Noise and electric field characterization of irradiated SrTiO$_3$

R. Guerrero$^{1,3,a}$, A. Solignac$^1$, M. Pannetier-Lecoeur$^1$, C. Fermon$^1$, P. Auban-Senzier$^2$, L. Lemberger$^2$, C. Pasquier$^2$, Y. Apertet$^3$, Ph. Lecoeur$^3$

$^1$ DSM/IRAMIS/SPEC- CNRS URA 2464, CEA Saclay, 91191 Gif sur Yvette Cedex France

$^2$ Laboratoire de Physique des Solides, Université Paris-Sud, CNRS, 91405 Orsay, France

$^3$ Institut d’Electronique Fondamentale, Université Paris-Sud, CNRS, 91405 Orsay, France

$^a$ Corresponding author: Ruben.guerrero@cea.fr

Abstract. SrTiO$_3$ (STO) is a band insulator with a perovskite crystallographic structure, widely used as substrate for the deposition of other perovskite materials, for instance manganites or cuprates. STO surface becomes conductive under Ar$^+$ ion irradiation, exhibiting similar properties to STO/LaAlO$_3$ interface or bulk reduced STO. We report the transport and noise properties as function of temperature and electric field of Ar$^+$ irradiated STO exhibiting at its surface a high mobility electron gas. This system shows metallic properties with low charge densities allowing mobility measurements. The low frequency 1/f noise presents an unexpected linear dependence with the mobility which cannot be described by the usual Hooge model. The effect of the electric field at a given temperature on the mobility, magnetoresistance and low frequency noise is also presented.

1. Introduction

Oxide based electronics is a new emergent field that shows a great variety of new applications, ranging from magnetism to high temperature superconductivity. Among them SrTiO$_3$ (STO) is one of the most interesting systems. It is a band insulator with a perovskite crystallographic structure, which has been widely used as substrate for other perovskites, for example manganites or high critical temperature superconductors (cuprates). Recently, field effect transistors have been developed based on this material [1-4]. Due to the possibility of being metallic, while it is transparent, it has been proposed as an interesting component for optoelectronic devices [5]. Besides that, the possibility of controlling the growing processes of STO and its surface has enabled the development of a high mobility electron gas in the interface of STO and LaAlO$_3$ (LAO) [6]. Even if the origin of this phenomenon is unclear [7-9], the properties of the interface are very interesting and promising for new potential applications.

In this work we present results on transport on Ar$^+$ irradiated STO. Under Ar$^+$ irradiation a nanometric layer of the material becomes conductive [5,10,11] exhibiting similar properties than STO/LAO interfaces [6] and bulk reduced STO [12-15]. Although those materials have been extensively studied, the irradiated STO properties have been poorly studied. Here we present in a first part general characterization using DC transport noise measurements. Secondly we study the effect of
an electric field applied through a backgate in the transport characteristics. Finally we investigate the magnetotransport in the studied samples.

2. Sample preparation and experimental techniques.

Samples were prepared using commercial STO substrates from Crystec, with dimensions 10mmx10mmx0.5mm and oriented along the (100) direction. On top of the substrate we defined several lines of different widths: 10, 20, 50 and 200µm using standard photo-lithography. After that, we irradiated the substrate during 15 minutes in order to define lines of conductive STO. The irradiation was done using an Ar plasma accelerated by 0.7kV, inducing a current of 8mA incident on the surface. In order to protect the samples from a long term re-oxygenation we covered the irradiated surface with a 25nm thick layer of Si₃N₄. This procedure maintains the properties of the samples during months when they are stocked in ambient conditions. Finally we deposited contacts on the top of the structure using a sputtering machine. Six contacts were deposited: 2 for current, 2 for longitudinal voltage and other two for Hall effect measurements. The contacts were composed of Ta(10nm)/Cu(150 nm)/Ta(10 nm). All the samples were contacted to a sample holder through Al wire bonding in order to perform their characterization.

![Graphs](image)

**Figure 1**: (a): Dependence on temperature of the sheet resistance of one of the studied samples; there is no indication of any superconducting transition down to 30mK. (b): Hall mobility of the irradiated film, the metallic like temperature dependence shown in a) is due to the increased mobility. The number of carriers (c) is diminished at low temperatures. This behavior is related to the thermally activated character of the generation of carriers. (d): Normalized noise as a function of the temperature.

Transport measurements were carried out in a He cryostat. A temperature controller allows us stabilizing the temperature between 200K and 4K. Resistance measurements were realized using the
four probes method. We use a Keithley 6221 current source to bias our samples, the voltage was detected using a DC amplifier and an acquisition card. Hall effect measurements were done in a magnetic field up to 1T using the same current source and a differential amplifier. In order to perform the noise measurement we used an AC coupled low noise amplifier and a battery fed current source. We also performed high field measurement measurements (up to 8T) in a dilution cryostat with a base temperature of 30mK. In this case a lock-amplifier was used to measure the resistance of the sample and the magnetic field was measured using a calibrated Hall probe.

3. Experimental results

3.1. Transport measurements and noise

In the patterned samples we have performed resistance measurements as function of the temperature. The dependence in all the studied samples was metallic-like, this behavior being attributed to the increase of the mobility when the sample temperature was diminished, instead of due to the increment of the number of carriers. This data are displayed in Fig. 1, panels a,b and c.

