Electric Field Dependence of the Magnetoresistance in $NbSe_3$ and Fe_xNbSe_3

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The transverse magnetoresistance of $NbSe_3$ and Fe_xNbSe_3 ($x \leq 0.01$) at magnetic fields in the range 100–220 kG shows a strong dependence on applied electric field in the temperature range 20 to 60 K. At 20 K and 206 kG, $[\rho(H) - \rho(0)]/\rho(0) = 4.5$ at 10 mV/cm and is reduced to 0.9 at 100 mV/cm for pure $NbSe_3$ while the threshold for charge-density-wave sliding motion is ≥ 100 mV/cm. Pinning and unpinning of the charge-density wave with changes of temperature or Fe impurity does not affect the magnetoresistance reduction induced by the electric field.

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The linear-chain compound $NbSe_3$ has been studied with great interest because of its unusual nonlinear conductivity.[1-3] This is associated with the presence of charge-density waves (CDW's) which form below temperatures of 144 and 59 K and can undergo a sliding motion[4] in applied electric fields above certain threshold values. The crystals grow in a monoclinic crystal structure and form needless and ribbons with the growth axis along the Nb chains (b axis).

The onset of the CDW transitions produces large resistive anomalies in the temperature dependence of resistance which are attributed to a reduction in the Fermi surface area[5] due to the formation of energy gaps induced by the CDW. At electric fields above the threshold values required for CDW motion these anomalies are reduced as the conductivity increases because of the current carried by the sliding CDW. The threshold electric fields required for CDW motion are as low as 5 mV/cm in pure $NbSe_3$ and are increased rapidly by decreasing temperature or by the addition of impurities.

In this paper we report measurements of the influence of the CDW structure and motion on the transverse magnetoresistance of $NbSe_3$ and Fe_x-$NbSe^3$. The crystals with small amounts of Fe impurity $x \leq 0.01$ have much higher threshold electric fields at given temperatures than observed for the pure $NbSe_3$ and are useful for comparing the magnetoresistance in the Ohmic and non-Ohmic regions of conductivity. In both cases below 50 K the electric field required for depinning increases as a power law of inverse temperature.

One of the main new results is the observation that the transverse magnetoresistance, $[\rho(H) - \rho(0)]/\rho(0)$, shows a strong electric field dependence which is independent of the major sliding motion of the CDW, and requires a new and unusual mechanism contributing to the magnetoresistance. In the temperature range 20–60 K the magnetoresistance is a maximum at low electric fields and is reduced by factors of ~ 5 or more as the electric field is increased in the range 20 to 200 mV/cm. This reduction of magnetoresistance occurs in both the pure and the Fe-doped $NbSe_3$ and is not correlated with the onset of sliding motion as will be shown by variation of both the temperature and the impurity pinning. The transverse magnetoresistance for pure $NbSe_3$ as a function of applied electric field at 206 kG and 20 K is shown in Fig. 1(a). The transverse magnetoresistance was recorded with the magnetic field perpendicular to the c axis and b axis and the current parallel to the b axis, although other transverse orientations of the magnetic field show similar results. All of the dc data points have been recorded while the current is held constant.

At 20 K no sliding motion of the CDW occurs for electric fields up to 100 mV/cm and the resistance at zero magnetic field remains Ohmic as also shown in Fig. 1(a). The threshold electric field required for the onset of the magnetoresistance reduction at 20 K is ~ 20 mV/cm for this crystal. A rapid reduction of magnetoresistance occurs at intermediate electric fields followed by an approach to saturation at electric fields above ~ 100 mV/cm while the CDW remains pinned up to 100 mV/cm.

