Towards superconducting spintronics with RuO2 and CrO2 nanowires

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Summary

CrO_2, a half-metal ferromagnet, has shown great promise for superconducting spintronics applications for nearly two decades. Josephson junctions consisting of superconducting (S) contacts on ferromagnetic (F) structures of CrO_2, have been shown to sustain remarkably high supercurrents (of the order of 10^{10} A/m^2) over hundreds of nanometers. However, advancements in this area have been hindered by the metastable nature of CrO_2 at ambient conditions. This results in a poorly controlled S-F interface transparency, which is critical for generation of spin triplets. This thesis explores the potential, challenges and possible solutions to overcome the issues with CrO_2 devices.

After an introduction of the subject matter in Chapter 2, in Chapter 3 we study the growth of high quality epitaxial CrO_2 wires on a TiO_2 substrate using Selective Area method via chemical vapor deposition. We focused on the wires grown along [001] *c*-axis and [010] *b*-axis of the substrate, which are the magnetically easy and hard axis of the wire, respectively. We investigated the morphology of the wires by high-resolution transmission electron microscopy (TEM) and measured their physical properties, in particular magnetoresistance (MR) and the Anomalous Hall Effect (AHE). TEM images showed that the morphology of the wires grown along the two axes is very different. For *c*-axis grown wires (the easy wires), the bulk of the CrO_2 grows epitaxially on the TiO_2 substrate, but some small regions near interface of TiO_2 and CrO_2 have a different crystal orientation than the TiO_2 substrate. The *b*-axis grown wire (the hard wire) has many crystal domains that are all rotated with respect to each other at specific angles. MR data show very sharp switching for the easy axis wires, even for quite large wire widths. In comparison, MR on hard wires reveal a dependence on the width. The AHE is found to be different for *c*-axis wires and *b*-axis wires, contradictory to the bars etched in films by Ar-ion etching. We argue this to be due to a different wire morphology on the nanoscale.

In Chapter 4, we investigate the pinning and depinning of a magnetic domain wall (DW), meaning the finite-volume interface separating two domains with different magnetization direction, in a nanowire, using using a triangular constriction (notch) in two ferromagnets. One is Permalloy (Py), which is used as a reference material, the other is CrO_2, to study a fully spin-polarized material. We designed a high

frequency setup to allow injection of current pulses to assist in depinning of the DW. We find that in general, the notch size affects the critical depinning current density (J_c). While a deep notch (> 50% of the wire width) increases the DW resistance, it also leads to a strong pinning potential for both Py and CrO_2 devices, which makes depinning difficult. Furthermore, and not surprisingly, we observe that CrO_2 devices are more sensitive to the notch depth, with a 5% deeper notch on a wire of similar size resulting in a 2.5 times higher J_c. The depinning critical current densities in CrO_2 are of the order of 10^{12} A/m^2 which is comparable to that of Py devices. It suggests that the high spin polarization does not necessarily lower J_c, contrary to some predictions. Additionally, we measured the domain wall resistance (DWR) and calculated its corresponding resistance-area product (RA_{DW}) in CrO_2. We found the DWR to decrease from 25 mΩ corresponding to RA_{DW} of $1.4 \times 10^{-16}\,\Omega\mathrm{m}^2$ at 10 K to 18.2 mΩ corresponding to RA_{DW} of $0.99 \times 10^{-16}\,\Omega\mathrm{m}^2$ at 80 K, then rise to roughly 23 mΩ at 300 K. The rise in DWR above 80 K could be attributed to spin disorder dominating over spin scattering which may be connected to the appearance of skyrmion-like topological defects in the magnetic state of CrO_2. The values of RA_{DW} are similar to the values reported for nanostructures of (La,Sr)MnO_3, another halfmetallic ferromagnet, and also similar to other conventional ferromagnets like Co and Py, suggesting that full spin polarization does not significantly change the values for DWRs.

In Chapter 5, we used a selective area chemical vapor deposition method to grow nanowires of RuO_2 on TiO_2 substrates, similar to CrO_2 wires growth. Subsequently, we characterize these RuO_2 nanowires through electrical and magnetotransport measurements. The Hall measurements indicate electron-like charge carriers and, interestingly, the charge carrier density decreases with temperature, which is unusual. Then we focus on making Josephson junctions (JJ) by depositing superconducting MoGe on top of RuO_2 nanowires, and making lateral gaps of varying size with a Focused Ion Beam. We find that such devices show a clear critical current, as well as a Fraunhofer-like damped oscillatory response to a magnetic field, for distances between the contacts below 70 nm. Such small distances point to pair breaking effects that are larger than expected for a normal metal. Rather, they are similar to what is found in weak ferromagnets. We estimate the induced singlet coherence length ξ to be about 12 nm, which seems a reasonable number when small magnetic moments are present.

As mentioned, CrO_2 holds great potential for superconducting spintronics but its reduction into insulating Cr_2O_3 at ambient temperatures makes the fabrication of Jospehson junction to show long range proximity effect difficult. In Chapter 6, we discuss the fabrication of CrO_2 junctions with two distinct methods to address this issue. The first method involves removing the Cr_2O_3 layer by standard

Ar-etching of the top surface of CrO_2. We evaluated the impact of etching on interface transparency in many (> 50) devices and observed a very wide spread of interface resistances for the same etch parameters, indicating lack of control and the consistency required to observe the desired effects. The second approach employs a protective layer of RuO_2 which was grown *in situ* with CrO_2 in CVD with customized arrangements. The RuO_2 layer results in low contact resistances of around 1 Ω. However, with our growth method, we found the thickness of RuO_2 to be above 50 nm for a very short growth time of 5 sec. Due to its short coherence length of 12 nm, the considerable thickness of RuO_2 prevents inducing long range proximity-induces supercurrents in these devices. Further optimization of growth settings is needed to attain the target thickness of around 5 nm.