Summary of Research Achievements using last DST SERB grant - SR/S2/CMP-72/2012

1) For the first time, we were **able to connect the concept of 'Negative Activation Energy' with 'Excitonic Bound States' using Impedance Spectroscopy which was rarely used to detect excitons in the past.**

2) Subsequently, we have started probing physics of excitons and excitonic many body effects using electrical measurements Our electro-optical impedance experiments dealing with **frequency dependent, thermodynamic signatures of 'dipolar' excitons proved to be very useful to experimentally detect and control excitonic like bound states**.

3) **Our all-electrical experimental technique to sense thermodynamic signature of 'dipolar' excitons can prove to be quite useful for probing the still elusive excitonic BEC and dark excitons.**

4) Most importantly, we are able to clarify widespread misconceptions by confirmatively detecting exciton like quasi particles **even when the exciton binding energy E_b < thermal fluctuation energy (k_BT). This is because the dissociation of excitons into electrons and holes inside a solid is a statistical mechanical process with probability ~$\exp(-E_b/(k_BT))$ where E_b is the exciton binding energy.** Along with the enhancement of excitonic binding energy inside a quantum structure, this allows **finite, non-zero probabilities of having some excitons even when $E_b < k_BT$**.

5) We have shown that **Photocapacitance is much more sensitive to detect Indirect Excitons as well as Trions in Single Barrier Quantum Heterostructure of GaAs/AlAs/GaAs as compared to ordinary dc-Photocurrent spectra and Photoluminescence spectra used in most studies in the past**.

6) We were able to demonstrate **how one can experimentally distinguish indirect and direct excitons from a mixed ensemble of both by comparing photocapacitance and dc-photocurrent spectroscopy**.

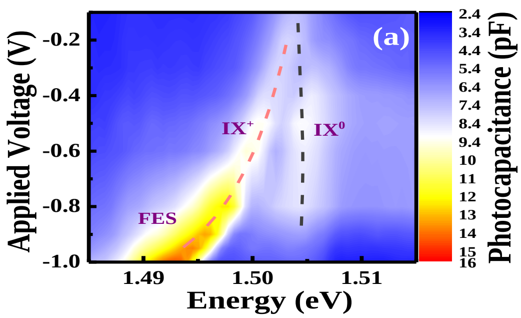
7) We are able to detect and study various excitonic quasi-particles in quantum confined light emitting devices including the identification of **different charged states of Trions, Bi-Excitons at low temperatures using simple Electro-optical technique like photocapacitance**.

8) We expect that all these results will lead to further developments of **bias and frequency dependent experimental control of Excitons, Trions and Bi-Excitons in next generation coherent light emitters**.

9) We were able to pinpoint the **excitonic Mott transition using all-electrical generation and detection of excitons in different classes of laser diodes**. This can be further extrapolated towards effective electrical injection and control of excitonic lasing in nanostructures.

10) Currently, we are **using the facilities procured under this grant for quantitative measurements of temporal and spatial coherence as well as photon statistics and optical shot noise measurements** of novel light emitting materials.

Few Ongoing Research Works:



⥣ Evolution of Fermi-Edge Singularity (FES) from Positively Charged Trions (IX+)

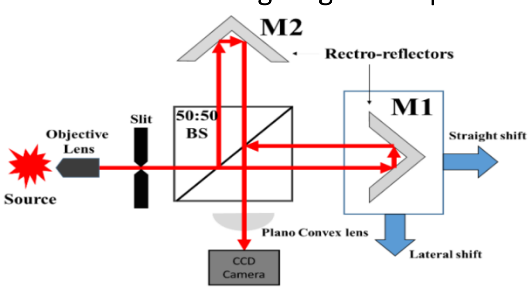
Phys. Rev. Applied 10, 044043 (2018)

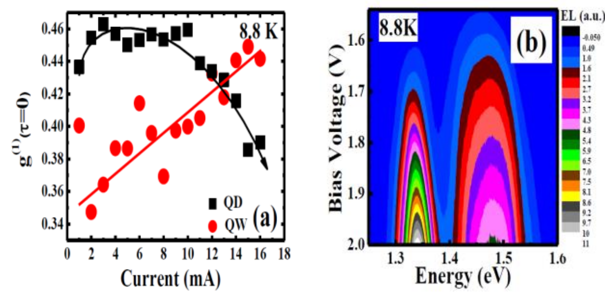
1) It is now possible to experimentally probe bias driven dipolar properties of excitons, trions using frequency dependent capacitance based techniques at sufficiently high temperatures.

2) Physical properties of interacting dipoles of excitons/polaritons were mostly overlooked by standard optical emission based spectroscopic techniques used in the past to probe excitonic BEC, excitonic superconductivity etc.

3) Complementarity of simultaneous optical & electrical experiments for manipulation and control of dipolar states of excitons/trions/Fermi-Edge Instabilities are being demonstrated by us.

