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Transport properties of $La_{0.5}Ca_{0.5}MnO_3$, a highly disordered charge–density wave system

S. Cox [a,*], J. Singleton [a], R.D. McDonald [a], A. Migliori [a], P.B. Littlewood [b]

[a] *National High Magnetic Field Laboratory, Los Alamos National Laboratory, MS-E536, Los Alamos, NM 87545, USA*
[b] *Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*

ABSTRACT

Differential resistivity and broadband noise measurements of $La_{0.5}Ca_{0.5}MnO_3$ reveal behaviour typical of a highly disordered charge–density wave system. In addition, the differential resistivity measurements reveal a large hysteresis, with the upper part of the hysteresis curve only appearing when the sample has been annealed by heating to room temperature and then cooling. The variation of the area of the hysteresis loop with temperature is found to be governed by a power law.

Charge–density wave (CDW) systems have long been known for their dramatic resistance properties [1]. More recently, the discovery of CDW type behaviour in cuprate [2,3] and manganite [4] systems has indicated that stripe phases which were attributed to strong charge localisation at atomic sites can sometimes be more accurately described by a CDW type model. Stripe phases are currently of great interest since the role of the stripe phase in the high temperature superconductivity mechanism in the cuprates is currently unknown.

The signatures of CDW sliding that can be observed in materials such as the cuprates and manganites are somewhat different than those observed in traditional CDW systems, due to the extremely high level of disorder. The short disorder lengthscale (i.e. an impurity spacing rather than a coherence lengthscale) in the manganites of around 25 Å [5] indicates that the disorder may be created by the mismatch between the two varieties of *A*-site cation. Because of this high level of disorder, it is not possible to observe a narrow band noise signal.

The observation of CDW sliding also raises the question: how strong is the electron–phonon coupling in these materials? If the electron–phonon coupling is weak, as expected in a sliding CDW system, it is difficult to explain the fact that these materials are insulating at high temperatures. One possible explanation is that the stripe phase is not fully destroyed at the transition; it still persists over short lengthscales [6,7]. Alternatively, if electron–phonon coupling is strong, sliding would only be observed if the coupling is frustrated, possibly by short range strain fields produced by a high level of disorder [8]. In this case disorder plays a key role in producing the CDW-type behaviour, since in its absence the system would manifest strong electron–phonon coupling, and it would not be possible to depin the superstructure.

Although the effect of very low levels of disorder on CDW systems has been studied [9,10], the equivalent experiments on highly disordered CDWs were lacking. Here we investigate the properties of the stripe phase of $La_{0.5}Ca_{0.5}MnO_3$, a highly disordered CDW. We find that, as would be expected, the high level of disorder leads to numerous pinning–depinning events, and thus a high level of broadband noise (see Fig. 1). However, we also observe a hysteresis effect which manifests as a difference between the first time the CDW is depinned after cooling, and subsequent electric field sweeps. Although this type of behaviour is expected in a CDW system, the magnitude of the effect is exceptionally large. The area enclosed by the hysteresis loop appears to follow a scaling behaviour with temperature.

An 80 nm thick $La_{0.5}Ca_{0.5}MnO_3$ thin film was grown on a $NdGaO_3$ substrate as described in Ref. [11] to produce a film with a uniaxial stripe phase which becomes detectable at 190 K and reaches a stable wavevector value at 90 K [11]. The superstructure was identified via superlattice reflections in a transmission electron microscopy selected area diffraction pattern [4]. For the resistance measurements, gold wires were attached to the thin film sample using graphite paint. Resistance measurements were carried out in two configurations: four point measurements for the resistivity and two point measurements for the noise measurements. The differential resistance measurements were carried out using a 17 Hz AC current plus a DC bias. The AC component of the voltage (proportional to the differential resistance) was measured using a lock-in amplifier.

The variation of the resistivity of $La_{0.5}Ca_{0.5}MnO_3$ with temperature showed no clear feature at the expected ordering temperature, as is seen in other prototypical CDW systems which have been doped with impurities [12–14]. This is interpreted as a large density of impurities, or a high level of disorder (as expected

* Corresponding author. Current address: Randall Division of Cell and Molecular Biophysics, King's College, London SE1 1UL, UK.
E-mail address: susan.cox@kcl.ac.uk (S. Cox).

