Solid State Communications, Vol.64,No.4, pp.417-419, 1987.
Printed in Great Britain.

0038-1098/87 $3.00 + .00
Pergamon Journals Ltd.

STRESS-DEPENDENT MAGNETORESISTANCE IN $NbSe_3$

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(Received 23 June 1987 by A. Zawadowski)

We have performed electrical resistance measurements on $NbSe_3$ in the lower charge density wave (CDW) state under the application of transverse magnetic fields and while the sample is under uniaxial stress. For zero stress, increasing the magnetic field results is an enhancement of the resistance anomaly consistent with previous measurements by Coleman et al. In zero magnetic field, increasing stress also enhances the resistance anomaly consistent with previous measurements by Lear et al. For combined stress and magnetic field, the resistance anomaly is not further enhanced, i.e. the effects are not additive. We examine the possibilities that magnetic fields and stress act on similar portions of the Fermi surface.

In the recent past, there has been considerable effort applied toward understanding the transport properties of quasi-one-dimensional and quasi-two-dimensional materials[1]. A common feature of low dimensional compounds is the formation of an insulating density-wave ground state (either charge-density-wave [CDW] or spin-density-wave [SDW]). The metal-insulator transition often occurs at temperatures below room temperature. The formation of the density wave is associated with the nesting ability of the Fermi surface [FS]: electronic states with $\Delta k = 2k_f$ mix and form an energy gap in the electronic spectrum. If the nesting is complete enough, then the material will undergo a full metal-insulator (or rather metal-semiconductor) transition; for example, this is the case for $(TMTSF)_2PF_6$, NbS_3, TaS_3, $(TaSe_4)_2I$, and $K_{0.3}MoO_3$[1]. When the nesting is substantial but incomplete, the transition may still occur but excess normal carriers can remain in metallic bands to give metallic or semimetallic behavior; this is the case for $NbSe_3$ which undergoes two CDW transitions (T_{P1}=144 K, T_{P2}=59 K), both of which have incomplete nesting. $NbSe_3$ shows resistance anomalies below T_{P1} and T_{P2}, but metallic behavior is recovered as $T \to 0$.

Recently, a great deal of theoretical and experimental work has been done on the effect of a magnetic field on incompletely nested systems in organic and inorganic low-dimensional materials. In the organics, the Bechgaard salts ($(TMTSF)_2X$; X = ClO_4, PF_6) show unusual magnetoresistance reminiscent of the quantum Hall effect; the magnetoresistance is the signature of magnetic-field-induced phase transitions from the metallic state through a cascade of SDW states[2]. The very low temperatures (T < 2K) and moderate to high magnetic fields (6 $\to$ 30 T) needed to observe this phenomena point to the quantization of orbital motion as being of primary importance in these quasi-two-dimensional systems. Indeed, the leading theoretical explanations contain the essential idea of a competition between the quantized orbital motion and the nesting properties of the FS[3].

In the inorganics, $NbSe_3$ shows an anomalously large magnetoresistance in the lower CDW state ($T < T_{P2}$)[4]. The initial evidence suggested that the magnetic field decreased either the number or the mobility of the normal electrons thereby enhancing the resistance[4]. Theoretical work by Balseiro and Falicov[5,6] showed that, in systems with a stable density-wave ground state, a magnetic field can enhance the energy gap through destruction of electron-hole pockets of the imperfectly nested Fermi surface. The theory implies that the *magnetic field can induce a direct conversion of normal carriers to CDW carriers*. Numerous experiments testing this carrier conversion picture have been reported. The evidence includes high electric field DC conductivity measurements[4], narrow-band-noise studies[7], thermopower[8], and high frequency conductivity[9] data all of which are consistent with the magnetic-field-induced carrier conversion.

