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Electron spin transport in graphene and carbon nanotubes

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A

Spin transport in a SWNT, Resistor Model

In this appendix we present a resistor model of a single-walled carbon nanotube contacted by four ferromagnetic electrodes. We show that the non-local signal of 20 Ohm which was measured experimentally (chapter 4) corresponds to a contact spin polarization α_F of 25%.

To extract the value of the polarization we developed a resistor model (Fig. A.1). We note that in this resistor model only a few assumptions are needed, as we mainly plug in measured (two-, three-, and four-terminal) resistance values. In this model we assume a spin dependent contact conductance per unit length between the nanotube and the ferromagnetic cobalt contact $\sigma_{i,\eta}=\sigma_{i,0}(1\pm\alpha_F)/2$, $0\leq\alpha_F<1$, where $\eta=\uparrow$ (+) corresponds to the majority spin species and $\eta=\downarrow$ (-) to the minority. We also assume a spin independent resistance ρ per unit length for the carbon nanotube and a spin flip scattering length λ_{sf} being much larger than the contact spacing. The resistor network in Fig. A.1 is constructed as follows. In total we have four contacts between the nanotube and the ferromagnetic leads and each individual contact can be modelled by a second resistor network containing a infinite number of resistor elements $2\rho dx$ and $(\sigma_{i,\eta}dx)^{-1}$. This is depicted in Fig. A.2A for the spin up channel. In this model the chemical potential of the spin species inside the carbon nanotube (underneath the cobalt contact) has the general form:

$$\mu_{i,\eta} = a \exp\left(-\frac{x}{\lambda_{i,\eta}}\right) + b \exp\left(\frac{x}{\lambda_{i,\eta}}\right) \tag{A.1}$$

with $\lambda_{i,\eta} = \sqrt{1/\rho_\eta\sigma_{i,\eta}}$ and $\rho_\eta = 2\rho$. The coefficients a and b are defined by the boundary conditions. The resistor network of a contact is equivalent to a model which contains the resistances $R_{i,\eta}$ and $r_{i,\eta}$ (Fig. A.2B). The two models can be shown to be related by:

$$\rho_\eta\lambda_{i,\eta}\frac{1+\exp\left(\frac{-2L_i}{\lambda_{i,\eta}}\right)}{1-\exp\left(\frac{-2L_i}{\lambda_{i,\eta}}\right)} = R_{i,\eta} + r_{i,\eta} \tag{A.2}$$

$$\rho_\eta\lambda_{i,\eta}\frac{1-\exp\left(\frac{-2L_i}{\lambda_{i,\eta}}\right)}{1+\exp\left(\frac{-2L_i}{\lambda_{i,\eta}}\right)} = r_{i,\eta} + \frac{r_{i,\eta}R_{i,\eta}}{r_{i,\eta}+R_{i,\eta}} \tag{A.3}$$

where L_i is the width of contact F_i. Equation A.2 is derived by taking $I_{(x=L)} = 0$ as a boundary condition ($I_b=0$ and the chemical potentials $\mu_c=0$, $\mu_a \neq 0$ in Fig. A.2B). In this case the total current passes through the series of resistances $R_{i,\eta}$ and $r_{i,\eta}$. For equation A.3 we use the boundary condition $\mu_{\eta(x=L)} = 0$ ($\mu_b=\mu_c=0$, $\mu_a \neq 0$. in Fig. A.2B) and the total current goes through the series resistances r_i and $r_{i,\eta} \parallel R_{i,\eta}$.