If the temperature is raised to 30 K the electric field threshold for CDW motion is reduced to ~ 10 mV/cm and the resistance drops from 9 to 5.7 Ω because of the sliding motion as the applied electric field increases from 10 to 100 mV/cm as shown in Fig. 1(b). For the same electric field range the transverse magnetoresistance at 206 kG also drops by a factor of 5 as also shown in Fig. 1(b). The magnitude of the magnetoresistance at 30 K is less than observed at 20 K because of the reduction in $\omega_c\tau$, but the percentage reduction of magnetoresis-

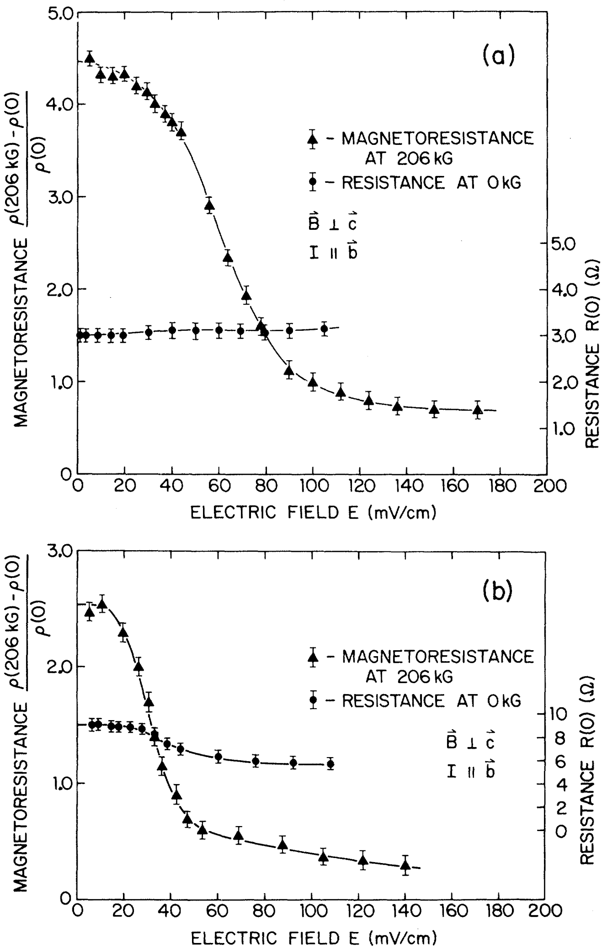

FIG. 1. Transverse magnetoresistance in $NbSe_3$ at 206 kG as a function of applied electric field (triangles); resistance as a function of applied electric field at zero magnetic field (circles), with scale at the right of the figure. (a) 20 K; (b) 30 K. At 30 K CDW motion begins above ~ 20 mV/cm while at 20 K the CDW remains pinned up to at least 100 mV/cm. At both temperatures the magnetoresistance drops by a factor of 5 as the electric field increases from 10 to 100 mV/cm.

tance induced by the applied electric field is comparable at both temperatures and does not appear to be related to the onset of the CDW sliding motion which occurs only at 30 K for this electric field range.

For Fe_xNbSe_3 crystals grown from powders with 1 at.% Fe the crystals incorporate enough Fe to increase substantially the pinning of the CDW so that at given temperatures much higher threshold electric fields are required for the onset of CDW sliding motion. The residual resistance ratios (RRR's) are reduced from ~ 150 for the pure crystals to ~ 15 for the Fe-doped crystals. The Fe impurities incorporated in this way produce less of a reduction in the RRR than 1 at.% of substitutional impurities such as Ta and we conclude that the Fe is very dilute or does not incorporate in the chain at this concentration. Our analytical techniques only measure the level of Fe impurity to ~ 1-at.% accuracy. Fe is incorporated in two of the chains for much higher Fe concentrations in the powder, but the crystal structure changes and only the high-temperature CDW is present as previously shown by Hillenius *et al.*[6] For the dilute Fe doping both CDW's are unchanged from those observed in the pure material [see inset, Fig. 2(b)]. The effects of impurity pinning on CDW motion have been examined both experimentally[7] and theoretically[8-10] in a number of publications.

At 30 K the magnetoresistance at 200 kG in the Fe-doped crystals is of the same magnitude as observed in the pure material at 30 K. The applied electric field also reduces the magnetoresistance by a factor of ~ 5, but much higher electric fields are required to obtain a comparable reduction as shown in Fig. 2(a) (~ 200 vs 100 mV/cm). At 30 K the CDW is also pinned up to electric fields above 200 mV/cm so that no zero-field–resistance reduction or sliding motion is observed as shown in Fig. 2(a). However, the magnetoresistance and the electric field reduction of magnetoresistance are of the same magnitude in both the pure and the Fe-doped material at 30 K.

