Superparaelectricity in soft matter for photonic and high-capacitance dielectric applications

Imagine a material that responds rapidly to an applied electric field, allows for the accumulation of huge amounts of charge, and at the same time is not a ferroelectric material. In a ferroelectric, there are spontaneously polarized regions called domains that exist despite the exclusion of the external electric field. Such a material is characterized by a very high electric permittivity, which means it is very susceptible to the influence of an electric field. Unlike a ferroelectric material, a paraelectric material is not permanently polarized. It can be polarized under the influence of an external electric field, but after its removal, it returns to its initial state. Such a material is characterized by a low value of electric permittivity.

In this project, we aim to create a superparaelectric material (SPE), which will be an intermediate state between ferroelectric and paraelectric. In superparaelectric, there will be short-range domain ordering, in contrast to the long-range ordering that occurs in the ferroelectric state. Unlike the well-known superparamagnetism, which is an analogous phenomenon in magnetism, the phenomenon of superparaelectricity is rarely observed in nature and remains poorly understood. Although numerous studies have been conducted on solid crystals, there are relatively few materials exhibiting such an intermediate state. The project aims to develop superparaelectric liquid crystal materials. We believe that the SPE state will be much easier to induce in liquid crystals than in solid crystal structures due to greater molecular mobility, lower energy barriers to reorganization, tunability by external fields, and greater possibilities for molecular design. Our research is inspired by recent discoveries related to the ferroelectric nematic phase. The scale of ferroelectricity in these liquid materials is very similar to that observed in solid ferroelectrics.

A fundamental aspect of our approach to superparaelectricity is to understand and control the delicate balance between ferroelectric and paraelectric states in self-organizing soft matter materials. To achieve the goal set in the project, we proposed novel highly polar liquid crystalline molecules. Using quantum-chemical calculations, we are able to predict their electrical properties by analyzing the electrostatic potential distribution along the long axis of the molecule. As part of international collaboration, the compounds and mixtures we have developed will be investigated for the advanced nanosecond optical switching effect.

The newly developed materials may find practical applications as an active medium in supercapacitors. Tunable liquid crystalline supercapacitors could achieve much higher capacitance than conventional dielectric capacitors, on the order of single farads. In such a capacitor, it will be possible to increase the capacitance without increasing the electrode area or reducing the distance between electrodes. This makes these capacitors particularly promising for micro or nanoelectronic applications. All commercially available liquid crystal displays (LCDs) operate in the paraelectric nematic phase, which is why we believe that the concept of superparaelectric liquid crystals will revolutionize photonic technology. The SPE state will be an ideal medium for ultrafast switching on nanosecond time scales, enabling advances in the design of technologies for virtual reality displays.

This project is a step towards a future in which intelligent soft materials will revolutionize our approach to energy storage and information processing.