

Spin-density-wave pinning in chromium

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Attempts were made to depin the three-dimensional incommensurate spin-density wave (SDW) found in chromium below 311 K. Pulsed electric fields were applied to high-purity single crystals at room temperature and 250 K, and in various orientations with respect to the crystal lattice. No electrical-conductivity nonlinearities were observed for applied fields as high as 100 V/cm. We contrast this behavior with the low depinning fields found for the SDW's in some low-dimensional organic conductors.

Recently, a great deal of interest has been shown in the dynamics of spin-density-wave (SDW) systems. Experiments on some quasi-1D organic conductors have shown nonlinear conductivity below the SDW onset temperature.¹⁻⁴ This has been attributed to depinning and sliding of the SDW above a threshold electric field in a manner analogous to the depinning and sliding of incommensurate charge-density waves (CDW's) in low-dimensional systems such as NbSe₃, TaS₃, K_{0.3}MoO₃, or tetrathiafulvalenetetracyanoquinodimethane (TTF-TCNQ).⁵

A CDW can couple to an applied electric field and thus be caused to slide with respect to the underlying crystal lattice. However, because it is pinned to the lattice by impurities, a finite threshold electric field is required to overcome the pinning forces, the necessary fields being around 10–1000 mV/cm. Theories predict similar behavior might be expected for an incommensurate SDW, despite the different nature of their interaction mechanisms.⁶⁻⁸ To the first order, a SDW has a uniform charge density (unlike CDW's), so it might be expected that pinning to nonmagnetic impurities would be weak. However, these theories suggest that an unperturbed SDW can be regarded as two CDW's of opposite phase, one with spin-up electrons, and the other with spin down. Nonmagnetic impurities will pin each CDW differently giving rise to a distortion of the electron density near the impurity site, modifying the electron-electron interaction and thus pinning the SDW. Calculations suggest the possibility of depinning the SDW by application of an electric field comparable to those found for CDW systems.⁷⁻⁹

These ideas have found recent support in experiments performed on the quasi-one-dimensional (TMTSF)₂X family of organic conductors [where TMTSF=tetramethyltetraselenafulvane and with X=NO₃ (Ref. 1), ClO₄ (Refs. 2 and 3), and PF₆ (Ref. 4)]. All three systems have a low temperature SDW state which has been confirmed by magnetic measurements (below 10, 5, and 12 K, respectively), and all have shown evidence for nonlinear conductivity in electric fields ranging from 1 to 40 mV/cm. There is also evidence for weak narrow-band noise seen for the ClO₄ salt.

An interesting question is whether this effect is limited

to one-dimensional systems. Many higher dimensional SDW systems exist, and it is instructive to look for similar effects in these materials. One such system which has been very widely studied in the past is pure chromium, which undergoes a first-order transition to a 3D incommensurate SDW state at 311 K.¹⁰ The nesting vector **Q** of the SDW is directed along a cubic axis of the structure, with the spin vector **S** being perpendicular to **Q**. The SDW wavelength is close to 80 Å which corresponds to approximately 28 unit cells. We have performed pulsed *I-V* measurements on samples of pure Cr in order to try and detect any nonlinear conductivity that may be the signature of a sliding SDW as found for the organic systems.

Single crystals of high purity chromium, grown by a vapor deposition technique, were used in this work. The impurity concentration was checked by an Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) technique and was found to be ~20 ppm Si, and <1 ppm Fe.

In order to give sufficiently large resistances, the crystals were cut and gently polished into foils about 15 μm thick, then sliced into ribbons having typical dimensions 5 mm×0.1 mm×15 μm. Surfaces were extremely smooth, with the maximum depth of scratches being 0.05 μm, the particle size of the polish used in the final stages of preparation. Samples with these typical dimensions gave four-terminal resistances of around 1.4Ω. Ribbons were cut so that their long axes corresponded approximately to the ⟨100⟩ crystal axis. A second set of samples was cut, with the long axes in a range of orientations with respect to the underlying crystal lattice.

In an attempt to remove any mechanical imperfections caused by the preparation process, the samples were annealed in mild vacuum at 600°C for 6 h, followed by a very slow cooling to room temperature taking 16 h. Evidence that the annealing process was beneficial was seen in the resistance versus temperature curves of annealed and unannealed samples (Fig. 1), with the annealed samples showing a much more obvious resistance increase at the transition temperature to the SDW state. All annealed samples showed the same 1.7% resistance increase at the transition, and all had residual resistance ratios [*R*(300 K)/*R*(4.2 K)] greater than 200. Contact resis-

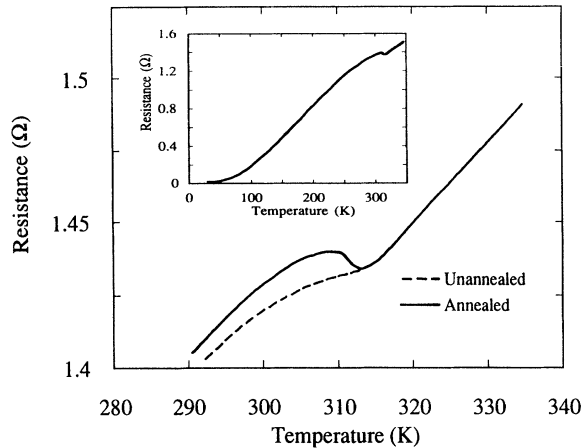


FIG. 1. dc resistance of a chromium single crystal around the SDW transition at 311 K, for an unannealed sample (dotted line) and an annealed sample (full line). The inset shows the resistance from 330 K down to 30 K for the annealed sample.

tances to freshly prepared samples were 0.1Ω using silver paint.

