Semimetal to semimetal charge density wave transition in 1T-TiSe$_2$

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We report an infrared study on 1T-TiSe$_2$, the parent compound of the newly discovered superconductor Cu$_2$TiSe$_2$. Previous studies of this compound have not conclusively resolved whether it is a semimetal or a semiconductor: information that is important in determining the origin of its unconventional CDW transition. Here we present optical spectroscopy results that clearly reveal that the compound is metallic in both the high-temperature normal phase and the low-temperature CDW phase. The carrier scattering rate is dramatically different in the normal and CDW phases and the carrier density is found to change with temperature. We conclude that the observed properties can be explained within the scenario of an Overhauser-type CDW mechanism.

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Charge density waves (CDW) and superconductivity are two important collective phenomena in solids. There has been tremendous interest in the interplay between these two states in condensed matter physics. The recent discovery of superconductivity upon intercalation of Cu into CDW-bearing 1T-TiSe$_2$ offers a good opportunity to study the transition between the two states. As a first step, understanding the parent compound 1T-TiSe$_2$ is essential.

The CDW state in 1T-TiSe$_2$ has been known for several decades, but remains poorly understood. It shows a lattice instability around 200 K, below which it enters into a commensurate CDW phase associated with a (2 × 2 × 2) superlattice and angular resolved photoemission spectroscopy (ARPES) measurements. At energies near $E_F$, 1T-TiSe$_2$ is governed by two bands: a hole-like Se 4p band close to the Γ point and a Ti 3d band around the L point. Due to the small energy differences involved, ARPES experiments have not unambiguously shown whether the compound is a semiconductor or a semimetal in either the normal or CDW states.

This issue is central to resolving the mechanism of the CDW phase transition, which remains problematic. Contrary to other 1T-type transition metal dichalcogenides, the CDW transition in 1T-TiSe$_2$ is not likely to originate from Fermi surface (FS) nesting or saddle-point singularities, as parallel FS sheets have neither been predicted nor observed. One picture for the driving force for CDW formation is exciton formation at low temperature. However, the available experimental results in support of this picture are controversial. There exist several other proposals for the driving mechanism, including an indirect Jahn-Teller effect, but no conclusive agreement has been reached. In this Letter, we study the change of the electronic structure as a function of temperature by optical spectroscopy. Although there exist several optical studies on this compound, most of them were performed only at room temperature or in the high energy region (above ~ 0.5 eV). A detailed study to low energy has been lacking. We argue here that Overhauser’s scenario for CDW formation due to electron-hole bound pairs offers the most likely explanation to account for all the observed features.

Single crystals with reflective flat surfaces were grown as previously described. The dc resistivity was measured by a standard four probe technique in a Quantum Design PPMS. Similar to the data reported earlier, the ρ(T) curve, as displayed in the inset of Fig. 1(a), shows a rather striking shape. The resistivity increases with decreasing T from 300 K and shows no distinct anomaly at the CDW transition near 200 K. After reaching a maximum near 150 K, it decreases on further cooling. This behavior is rarely seen in metallic or semiconducting compounds, and is also not seen in conventional CDW-bearing materials.

The frequency-dependent reflectance spectra R(ω) at different T were measured by a Bruker IFS 66 v/s spectrometer in the range from 50 to 25,000 cm$^{-1}$ and a grating-type spectrometer from 20,000 to 50,000 cm$^{-1}$. The sample was mounted on an optically black cone on the cold-finger of a He flow cryostat. An in situ gold (50 ~ 15,000 cm$^{-1}$) and aluminum (9,000 ~ 50,000 cm$^{-1}$) overcoating technique was employed for reflectance measurements. A Kramers-Kronig transformation of R(ω) was used to obtain the other optical response functions. A Hagen-Rubens relation was used for low frequency extrapolation, and a constant extrapolation for high-frequency to 300,000 cm$^{-1}$ followed by an $ω^{-2}$ function was used for the higher energy side.

Fig. 1 (a) shows the R(ω) spectra at different T over the frequency range from 50 cm$^{-1}$ to 6,000 cm$^{-1}$ and Fig.
carrier scattering. With decreasing T, R(ω) is the well-known overdamped behavior, similar to the normal and CDW phases. The R(ω) at high T displays a linear-ω dependence up to an edge of 1,100 cm\(^{-1}\). This is the well-known overdamped behavior, similar to the situation in high-T\(_c\) cuprates, indicating rather strong carrier scattering. With decreasing T, R(ω) at low ω decreases, leading to an edge shift towards the low energy region. At the same time, R(ω) between 1,000 and 5,000 cm\(^{-1}\) increases. When the sample is cooled below 150 K, a sharp, well-defined plasma edge appears and then shifts slightly to higher ω with decreasing T. The screened plasma edge frequency is located between 300-350 cm\(^{-1}\) (40 meV) at low T, which is almost two orders of magnitude lower in frequency than for usual metals. The extremely low plasma edge frequency reveals a very small carrier density. Such a well-defined plasma edge is an indication of rather small carrier damping.

