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Electron spin transport in graphene and carbon nanotubes

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2008

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Tombros, N. (2008). *Electron spin transport in graphene and carbon nanotubes*. s.n.

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Download date: 05-10-2024

Summary

The electron is a very important particle for both, electronic and spintronic devices. The only difference is that an electronic device uses the charge of the electron and a spintronic device its intrinsic magnetic moment (spin). If we measure the magnetic moment of an electron then we obtain only two possible states, the spin-up state and the spin-down state. Those states can be used for Boolean calculations in spintronic devices, in a similar way as the states 0 and 1 are used in the computer language. Scientists search for materials which can be used to store spin information enabling the construction of memory elements. Also a lot of effort is made in designing spintronic devices in which spin information can be manipulated. A spin-transistor is an example of a spintronic device in which spins are manipulated using a gate electrode. If those elementary devices are available then a computer chip can be built containing almost entirely spintronic devices. This would enable the construction of a quantum computer which theoretically should be able to perform calculations with huge speeds compared to speeds found in nowadays computers. However, first the basic spintronic devices have to be build.

Spin information is expected to survive for long time in organics and therefore scientists show a lot interest in the development of organic based spintronic devices. Organic materials contain mainly carbon atoms which have an atomic number $Z = 6$ and therefore the main mechanism of spin relaxation, the spin orbit interaction, is very small since it has a Z^4 dependency. Using an anorganic material, for example silicon is also possible since it has an atomic number $Z = 14$, however using gold for spin transport would be unwise as gold has $Z = 79$, giving a relaxation time which is about 1000 times smaller than what is expected for an organic system. In this thesis we investigate experimentally spin transport properties in two organic systems, a single layer of graphene and a carbon nanotube.

Before presenting the experimental results I introduce a number of basic theoretical concepts used in spintronics. In chapter 2 I discuss the conventional spin valve device and introduce the non-local spin transport technique. Here a spintronic device is fabricated using as basic material a graphene layer or a carbon nanotube. The carbon based system is contacted by four ferromagnetic electrodes, two of them to produce a spin current in the carbon based system and the remaining two electrodes are used as voltage probes to measure spin transport. Using four probes allows us to perform the so-called non-local technique. Using this technique one is able to completely separate the spin current path from the charge current path. The advantage here is that we measure only the spin dynamics since we separate spin transport from other effects, such as Hall effects, anisotropic magnetoresistance, interference effects and magneto-coulomb effects. Furthermore, in chapter 2 I develop a model for spin transport and precession in a nonmagnetic material taking in account possible spin relaxation at the ferromagnetic contacts. The techniques used to fabricate a spintronic device based on graphene or a carbon nanotube are presented in chapter 3. In this chapter we show that optical microscopy can be used to distinguish a graphene layer from multilayers of graphene when placed on top of a SiO_2 substrate. Graphene is also visible when placed on a polymer layer. A controlled removal of the polymer using electron beam lithography and chemicals should allow the production of free standing graphene devices.

In chapter 4 I present experimental results obtained from non-local measurements on a single walled carbon nanotube. A resistor model (appendix A) shows that the spin relaxation length in a carbon nanotube, which is the distance from the spin injector at which the spin signal decreases by a factor $\sim$3, has to be at least 1.5 μm. We have also found that the spin injection can be very efficient since we found a polarization of 25 %.

The magneto-coulomb effect (MCE) is discussed in chapter 5. Here, our model shows that when two ferromagnets are weakly connected to a Coulomb island, the application of an external magnetic field results to a change in resistance of the conventional spin valve device. This effect can obscure the spin dynamics since in the conventional spin valve device the spin and charge currents flow through the same path. We show that the MCE can induce magnetoconductances of several per cents or more, depending on the strength of the Coulomb blockade.

In chapter 6 I present non-local spin transport measurements in a single graphene layer. A remarkable result is that spin transport is possible at room temperature, showing spin relaxation lengths around 2 μm. This opens the road to graphene based spintronic devices working at room temperature. The relatively short spin relaxation times (150 ps) suggest an important role of spin-orbit (SO) interaction in graphene. Valuable information about the SO interaction can be obtained by investigating the anisotropy of spin relaxation in the system. In chapter 7 I present non-local experiments showing that spins injected perpendicular to the graphene layer have a relaxation time which is about 20% smaller compared to spins injected parallel to the graphene layer. Anisotropic spin relaxation of comparable size (50 %) is expected when the spin-orbit effective magnetic fields are exclusively in the graphene plane. Our measurements show that probably the Elliot-Yafet and not the Dyakonov-Perel mechanism is responsible for the spin relaxation in graphene. In this case the use of high mobility graphene layers should give a larger spin relaxation length.

Application of an strong in-plane electric field E along the spin transport direction allows us to study the drift of spins in the system. Since the mobility μ in graphene is high, a small electric field is needed to obtain a drift velocity ($=\mu E$) with a magnitude comparable to the Fermi velocity $v_F = 10^6$ m/s. In chapter 8 we present experiments in which we study the drift of electron spins in single layer graphene spin valves in a field effect transport geometry. Electric fields of about ±70 kV/m applied between the spin injector and spin detector and in the metallic conduction regime result to a change in the spin valve signal as much as ±50%. We observe a clear sign reversal of the drift effect when switching from hole to electron conduction. In the vicinity of the Dirac neutrality point the drift effect is strongly suppressed. A drift-diffusion model of spin transport quantitatively fits the experimental results.

A completely different type of experiment is presented in chapter 9, where we are not interested in spin dynamics but in the superconducting properties of very thin tin nanowires. I present electronic measurements in superconducting tin nanowires encapsulated in multiwalled nanotubes contacted with gold electrodes. This system is unique since the multiwalled carbon nanotube protects the monocrystalline tin nanowire from oxidation and shape fragmentation. This allows the investigation of stable tin wires with diameters as small as 25 nm. We found that superconductivity in tin nanowires is strongly influenced by the gold contacts through the proximity effect. To be able to measure the intrinsic superconducting properties of thinner monocrystalline tin wires and to investigate quantum phase slip processes, it is necessary to contact them with superconducting electrodes having a critical temperature higher than tin.