Electronic and magnetic properties of strontium ruthenate thin films

Final Report

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DECLARATION

I have read and understood the College and Department's statements and guidelines concerning plagiarism.

I declare that all material described in this report is all my own work except where explicitly and individually indicated in the text. This includes ideas described in the text, figures and computer programs.

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ABSTRACT

SrRuO_3 is an itinerant ferromagnet with a Curie temperature of ~ 160 K. There has been a sharp increase in scientific interest towards this material and its' intriguing features, such as its magnetic anisotropy, and anomalous transport properties which are incompatible with Drude model. In this study, several thin films of strontium ruthenate were grown and characterised in quality and quantity, employing techniques such as X-ray diffraction and atomic force microscopy. The results are presented and described as crystallographic and topographic findings; finally, based on the findings, adjustments and further study are proposed.

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1. INTRODUCTION

In recent years, a great interest in a newly developing area of science has arisen. The problems of the ever-evolving need for more efficient information storage and computational power may have found their future solution in spintronics - an electronics field that, rather than relying on the current carried by electronic charge, takes advantage of their quantum mechanical property called **spin** (1). Analogous to high and low current in traditional transistors, the binary states of the spin - up and down - can represent the same data. Spintronic devices are highly advantageous compared to conventional technology: they require less power to operate, as spin is measured and manipulated very easily. Moreover, spin is a non-volatile property, so information can be stored without additional power expences. Figures as high as 80% have been achieved in power cutback for MRAM (magnetic random-access memory) (2).

Ferromagnetic thin films are currently studied(3) with intent to be used in spintronic computation and data storage, while also finding applications in semiconductor device fabrication and optical coating (4). In particular, epitaxial thin films and heterostructures of perovskite oxides such as strontium ruthenate (SrRuO_3) have been of great interest to researchers due to its unusual properties. SrRuO_3 is a d-band metal, undergoing ferromagnetic transition at $\approx 160 \text{ K}$ (5). It shares many similarities with other complex oxides but it is quite special: the properties of interest are easy to study in the undoped material, allowing to evade the complications of disorder arising from impurities. For instance, in recent studies, its anomalous transport properties - Fermi liquid behaviour vs bad metal behaviour - have been discussed(6),(7).

Moreover, at very low temperatures SrRuO_3 has been reported to exhibit characteristics of a spin glass type material (8), (9). In a spin glass system, which is a magnetically disordered system, competing magnetic interactions exist, leading to the spins «freezing» below a certain temperature, giving rise to exchange bias phenomena and suggesting low-temperature nanoelectronic applications of SrRuO_3 films (10).

Those and other characteristics of strontium ruthenate make it an attractive topic of study. In this project, we set out to grow several thin films of SrRuO_3 on SrTiO_3 substrates and inspect their physical properties, as well as perform transport measurements.

Chapter 2 begins by laying out the theory behind the study, including a short introduction to how magnetism arises in matter. Background on various properties of SrRuO_3 is given to help to put the findings of the experiments in context. Chapter 3 describes the practical work done in the project and gives details of the measurement techniques as well as presents the results. Results of the project are then summarised in chapter 4 and further study is suggested.

2. BACKGROUND

2.1 Magnetism

... one can still say that quantum mechanics is the key to understanding magnetism. When one enters the first room with this key there are unexpected rooms beyond, but it is always the master key that unlocks each door.

John Hasbrouck van Vleck, 1977.

According to the Oxford English Dictionary, a magnetic field is «a region around a magnetic material or a moving electric charge within which the force of magnetism acts» (11). Magnetic and electric fields can be fully described by a set of Maxwell equations; however, to understand the origin of magnetism and various magnetic phenomena one must turn to the microscopic scale.