In the lower CDW state of $NbSe_3$, there is another anomaly in the resistance if the crystal is longitudinally stressed along the chain axis. In a very careful and complete set of stress and resistance measurements, Lear et al[10] showed that applied stress greatly enhances the magnitude of only the lower CDW state resistance anomaly. Stress was also found to decrease the temperature of both CDW transitions. Although it is clear that the effects of stress and magnetic field are not entirely equivalent in $NbSe_3$ (Stress changes the transition temperature while the magnetic field gives little or no change.), one can ask if they affect the CDW system in similar ways. This question is addressed in this series of experiments.

We have performed magnetoresistance measurements on $NbSe_3$ under uniaxial stress and find that a large stress greatly reduces the magnetoresistance. Similarly, a large magnetic field reduces the effect of stress on the resistance. The results are consistent with the magnetic field and uniaxial stress acting on similar portions of the FS.

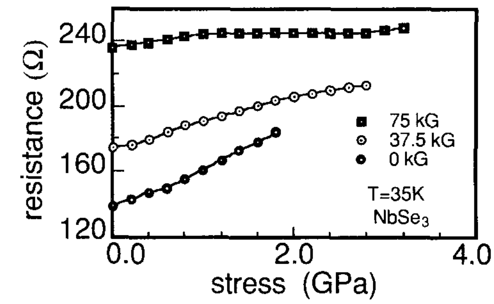
Single crystals of $NbSe_3$ were mounted in a four-probe contact configuration using silver paint and one mil gold wires. In addition, a cyanoacrylate glue was applied over all the contacts to prevent the sample from breaking free under stress; thus the portion of the sample under stress was between the voltage contacts. The experimental setup allowed strain to be applied while the sample was in a magnetic field oriented perpendicular to the chain (b) axis of the crystal. A 200 Hz low-level AC current was applied to the sample and the resistance was measured using a lock-in with a bridge. The stretching apparatus consists of a differential-screw micrometer connecting a stainless-steel rod to a sapphire block via a lever arm. Another sapphire block is fixed in close proximity to the first and the sample is mounted between the two blocks. The lever arm is needed to translate the motion of the micrometer into a motion perpendicular to the magnetic field which then gives the desired orientation of the crystal to the field. When the temperature of the apparatus was changed, the samples were bowed with the stretcher in order to prevent damage to the crystal due to thermal contraction. At the temperature where measurements were made, the zero of strain was taken to be at the micrometer reading where a resistance change was first detected. Thus, the apparatus allowed a given strain to be applied and the stress was calculated from the previously measured Young's modulus[11] and resistance studies[10].

Figure 1 shows typical resistance versus stress curves at various magnetic fields for sample #1. The lower curve was made with no magnetic field applied while the upper two curves had fields of 37.5 kG and 75 kG respectively. The curves have not been shifted with respect to one another; their displacement results solely from the magnetoresistance. The data here clearly demonstrates that as the magnetic field increases, the change of the resistance due to stress decreases; <u>there is little stress dependence on the resistance in the presence of a large magnetic field</u>.

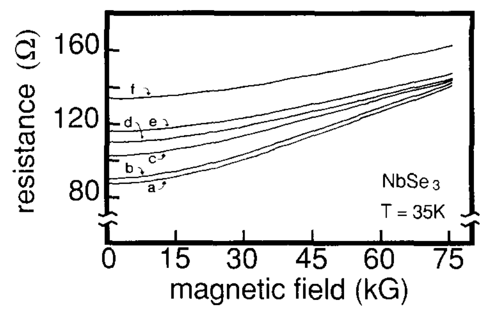
Similarly, figure 2 shows resistance versus magnetic field at various stress for sample #2. Again, the curves have not been shifted with respect to each other; the displacement is caused by the resistance change due to the applied stress. As the field increases, the slope of the curves also increase; however, at a given strength of the magnetic field, the slope of curves with less stress is always greater than or equal to the slope of curves with more applied stress. As a result, the net change in the resistance due to magnetic field is less when stress is applied compared to that of no stress: <u>Stress eliminates additional magnetoresistance</u>.