For the Fe-doped crystals higher temperatures are required to observe the CDW sliding motion. At 43 K the electric field threshold is reduced to ~ 40 mV/cm as shown for the $R(0)$-vs-E curve in Fig. 2(b). The magnetoresistance also shows a strong reduction over a reduced electric field range of 50 to 80 mV/cm just above the onset of CDW motion. The relative reduction in magnetoresistance is also a factor of ~ 5 although the magnitude of the magnetoresistance is reduced because of the decrease in $\omega_c\tau$ at the higher temperatures.

In these experiments we have used temperature and Fe impurities to pin and unpin the CDW in different ranges of electric field and temperature. In all cases an electric-field–dependent magnetoresistance is observed and does not appear to be directly correlated with the CDW sliding motion. Additional impurity pinning increases the threshold and range of electric field required for the magnetoresistance reduction at comparable temperatures, but does not change the relative magnitude of the magnetoresistance or the reduction caused by the electric field.

The possibility of a strong magnetic field depen-

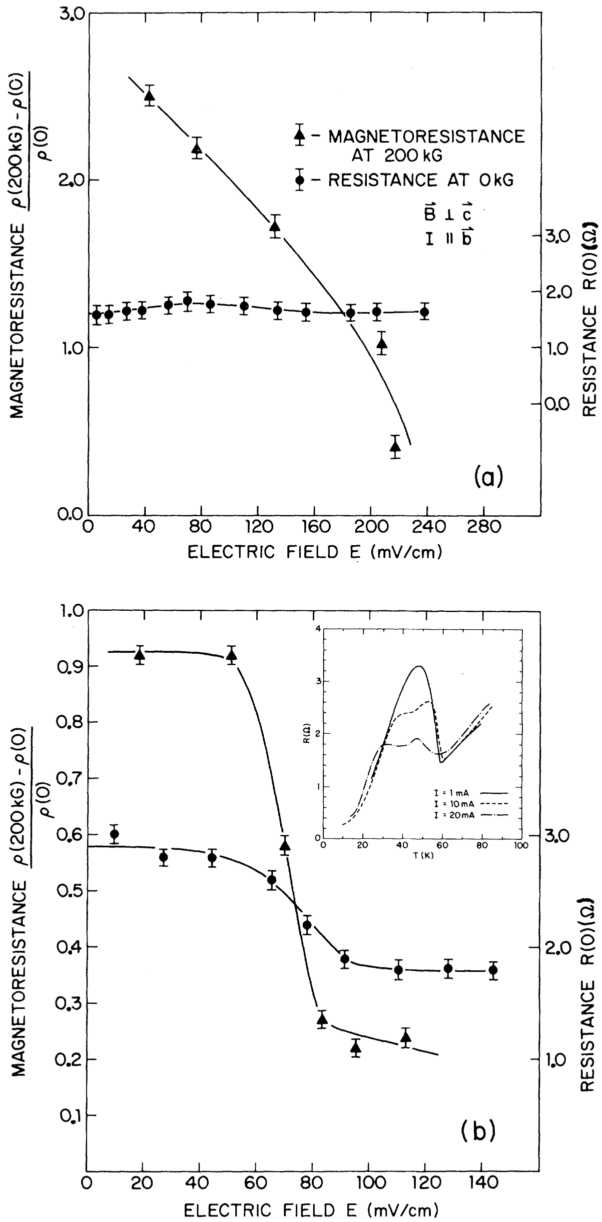

FIG. 2. Transverse magnetoresistance in Fe_xNbSe_3 ($x \leq 0.01$) at 200 kG as a function of applied electric field (triangles); resistance as a function of applied electric field at zero magnetic field (circles), with scale at the right of the figure. (a) At 30 K, the Fe impurity causes the magnetoresistance reduction to occur over a larger electric field range than in the pure material. At 30 K reduction occurs over 200 vs 40 mV/cm. (b) At 43 K, the higher temperature reduces the electric field range required for the magnetoresistance reduction. CDW motion begins above ~ 40 mV/cm. B and I have the same orientation as specified in (a). Inset: the temperature dependence of resistance of this crystal at currents of 1, 10, and 20 mA. At 10 and 20 mA CDW motion occurs between 30 and 59 K.