The over-simplified, planetary model of the atom consists of a nucleus and one, or more, electrons orbiting around it in a circular manner – essentially creating a current in a loop. According to Faraday’s law (12), a flow of current $\mathbf{J}$ will produce a magnetic field $\mathbf{H}$ that circles the current:

$$\nabla \times \mathbf{H} = \mathbf{J}$$

Eq.1: Ampere’s law, static model (no displacement current)

Consequently, the electron possesses a magnetic moment associated with its orbital motion. Additionally, it has an intrinsic property called the *spin*, for which there is no adequate classical analogy, and which must be considered as a purely quantum concept. The resultant angular momentum is the vector sum of both and is quantised according to the atoms’ angular quantum number l . There are altogether four quantum numbers characterising a given electron – n , l , m and s (13). The Pauli exclusion principle states that in a single instant, no two electrons in an atom can occupy the same quantum state; i.e. if all n , l states are taken, the resultant spin dipole and orbital dipole momentum will be zero due to s and m states cancelling each other out. That is representative of a closed shell configuration, and one can conclude that only atoms with free, or valence, electrons will contribute to the dipole moment (14). This is typical for elements with partially filled **3d**, **4d**, **4f**, **5d** and **5f** shells.

There are several types of behaviour that materials exhibit towards magnetic fields. First of all, all matter is *diamagnetic* to some degree (15) – as a consequence of Lenz’s law. According to the

fact that an induced current will always oppose the change that caused it, the electron spins will align opposite to the external magnetic field so as to cancel it.

To provide the most energetically favourable configuration, electrons tend to align with their spins antiparallel to each other. However, in ferromagnetic materials, **d**- and **f**-shells extend remarkably far from the nucleus and tend to overlap, leading to the electrons attempting to adhere to Pauli principle with regards to both atoms. This results in strong coupling throughout the material, permanent magnetisation, and nonlinear behaviour known as hysteresis.

Hysteresis is the reason behind the itinerant magnetisation of ferromagnetic materials and occurs due to existence of magnetic domains - areas, spontaneously magnetised in one direction. Usually micrometers in scale, domains are separated by Bloch walls and rotate relative to each other when a magnetic field is applied (15). Once the spins of electrons are aligned, the saturation value is attained. As the field is reduced, the restricted motion of the domains through impurities and against each other results in the hysteresis curve not following the same path - when the external field reaches zero, some residual magnetisation stays. If a reverse field is applied, reverse saturation can be reached, as shown in the hysteresis curve in **fig. 2.1**

Fig. 2.1: Hysteresis curve, indicating the saturation magnetisation M_s and the residual magnetisation M_r (16)

2.2 Transition metal oxides

From the metallic TiO to insulating Mn₃O₄, transition metal oxides (TMOs) are one of the most diverse classes of inorganic solids. They have proven useful across several areas of science and technology, such as heterogeneous catalysis, chemical sensing, and optical devices. Some important properties such as superconductivity, magnetoresistance, ferroelectricity and multiferrocity are attributed to those materials (17). TMOs exist in a variety of structures – rock salt, wurtzite, fluorite, spinel, but the structure of interest to this paper is perovskite.

An ideal perovskite model belongs to the $Pm\bar{3}m$ space group and represents a corner-sharing octahedra with a cation atom occupying the position in the centre of eight such octahedra (18). However, the cubic model is often not presentational of the structure, as it undergoes distortion. The general formula for perovskites is ABX₃, where X is often oxygen, although large anions like fluoride or chloride are also possible. A and B ions are widely variable, bringing diversity into the group.

Fig. 2.2, Orthorhombic structure of strontium ruthenate (20)

2.2.1 Strontium ruthenate

Strontium ruthenate, SrRuO₃, is a 4d perovskite. Due to rotation of RuO₆ octahedra, it crystallises in an orthorhombic structure with a space group Pnma, however it may be considered pseudocubic with a lattice constant of 3.93Å (19). **Fig. 2.2** shows the SrRuO₃ structure with strontium atom in the centre and ruthenium ions occupying the corners. In bulk it is a black metal with a relatively high Curie temperature of approximately 160 K, and is a rare example of a 4d ferromagnetic material (5).