From equations A.2 and A.3 we extract $R_{i,\eta}$ and $r_{i,\eta}$:

$$R_{i,\eta} = 2\rho_\eta\lambda_{i,\eta}\frac{\exp\left(\frac{-L}{\lambda_{i,\eta}}\right)}{1-\exp\left(\frac{-2L}{\lambda_{i,\eta}}\right)} \tag{A.4}$$

$$r_{i,\eta} = \rho_\eta\lambda_{i,\eta}\frac{\left(1-\exp\left(\frac{-L}{\lambda_{i,\eta}}\right)\right)^2}{1-\exp\left(\frac{-2L}{\lambda_{i,\eta}}\right)} \tag{A.5}$$
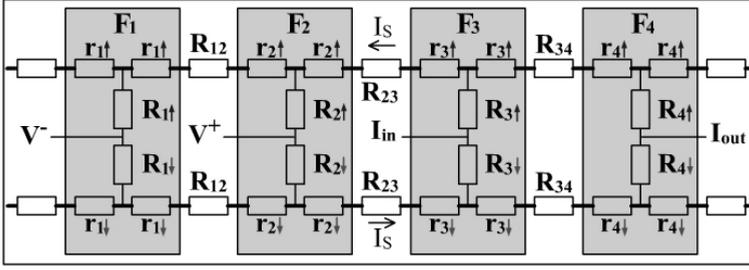
Figure A.1: A resistor model of our system (here, all four electrodes are assumed magnetized in the 'up' direction). The upper half of the resistor network corresponds to the spin up ($\uparrow$) transport channel in the nanotube. The lower half to the spin down ($\downarrow$) channel. The resistance of the carbon nanotube between the cobalt contacts F_1-F_2, F_2-F_3 and F_3-F_4 is equal to $R_{12}/2$, $R_{23}/2$ and $R_{34}/2$, respectively. The contact between the carbon nanotube and ferromagnet F_i (i=1,2,3,4) can be represented by a number of spin-dependent resistances $R_{i,\eta}$ and $r_{i,\eta}$, where $\eta = \uparrow, \downarrow$ denotes spin. Assuming spin up to be the majority species, we have $R_{i,\uparrow} < R_{i,\downarrow}$ and $r_{i,\uparrow} < r_{i,\downarrow}$. Due to the spin-dependent resistances in the current circuit (F_3 and F_4), the charge current I produces a finite spin current I_S. Due to the spin-dependent resistances in the voltage circuit (F_1 and F_2), a non-zero voltage difference $V^+ - V^-$ consequently develops, leading to a finite non-local resistance $R_{non-loc} \equiv (V^+ - V^-)/I$.

A Taylor expansion allows us to write down the resistances in the form $R_{i,\eta}=2R_{i,0}(1\pm\varepsilon_i)$ and $r_{i,\eta}=2r_{i,0}(1\pm\delta_i)$, i=1...4 (for F_1...F_4). Here, the resistances $R_{i,0}$ and $r_{i,0}$ are given by equations A.4 and A.5, respectively, with the following substitutions $\rho_\eta \to 2\rho$ and $\lambda_{i,\eta} \to \lambda_{i,0}$ with $\lambda_{i,0}=\sqrt{\frac{1}{\rho\sigma_{i,0}}}$

Furthermore, ε_i and δ_i are given by:

$$\varepsilon_i \approx \frac{1}{2}(1 + \frac{1}{\tanh\left(\frac{L}{\lambda_{i,0}}\right)} \frac{L}{\lambda_{i,0}})\alpha_F \tag{A.6}$$

$$\delta_i \approx \frac{1}{2}(1 - \frac{1}{\sinh\left(\frac{L}{\lambda_{i,0}}\right)} \frac{L}{\lambda_{i,0}})\alpha_F \tag{A.7}$$

Next step is to calculate the non-local signal expected in the resistor model for the situation in which the current injector F_3 switches from parallel ($\uparrow\uparrow$) to antiparallel ($\downarrow\uparrow$). In this case the spin current I_S which passes through the spin up channel in the carbon nanotube part R_{23} (Fig. A.1) changes by:

