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Electric field modulation of spin and charge transport in two dimensional materials and complex oxide hybrids

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SUMMARY

In today's world more and more technologies based on nano electronics enter our daily lives and every decade or so, a new application is found. These new applications emerge due to the constant miniaturisation of integrated circuits. Recent examples include the laptop, smart phone and wearable electronics such as smart watches.

For years the miniaturization of electronic components was possible without increasing the energy consumption of the total chip. Around the year 2000 this trend ground to a halt. It was no longer possible due to the fact that components hit the limits of what was physically possible: barriers became so thin that electrons could tunnel through them. This tunnelling caused leakage currents, even when a component was switched off. In order to combat these problems researchers and manufactures are looking for alternative technologies combined with new materials.

A possible future technology utilises the spin of an electron, instead of it's charge which is used today, to transport, manipulate or store information. Because of the use of the electron spin, this field is also called *spintronics*. Spintronics has the potential to be more energy efficient, because a spin current does not require a (heat generating) charge current.

The utilisation of electron spins in computers is not new; spintronics has been used in hard drives for several decades already. However in hard drives a charge current is still part of the equation. In order to reduce the charge component and/or to make other computer elements based on spintronics, new materials are being investigated.

A promising material for spintronic applications is graphene. Graphene is a two-dimensional material which consists of carbon atoms which are arranged in a honeycomb lattice. Among its extraordinary properties is its ability to transport electron spins over record lengths at room temperature. This makes graphene a promising candidate for spintronics.

However graphene's two-dimensional nature makes it very prone to influences from the environment. Among the properties which are influenced by this is the spin relaxation length. In order to maximise this spin relaxation length a lot of research is done.

This thesis contributes in that respect starting in chapter 4, where we placed graphene on a $SrTiO_3$ substrate. $SrTiO_3$ is a material which has a permittivity which is a factor 100 higher than SiO_2 at room temperature. Additionally the relative permittivity is temperature dependent and it reaches values of 2×10^4 at 4 K. By performing temperature dependent measurements we investigated the effects of a high and variable dielectric environment on the spin transport in graphene.

We found that a spin relaxation length at room temperature in graphene on $SrTiO_3$ of 1 µm which is similar for graphene on SiO_2. We observed slight changes in the spin relaxation length with decreasing temperature, it first increased to 2 µm at around 200 K and thereafter decreased to 1 µm at 4 K.

We believe that the origin of the variation in spin relaxation length with temperature is due to changes in the carrier density of graphene. These changes were also observed in independent Hall measurements. The origin of this variation is likely

due to the changes in dielectric permittivity of $SrTiO_3$, which alter the strength of an electric field. This electric field originates from intrinsic dipoles at the $SrTiO_3$ surface.

In chapter 6 we explore another crucial part of graphene spintronic devices, namely the tunnel barrier. Previous studies have shown that the quality of the tunnel barrier can greatly influence the spin relaxation length. Here we investigate the possibility of using MoS_2 as a tunnel barrier. MoS_2 is a layered two-dimensional semiconductor. Possible advantages of MoS_2 over traditional tunnel barriers are its pinhole free nature and the fact that the thickness is easier to control.

We sandwiched MoS_2 between Au/Ti contacts and a graphene channel to investigate the electronic behaviour of the tunnel barriers by performing charge based measurements. The results of these measurements were then compared to the Rowell criterion. These criterion were used to assess whether tunnelling is the dominant transport process through the MoS_2 barrier.

The Rowell criterion state that: 1) the resistance of the barrier at zero bias should increase slightly when the temperature is decreased; 2) the resistance of the barrier should increase exponentially with increasing thickness of the barrier; and 3) the conductance of the barrier should show a parabolic behaviour with bias voltage and additionally should be fitted using a theoretical model such as those from Brinkmann or Simmons.

We find that the first two criteria are satisfied, but the third is a little harder to confirm. We do indeed observe a non-linear conductance with voltage bias, however we can not fit it using the Brinkmann or Simmons model with realistic values. This is likely due to the fact that these models assume the use of metallic contacts, whose density of states varies only very slowly compared to the electron wave length within the experimental energy range. Since we are using graphene on one side, which has a density of states which is highly energy dependent, these models are likely not valid. Finally we can also *use* the variability of graphene's density of states (through gating) to tune the conductance of the barrier by a few factors.

In chapter 5 we explore the possibility to tune the size and sign of the spin signal. This is a very important parameter for applications, since this gives us a ‘knob’ to manipulate the spin signals. We do this by studying spin accumulation underneath Co contacts in the semiconductor Nb doped $SrTiO_3$. In this system we find that the spin signal increases with increasing bias, but upon cooling down the sign of the spin signal reverses below ~ 130K. Furthermore below 130 K we can use the bias voltage across the junction to tune the sign of the spin signal between positive and negative.

We think that the origin of the sign reversal is due to the highly non-linear behaviour of Nb doped $SrTiO_3$'s dielectric permittivity. Since the permittivity depends on both the temperature as well as the electric field in the Nb doped $SrTiO_3$, this leads to changes in the Schottky barrier profile when either of these parameters are changed. The shape of the Schottky barrier can have a large influence on the polarisation of the tunnelling electrons and can possibly even reverse the polarisation in certain cases.