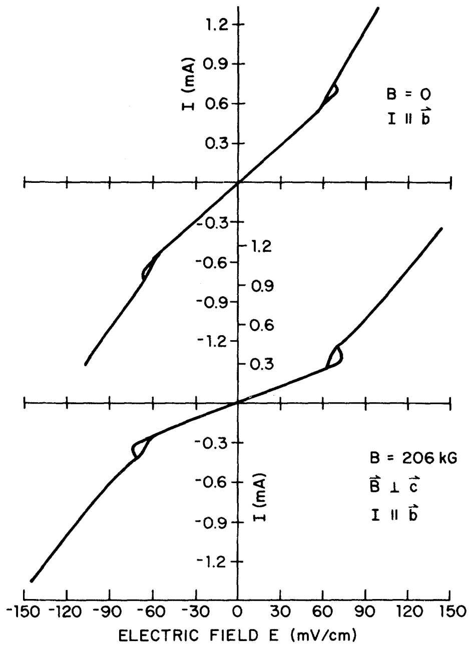

FIG. 3. I-vs-E curves recorded for Fe_xNbSe_3 ($x \leq 0.01$) at 43 K. The curves represent oscilloscope traces recorded at 100 Hz. The upper curve was recorded at zero magnetic field. The lower curve was recorded in a magnetic field of 206 kG. The threshold electric field is ~ 60 mV/cm at $B=0$ and ~ 63 mV/cm at $B=206$ kG. The hysteresis centered near threshold also grows larger in the applied magnetic field.

dence of the threshold electric field required for CDW motion has been investigated and no evidence of a major change with magnetic field has been found. I-vs-E curves measured at 100 Hz for a Fe_xNbSe_3 crystal are shown in Fig. 3 for magnetic field values of 0 and 206 kG. The threshold electric field for CDW motion is ~ 60 mV/cm at zero magnetic field and increases to ~ 63 mV/cm at 206 kG as can be clearly identified by the hysteresis loops at the threshold points. The ac electric field experiments show slightly higher thresholds than the dc experiments, but none of the many experiments on I-vs-E data in the range 0 to 200 kG show any major dependence of the CDW sliding motion threshold on magnetic field.

The electric-field-dependent magnetoresistance is correlated with the resistive anomaly due the CDW in the range 20 to 59 K. No electric-field-dependent magnetoresistance is observed at 4.2 K where the resistive anomaly has died out and the CDW is pinned to very high electric fields. The magnetoresistance should be associated mainly with the dynamics of the normal electrons rather than with the CDW condensate. These experiments therefore suggest that in the presence of a magnetic field the electric field has a strong effect on the interaction of the normal electrons with some feature of the CDW structure and contributes an additional term in the magnetoresistance. This could involve phasons, discomensurations, or dislocations which may be excited prior to the onset of the major sliding-mode conductivity. Certainly these are suggested to play a role in the poorly understood problem of the power-law temperature dependence,[11] $T^{-\alpha}$ ($\alpha = 3$ or 4), observed for the threshold electric fields associated with the depinning process. The electric field thresholds for magnetoresistance reduction are a function of pinning strength and thermal activation as shown in the examples, but have a range of values generally less than and not directly correlated with the depinning thresholds.

Hall measurements at low magnetic fields ≤ 14 kG by Tessema and Ong[12] lead to the conclusion that σ_{xy} was unaffected when the condensate became depinned. The present magnetoresistance reduction should be accompanied by a strong change in the Hall resistance. This would occur before the onset of sliding motion and may be a separate high-field effect which is also unaffected by the depinning as the present experiments would suggest for the magnetoresistance in the chain direction.

In the Fe-doped material large hysteresis and switching phenomena in the CDW motion are observed,[13,14] but do not appear to influence the electric field dependence of the magnetoresistance reported here which is intrinsic to both the pure and the Fe-doped $NbSe_3$.

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