The formation of the plasma edge and its evolution with T can be seen more clearly from the energy loss function, Im[-1/ε(ω)], shown in Fig. 2. In the energy loss function, the peak position indicates the screened plasma frequency, while the peak width is related to the carrier damping rate. As T decreases from 300 K to 150 K, the screened plasma frequency decreases from 1132 cm\(^{-1}\) to 300 cm\(^{-1}\), but it then increases from 300 cm\(^{-1}\) to 347 cm\(^{-1}\) as the compound is cooled from 150 K to 10 K. At the same time, the spectral shape changes from a broad feature to a sharp peak structure, suggesting a dramatic reduction of the carrier damping at low T. The peak-like feature near 4,000 cm\(^{-1}\) is not the plasma edge, but is the interband transition due to the formation of a gap.

To quantitatively analyze the carrier density and damping, we fit the experimental reflectance to a simple Drude-Lorentz model:

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ε(ω) = ε_∞ - \frac{ω_p^2}{ω^2 + iω/τ} + \sum_{i=1}^{2} \frac{ω_i^2 - ω^2 - iω/τ_i}{ω_i^2 + iω/τ_i}.
\]  

This expression contains a Drude term and two Lorentz terms, which approximately capture the contributions by free carriers and interband transitions. As shown in the inset of Fig. 1(b), this simple model can reasonably reproduce the R(ω) curves: the calculated curves at 300 K and 10 K are displayed. In the inset of Fig. 2, we plot the plasma frequency ω\(_p\) and scattering rate 1/τ obtained for the Drude term as a function of T. Both parameters show a dramatic change in the temperature range of 150-200 K, in conjunction with the CDW phase transition. An ε\(_∞\)=19 is obtained by fitting. (As the interband transitions are not our focus here, we do not show the parameters for the Lorentz terms.) From this approach, we obtain the unscreened plasma frequency ω\(_p\)≈8000 cm\(^{-1}\) at 300 K, which gives a carrier density of \(7.1 \times 10^{20}\) 1/cm\(^3\). If m=m\(_{e}\) is assumed, which is in good agreement with band structure calculation\(\text{[3]}\). At 10 K, the value of ω\(_p\)≈2700 cm\(^{-1}\) implies a carrier density of \(8.1 \times 10^{19}\) 1/cm\(^3\).
Previous experiments have not conclusively shown whether 1T-TiSe$_2$ is a semiconductor with a very small energy gap or a semimetal with very low carrier density. As a bulk probe with very fine energy resolution, the present optical measurements reveal clearly that the compound is a semimetal with very low carrier density both above and below the CDW transition. Our data, in combination with results obtained from ARPES experiments, lead us to propose a schematic picture for the evolution of the electronic structure with T, displayed in Fig. 4. At room T, small numbers of Se 4p holes $n_h$ and Ti 3d electrons $n_e$ exist near $\Gamma$ and $L$, respectively. Charge neutrality based on the stoichiometry of 1T-TiSe$_2$ requires the same number of holes and electrons. This semimetallic picture, shown in Fig. 4(b), is in agreement with the band structure calculation by Zunger [1]. In this case, the plasma frequency reflects the contribution of two kinds of carriers with $\omega_p^2 = 4\pi\varepsilon\sigma(\omega_0^2 + \omega_m^2)$, where $m_h$ and $m_e$ are the effective mass of $p$ hole and $d$ electrons, respectively.

On decreasing T from room temperature, the carrier density is expected to decrease due to the reduction of the thermally excited carriers for such a semimetal with small negative gap. This is the reason why the plasma edge shifts to lower $\omega$. The increase of the dc resistivity in this temperature regime can be ascribed to this reduction of carrier numbers. An important consequence of the carrier number reduction is that the Coulomb interaction between electrons and holes becomes poorly screened. When the carrier density is low enough, the Coulomb interaction can lead to a bound state between an electron and a hole, i.e., an exciton. As a result, the free carriers are largely removed from the FS below 200K.