Experimental data for SrRuO₃ has reported low-temperature magnetic moments in range 0.8 – 1.6 μ_B / Ru⁴⁺(5), (21); however, according to its electronic configuration $t_{2g}^4 e_g^0$ and the Hund's rule(22), the value should equal 2 μ_B / Ru⁴⁺. It has been argued that the phenomenon correlates with structural distortion of the perovskite (23) as well as with its high degree of magnetocrystalline anisotropy (5), which has been reported to exist up to 10 T along the $(\bar{1}10)$ axis (24).

2.2.2 Strontium titanate

Strontium titanate, or SrTiO_3 , is another material involved in this investigation. Being a perovskite, it shares many similarities with SrRuO_3 . It exists in a pseudocubic structure with lattice constant of $3.905\text{\AA}$ and exhibits 3 phase transitions upon cooling, including tetragonal, orthorhombic, and possibly rhombohedral(25). It is a good insulator with a bandgap of $\approx 3.2\text{ eV}$ at 0 K(26) and its conductive properties depend highly on concentrations of oxygen vacancies, which form due to weak binding of the oxygen and its high mobility(27).

2.3 Epitaxial films

During the course of the project, several thin films were grown epitaxially. In epitaxial growth, the film-substrate bonding energy is minimised when the film lattice constant (t_f) distorts to match that of the substrate (t_s). Assuming the crystal is symmetrical enough, the strain ε can be measured:

$$\varepsilon = \frac{t_s - t_f}{t_s}$$

Eq. 2: Strain (lattice mismatch) measurement

The amount of strain that a specific film can withstand is linearly dependent on its thickness; once over the strain threshold, the film will relax and lose some or all similarity to the substrate(28). Since it affects the crystal as a whole, this type of stress is a *macrostress* and will cause a relative shift in the diffraction peaks.

To relieve the strain, misfit dislocations may form on the surface and their intensity results in the rocking curve broadening. Dislocation density ρ is proportional to B , the rocking curve broadening in radians, and b , the *Burgers vector* (that represents the magnitude of the lattice distortion due to dislocation) in centimetres (29):

$$\rho = \frac{B^2}{4.35b^2}$$

Eq. 3: Dislocation density measurement

Any stress caused by a combination of tensile and compressive forces is a *microstress* and will result in a symmetric peak broadening about the original position(30). It is especially noticeable in samples produced by sputtering; in magnetron sputtering, very low pressure is preferable so that the mean travel path of the atoms ejected from the target is longer so as to achieve a smoother film texture.

Multiple sources can increase overall microstress, including dislocations, defects, and thermal expansions and contractions. The peak broadening has shown the following dependence (31) on residual strain :

$$B = 4\varepsilon \tan \theta$$

Eq. 4: Peak broadening due to microstress

2.4 Transport properties

2.4.1 Electrical resistance

When transport properties of strontium ruthenate were first studied (5) a ferromagnetic transition in resistivity was observed at $T \approx 160$ K (fig. 2.3). Its unusual properties have also been reported, noting that the resistivity does not saturate at temperatures as high as 1000K, despite a very short mean carrier path.

Fig. 2.3: Temperature-dependent resistivity in SRO

It has been further claimed (24) that at high temperatures (>300 K) strontium ruthenate demonstrates so called *bad metal behaviour*. Exhibiting approximately linear dependence on temperature, its resistivity increases until the electrons' mean travel path is less than interatomic distance, which leads to failure of the Drude model of conductivity. It is shown (32) that in bad metals quantum fluctuations of the phase of the superconducting order parameter push the

ferromagnetic transition temperature T_c below its mean-field value. Another study (33) by terahertz time-domain spectroscopy and infrared reflectivity shows the SrRuO_3 conductivity to follow a phenomenological form of an observed power-law dependence on frequency.

