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Softening of the shear modulus C_{44} in $(\text{TaSe}_4)_2\text{I}$ due to sliding charge density waves

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Abstract

Acoustic velocity of the shear mode C_{44} of quasi-one-dimensional $(\text{TaSe}_4)_2\text{I}$ has been measured at 15 MHz frequency with the ultrasonic technique. It is found that the elastic constant C_{44} decreases when applied electric fields greater than the threshold E_T are applied for charge-density wave (CDW) depinning. The decrease $\Delta C_{44}/C_{44} \sim 10^{-4}$ observed at 15 MHz for $E \sim 10 E_T$ is two orders of magnitude smaller than the decrease reported at low frequency (kHz). Present results are compared with the effects of CDW depinning on the elastic properties predicted by several models.

1 Introduction

The phenomenon of sliding charge density wave (CDW) is observed in quasi-one-dimensional compound such as $(\text{TaSe}_4)_2\text{I}$ [1]. The sliding of the CDW is induced by application of an electric field E in excess of a threshold E_T . The sliding yields a decrease of the electrical resistivity with field which has been reviewed in [1] and is also accompanied by a mechanical effect: the softening in elastic stiffness [2-5]. Most experimental studies have concentrated on the properties of the Young's modulus measured at low frequencies (kHz) [2,4]. In this paper we report a study by ultrasonic measurements of the shear modulus C_{44} of $(\text{TaSe}_4)_2\text{I}$. Elastic constant C_{44} of $(\text{TaSe}_4)_2\text{I}$ has a very small value $1.2 \times 10^9 \text{ N/m}^2$ [6]. Such a small value reflects the weak (Van der Waals) interchain bounding in quasi-one-dimensional compounds [4].

2 Experimental results

Large crystals (typical dimension $3 \times 2 \times 2 \text{ mm}^3$) were used and shear mode with wavevector $\mathbf{q} \perp [001]$ and polarization vector $\mathbf{u} \parallel [001]$ was generated. This elastic mode corresponds to the elastic constant C_{44} with the tetragonal symmetry of $(\text{TaSe}_4)_2\text{I}$. Standard pulse echo technique was used at 15 MHz with two LiNbO_3 transducers and the sound velocity was measured by a phase coherent detection. The electrical field effect on the sound velocity of the elastic mode C_{44} was measured with electric field parallel to the c axis. Thin copper film $5000 \text{ \AA}$ was deposited on the two surfaces perpendicular to the c axis in order to obtain good electrical contacts. Care was taken to avoid spurious effects due to sample heating by the electric pulses.

We have used an experimental procedure similar to that described in ref 5. A 30 μs wide electric pulse was applied and its position was adjusted in order to cover completely the travel period about 5 μs of a selected acoustic echo 1 μs wide. Velocity of the selected echo was measured while the electric pulse was progressively delayed until the selected echo was outside the electric pulse. The field effect on the amplitude of the acoustic echo was too small to be accurately measured below the Peierls transition $T_p=263$ K electric field effects were observed on both electrical resistance R and sound velocity V as shown in fig 1. R was deduced from measurements of the electric pulse amplitude U .

Fig1: Electrical resistance function of voltage and voltage dependence of the sound velocity of the C44 mode $q_{\perp}[001]$ and $u_{\parallel}[001]$

The threshold voltage U_T is defined as the voltage where electric resistance starts to deviate from the constant ohmic value R_0 [1]. U_T has been shown to exponentially increase when temperature decreases and consequently we have only performed field effect measurements around 250 K. In fig1 it can be seen that for $U=10 U_T$ the decrease of the sound velocity is $\Delta V/V \approx 5 \times 10^{-5}$. The charge density current $ICDW$ was calculated with the relation $ICDW = I - U/R_0$, where I is the total current [1]. We show in fig2 that the decrease $\Delta V/V$ follows the $(ICDW)^{0.5}$ law for small $ICDW$ and saturates at high value in fig 2. As do Young's modulus[3] and torsional modulus[4].

The shear modulus C_{44} decreases when CDW slides but the effect measured at high frequency (15 MHz) is two orders of magnitude smaller than for the other techniques which are performed in the frequency range of kHz.

Fig2: Sound velocity changes as a function of the CDW current component.

3 Discussion and Conclusion

Present results obtained on $(\text{TaSe}_4)_2\text{I}$ at 15 MHz are similar to those found on TaS_3 [5] at the same frequency. They confirm the frequency dependence of the field effect on the elastic properties as pointed out in [7] the modulus depinning anomalies decrease with frequency. Several models reviewed in ref [8] have been proposed to explain the elastic behaviour associated with the depinning of the CDW but its interpretation is still uncertain and only qualitative agreements are found. An early proposal was that the acoustic velocity was directly affected by the CDW motion[9] but the predicted shift is too small to explain the measurements. The decoupling model [10] proposed that the CDW must distort with the same wavevector as the underlying lattice because the pinning couples together CDW and lattice, so that the measured stiffness is the sum of the stiffness components K of the CDW and C of the lattice. Magnitude of the CDW elastic stiffness K is about one order of magnitude smaller than C_{44} [2]. When the CDW slides the net stiffness is reduced. The screening model [11] considers the effect of CDW screening on phonons. It is assumed that while the pinned CDW could not contribute to screening the depinned could and the gradual softening is due to a distribution of threshold fields. Finally relaxational models have been proposed [4,7] to explain the frequency dependence. Softening is due to relaxation of some defects in the CDW, but the microscopic nature of these defects is not known.

Elastic constant C_{44} decreases by about 10^{-4} with CDW depinning. This result suggests that CDW motion affects the interchain forces. The decrease of C_{44} is probably due to a change in the CDW transverse phase coherence with applied voltage [4].

In conclusion explanation of the elastic effects observed in one-dimensional compound such as $(\text{TaSe}_4)_2\text{I}$ when the CDW is put into motion is not satisfactory and measurements in a large frequency range should give useful information.

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