$$\Delta I_S = I_S^{\uparrow\uparrow} - I_S^{\downarrow\uparrow} = 4R_3 \frac{\varepsilon_3(r_3 + r_4 + R_4 + \frac{R_{34}}{2}) - \delta_3 r_3}{4R_3(r_3 + r_4 + R_4 + \frac{R_{34}}{2}) + S(r_3 + R_3 + r_4 + R_4 + \frac{R_{34}}{2})}I \tag{A.8}$$
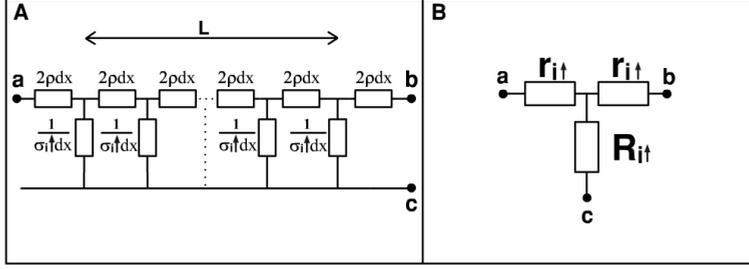
Figure A.2: Resistor models for a single contact F_i between a cobalt electrode and a carbon nanotube for the spin up channel. (A) A resistor network for the contacts. This network contains a series of resistances along the nanotube, each individual resistance has a magnitude $2\rho dx$ (ρ being the resistance of the carbon nanotube per unit length). We assume a spin dependent conductance $\sigma_{i,\eta}$ ($\sigma_{i,\uparrow}$ in this picture) per unit length between the nanotube and the ferromagnetic cobalt contact, giving a resistance equal to $(\sigma_{i,\eta}dx)^{-1}$. This model contains a infinite number of infinitesimal resistances (n$\to \infty$, dx$\to$ 0). (B) Model which is equivalent to A but contains only three resistances which are all spin dependent.

where
$$S = 4(r_3 + \frac{R_{23}}{2} + r_2 + \frac{R_2(r_2 + \frac{R_{12}}{2} + r_1 + R_1)}{R_2 + r_2 + \frac{R_{12}}{2} + r_1 + R_1}) \qquad (A.9)$$

S ($\approx$42.4kΩ) is the equivalent resistance of the resistor network to the left of the nodes in contact F_3. $R_{ij}/2$ is the resistance of the nanotube between the Co leads F_i and F_j and I is the total current injected into the system.

The non-local resistance changes by:

$$\Delta R_{non-loc} = 2\frac{N}{N + R_2}(R_2\varepsilon_2 - \frac{R_2}{N}(r_2\delta_2 + r_1\delta_1 + R_1\varepsilon_1))\frac{\Delta I_S}{I} \qquad (A.10)$$

with N =R_1+r_1+R_{12}/2+r_2

An approximation of the above equation is:

$$\Delta R_{non-loc} = 2\frac{N}{N + R_2}R_2\varepsilon_2\frac{\Delta I_S}{I} \qquad (A.11)$$

using the fact that $\frac{R_2}{N} \approx \frac{1}{60}$

From the 4-terminal, 3-terminal and 2-terminal measurements we extract the values for R_2 and R_3 being 0.5 kΩ and 2.7 kΩ, respectively. To proceed we have to assume a reasonable value for ρ, the resistance of the nanotube per unit of length. We use the value ρ = R_{23}/150nm with R_{23} = 10.3kΩ - (r_2+r_3). By iteration we obtain a value of ρ = 47 Ω/nm. Now we can characterize approximately the contacts F_2 and F_3 ($r_2 \approx$ 1.3 kΩ, $\lambda_{2,0} \approx$ 36nm, $\sigma_{2,0} \approx$ 1.6 10^{-5}/Ωnm and

$r_3 \approx 1.9$ kΩ, $\lambda_{3,0} \approx 80$nm, $\sigma_{3,0} \approx 3.4 \ 10^{-6}/\Omega nm$), extract the values for ε_2 and ε_3 and finally calculate α_F using equation A.11 with $\Delta R^{nonlocal}$=20Ω. We obtain $\alpha_F = 0.26$. Interestingly, from this we can also calculate the size of the spin accumulation which we should expect for the local spin-valve geometry. We obtain a value of 70 Ω which is about 10 times smaller than the one we measured in Fig. 4.2a (see chapter 4) ($\approx$700Ω). From this we conclude that the largest part of the magnetoresistance signal we measure in the local spin-valve experiment is not related to spin accumulation.