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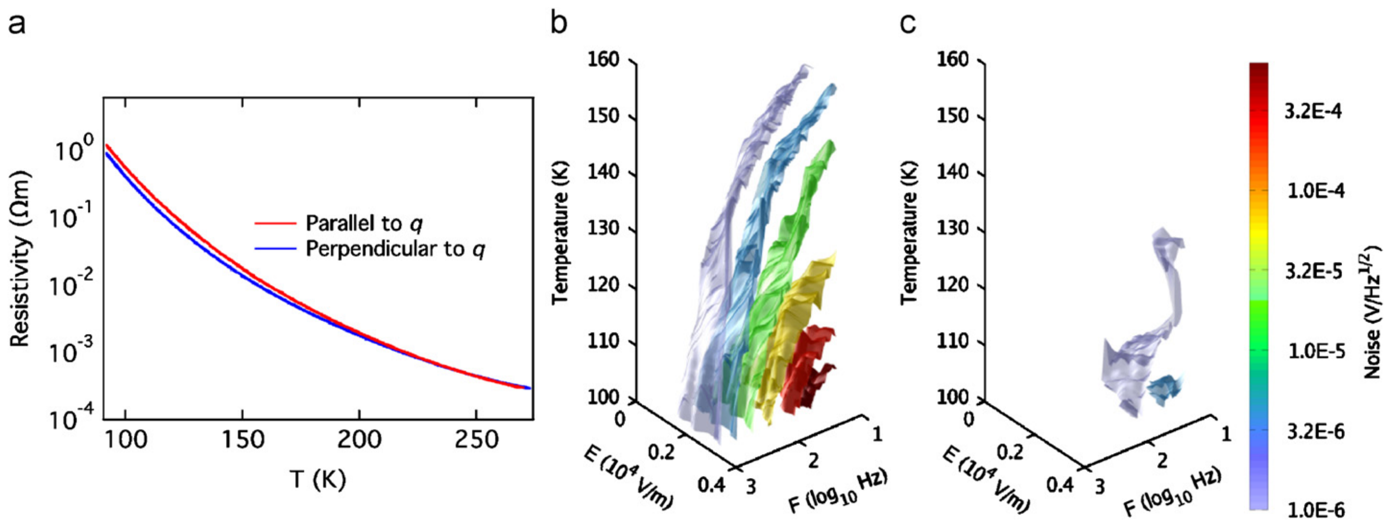

Fig. 1. (a) Variation of differential resistivity with temperature. (b, c) Variation of the magnitude of the broadband noise with temperature, frequency and applied electric field. (b) current passed parallel to the superstructure wavevector, (c) current passed perpendicular to the superstructure wavevector. The noise value is taken at 300 Hz and 10 V. The coloured surfaces are noise equipotentials, with the magnitude of the noise at the equipotentials indicated by the colour scale on the right.

