

Marriage between metamaterials and single-electron transistors as a path to a new class of optoelectronic components

Abstract for the general public

The rapid development of the information society and the growing demand for efficient information processing and storage systems are reflected in the scientific community's efforts to extend the range of available devices. This trend is observed within the approach focused on further miniaturisation of classical electronic components utilising silicon and germanium and involving increasingly advanced fabrication techniques. This path falls under the concept of "More Moore" (MM), which refers to Moore's Law describing the dynamics of the development of computer components and computational power.

On the other hand, we observe a growing interest in unconventional computing devices that utilise information carriers other than electric current (e.g., light, chemical molecules, etc.), a wider variety of materials, and new computational paradigms (e.g., multivalued logic and neuromorphic engineering, which mimic specific functions of biological structures). This direction aligns with the "More than Moore" (MtM) approach. Among the many promising MtM concepts, the use of light as an information carrier appears particularly attractive for data processing and sensor design, as well as for developing efficient communication techniques.

One of the proposed solutions within MtM is the development of single-electron transistors (SETs). These miniature devices, which enable the control over individual electrons, have been the subject of intense research due to their wide range of potential applications – from sensors and logic gates to components of quantum computers – as well as their energy efficiency and straightforward way of miniaturisation. However, two aspects of SETs' operation remain challenging in certain applications: many of these devices require ultralow temperatures to work properly, and their functionality is typically limited to processing electrical signals only.

In this project, we aim to expand the applicability of SETs by drawing inspiration from the research on metamaterials (where a key factor lies in designing specific electrode geometries that can act as plasmonic antennas), enabling the control over the electrical response of the device through mid-infrared (mid-IR) light excitation. Plasmonic antennas absorb light within a narrow energy range, which results in a change in the electric field distribution. Interestingly, appropriately designed structures with nanometer-wide gaps can exhibit significant field enhancement – up to several thousand times – within the gap.

Placing a semiconductor or metallic nanoparticle – an active part of the SET that acts as a "valve" for current – in this gap allows its electronic properties to be controlled via the electric field. This should enable manipulation of the transistor's state by irradiating it with a laser beam tuned to the shape and size of the electrodes. This novel approach is expected to provide precise control over the current flow through the device, with the possibility of high-speed switching on the scale of billionths of a second.

Another ambitious goal of the project is to achieve room-temperature operation for selected SET designs. As mentioned earlier, most devices of this type are designed to work at ultralow temperatures due to stability requirements. By carefully selecting materials and using modern fabrication techniques supported by advanced computer simulations, we aim to develop transistors that can not only be controlled optically but also maintain functionality at room temperature.

Achieving success in these endeavours could pave the way for a new generation of optoelectronic devices that are faster, more energy-efficient, and capable of functioning in complex information processing systems. The ability to integrate these devices with CMOS-standard systems could significantly expand their range of applications. Additionally, the project aims to deepen our understanding of light-matter interactions at the nanoscale, which could positively impact the development of optoelectronics and nanotechnology.