The final question is why we do not observe the switching of F_4 and F_1 in the non-local measurements in Fig. 4.3a-c(see chapter 4). From the resistor model we obtain a change in the nonlocal signal by a factor (taking $\varepsilon = \varepsilon_i$ and $\delta = \delta_i$)

$$\frac{\delta r_4 + \varepsilon R_4}{\varepsilon(r_3 + r_4 + R_4 + R_{34}/2) - \delta r_3} \tag{A.12}$$

when F_4 switches from parallel to antiparallel orientation with respect to the current injector F_3. Since $\delta \ll \varepsilon$, $R_4 \approx$0.35 and $r_3 + r_4 + R_4 + R_{34}/2 \approx$11.9 kΩ we obtain a change in the signal by $\approx$3 %, corresponding to a nonlocal signal of $\approx$1Ω. This signal is small and difficult to distinguish from the measurement noise. Similarly, only a small contribution to the non-local signal is expected for a switching in contact F_1. The situation is different for Fig. 4.3d (picture in Chapter 4). In this graph we observe a clear switching of F_4 (or F_1) at |B| $\approx$55 mT as large as 16 % of $\Delta R_{non-loc}$(5 Ω of 30 Ω). This comes from the increase in contact resistances after a thermal annealing step. An increase in R_4 to 2 kΩ, is enough to fit the observed effect.

Finally we emphasize that we use a model in which as few assumptions as possible are needed. Nevertheless, we presume a contact between the carbon nanotube and the cobalt electrode which is homogeneous along its total length. How close this picture is to the real physical nature of the contact is unknown. As discussed above, we observe a factor of 5 difference in resistance between contacts F_2 and F_3. Despite this uncertainty, we expect the actual value of α_F to be comparable with the number we extracted from our model. The reason for this is that we compute α_F from a set of measured resistance values: two-, three-, and four-terminal resistances as well as the non-local magnetoresistance. Therefore, if the contacts are not homogeneous, this is already included in these resistances.

B

EBL recipes

In this appendix I present in detail the recipes for the production of a carbon nanotube (or a graphene) based spintronic device. I also give the recipe for the fabrication of a tin nanowire based electronic device.

B.1 EBL Recipe: fabrication of markers

The fabrication of markers on a substrate is a common step for all types of devices (nanotube, graphene and tin nanowires based). The production goes as follows:

- Spin PMMA 950 K (2% in ethyllactat-n-Butylacetat, AR-P 67902 from ALLRESIST GmbH) at a speed of 2000 rpm and on a Si wafer (500nm SiO_2 layer, highly doped (n-doped, 0.0015-0.007 Ωcm, from Silicon Quest International). Anneal it in the oven at 170°C for 30 minutes.

- Use HF wet etching to remove the oxide from the back site of the wafer.

- Evaporate 5 nm Cr and 100 nm Au on the back site of the wafer at P$<10^{-6}$ mbar. Now the highly doped Si can be used as a gate electrode for our devices.

- Cut the Si wafer in rectangles of approximately 2.5 x 3 cm^2. For this use a diamond cutter.

- Remove contamination from the substrates. For this ultrasonicate the cut pieces in warm (30°C) acetone (Analytical Reagent A.R. from LAB-SCAN) for several minutes. Clean once again but now using acetone at room temperature. Dry each part separately using nitrogen gas.

- Spin PMMA 950 K (2% in ethyllactat-n-Butylacetat, AR-P 679.02 from ALLRESIST GmbH, thickness: 70 nm at 4000 RPM spinning) at a speed of 4000 rpm and anneal it in the oven at 170 ^{o}C for 1 hour.

- Using an electron beam lithography machine (eLiNE Raith) we expose markers and bonding pads on the SiO_2 substrate. The goal is to obtain an area of 1 x 1 cm^2 completely covered with markers (separation between markers $\sim$15 μm). On a 2.5 x 3 cm^2 substrate 4 of those areas can be produced. High electron current is used to minimize exposure time for the bonding pads. Low current (50 pA) is used for the production of the markers.