The low-temperature behaviour of SrRuO_3 seems to be approximately quadratic (34) and is susceptible to disorder (arising from chemical impurities and structural defects). Disorder seems to affect the absolute minimum resistivity, which might suggest that non-magnetic disorder localises the neighbouring magnetic states. It may also be the cause of the resistivity minima shifting to higher temperatures as the residual resistivity (which indicates degree of disorder) increases.

2.4.2 Magnetoresistance

Magnetoresistance is defined as change in electrical resistance induced by a magnetic field:

$$MR = \frac{\rho(H) - \rho(0)}{\rho(0)} \times 100\%$$

Eq. 5: Magnetoresistance expressed as percentage

Study of anisotropic magnetoresistivity (AMR), or, how magnetoresistance depends on magnetisation direction, is complicated by both magnetocrystalline anisotropy and the fact that in SrRuO_3 films, as opposed to bulk material, AMR depends on the angles of current and magnetization relative to the crystal axes (35). The largest MR value exists typically around the Curie temperature due to rapid change in spin. However, in ruthenium deficient SrRuO_3 the magnetoresistance shows (36) additional major fluctuation towards the lower temperatures. That, together with an identified reduced saturation magnetic moment of $1.322\mu_B / \text{Ru}^{4+}$ at $T = 2 \text{ K}$, predicts spin glass behaviour (8) and possibility of cryptic magnetic ordering at low temperatures.

3. EXPERIMENT

3.1 Sample fabrication

3.1.1 Set-up

For the film deposition process it was decided to use off-axial sputtering technology, which is a physical vapor deposition technique. A schematic illustration of the apparatus is presented in **fig. 3.1**.

Fig. 3.1: Magnetron sputtering chamber (37): 1-Water cooling, 2-Heating resistors, 3-Substrates, 4-Target, 5-Permanent magnet, 6-Shield, 7-Insulator, 8-RF cable, 9-Thermocouple, 10-Gas inlet, 11-Pumping system

This method is based on ejecting atoms from a prepared material and depositing them onto the substrate. This is done by injecting the vacuum chamber with argon gas and applying a strong electric field between the substrate (cathode) and the deposition chamber (anode), thus ionising the gas. Highly energised Ar^+ atoms hit the target, causing the atoms to be ejected and to settle on the substrate. Eventually, as those atoms bond, they form a thin atomic layer. Depending on deposition time, multi-layer films can be created.

Compared to a basic sputtering process, in magnetron sputtering a strong magnetic field (usually 13.56 MHz) is placed around the substrate to increase the process yield. This has two advantages. Firstly, it confines the plasma in one region, preventing it from travelling to the target and causing damage. Secondly, in the presence of a magnetic field, electrons released via ionisation travel

further, making them more likely to hit an argon atom and cause further ionisation, thus improving the efficiency of the process (38).

Overall, magnetron sputtering deposition is a highly advantageous method in growing oxide samples.

3.1.2 Film growth

The samples were prepared as follows: previously cut (001) STO substrates sized approximately 4x4x1 mm were bathed in an ultrasonic cleaner using acetone and ethanol solutions. Then, the bottom side of the substrate was covered in silver paste and heated to 180 C° for 40 minutes. Once the sample was fixed on the plate and placed in the sputtering chamber, the growth process would go ahead at conditions listed in **fig. 3.2**. On completion of growth and cooling down the sample would be ready for inspection.

Sample	T(°C)	Power (W)	O ₂ (ccpm)	Ar (ccpm)	p (mTorr)	t (min)
E16001	640	60	3	60	100	240
E16002	640	60	3	60	120	240
E16003	640	60	3	60	140	240
E16004	640	60	3	60	160	240

Fig. 3.2: Sample growth properties

3.2 X-ray diffraction

3.2.1 Set-up

HRXRD, or High-resolution X-ray diffraction, is a non-destructive technique used to analyse epitaxial thin films and determine properties such as their composition, thickness, strain, and lattice parameters. In this study, a Rigaku SmartLab® diffractometer (approximate schematic of chamber in **fig. 3.3**) was used. It is featured with a high power theta-theta goniometer for horizontal sample mounting and is accompanied by a data collection and analysis software. In this subsection the procedure is described for all samples consecutively the findings, which are to be discussed in chapter 4, are illustrated.