Longitudinal stress causes two actions: elongation along the chain direction and contraction transverse to the chains. Lear et al[10] have estimated the Poisson ratio and found there to be significant transverse contraction. As mentioned previously, uniaxial stress lowers both the CDW transition temperatures in $NbSe_3$, while enhancing the lower CDW resistive anomaly. In comparison, hydrostatic pressure also lowers the transition temperatures, but inhibits the lower CDW resistive anomaly[12]. Eventually with increasing hydrostatic pressure, the CDW transition is suppressed at ≈ 6 kbar; under this pressure the specimen becomes superconducting at ≈ 3 K[13]. Pressure decreases the amplitude of the CDW gap and the number of condensed carriers[14]. Apparently, the <u>inter</u>chain coupling dominates in affecting the transition temperature and the <u>intra</u>chain coupling affects the resistive anomaly.

The above data shows that the effects of magnetic field and stress on $NbSe_3$ in the lower CDW state are interrelated. The exact nature of this interrelationship still remains unclear. As was mentioned previously, there exists strong evidence suggesting that the magnetic field induces a carrier conversion from the normal to the CDW state. If stress caused a similar action, then the application of stress would give a smaller magnetoresistance since there would be less normal carriers available for



<u>Fig. 1.</u> Resistance versus the applied stress at various magnetic fields. As the field increases, the resistance change due to stress decreases. The curves have not been shifted with respect to one another.



<u>Fig. 2.</u> Resistance versus magnetic field at various stresses: a) 0 GPa, b) 0.2 GPa, c) 1.1 GPa, d) 1.6 GPa, e) 2.0 GPa, and f) 3.1 GPa. The magneto-resistive increase is less when stress is applied. The curves have not been shifted with respect to one another.

conversion. By assuming that stress and the magnetic field do indeed convert carriers, one can estimate the magnitude of CDW carrier concentration (n_{cdw}) conversion by the change in the ohmic resistance[15]. Data shown in figure 1 was used to calculate the effect that the magnetic field (H) has on stress-induced conversion while data illustrated in figure 2 gives the effect stress (σ) has on magnetic -field carrier conversion. The unperturbed CDW carrier concentration will be estimated as $n_{cdw} \approx 10^{21}$ carriers/cm^3. The value for H-field carrier conversion at zero stress is then $dn_{cdw}/dH = 3.5 \times 10^{18}$ carriers/cm^3-kG and is in good agreement with previous studies[7,9]. With application of stress, this value is reduced by 40% at $\sigma = 1.6$ GPa and by 66% at $\sigma = 3.1$ GPa. Similarly, the zero H-field value for $dn_{cdw}/d\sigma$ ($\approx 9 \times 10^{19}$ carriers/cm^3-GPa) is reduced by 66% at 37.5 kG and by 89% at 75 kG.

It would be extremely interesting if, by the action of stress or magnetic field on $NbSe_3$, the sample became completely insulating due to complete destruction of the Fermi Surface. A study could then be made on the importance of the degree of nesting of the FS on the properties of the CDW and the effect the presence of free carriers has on the CDW system. From the above estimates, it would seem that the application of a magnetic field is the more appropriate method in attempting to induce a metal-insulator transition. This is not surprising since stress lowers the CDW transition temperature (T_{P2}) and the resulting increase in the normalized temperature (T/T_{P2}) inhibits the effectiveness of stress on the CDW system; furthermore, the maximum stress allowed is limited by the mechanical strength of the sample. The effect of the magnetic field is not limited in these ways. In fact, it could be speculated that the increased normalized temperature caused by stress is partly responsible for the effect on the H-field carrier conversion which is highly temperature dependent[7,8,9]. More work is needed to answer such queries. Further experiments (such as narrow-band-noise studies) would be useful in determining directly the carrier conversion rate with increasing stress; such experiments are presently underway.

This work supported by NSF DMR 83-51678. One of us (A.Z.) is the recipient of a National Science Foundation Presidential Young Investigator Award and an Alfred P. Sloan Foundation Fellowship.

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