- Develop in a 1:3 mixture of MIBK:IPA (methylisobutylketone 99.5 % from ACROS ORGANICS, Propan-2-ol Analytical Reagent A.R. from LAB-SCAN) for 2 minutes, clean up in IPA for 20 s. Blow dry using nitrogen gas.

- Remove the PMMA using oxygen plasma etching for 30 seconds. The etching speed of PMMA is about 1 nm/s for the oxygen plasma etching conditions used (RF5S RF Plasma Products Inc, power: 40W, O_2 flow: 9 sccm, pressure: 9 mbar)

- Evaporate about 3 nm of Ti as adhesion layer and on top of it 27 nm of Au (P<10^{-6} mbar). Final result is a pattern containing the gold markers and bonding pads.

- Cut the substrate in 4 pieces. Each piece contains a 1 x 1 cm^2 patterned area.

B.2 Single-walled carbon nanotube device on a SiO$_2$ substrate

Here I present the steps needed for the preparation of a single-walled carbon nanotube spintronic device.

- For the deposition of the SWNTs we use the dielectrophoresis technique. On the 1 x 1 cm^2 gold marked substrate we need to produce one pair of gold electrodes (width 100 nm, length $\sim 500 \mu m$) per 2.5 x 2 mm^2 area. The electrodes are made by EBL in such a way that the one endpoint of each electrode is contacted to bonding pads and the other ends almost touch each other (a gap of ~ 1 μm should made in between). The gap of the electrodes should be positioned at the centrum of each 2.5 x 2 mm^2 area. The use of the dielectrophoresis technique ensures that the nanotubes are deposited close to the electrodes.

- Cut the 1 x 1 cm^2 substrate in 2.5 x 2 mm^2 parts.

- Remove contamination from the substrate. Ultrasonicate for 1 minute in warm acetone (30° C). Dry using nitrogen gas, or spin dry using the spinner.

- Clean up the samples from PMMA remains using oxygen plasma etching.(time: 3 min, power: 40W, O$_2$ flow: 9 sccm, pressure: 9 mbar)

- Glue one sample on one chip carrier and bond the bonding pads (which are connected to the electrodes for the dielectrophoresis technique) to the chip carrier.

- Make a suspension of 1 mg of single-walled nanotubes (SWNTs, 90 % OD 1-2 nm from Nanostructured and Amorphous Materials Inc.) in 100 ml chlorobenzene (99.9% HPLC grade from SIGMA-ALDRICH). Be aware that chlorobenzene is hazardous for health!

- Ultrasonicate at a power 100 W for 10 min. A suspension of 100 ml can be used for several years. Take care that it is stored in a dry place.

- Deposition of SWNTs on the sample using the dielectrophoresis technique. Put a droplet from the suspension on the sample surface. While the droplet is on the sample apply a 1 V ac voltage modulation (1 Mhz) on the two metallic electrodes. Adding a small dc bias ($\sim$10mV) on the ac modulation should give better results. Tune the parameters (time, dc bias voltage) in such a way that the number of SWNT's at the area around the electrodes is higher compared to all other particles (Inspection by atomic force microscopy). Also make sure that we do not obtain too many SWNT's (no more than 1 SWNT per 10 x 10 μm^2)on that area otherwise contacting a single nanotube becomes difficult.

- Select a number of SWNT's using atomic force microscopy (AFM, NanoScope IV from Digital Instruments, Veeco Metrology Group) for the production of a spintronic device. Here we select the nanotubes with thicknesses not larger than 3 nm. An AFM picture should contain the carbon nanotube we would like to contact and at least one gold marker. In this case we can define with high precision the position of a nanotube with respect to the marker.

- Spin PMMA 950 K (2% in ethyllactat-n-Butylacetat) at a speed of 4000 rpm and anneal it in the oven at 170 degrees Celcius for 1 hour.

- Electron beam lithography. The total amount of dose for each contact on the nanotube is 280μC/cm^2 for a 70 nm width contact, 180μC/cm^2 for a 120 nm width contact and 130μC/cm^2 for a 250 nm width contact.

