Popular summary in English

Contrary to what teachers used to say, we are carrying a calculator with us at almost all times. With the computing power of many times what was used for the moon landing our mobile phones are more than overpowered for double and triple checking the calculations we do in our heads. This power is to a large extent based on our ability to create smaller and smaller electric circuits and components. We are reaching length scales, where important parts of these components are only made up of a few atoms. At these length scales the classical picture of an electric current is not necessarily a full description of what is happening anymore. We have to take into account quantum mechanical effects to fully understand what is happening. Quantum mechanics is the theory used to described the strange world of single electrons and atoms. Of course, this can also be turned around: the ability to create and control tiny systems allows us to look for new and interesting quantum mechanical effects that we would not see otherwise, and perhaps use these effects to make better devices. In this thesis we theoretically investigate two examples of what can happen when the systems get small in all three or only one spatial dimension, respectively.

To make this summary a little more fun, we will tell a story about electrons and how they travel the world. Electrons share a surprising amount of properties with us humans. For example, they have a strong desire for personal space. They are negatively charged, so they do not like to be close to each other. This is called *Coulomb repulsion*. When the electrons go on vacation to a nice little tropical island, the first one hops on it quite easily. The second electron however will need a lot of convincing to share the space with the one that is already there. We call these little islands *quantum dots*. The larger landmasses, where the electrons spend their non-vacation time, are the *electric contacts* and an incredibly large amount of electrons lives on these contacts. When two of these big landmasses are close to the island, some electrons will occasionally jump onto the island, this is the famous *tunnel effect*. Sometimes they also hop to the other side, as you can see in Fig. A. If enough electrons jump across in one direction, we have a current that we can measure. The current

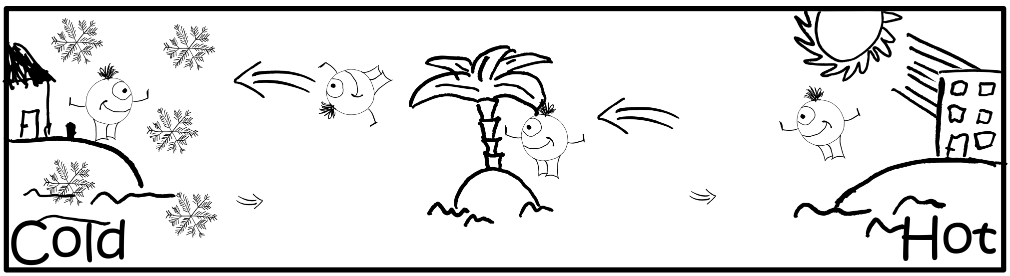

Figure A: Electrons hopping between main landmasses, cold (left) and hot (right), and the island in the middle.

can depend on many things, for example how far it is between the island and the main land, so how easy it is for the electrons to jump. This is called the *tunnel coupling*. Other factors can be how high the island is, the energy of the so-called *dot level*, and also how many electrons are on the main land, the *chemical potential* of the contact. When one of the main landmasses has a lot more electrons on it, electrons on the island are more likely to jump to the less populated side. The difference in population between the main landmasses is called *potential difference* or *voltage*.

We can modify this setting in many ways. What happens if we put two islands between the main lands? This is called a *double quantum dot*. How does this setup react, if we slightly alter the distance to the main land or the height of the islands? This corresponds to changing the tunnel couplings and the dot level, respectively. By sitting on the main land and counting how many electrons come from the island, can we learn something about a third island, that sits close by? If we for example find out, whether there are electrons on the third island, this is called *charge sensing*. This is the topic of paper I, where we investigate a parallel double dot and potential applications as a charge sensor.

So far we have not really cared about the weather. Which way will electrons go if it is very hot on one side of the island and really cold on the other, like the situation in Fig. A? If we can convince electrons to jump to the side with more electrons, we have used *heat* from the hot side to do *electrical work*. This is the concept of a *heat engine*. What if we bring the island and mainlands close enough together, so two electrons can shout at each other and coordinate their jumps, or one of them can jump twice in a very short time? The processes that involve two coordinated jumps are called *cotunneling* events. Allowing these arrangements between electrons does not only change how many electrons jump on average, the *current*, but also how the number of electrons that jump fluctuates around the average This is called the *noise*. It also affects the *efficiency* of the heat engine. In paper II we investigate these effects and also look at a trade-off between the current, noise and the efficiency in the so-called *thermodynamic uncertainty relations*.

Of course, not all electrons hang out close to these little island in the sea all the time. Some of them have regular jobs and have to commute along a coastal highway, the sea on one side and a impassable landscape on the other, as sketched in Fig. B. The highway also has somewhat special traffic rules: in one direction only blue cars are allowed and in the other direction only red cars. They call this rule *spin-momentum locking* and the countries where that happens *topological insulators*. In these very special countries the electrons are also very environmentally friendly and have to carpool. They also have somewhat funny cars. Depending on which of the seats in the car are occupied the color of the car is either red or blue. This property is called the *spin projection* and determines which way the electrons are allowed to go. When the car hits a speed bump, they call them *magnetic impurities*, the electrons are sometimes thrown up from their seats. If after this *scattering event* they sit in different places the car can change color. If they hit a speed bump on the highway and

Figure B: Illustration of the coastal highway with the strange traffic rules: red cars can only go on the right, blue cars on the left in the opposite directions. The speed bumps are drawn in orange.

the car changes color they of course have to turn around. This can make the traffic quite challenging. If a car enters on one end of the coastal highway, the likelihood of making it to the other side is called the *transmission*. In paper III we look at how the speed bumps affect the traffic and how likely it is for electrons to arrive where they had planned to go. And since that is not strange enough already, we also let the speed bumps rotate.

With this thesis we hope to contribute to the understanding of the travel habits of electrons, so they can be used in this strange and wonderful quantum world that we and the electrons live in. The vacation and car pooling habits of electrons could in the future be used in many technical applications. From using quantum effects to make existing electronics more efficient, to using them to measure things we could not before or even develop entirely new types of computers, a huge number of things seem possible.