Nonlinear conductivity was checked for by passing rectangular current pulses through the sample and monitoring the resulting voltage on an oscilloscope. $3\text{-}\mu\text{sec}$ pulses, with a repetition rate of 8 Hz, were applied to the outer current contacts of the sample, with the resulting voltage being monitored across the inner contacts. In this manner, electric fields up to 30 V/cm could be attained before heating effects became noticeable. In two exceptional samples (one annealed and one unannealed) fields in excess of 100 V/cm were attained. These experiments were performed on the samples with long axes parallel to the $\langle 100 \rangle$ crystal direction, and on the set of samples with other orientations, at room temperature ($\sim 15\text{ K}$ below the transition temperature) and at 250 K ($\sim 60\text{ K}$ below). In no case was any nonlinearity seen for any of the samples. These electric fields are $10^2\text{--}10^4$ times higher than typical depinning fields in CDW systems, or for the quasi-1D organic SDW systems mentioned in the Introduction.

We now discuss the implications of these results. Maki and Virosztek⁸ have recently derived the following expression for the SDW threshold field for a strongly pinned two-dimensional system at $T=0$:

$$E_T^S(0) = \frac{Q}{e} \frac{n_i}{n} (\pi N_0 V)^2 \Delta(0).$$

Here, $Q = 2k_F$ is the SDW wave vector, e is the electronic charge, (n_i/n) is the impurity concentration, N_0 is the electronic density of states, V is the impurity potential, and $\Delta(0)$ is the SDW gap at $T=0$. The temperature dependence was shown to be weak, with $E_T(T)/E_T(0)$ increasing from unity at $T=0$, to 1.33 at the transition temperature. The threshold fields found for the SDW in the 1D organic materials ($\sim 10\text{ mV/cm}$) are found to be

consistent with this theory.

A typical value of N_0V for the organic systems is 0.1. Combining this with $Q = 2k_F = \pi/\lambda$, ($\lambda = \text{SDW wave-length} = 80\text{ \AA}$), $n_i/n \sim 20\text{ ppm}$ and $\Delta(0) = 100\text{ meV}$ (Ref. 11) for our chromium samples we find a predicted value of $E_T = 300\text{ mV/cm}$, around 300 times lower than the minimum value of 100 V/cm found from our experiment.

This difference between experiment and theory could reflect the fact that coupling of a three-dimensional SDW to an applied electric field is actually much weaker than in one or two dimensions, so that the SDW is intrinsically much harder to depin. This idea finds some support in that depinning also seems to be restricted to quasi-one-dimensional CDW materials, there being no known 2D or 3D examples.

Alternatively, it may indicate that the pinning mechanism in Cr is different and much stronger than the mechanism found in the organics or CDW systems. Here it should be noted that theories predict a greater pinning energy if the SDW is pinned via a magnetic impurity.⁷

Further possible explanations might relate to the relative orientation of the electric field E and the SDW wave vector Q . It might be expected that if the SDW were to depin, then its motion would most likely occur along a $\langle 100 \rangle$ direction, i.e., parallel to Q (as for CDW systems). The crystals in this investigation were cut with their long axis close to a $\langle 100 \rangle$ direction so that the applied electric field would give the greatest coupling to Q . Even if the samples were not cut exactly parallel to $\langle 100 \rangle$, a major component of E should still be parallel to Q does not provide the best coupling. However, crystals cut to give other orientations between E and Q , showed no nonlinear conductivity either.

A final possibility relates to the microscopic nature of the SDW in Cr. Neutron scattering and de Haas-van Alphen studies have shown that Q does not adopt a simple cubic symmetry in keeping with the underlying crystal lattice, but rather consists of many domains in which Q is directed along a single $\langle 100 \rangle$ axis.¹² These tetragonal, single- Q domains were shown to be distributed randomly along the three cubic axes if cooled through the transition in zero magnetic field. However, if cooled through the transition in a strong field ($\sim 3\text{ T}$) parallel to a $\langle 100 \rangle$ axis, a single domain sample resulted, with Q oriented parallel to the field.¹³ Further complicating this picture is the fact that the very purest samples sometimes showed a single domain structure even when cooled in zero field.¹² So without using neutron scattering techniques to check the SDW orientation before experiment, the microscopic nature of the SDW is rather unclear. Polydomains might not support SDW motion due to incoherency across boundaries, or because pinning is much stronger in these regions.

An interesting experiment would be to repeat the above measurements for samples in which a single- Q domain had been prepared by cooling in a magnetic field.

In conclusion, we have shown that, in contrast to the electric fields around 10 mV/cm required to depin the incommensurate SDW in the quasi-2D organic systems, fields more than 10^4 times greater are still insufficient to

depin the 3D incommensurate SDW in chromium. We argue that this may be related to the different nature of the pinning mechanism in three dimensions, or to the microscopic nature of the SDW in chromium.

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