- Develop in a 1:3 mixture of MIBK:IPA for 2 minutes, clean up in IPA for 30 s. Blow dry using nitrogen gas.

- Evaporate 50 nm of cobalt (e-gun evaporation) at a rate of 0.2nm/s and at a pressure of $\sim$5 10^{-7} mbar.

- Lift off is done in warm acetone at a temperature of about 30 ^{o}C.

- Clean up the sample in IPA and blow it dry using nitrogen gas.

- Do not keep the sample too long in open air since the contact properties (resistance, spin injection efficiency) change within hours. Sample degradation is found to be slower in vacuum.

- Bonding. Glue the sample on a chip carrier using varnish from Oxford Instruments (only if the back gate is not used) or silver paste (ACHESON ELECTRODAG 1415M) if the back gate has to be connected to an electrode of the schip carrier. Connection between the samples and the sample

holders is made using ultrasonic wire bonding (wire bonder Autosonic-10 from Buyfield ELECTRONICS). The sample is ready for measurements.

Note

Once a single-walled carbon nanotube is on top of a SiO_2 surface the use of ultrasonication is permitted. The Van der Waals force is so large that the nanotube sticks strongly on the substrate. This is not the case for larger objects, like large bundles of nanotubes, large multiwalled nanotubes and big contamination particles which can be removed by ultrasonication.

B.3   Tin nanowire device on a SiO_2 substrate

For the preparation of a tin nanowire device we follow the next steps:

- Make a Sn nanowire suspension in chlorobenzene (1 mg $/l$)

- Cut the 1 x 1 cm^2 substrate (which contains the gold markers) in 2.5 x 2 mm^2 parts.

- Remove contamination from the substrate. Ultrasonicate for 1 minute in warm acetone (30° C). Dry using nitrogen gas, or spin dry using the spinner.

- Clean up the samples from PMMA remains using oxygen plasma etching. (power: 40W, O_2 flow: 9 sccm, pressure: 9 mbar)

- Deposition of nanowires (from L. Jankovic, *et al.*, *Nano Lett.* **6(6)**, 1131 (2006)) on the SiO_2 surface. We put a droplet of the suspension on a SiO_2 substrate and blow it dry with nitrogen gas. If the surface contains too many nanowires it is advised to dilute the suspension in more solvent.

- Selection of nanowires using optical microscopy and scanning electron microscopy. By optical microscopy we select the best candidates for a device. Use Scanning electron microscopy (SEM) at an acceleration voltage of 5 keV to locate the Sn-CNT's on the SiO_2 surface and to measure their thickness.

- Spin PMMA 950K (4% in ethyllactat-n-Butylacetat, AR-P 679.04 from ALLRESIST GmbH) at 4000 RPM to obtain a 250 nm thick polymer layer and anneal it for at least one hour to remove the solvent.

- Using electron beam lithography we define the positions at which we like to produce the contacts to the nanowire. For a 250 nm PMMA layer and 10 keV EBL exposure the distance between neighboring contacts should not be smaller than 250 nm otherwise the PMMA mask can collapse.

- Argon ion etching in the Varian system (homemade e-gun evaporation and argon etching system). The axis of the argon source should be perpendicular to the sample surface. Use etching times between 13 and 75 seconds (20 Watt power at 800 V acceleration). Etching removes partially the carbon nanotube walls around the tin nanowire. Take care that the etching speed of tin (26 nm/s) is much higher than of graphite (0.4 nm/s).

- Evaporate 1.2 nm of Ti as adhesion layer using the e-beam evaporating system of the Varian system at $1.0 \cdot 10^{-6}$ mbar and 4 nm of Au.

- Evaporate 160 nm of Au by thermal sublimation at $5.0 \cdot 10^{-7}$ mbar.

- Lift off in warm acetone (30 ^{o}C)

- Clean up the sample in IPA and blow it dry using nitrogen gas.

- Do not keep the sample too long in open air since the contact properties change within hours. Sample degradation is found to be slower in vacuum (changes in sample properties become measurable after a couple of weeks).

