PEREP
Plasmon Enhanced Rydberg Exciton Physics

When a valence electron in a semiconductor absorbs a photon with appropriate energy, it becomes free, leaving an empty spot behind - a positively charged hole. In terms of energy, we say that the electron moves from valence band to conduction band. However, if the photon energy is a little less, the electron will still remain weakly bound by the electrostatic attraction with the hole. The whole electron-hole pair resembles a hydrogen atom, with the hole taking the role of the nucleus. This is called an exciton. Like in the atom, the electron can occupy states (orbits) characterized with various quantum numbers, in particular principal quantum number n.

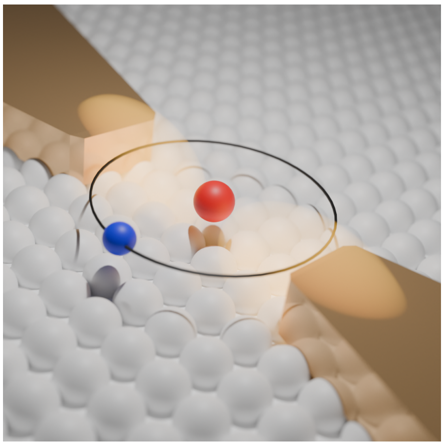

Figure 1: Schematic representation of an exciton in a bow-tie antenna.

The concept of excitons has been known since 1930's. However, unexpectedly, in 2014 excitons with $n > 20$ have been observed in Cu_2O. Such a highly excited states have been known in atomic physics, where they are called Rydberg atoms. Analogously, this new discovery has been named Rydberg excitons. In other semiconductors, states with $n > 3$ are already extremely hard to observe due to their instability. Now the question is, what exactly a large value of n means and how it can be useful?

If we recall atomic orbits, they form consecutive layers around nucleus, with each one being larger than the previous. In fact, the radius of an atom is proportional to n^2. The same holds for excitons. For large n, they can get truly enormous, with the radius of the order of micrometers. This is unprecedented - we are dealing with a fully quantum object (very similar to hydrogen atom) that spans a distance comparable to he width of a hair! In other words, Rydberg excitons exist on the border between classical and quantum world.

Light plays a central role in exciton physics. The exciton is created by absorption of a photon and after that, it can interact with incident electromagnetic radiation, changing the optical properties of the semiconductor. The forms of light may vary; freely propagating waves, standing waves, waveguide modes... Among them, there is one particularly curious form of electromagnetic radiation - surface plasmons. When light shines on a metallic surface, it can excite collective oscillations of the free electrons in the metal, where billions of electrons move in unison in response to the electric field of an electromagnetic wave. The entire ensemble of the field and electrons forms a plasmon, which is a type of wave that can propagate along the metal surface. By designing a metallic structure (nanoantenna) with specific shape, one can guided and focus plasmons to a greater degree than regular waves. The whole plasmon oscillation involves great number of electrons and is quite macroscopic. For this reason, surface plasmons are usually treated as classical objects, but they can exhibit some quantum properties.

Here we arrive at the key idea of this project: what happens when we take two objects on the border between quantum and classical realm and merge them together? So far, nobody knows. While interaction between low n excitons and plasmons is a recent, but fairly well researched topic, Rydberg exciton-plasmon interaction is a completely new area. For the first time, we have a capability to engineer interactions between plasmons and individual excitons that match the size of the said plasmons or the entire nanoantenna. Another nice coincidence is that the lifetime of Rydberg excitons is extremely long, matching the plasmon lifetime as well. Thus, the two objects have plenty of time and space to interact with each other. Finally, when more than one exciton is involved, their large size means that they will interact at a long distance, leading to all sorts of interesting nonlinear phenomena. With a plasmonic structure, we can possibly control and enhance these effects by manipulating the spatial distribution of excitons.