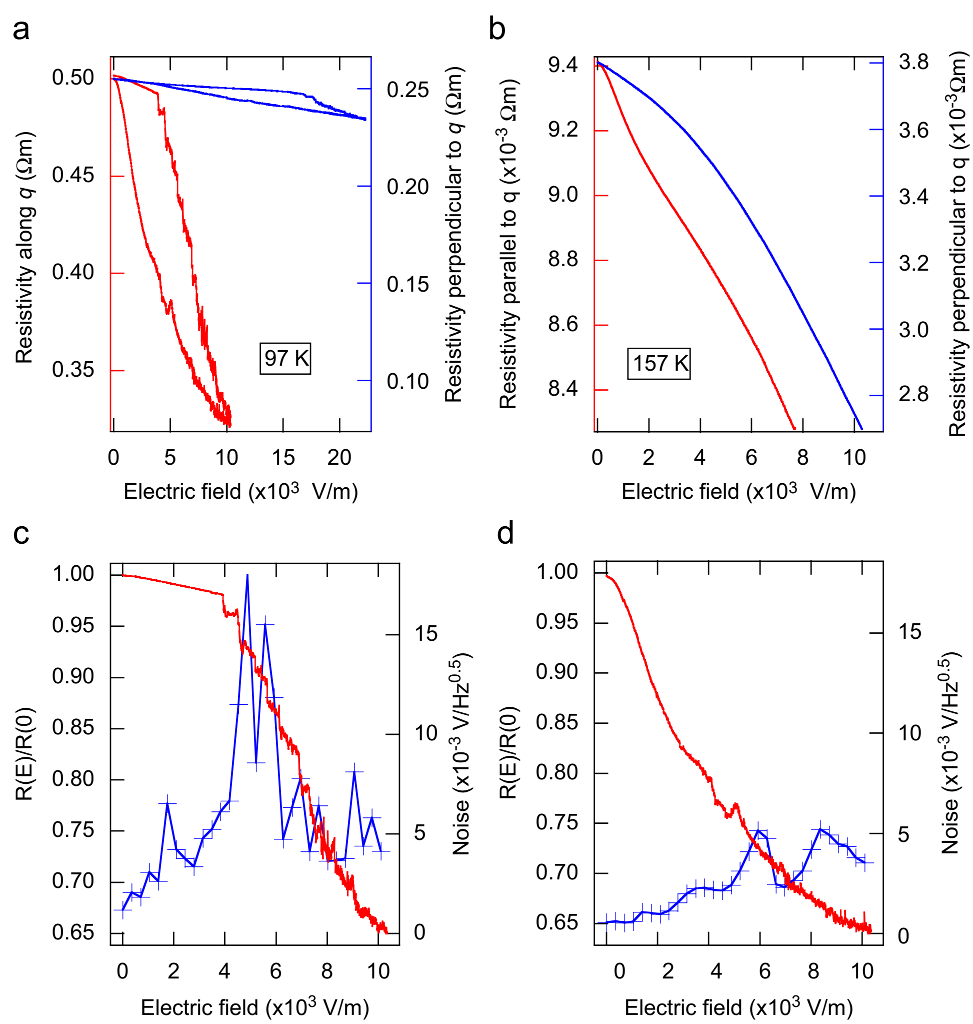

Fig. 2. (a, b) Variation of the differential resistance with current at different temperatures and with the current passed parallel and perpendicular to the superstructure. Differential resistivity of $La_{0.5}Ca_{0.5}MnO_3$ versus DC bias with bias applied in the *a* (red) and *c* (blue) directions at various temperatures. In each case the upper curve is the differential resistivity obtained after cycling the temperature to 300 K, and the lower curve is the path followed by subsequent bias sweeps. (a) is data taken at 107 K and (b) is data taken at 156 K. (c) Resistivity displayed as $R(E)/R(0)$ (red), and noise signal at 300 Hz (blue) for the first time current is passed parallel to the superstructure after cooling from 300 K. (d) Resistivity (red) and noise (blue) for the second time current is passed (after Ref. [4]).

from the heat capacity data [5]), blurring the transition so as to make it unobservable. $La_{0.5}Ca_{0.5}MnO_3$ is an insulator at room temperature, as is found in cuprate ladder compounds which also exhibit sliding density wave behaviour [2,3] below $T \simeq 200$ K. $La_{0.5}Ca_{0.5}MnO_3$ shows similar activated behaviour of the resistivity with temperature to the cuprate ladder compounds (see Fig. 1).

The Fourier spectra of CDW systems exhibit significant broadband noise with $f^{-\alpha}$ dependence [15–23]. We observe significant broadband noise in the superstructure direction, parallel to a and the superstructure wavevector, with the amplitude of the noise decreasing with increasing temperature (see Fig. 1). The amplitude of the broadband noise in the superstructure direction is much larger than that in the non-superstructure direction, parallel to c and perpendicular to the superstructure wavevector (see Fig. 1). For $La_{0.5}Ca_{0.5}MnO_3$ the effective noise temperature at 300 Hz is $\sim 10^{11}$ K for a sample temperature of 100 K, while in $NbSe_3$ the effective temperature is $\sim 10^{6}$ K. This difference is due to the large amount of disorder known to be present in $La_{0.5}Ca_{0.5}MnO_3$ [5], which means that there are many more pinning–depinning events in $La_{0.5}Ca_{0.5}MnO_3$ compared to traditional, low impurity CDWs. Although broadband noise has previously been observed in impurity pinned CDWs [24], narrow band noise has not been observed in an impurity doped or radiation damaged sample, probably due to the fact that the width of the narrow band noise peak is proportional to the magnitude of the broadband noise [21]. Therefore, a high level of disorder or impurity pinning would be expected to give rise to a high level of broadband noise, as we observe in $La_{0.5}Ca_{0.5}MnO_3$, and unobservably small narrow band noise.