Once the diffractometer was turned on, set-up proceeded as follows: the water valve was opened and the cooling water supply was turned on. When the temperature had settled steadily on 20 C°, the operating software was launched and X-ray ageing began. The software selected the right ageing time and made sure the power was increased to the maximum value of 9 kW (operating at 45 kV and 200 mA). During the aging, an entry was made into the logbook and samples were prepared for analysis by sequentially cleaning them in ethanol and acetone solutions using a

sonic heater. Finally, the desired experiment options were set in the software – a high-resolution Ge(002) Bragg-Brentano scan, where care was taken to follow the instructions and perform the optical alignment of the machine parts.

Fig. 3.3: An X-ray diffractometer chamber

The theory behind XRD is fairly simple: since X-ray spectrum wavelengths are comparable in scale to atomic spacing, beams scatter coherently off atoms and produce a diffraction pattern dictated by the Bragg condition (39):

$$n\lambda = 2d_{hkl} \sin \theta$$

Eq. 6: The Bragg equation

Where n is order of diffraction (an integer number), λ is the X-ray wavelength, d_{hkl} is the lattice spacing and θ is the incident angle. For this experiment, the characteristic X-ray wavelength is $\lambda = 1.5406\text{\AA}$ and lattice spacing is $d_{hkl} = 3.905\text{\AA}$; we can therefore calculate the first- and second-order angles of observable diffraction:

$$2\theta_{001} = 23.24^\circ \quad 2\theta_{002} = 46.47^\circ$$

Eq. 7, 8: First- and second-order diffraction angles

3.2.2 Scans

The **first** scan was done to make sure the sample was mounted correctly. The **Z** ordinate was set to the one used before, since it was likely that the new **Z** would be very close to it, and a scan was performed 1 millimeter forward and backward. The resolution needs to be high to ensure a precise measurement. Once the graph was ready, the mid-point value was calculated and was set as the new **Z**.

Next, the actual value of ω was determined by performing an omega scan around the theoretical value calculated in eq. or eq. ; that value was assigned to ω .

To work out the positions of a diffraction peak, an $\omega - 2\theta$ scan was carried out. It differs from the $\theta - 2\theta$ scans in that the incident angle varies not by $\omega(\theta) = \frac{1}{2}(2\theta)$ but by $\Delta\omega = \frac{1}{2}\Delta(2\theta)$, so that the diffraction can be observed in a way that is dependent on the tilt of the sample. **Fig. 3.4** shows an $\omega - 2\theta$ scan for (002) peaks in sample 2. Note the characteristic fringes that are arranged periodically on both sides of each peak – those appear in thin films due to interference of X-rays reflected from the film surface and the film-substrate interface.

Fig. 3.4: Omega - 2-theta scan, e16002, (002)

Once all peaks had been identified, omega scans were done for each to obtain **rocking curves**. **Fig. 3.5** shows the rocking curves for (001) SRO and STO peaks in sample 1. The broadening is measured at FWHM (full width at half maximum) and is quite severe, indicating dislocations and surface defects of the sample. The effect is also seen in the (002) rocking curves (**fig. 3.6**)

Fig. 3.5: Rocking curves (omega scans), e16001, (001)

Fig. 3.6: Rocking curves (omega scans), e16001, (002)

3.2.3 Simulation

A Matlab simulation was used to further analyse the XRD results. The code (40), which was written by a department member and is highly customisable, is well-suited to study thin films and film superlattices.

The program was used to simulate the experiment that had been done in the laboratory. By comparing the results and adjusting the variables, it was possible to approximate the film thicknesses and the lattice strain.