Reduced bulk STO exhibit a superconducting transition at temperatures below 0.5K. In this material the critical temperature \( T_C \) depends on the density of carrier. \( T_C \) is maximal at about \( 10^{20} \) cm\(^{-3}\) and it extend about one order of magnitude above and below that value. Due to the pairing mechanism \( T_C \) diminishes for carrier densities one order of magnitude above and below the maximum one [16]. In our samples we have estimated the bulk carrier density in about \( 10^{20} \) cm\(^{-3}\). To obtain such a data we used the irradiation parameters to estimate the thickness of our conducting layer, which yields a thickness of about 10nm. Therefore we would expect to observe a superconducting transition at about 0.5K. Nevertheless, such a transition is not observed down to 30mK. In our opinion the disorder induced during the irradiation process might destroy the superconductivity. We cannot rule out the possibility that the extension of the conductive region is in the µm range as it is proposed in ref. [17]. In this case the volume density of carriers would be smaller than the minimum density required to observe a superconducting transition.

The noise in the studied samples is mainly of 1/f type. We have not found any generation-recombination noise, which usually exhibits a Lorentzian like dependence on the frequency. In order to characterize the noise in each temperature we use the parameter \( \alpha \), defined as:

\[
\alpha = \frac{S_V(f)A}{V^2}
\]

Where \( V \) is the voltage in the sample and \( A \) is the corresponding area. This parameter normalizes the 1/f noise and allows us comparing the noise at different temperatures. Interestingly the noise increases when the temperature decreases and is directly correlated with the mobility. A full discussion about this behavior has been published in [18].

3.2. Effect of the electric field

In order to test further the low temperature regime we apply an electric field in the samples. We do that by placing a counter electrode in our substrates that allow us applying a voltage up to 350V. In
figure 2 we present the dependence of the resistance (a), the mobility (b) and the surface density of carriers (inset) as a function of the backgate voltage ($V_{\text{backgate}}$).

![Graphs of figure 2](image)

**Figure 2:** Dependence on the backgate voltage of the resistance (a) and the mobility (b). The resistance graph shows several consecutive sweeps, the arrows show the direction of the sweep. The non reproducibility of the resistance could be explained by diffusion and pinning of oxygen vacancies, thus making the effect of applied electric field non reversible. Graph b and the inset shows the Hall mobility and surface density of carriers obtained in one sweep.

Firstly we can observe that the resistance of the conducting layer does not return back to the 0V value after several sweeps. This effect has been already reported in STO [2] and it is attributed to the movement of oxygen vacancies in the substrate/conducting layer system, the movement changes locally the electric field felt by the conduction electrons, thus changing the resistance in a different way each sweep of the electric field. In the figure 2a it is clear that the resistance of the samples decreases as $V_{\text{backgate}}$ increases. This change in resistance is due to the increase in the mobility, Fig. 2b, whereas the number of carriers is slightly modified, inset in Fig 2b.

3.3. Magnetoresistance

At low temperatures the samples exhibit a positive magnetoresistance (MR) when the magnetic field is applied perpendicular to the substrate. An example of the observed perpendicular MR is shown in Fig. 3a. At low magnetic field ($H<1T$) the dependence of MR with the magnetic field is proportional to $\mu^2 H^2$, which is the usual behavior in metals when the product $\omega_c \tau \ll 1$ [19], where $\omega_c$ is the cyclotron frequency and $\tau$ is the relaxation time. This has been tested using the Kohler law, which is followed down to 5K. At high magnetic fields the behavior of the magnetoresistance depends on the material and the crystalline orientation. In our case the magnetoresistance seems to saturate into a linear regime. Typically this effect happens when the number of electrons (holes) is much bigger than the number of holes (electrons) [19].

In the studied samples we can also notice that we do not observe Shubnikov-de Haas (SdH) oscillations, like it has been been reported in bulk reduced and Nb doped STO [20], or in STO/LAO systems [21] and high mobility STO [22]. Our samples do not exhibit such a behavior down to
temperatures of 100mK as can be seen on Fig. 3a. This oscillations in the resistance as function of the magnetic field are due to the splitting of the Landau levels, given by $\delta E = \hbar \omega_c$. In order to be observable at reasonably low magnetic fields the temperature should be small and the product $\omega_c \tau >> 1$, those conditions disable the smearing of the different levels due to the thermal energy and the disorder, respectively. In our case seems that at 8T the smearing of the levels due to the collisions is

![Graphs](image)

**Figure 3:** Magnetoresistance of a STO irradiated sample in perpendicular magnetic field at 100mK. At low field (b) the parabolic behavior is evident while at $H>1T$ (a) the MR trends to a linear behavior. In order to increase the mobility we applied an electric field by using the backgate. As we increase the mobility the magnetoresistance increases, however at high field the SdH oscillations still are not visible.

big enough to attenuate the oscillations. Considering that the mobility in sample shown is about $2500cm^2/Vs$, at 8T the factor $\omega_c \tau \approx 1.8$ which is not enough to observe the SdH oscillations. An applied magnetic field up to 25T would be then necessary to see the expected behavior. The increase of the mobility by applying 350V in the backgate is still not enough to observe such phenomenon.

4. Conclusions

In conclusion we have studied in detail the transport in irradiated STO. Changes in the resistance are improved by the enhancement of the mobility rather than the generation of carriers, both as function of the temperature and the use of a backgate. The magnetotransport measurements display a behaviour that is proportional to $\mu^2 H^2$ at low field, whereas at high field it trends to a linear regime. SdH oscillations have not been observed in fields up to 8T, probably due to the relatively low mobility.
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