At higher temperatures (e.g. 157 K) the differential resistance showed a similar drop in resistance with increasing DC bias in the two directions (respectively, a parallel to and c perpendicular to the superstructure). At low temperatures ($\lesssim 140$ K) the differential resistance undergoes a far larger drop in the a direction compared

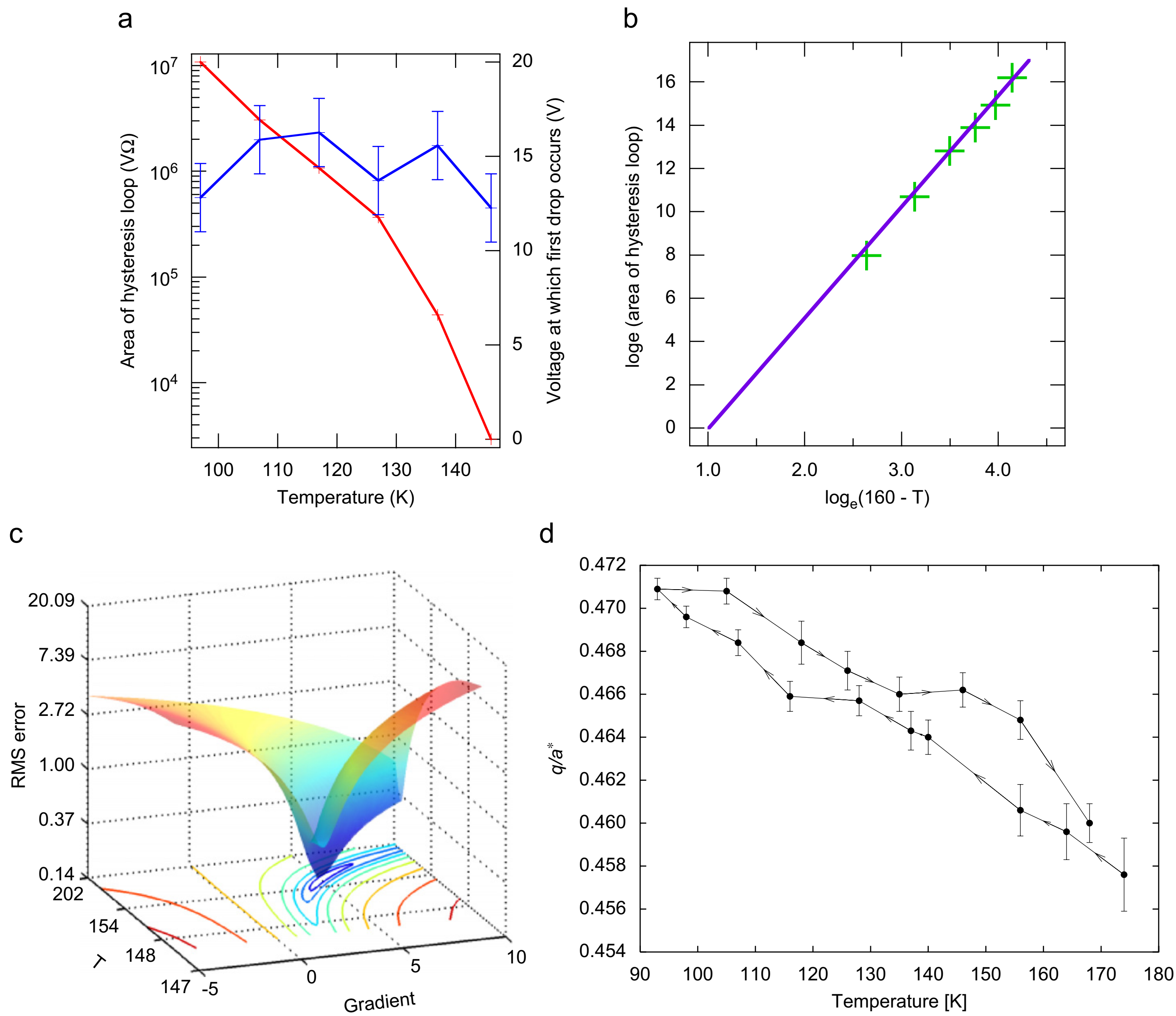

Fig. 3. (a) shows the variation of the area enclosed by the hysteresis loop for bias applied in the a direction with temperature (red) and the variation of the threshold electric field with temperature (blue). (b) shows the variation of the natural logarithm of the area of the hysteresis loop against the natural logarithm of $T_c - T$, where T_c here is 160 K. Note that the temperature at which the hysteresis loop disappears is different to the temperature at which broadband noise effects disappear. (c) shows the variation of a straight line fit to the data with T_c and gradient of the line. (d) shows the variation of the superstructure wavevector q with temperature in a similar thin film (after Ref. [11]).

to the c direction (see Fig. 2). Such dramatic resistance effects are typical of CDW systems [1]. In addition, there is a large hysteresis in the a direction between the first bias sweep after a cooldown from 300 K and subsequent measurements. The small amount of hysteresis in the c direction is attributed to imperfect contact geometry such that the current was not passed exclusively in the c direction. The area enclosed by the hysteresis loop increases rapidly with decreasing temperature.

