Transport in nanowire-based quantum dot systems: Heating electrons and confining holes

Dorsch, Sven

2022

Citation for published version (APA):
Dorsch, S. (2022). *Transport in nanowire-based quantum dot systems: Heating electrons and confining holes*. Department of Physics, Lund University.

Total number of authors:
1

Popular science summary

The era of computers began with the invention and development of transistors in the late 1940s. Today, transistors are the elementary building block of computers and great efforts are aimed at increasing the computational power by squeezing more and more transistors into the same area. In recent years, however, the trend has shifted from plain power increases to the development of new computation concepts. Many new approaches are closely linked to novel materials and the use of quantum effects. A key ingredient to the realization of a new generation of electronic devices is understanding the physics and underlying processes in the limit of tiny device dimensions. Here, this thesis contributes through studies of how current flows through tiny semiconductor segments.

Semiconductors are a type of material where the ability to conduct current can be manipulated — a principle that is used in modern transistors. In this thesis, tiny semiconductor segments with dimensions as small as a billionth of a meter, 10000 times smaller than the diameter of a human hair, are embedded in an electronic circuit. Within such structures, current flow obeys different rules compared to macroscopic conductors. Current flow, on a basic level means transporting charge. Charge is carried by electrons, which are elemental particles, essentially turning current flow into a stream of electrons.

In regular transistors, current through a semiconductor channel is controlled via a voltage applied to a so-called gate electrode. Translating this to a simple picture, we can think of a broad tunnel with a constant stream of people passing through. Changing the voltage on the gate electrode, in that picture could be translated to slowly closing a physical gate within the tunnel. The more closed the gate is, the less people can pass the tunnel at a time, but a description of the human current requires only an understanding of the crowd dynamics. This changes drastically if we introduce a paternoster, significantly confining the available area to move. Here, suddenly the nature of individual people becomes relevant. Once a person steps onto a lift car, no second will follow, respecting the concept of personal space. In order for the next person to enter, this repelling force has to be overcome, which can for instance be achieved by moving the paternoster downward, making the next lift car available.

In the same way we experience the concept of personal space, electrons are charged and thus experience the so-called Coulomb repulsion, a repelling force. Within the limited space of a tiny semiconductor segment or quantum dot, electrons cannot avoid one another and the nature of individual electrons dominates the current through the quantum dot. Only one electron at a time can enter the quantum dot and in order for the next electron to enter the segment enclosed by the metallic contacts, the first electron either has to leave or energy must be added to the system. Energy can be added to the system via the gate electrode.

The devices studied in this thesis contain two quantum dots directly connected in series. In our simple analogy, this translates to the rather unusual situation of two paternosters that have to be passed in series in order to move forward. Here, my role as a scientist mirrors that of the paternoster operator, who can precisely control the motion, position and number of electrons in these devices by aligning or detuning the metaphorical lift cars against each other via tuning voltages on gate electrodes. Based on the above described, so-called serial double-quantum dot, model system this thesis presents results on two separate topics.

The first topic makes use of the ability to precisely trap individual electrons in the lift cars of such serial double quantum dot devices. This allows scientists to look closely and study, even control the behavior of individual electrons — a concept applicable for quantum computation: Electrons possess a quantum mechanical property, the so-called spin, which at its essence means that electrons behave like tiny bar magnets. The orientation of the poles of these bar magnets can be used to encode information and by controlled rotation of the magnet‘s orientation computations can be performed. Such devices are then called spin qubits and form one approach to design the basic building block of a quantum computer. In a classical computer, information is encoded in two states, described by 0 or 1. In contrast, spin qubits can essentially take a continuum of states, where each state describes a certain rotation of the magnetic poles of the electron‘s spin. Consequently, a quantum computer running clever algorithms which make use of this continuous range of available states can solve selected problems significantly faster compared to traditional computers.

A challenge for the practical realization of a spin qubit is that the precise orientation of the electron’s magnetic orientation must remain fixed during computational processes. In many common materials, however, a variety of other bar magnets are present which interact with the electron’s spin. This unwanted interaction results in the uncontrolled rotation of the electron spin. One approach to tackle this problem is based on making use of materials where instead of electrons, vacancies of electrons, so-called holes contribute to the current flow. Holes much like electrons possess a spin, but in contrast to electrons interact less with other spins in the qubit’s host material. In this thesis, I study GaSb, a compound semiconductor material where holes carry the current. I develop suitable device designs for the realization of a GaSb spin qubit and test if the material’s properties are suitable for quantum computation.

The second research topic discussed in this thesis evolves around converting heat to currents in serial double quantum dot devices. Conventionally, electrons obtain their incentive to travel from one end of the device to the other by the application of an external voltage bias. Whether current can flow or not then depends on how the metaphorical lift cars of the two paternosters or quantum dots are positioned relative to each other. In this thesis, I study currents that are driven by local heating of the device rather then by the application of an external voltage bias.

I therefore develop device designs where tiny electrical heaters are placed on different locations along the serial double quantum dot device. Then, I identify for which lift car configurations heat driven currents, so-called thermocurrents, can flow across the device. Here, I find two effects that contribute to the thermocurrents: First, if a temperature difference within the electronic circuit of the device exists, electrons gain incentive to travel through aligned lift cars between the two quantum dots in an attempt to even out the temperatures. Second, if the surroundings of the device is hotter than the electronic circuit itself, electrons climb through misaligned lift cars and cool the environment in the process. Because both processes essentially convert heat to current, which could be used to for instance charge a battery, the devices discussed in this thesis can be seen as tiny engines which produce electrical power. Because in the here discussed quantum dot-based devices researchers have tremendous control over the current by tuning the positions of the metaphorical lift cars, these tiny engines offer an ideal experimental playground to study fundamental concepts that are otherwise only discussed theoretically.