- Inspect each device on the sample using the scanning electron microscope (JEOL JSM-7000F). Select the devices which do not look damaged and look fine for electronic measurements.

- Bonding. Glue the sample on a chip carrier using varnish from Oxford Instruments. Connection between the samples and the sample holders is made using ultrasonic wire bonding. The sample is ready for measurements.

Note

Once the nanowire is on top of a SiO_2 surface, ultrasonication of the sample results to its removal from its original position. If some contamination particle is found on the sample and it is crucial to remove it, then try to use a more gentle cleaning method.

B.4   Graphene spintronic device on a SiO_2 substrate

For the production of a graphene based spintronic device we need to follow the following steps:

- Oxygen plasma cleaning of the SiO_2 surface containing the 1 x 1 cm^2 gold marked area. (time: 3 minutes, power: 40W, O_2 flow: 9 sccm, pressure: 9 mbar). At this moment it is not known if this cleaning procedure induces trapped charges in the SiO_2. If trapped charges are induced then a better way to clean up the sample is to put it for 1 hour at 250°C in a Ar/H (95 %/5%) environment.

- Deposition of graphene on the SiO_2 surface using the mechanical exfoliation technique. Use high quality Highly Oriented Pyrolytic Graphite (HOPG) from Advanced Materials (quality: Grade B) as basic material for the graphene spintronic devices. In this procedure any type of tape can be used. Glue the tape on the HOPG surface. Pull off the tape from the HOPG. This results to cleaving the HOPG. Press the freshly cleaved surface (which remains on the tape) on the SiO_2 substrate, for this we use a rubber eraser. A rubber eraser is flexible and distributes the pressure on a large part of the substrate, by this we avoid damaging it. Take care that environmental conditions (humidity) can play a role in the sticking behavior of the graphene flakes on the SiO_2 sample. At this moment we do not know what conditions are optimal for this technique.

- Selection of a graphene layer. Use optical microscopy to select graphene layers. Highest contrast for a 500 nm thick SiO_2 layer is obtained using green or blue filters. Make a digital picture of the graphene layers on the SiO_2. Convert this picture to gray scale. Measure the contrast by measuring the difference in light intensity at two positions: on the SiO_2 (I_{SiO_2}) itself and on the graphene flake (I_g). If the contrast C = 100%(I_{SiO_2} - I_g)/I_{SiO_2} is around 8 % then it is a single layer, if it is around 16% it is a double layer. If you are not 100% sure then use Raman spectroscopy to ensure if the layer is indeed grahene.

- Use atomic force microscopy to investigate the homogeneity and thickness of the graphene layer.

- Produce a 0.6 nm Al layer on the sample at UHV conditions and at liquid nitrogen temperature. Oxidize it to produce a 0.8 nm thick Al-oxide layer.

- Electron beam lithography. The total amount of dose for each contact on the nanotube is $280\mu C/cm^2$ for a 70 nm width contact, $180\mu C/cm^2$ for a 120 nm width contact and $130\mu C/cm^2$ for a 250 nm width contact.

- Develop in a 1:3 mixture of MIBK:IPA for 2 minutes, clean up in IPA for 30 s. Blow dry using nitrogen gas.

- Evaporate 50 nm of cobalt (e-gun evaporation) at a rate of 0.2nm/s and at a pressure of $\sim 5 \ 10^{-7}$ mbar.

- Lift off is done in warm acetone at a temperature of about 30 ^{o}C.

- Clean up the sample in IPA and blow it dry using nitrogen gas.

- Do not keep the sample too long in open air since the contact properties change within hours. Sample degradation is found to be slower in vacuum.

- Bonding. Glue the sample on a chip carrier using silver paste (ACHESON ELECTRODAG 1415M). Connection between the samples and the sample holders is made using ultrasonic wire bonding. The sample is ready for measurements.

Note

Once the graphene layer is on top of a SiO_2 surface, ultrasonication of the sample can result to the removal of the graphene from its original position. However in some cases ultrasonication is needed, for example to remove a contamination particle. Tests show that low power ultrasonication ($<<40W$) is enough to remove the contamination without removing the graphene layer.