- e16001: 150 SRO layers, lattice constant strained to 3.955Å. Thickness is ≈ 59.3 nm.

Fig. 3.6: Theta - 2-theta simulation, e16001, (001)

- e16002: 130 SRO layers, lattice constant strained to 3.978. Thickness is ≈ 51.7 nm.

Fig. 3.7: Theta - 2-theta simulation, e16002, (002)

- e16003: 120 SRO layers, lattice constant strained to $3.975\text{\AA}$. Thickness is $\approx 47.7\text{ nm}$.

Fig. 3.8: Theta - 2-theta simulation, e16003, (001)

- e16004: 100 SRO layers, lattice constant strained to $3.985\text{\AA}$. Thickness is $\approx 39.8\text{ nm}$.

Fig. 3.9: Theta - 2-theta simulation, e16004, (001)

3.3 Atomic force microscopy

Atomic force microscopy (AFM) is an imaging method that allows 3D imaging of practically any surface in air, liquid, and vacuum(41). Data collection starts as a small cantilever, usually made of silicon or silicon nitride, is brought close to the surface of the sample and the sum of forces arising between the sample and the cantilever tip (electrostatic, magnetic, and van der Waals) cause it to deflect. The deflection is measured and a force-distance curve is plotted to create an image of the sample surface. To avoid damage to the tip which might come about in case of its direct contact with the surface, a precaution is used in dynamic force microscopy. Excited by a piezo element, the cantilever vibrates at a given frequency; when it experiences a deflective force, its amplitude decreases and is detected by a laser beam, which is used to work out the surface topology (42).

To outline the samples' surfaces, a NanoSurf easyScan 2® machine was used, with a cantilever resolution of 10 μm (fig. 3.10).

Fig. 3.10 Nanosurf easyScan 2 setup (42)

Data collection was implemented as follows: to start the experiment, the controller and the software were initialised and set to desirable options. The sample was carefully mounted on the stage and the microscope camera was used to confirm that the cantilever tip was directly above the sample surface.

Before starting the data acquisition, a frequency sweep was performed to make sure the cantilever was at the resonance frequency, which is approximately 152.6 kHz (fig. 3.11). The sample was approached extremely carefully as any mechanical impact could seriously damage the cantilever; once the approach was complete, the scan could be started.

After any calibrations to get the best quality image, the data was saved and the mean roughness of the sample was noted down. This was repeated for the next samples.

AFM results are shown in **fig. 3.12-15**, in form of 2D colour maps where lighter regions represent the peaks and darker regions represent the valleys. 3D mapping is also possible (**fig. 3.16**)

Fig. 3.11: Fine frequency sweep

Fig. 3.12: Surface image, e16001

Fig. 3.13: Surface image, e16002

Fig. 3.14: Surface image, e16003

Fig. 3.15: Surface image, e16004

Fig. 3.16: 3D surface image, e16001

Mean roughness values of the films are presented in the chart below:

Fig. 3.17: Mean roughness for each sample

3.4 Transport measurements

To obtain the transport measurements it was decided that it would be best to use a 4K liquid helium cryostat. The samples were to be fixed permanently to a printed circuit board (PCB); so it was of high importance to ensure all other measurements were finished before this stage of research.

A 7-pin PCB was designed in DipTrace® software (**fig. 3.18**). Pins 6 and 7 were to let constant current through the 4 samples connected in series. Pins 1 to 5 were to measure the voltage drop across a particular sample. The board was printed out, wires soldered to it and samples glued in respective places between contacts with low-temperature adhesive (**fig. 3.19**).

