable. They were lasing at 685 nm in the vicinity of the second reflectivity minimum after the stop band of the sample.

The main disadvantages are the low force, the use of two diodes in a perpendicular polarization and orientation in order to couple them in the same excitation path without losing information. The multimode emission had a mode spacing of the order of nearly 25 GHz with extremely small cavity length. The fluctuations of resultant intensity have much rapid time span than that for controlling the excitonic reservoir. In contrast, when mono-mode laser is excited with the diodes, it has been seen that a high number of condensate modes is visible on average. This gives the conclusion that the rapid time span noise of the diodes produces additional excitations to the condensate.

Continuous Wave (CW) Monomode Titanium Sapphire

The way of resolving all the excitation noise induced problems is the use of a true monomode laser. The monomode laser is a coherent model MBR-EL that is a bow-tie ring cavity. It contains a thin etalon and electronic stabilization for mode-hoping free single mode operation. To get unidirectional lasing, an isolator is added in the cavity that forces the photons to circulate only in one direction. Coarse tuning is done by a birefringent filter and fine tuning is implemented by tilting the thin etalon.

SUBJECT INDEX

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