Other mechanisms such as avalanche breakdown or sample heating cannot account for the data shown in Fig. 2. Whilst these effects could produce a falling differential resistivity with increasing field, they would not produce a history dependent result, since on removing the field the sample would return to its initial state. Furthermore, while the DC resistivity for currents parallel to c is twice that for currents parallel to a, the maximum observed drop in differential resistivity is five times greater for currents parallel to a. This anisotropy fits naturally into the CDW picture and excludes heating and breakdown as possible mechanisms. The model of percolating ferromagnetic domains, which has been used in ferromagnetic manganites, can be ruled out since the nonlinear resistivity shows activated behaviour for both low and high electric field biases, indicating that in both states the material is insulating, rather than one of the states having a strong metallic component, and in addition there is no evidence from the TEM data that a ferromagnetic phase is present [4].

It is known that the threshold field required to depin a CDW, E_T, increases with the level of impurities or other disorder in the sample, due to the increased number of pinning sites [9,10]. Two forms of pinning are typically observed in CDW systems; of these two forms, typically, weak pinning arises from impurity doping, and strong pinning arises from radiation damage [9,10]. For both forms of pinning the logarithm of the threshold field for depinning a CDW, E_T, has been found to be directly proportional to the logarithm of the impurity concentration, or level of damage (for radiation damaged samples) [9,10]. In $NbSe_3$, for example, the threshold field varies from 1 V/m for around 0.02% doping to 20 V/cm at 1% doping. Thus the high disorder level in $La_{0.5}Ca_{0.5}MnO_3$ [5] can explain the high threshold field that we observe in this sample.

The hysteresis that we observe can be explained using the Lee–Rice model for CDWs. In this model, increasing the field above E_T and then reducing it to its initial value will not return the CDW to the same initial state; the effect of increasing and decreasing the field is to leave the CDW pinned in a high-energy metastable state which is characteristic of the highest field reached [25].

The variation of the area of the hysteresis loop with temperature was found to obey a power law, as shown in Fig. 3b.

In the Lee–Rice [26] model for a pinned CDW discussed above, the threshold field E_T can be used to estimate the characteristic pinning length L over which impurities or disorder deform the CDW sufficiently to pin it, that deformation being resisted by the elastic modulus κ of the CDW. This is described by the equation

$$H = \int d^3r \frac{1}{2}\frac{nm_L}{Q^2}\dot{\phi}^2 + \frac{1}{2}\kappa|\nabla\phi|^2 + V\sum_i \delta(x-R_i)\cos(Qx+\phi) - \frac{\rho_c E\phi}{Q}$$

where $\rho(x) = \rho_c + \rho_o\cos(Q.x + \phi(x))$, and the phase $\phi(x)$ varies on a lengthscale L. The first term of the equation arises from the inertia of the CDW, the second from the stiffness of the CDW, the third from pinning effects and the fourth from the application of an electric field. One obtains $L = \sqrt{E_F/eE_TQ}$, and estimating a Fermi energy $E_F{\sim}1$ eV [27], the threshold depinning field $E_T{\sim}10^3\,\mathrm{Vm^{-1}}$ (this work) and superstructure wavevector $Q{\sim}10^{10}\,\mathrm{m^{-1}}$ [10], we find that $L \approx 300$ nm. This method of estimating L is independent of any model of screening, because the screened interaction will enter the pinning potential, which will then affect both L and E_T (see Ref. [28] for an alternative treatment of screening). The value of $L \approx 300$ nm is much larger than the estimated disorder lengthscale of 25 Å [5]. Therefore, the CDW is only being pinned at a small proportion of the potential pinning sites. This justifies the weak pinning approximation which we have used. As a corollary, oscillation of the CDW in the pinned potential would be predicted to occur at a characteristic pinning frequency $\omega_p{\sim}(m/m_L)^{1/2}10^{12}$, which we estimate to be around 1 THz. This is in the same frequency range as an earlier reported feature in a striped manganite of a different composition, that was tentatively assigned to a pinned CDW mode [29].

In conclusion, the stripe phase of $La_{0.5}Ca_{0.5}MnO_3$ is a highly disordered CDW system. Depinning of the CDW induces a massive broadband noise signal for fields applied parallel to the CDW wavevector. In the differential resistance a large hysteresis is observed between first and subsequent current sweeps, which can only be reinduced by cycling the sample up to room temperature. The area of this hysteresis loop appears to be governed by a power law.

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