Fig. 3.18: Printed circuit board prototype

Fig. 3.19: Printed circuit board with samples and connections

Fig. 3.20: 4K Helium cryostat in London Centre for Nanotechnology

The structure was then placed in the sample chamber (bottom of **fig. 3.20**) and connected to the outer wiring, ensuring all pins were placed correctly (**fig. 3.18**). A current of $0.1\mu\text{A}$ was let through the set-up via pins 6 and 7, and voltages across each sample were measured with 4 separate voltmeters. Once the cooling process had begun, a computer program started to record the data once every second. Temperature was monitored by an external controller.

An extract from the digital output is below:

t (s)	T (K)	V4(μV)	V3(μV)	V2(μV)	V1(μV)
3707	138.9788	12.539	10.576	10.326	14.692
3708	138.9451	12.547	10.565	10.326	14.692
3709	138.9093	12.547	10.565	10.326	14.692
3710	138.8743	12.547	10.565	10.326	14.692

Once the approximately 2-hour cycle was complete, all data were analysed. Firstly, a graph of cooling rate was plotted (**fig. 3.21**), which shows two stages of cooling, with the rapid stage beginning at around 35 K. Once the temperature reached $\approx 4.5\text{K}$, it oscillated slightly but would not go lower than $\approx 4.4\text{ K}$. This is due to energy that needs to be supplied to the cryostat to keep it at the lowest temperature possible.

Next, it was possible to look at temperature-dependent transport properties. In **fig. 3.22**, the samples' resistances are plotted against the temperature. Sample 4 immediately stands out, clearly exhibiting a ferromagnetic transition around 150 K, in agreement with results of studies referenced in chapter 2. Furthermore, the respective resistivities of samples are compared (**fig. 3.23**), which again confirms that sample 4 is of the best quality among all, showing a sharp 150 K transition and a higher decrease rate compared to samples 2 and 3. Sample 1 seems to be an outlier, and the cause of its poorer quality will be discussed later.

Fig. 3.21: Cryostat cooling rate

Fig. 3.22: Temperature-dependent resistances of samples

Fig. 3.23: Temperature-dependent resistivities of samples

4. DISCUSSION

Overall, the XRD and the AFM results indicate good quality of the films – the peaks are clearly traced in the diffraction results, and topography images of the surface confirm fairly low roughness (**fig. 3. 17, 4.1**). Roughness of a film affects multiple properties, including its conductivity and reflectivity, which are vital for SRO thin film applications.

Fig 4.1: Lattice strain and pressure in percentage for samples 1 to 4

However, the broad rocking curves for some samples indicate large amounts of dislocations and defects on the surface. It will undoubtedly affect the sample conductivity and as seen in **fig. 3.22-23**, sample 1 fails to illustrate the ferromagnetic transition effectively; however we see it clearly in sample 4, which shows a rapid decline in resistivity under ~ 150 K.

A further study of strontium ruthenate transport properties, with thinner and smoother films, would be beneficial. It would be interesting to look into its less known behaviours, such as the anomalous Hall voltage and the metal-insulator transition at temperatures close to 0 K.

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APPENDIX A: FULL XRD DATA

Fig. A.1: Omega - 2-theta scan, c16001, (001)

Fig. A.2: Omega - 2-theta scan, c16001, (002)

Fig. A.3: Omega - 2-theta scan, c16002, (001)

Fig. A.3: Omega - 2-theta scan, c16003, (001)

Fig. A.5: Omega - 2-theta scan, c16003, (002)

Fig. A.6: Omega - 2-theta scan, c16004, (001)

Fig. A.7: Omega - 2-theta scan, e16004, (002)

Fig. A.8: Omega scan (rocking curve), e16002, SRO (001)

Fig. A.9: Omega scan (rocking curve), e16002, STO (001)

Fig. A.10: Omega scan (rocking curve), e16003, SRO (left) and STO (right) (001)

Fig. A.11: Omega scan (rocking curve), e16003, SRO (left) and STO (right) (002)

Fig. A.12: Omega scan (rocking curve), e16004, SRO (left) and STO (right) (001)

Fig. A.13: Omega scan (rocking curve), e16003, SRO (left) and STO (right) (002)