Kohn and others have proposed an exciton driving mechanism for a CDW instability in a semiconductor or semimetal with a small indirect energy gap [22, 23]. In the semimetal case, the electron-hole coupling acts to mix electron bands and hole bands that are connected by particular wave vectors which match the superlattice of CDW phase. The associated CDW transition, driven by the energy gain that arises from the gapping of the FS, is referred to as Overhauser type [22, 24]. Considering charge neutrality, it appears that a direct mixing of the hole band near $\Gamma$ and electron band near $L$ can only lead to a hybridization gap at $E_F$, and thus an insulator in the CDW phase, in contradiction to experiments. 1T-TiSe$_2$, however, appears to be a very special case. Because the ordering wave vector is commensurate, $2 \times 2 \times 2$, the new Brillouin zone is reduced in all three directions. Then, all the four points, $\Gamma, A, L$ and $M$ shown in Fig. 4 (a), become new zone center of the $2 \times 2 \times 2$ superlattice. In this case, we need to consider all possible band mixing associated with the superlattice of CDW phase. A band anisotropy can clearly be identified in the band structure calculations [1], which is an essential ingredient for such a semimetal-semimetal transition [22]. In addition to the hole and electron bands that cross $E_F$ near $\Gamma$ and $L$, re-

Figure 3 shows the optical conductivity $\sigma_1(\omega)$ at different T below 6,000 cm$^{-1}$. There are two important features. One is the dramatic suppression of the spectral weight at low $\omega$ below 200 K. The lost spectral weight roughly shifts to the region between 2,000 cm$^{-1}$ and 5,000 cm$^{-1}$, leading to a very pronounced peak centered at 3,200 cm$^{-1}$ (0.4 eV). This is a clear indication of the formation of a gap in the charge excitation spectrum. The gap value can be roughly defined by the linear extrapolation of the peak edge, about 1,250 cm$^{-1}$ (0.15 eV) at lowest T. The second is the Drude-like response at both high and low T, if the very strong phonon contribution is subtracted. The conductivity value at the low frequency limit, which decreases as T decreases from 300 K to 150 K but increases from 150 K to 10 K, matches well the T-dependent behavior of the dc resistivity. A very narrow, sharp Drude component develops below the gap frequency in the CDW phase.
spectively, the Ti 3d band near $M$ is slightly higher than $E_F$, and the Se 4p band near $A$ is slightly lower than $E_F$. Apparently, the mixing of the band near $M$ with that near $L$ leads to a hole-like sub-band (the split upper part of bands may not touch $E_F$), while the mixing of the band near $A$ with that near $L$ leads to an electron-like band (Fig. 4(c)). Therefore, the compound enters into another semimetal state with a new balance of holes and electrons below the CDW transition. As indicated by Kohn, the new hole and electron bands have to be along different $k$ directions. This is precisely what occurs for 1T-TiSe$_2$. The above picture can explain very naturally the coexistence of the gap opening (due to the $\Gamma$-$L$ band mixing) and metallic conduction in the CDW phase.

In the CDW state (below 200 K) the scattering of carriers is strongly reduced, leading to the rapid sharpening of the plasma edge in $R(\omega)$. The reduction of scattering can be attributed to the loss of a scattering channel by FS gapping. The sharp reduction of the conducting carrier density and the sharp reduction of carrier scattering leads to a peak in the dc resistivity near 150 K. Below 150 K, the carrier numbers do not further decrease, instead they increase slightly. The reduction of the dc resistivity on cooling below 150K is dominated by the small and further decreasing carrier scattering rate.

The Overhauser-type CDW picture driven by strong electron-hole coupling appears to provide a good explanation for the variation of the dc and optical transport properties through the CDW transition in 1T-TiSe$_2$. Excitons in semiconductors are a commonly observed phenomenon. However, such excitons are usually created by shining light on the semiconductor, which creates an equal number of electrons and holes. Such optically generated excitons have a very short life time, decaying quickly via the emission of light. The situation in 1T-TiSe$_2$ is very different. It has an equal number of electrons and holes in $K$ space in different bands. The very small carrier density leads to a stable formation of excitons at low T. 1T-TiSe$_2$ might be the only real material for which the CDW transition is realized by the exciton condensation mechanism proposed by Kohn and others.$^{22,23,24}$ A closely analogous phenomenon is the Bose condensation of an electron-hole bound state (exciton) realized in connection with the quantum Hall effect observed in semiconducting bilayer systems.$^{25}$

To summarize, the optical measurements reveal that: (1) 1T-TiSe$_2$ is a semimetal with very low carrier density both above and below the CDW transition temperature; (2) the carrier density changes with temperature, decreasing from room $T$ to roughly 150 K, and then increases slightly with further decreasing $T$; (3) an energy gap $\sim$0.15 eV develops below 200 K in the CDW phase; and (4) dramatically different carrier scattering rates are present in the normal and CDW phases. The experimental data strongly suggest the presence of an Overhauser-type CDW transition in 1T-TiSe$_2$. Further study will help to understand why such an unusual CDW-bearing parent compound becomes a superconductor when a small percentage of excess electrons are doped into it via Cu intercalation.

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