Ongoing experimentations of Temporal and Spatial Coherence using Single Set up

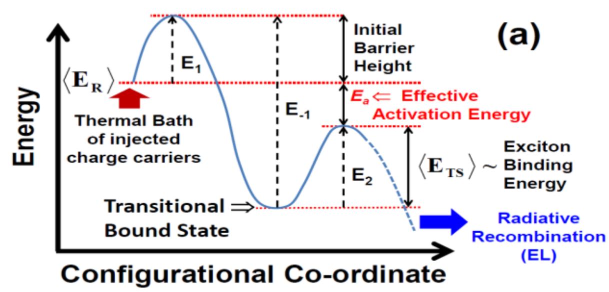




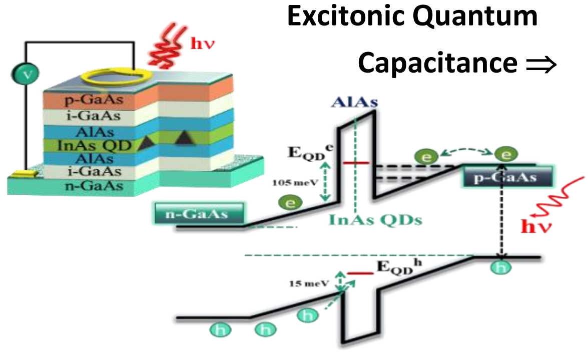
J. Phys. D: Appl. Phys. 52, 095102 (2019).

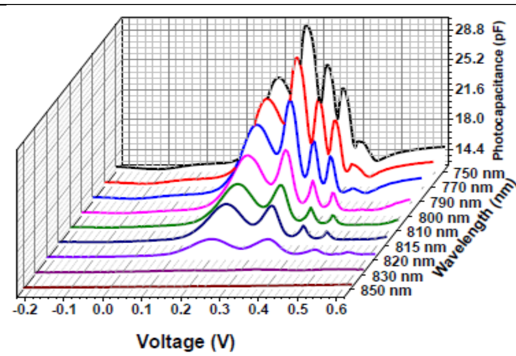
Dielectric Signatures of **'Negative Activation Energy'** and configurational changes of Excitonic bound state emitting light under MHz modulation ⇒

Journal of Applied Physics 120, 144304 (2016).



Excitonic Quantum Capacitance ⇒





Future Research Plans in Quantum Fluids of Excitons:

- Due to their small effective mass, both excitons (electron-hole bound pairs) as well as exciton-polaritons (quasi particles of excitons & cavity photons under strong coupling) are expected to undergo Bose-Einstein Condensation (BEC) below their respective quantum degeneracy temperatures which can be **around few Kelvins to even room temperature**. Therefore, compared to atomic systems, these bosonic quasiparticles are promising candidates for observing BEC and superfluidity even at such elevated temperatures.
- **Polaritonic BEC and electrically injected exciton-polariton lasing is already demonstrated around room temperature. However, still there is no full proof experimental evidence for BEC of only excitons.**
- Both excitons and exciton-polaritons undergo strong radiative recombinations. This directly reduces the number density of these **dipolar, interacting bosons** which can undergo condensation. Excitons which endure very fast radiative decay and emit light are called bright excitons. BEC of these bright excitons and polaritons were **so far being probed 'indirectly' using luminescence based spectroscopies**. However, it is now understood that those **light emitting excitons/polaritons were possibly not a part of the ensemble of excitons which forms the real condensate!**
- Moreover, due to spin selection rules, a fraction of excitons do not undergo fast radiative recombination. These are the so called ***'Dark' Excitons***. Energy levels of 'Dark excitons' are also lower than these 'Bright excitons'. Repulsive inter-band Coulomb processes force bright exciton levels (J= ± 1) above the dark exciton levels (J= ± 2). Therefore, only these **'Dark excitons' are actually expected to form the true BEC ground state**. It is obviously difficult to probe these 'Dark' Excitons' with standard optical emission based spectroscopies. **Therefore, all past experimental studies of excitonic BEC were mostly incomplete!**
- We have been developing few experimental strategies **to study the dielectric signatures of *'dipolar'* excitons using capacitance measurements.** These electrical experiments are **sensitive to both types of excitons including Dark excitons** and can therefore be **instrumental in probing the 'still elusive' Excitonic BEC, Excitonic Superconductivity conclusively**. We want to extend these dielectric investigations of interacting dipoles of excitons and exciton-polaritons in **2D heterostructures** having high excitonic binding energies.
- **In fact, spatially indirect, 'dark excitons' can have very large dipole moments and large radiative lifetimes** of the order of many microseconds or more. This also makes these dipolar excitons suitable candidates for observing thermodynamically stable BEC.
- Ongoing research activities in our laboratory clearly indicate frequency dependent electrical signatures of bias driven and/or photo generated **indirect excitons, trions** and **Fermi-edge singularities** even at elevated temperatures. Therefore, such experiments can be extended to **study condensed matter physics of quantum fluids of dipolar, interfacial excitons which involve excitonic BEC and lasing, excitonic superconductivity, hybrid Bose-Fermi mixtures, excitonic cavity QED etc. and even related topological properties of two dimensional excitons and/or exciton-polaritons in both frequency and time domains.**