Structural and electrical properties of $TaSe_3$ ring crystals

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Abstract

We have investigated structural and electrical properties of "ribbon-knot" crystals of $TaSe_3$ (superconductor) and $NbSe_3$ (charge density waves conductor) having nontrivial topological structures. These new group of materials can be categorized by a ribbon knot topological invariant in the mathematics field. Hence they are called topological matters. Cutting operation was performed for 29 specimens of the $TaSe_3$ ring crystal using focused ion beam (FIB) sputtering to investigate the structural property. The cut specimens of the ring crystal transformed to arc-shape with homogeneous curvature. At low temperature, whisker and thin ring crystal of $TaSe_3$ showed superconductivity, however, thick ring showed non-metallic behavior. The experimental results suggest that the ring shape structure affect the electrical behavior in the $TaSe_3$ ring crystal.

Key words: $TaSe_3$, ring crystal, topological matters, superconductor

1. Introduction

Geometry effect, which become from the parameter space topology, such as Berry's phase[1], have been a profound theme for theoretical and experimental physics. We succeeded in synthesizing the topological matters, which are ring, Möbius strip, and 2π-twisted-loop crystals of $TaSe_3$ and $NbSe_3$, to observe the effect caused by the global real-space topology in the condensed-matter system[2].

$TaSe_3$ and $NbSe_3$ have unique properties because of competition system of quasi-one-dimensional superconducting and CDW state. So they are highly sensitive from structural modulations. In those materials, the effect of the structural property cannot be neglected to consider electrical property. Under the topological matters, we propose a way of direct observation of the structural property by topological change, which is non-continuous transformation, such as cutting and holing operation. It is considered that the operation of the topological change is a unique and powerful way to expose the topological effect.

To give topological change to our topological matters to investigate the structural property, the cutting operation was performed for specimens of $TaSe_3$ ring crystal. Electrical measurement of the $TaSe_3$ ring crystal was also performed at low temperature around T_C of $TaSe_3$. In this letter, we report structural property given by the cutting operation and comparison with result of the electrical measurement.

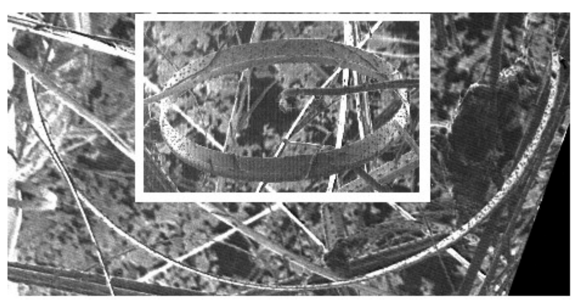


Fig. 1. FIB images of a typical thin specimen of the $TaSe_3$ ring crystal having radius of 18.2 μm and thickness of 0.47 μm. The specimen opened and transformed to arc-shape with homogeneous curvature after cutting operation.

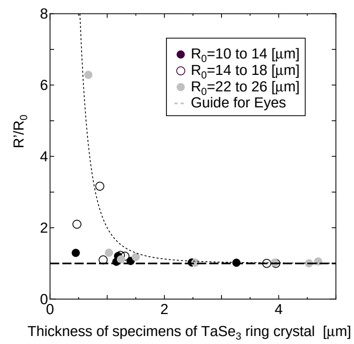
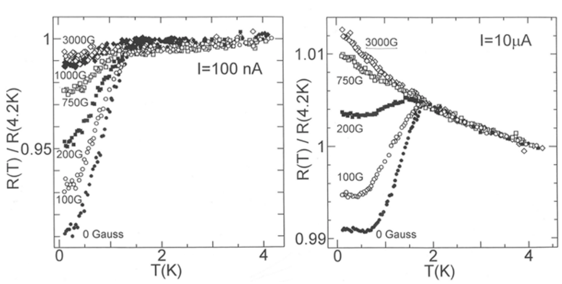


Fig. 2. Thickness dependence of change of curvature by cutting operation. R_0 and R' are radius of curvature before and after the operation respectively. R'/R_0 is larger in the specimens less than 1 μm thickness. As thickness is more than 2 μm, R'/R_0 is almost unity.

2. Experiment

The cutting experiment was performed by focused ion beam (FIB) sputtering. We choose 29 specimens excluding elliptic ring and cut them along radial direction. The cut specimens transformed to arc-shape having homogeneous curvature but no specimen transformed to straight line like whisker (Fig. 1). Thinner specimens than 1 μm opened after cutting operation, but thicker specimens strongly tended to keep their original curvatures (Fig. 2).

Measurement of resistance for specimens of $TaSe_3$ ring crystal was performed at low temperature. Whisker and thin ring showed superconductivity below 2 K. However, our specimens of thick ring crystal showed nonmetallic behavior that was an increase of resistance for decreasing temperature above superconductive transition (Fig. 3).



(a) (b)

Fig. 3. Temparature dependence of nomalized-resistance of two specimens of the $TaSe_3$ ring crystal while applying magnetic-field. Specimen of (a) has outer radius of 40 μm and thickness of 4 μm. Specimen of (b) has outer radius of 38 μm and thickness of 5.5 μm. Figure of (b) shows nonmetallic temperature dependence.

3. Discussion

The result of the cutting experiment says that ring crystals have homogeneous bending stress and plastic deformation inside. The plastic deformation is caused by shears in the chain structures of $TaSe_3$. Because $TaSe_3$ crystal has chain structures bound with weak van der Waals force, it originally tends to make shears in the chain axis when force is applied. Because the thin specimens opened elasticaly, the crystal structure must be a near-perfect single crystal, but incommensurate due to the induced shears.

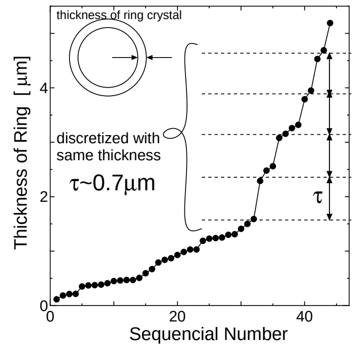


Fig. 4. The cut specimens arrenged in order of the thickness. Thickness of the ring crystal larger than 1.5 μm is discretized with almost constant length.

A conceivable reason of that the non-metallic behavior of the thick specimen of ring crystal would be caused by CDW transition. The enhancement of CDW is caused by defects. Fig.4 shows that thickness of ring crystal is discretized with constant length (about 0.7 μm). It must be caused by another type of defects. During thickness would grow, growing speed would be slower for increasing of bending stress. If the stress induced defects on circumference, growing speed must recover for absence of the bending stress. Due to this mechanism, the thickness of the ring crystal must be discretized. In thick ring having a lot of defects inside, CDW would be enhanced because superconducting state would be broken by the defects.

The topological change by cutting operation proved to be a useful way to investigate crystal structures. For the comparison in order of thickness, we showed experimental proof of that the shape of ring crystal governs the induced defects, and secondary affects the electrical property.

References

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