Superconductivity in Topological Crystalline Insulators (Pb1-xSnx)1-yInyTe

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Abstract

This report presents a concise exploration of topological crystalline insulators (TCIs), specifically focusing on the $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ system and its transition from an insulating to a superconducting state induced by indium substitution. Notably, superconductivity emerges at indium doping levels above approximately 6%, with transition temperatures reaching up to 4.7 K, as highlighted in recent studies [2]. This phenomenon is accompanied by the appearance of nontrivial topological surface states, illustrating a significant interplay between topological insulator states and superconductivity.

The report investigates how indium substitution alters the electronic and structural properties of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$, affecting its superconducting behavior. Key concepts such as band inversion and topological protection are explored to understand their manifestation in superconductivity. The findings have broad implications in condensed matter physics, particularly in understanding the relationship between topological insulators and superconductors, and open potential avenues for applications in quantum computing and advanced technologies [1].

1 Introduction

The exploration of topological materials, particularly topological crystalline insulators (TCIs) like $(Pb_{1-x}Sn_x)_{1-y}In_yTe$, represents a significant stride in condensed matter physics. The journey into understanding these materials

traces back to the early 20th century with the discovery of superconductivity by Heike Kamerlingh Onnes in 1911 [3]. This groundbreaking discovery laid the foundation for a century of advancements, leading to the exploration of complex quantum phenomena in materials like $(Pb_{1-x}Sn_x)_{1-y}In_yTe$.

In recent years, the study of TCIs has garnered attention due to their unique electronic properties and potential applications in technology and quantum computing. The $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ system, in particular, has been a subject of intense research. This material exhibits a fascinating interplay between its crystal structure, electronic band structure, and superconducting properties, all of which are influenced by indium concentration [2, 1].

This report aims to provide an in-depth analysis of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$, drawing from a collective body of research. We will delve into the material's crystal and band structures, examining how these fundamental aspects contribute to its unique thermal, vibrational, and magnetic properties. The focus will then shift to its superconducting behavior and electronic transport properties, exploring how these are affected by various experimental conditions and synthesis techniques.

Through this comprehensive overview, the report will not only shed light on the intricate properties of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ but also highlight its significance in the broader context of modern physics and material science.

2 Crystal Structure

The crystal structure of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$, as detailed in Zhong et al. 2017, is a fundamental aspect that defines its properties as a topological crystalline insulator. This material crystallizes in the cubic rocksalt structure, a characteristic configuration for IV-VI semiconductors. The lattice parameters and space group of this compound are crucial in defining its electronic behavior.

In the study by Zhong et al., the lattice parameters of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ are shown to vary with the concentrations of indium and tin. This variation is attributed to the differences in atomic sizes and bonding characteristics of Pb, Sn, and In. Specifically, the substitution of Sn with Pb leads to an increase in the lattice constant, while In substitution results in a decrease. These changes in lattice parameters affect the crystal symmetry and are directly linked to the electronic band structure of the material.

The X-ray powder diffraction (XRD) patterns presented in Zhong et al.

2017 illustrate these variations in lattice parameters. The study shows how Pb doping increases the lattice constant compared to the parent compound SnTe, and subsequent In doping decreases it, affecting the overall symmetry and electronic structure of the material [2].

The response of the rocksalt structure to elemental substitution is key to understanding the formation of electronic bands, including the topologically non-trivial bands that are central to the material's unique properties. The detailed analysis of the crystal structure provided by Zhong et al. offers insights into how these structural changes influence the topological characteristics and superconducting behavior of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$.

3 Band Structure

The band structure of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ is a critical aspect of its electronic properties, particularly in the context of topological crystalline insulators. A key feature of this material is the band inversion, a phenomenon observed in both PbTe and SnTe, which are the end members of this compound series.

In PbTe and SnTe, band inversion occurs at the L points of the Brillouin zone. This inversion is a result of the strong spin-orbit coupling and is essential for the emergence of topological surface states. In $(Pb_{1-x}Sn_x)_{1-y}In_yTe$, the extent of band inversion is influenced by the relative concentrations of Pb, Sn, and In. Indium doping, in particular, plays a significant role in modifying the band structure. As indium is introduced into the lattice, it affects the size of the band gap and alters the electronic states near the Fermi level.

The reduction in the band gap size with increasing indium concentration is crucial for the material's transition from a trivial insulator to a topological crystalline insulator. This transition is accompanied by the appearance of Dirac-like surface states, indicative of the material's topological phase. The precise nature of these topological states and their evolution with indium doping are central to understanding the electronic behavior of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$.

The band structure of $(Pb_{1-x}Sn_x)_{1-y}In_yTe$, particularly the behavior of band inversions and the influence of indium doping, is fundamental to the material's potential applications in spintronics and quantum computing, where topological properties are of paramount importance.

4 Topological Surface States

The topological surface states in $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ are a distinctive feature that defines its behavior as a topological crystalline insulator. These states emerge as a direct consequence of the unique band structure of the material, particularly due to band inversions induced by the specific stoichiometry of Pb, Sn, and In.

In $(Pb_{1-x}Sn_x)_{1-y}In_yTe$, the presence of topological surface states has been confirmed through advanced spectroscopic techniques. Notably, angle-resolved photoemission spectroscopy (ARPES) studies have revealed the existence of Dirac cones in the electronic structure, a clear signature of topological insulators. These Dirac cones, observed at the material's surface, are indicative of the linear dispersion of the surface states and are closely tied to the topological nature of the material.

The indium concentration in $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ plays a crucial role in the manifestation of these topological surface states. As the indium content increases, there is a notable impact on the band structure, particularly affecting the band gap and the nature of the surface states. This variation leads to a modulation in the topological properties of the material, transitioning from a trivial insulator to a topological crystalline insulator with distinct surface states.

These topological surface states are not only of fundamental interest but also hold potential for practical applications. Their robustness against external disturbances, a result of topological protection, makes them promising for use in spintronics and quantum computing technologies. The exploration of these states in $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ is pivotal for understanding the interplay between topology and material properties, offering insights into novel quantum phenomena.

5 Superconductivity in $(Pb_{1-x}Sn_x)_{1-y}In_yTe$

Superconductivity in $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ is a phenomenon of particular interest due to its coexistence with the material's topological properties. The onset of superconductivity, characterized by zero electrical resistance and the Meissner effect, is significantly influenced by indium doping in this compound.

The introduction of indium into the $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ lattice leads to

notable changes in its superconducting behavior. As reported by Zhong et al., increasing the indium concentration results in a transition from an insulating to a superconducting state. This transition is accompanied by a variation in the critical temperature, which is observed to increase with higher levels of indium doping, suggesting a direct relationship between indium content and the onset of superconductivity [2].

Furthermore, the study by Pletikosić et al. explores the nature of superconductivity in relation to the topological aspects of the material. The presence of topological surface states, along with the conventional electron-phonon coupling mechanism, indicates a complex interplay contributing to the superconducting state in $(Pb_{1-x}Sn_x)_{1-y}In_yTe$. The interaction between these topological states and superconducting electrons is a subject of ongoing research, offering insights into the material's unique electronic properties [1].

The investigation of superconductivity in $(Pb_{1-x}Sn_x)_{1-y}In_yTe$ is not only crucial for understanding the fundamental physics of superconductors but also holds potential for applications in quantum technology, where both superconductivity and topological properties are of paramount importance.

6 Material Synthesis and Experimental Techniques

6.1 Synthesis

6.2 Experimental Techniques

7 Summary

Figures

References

References

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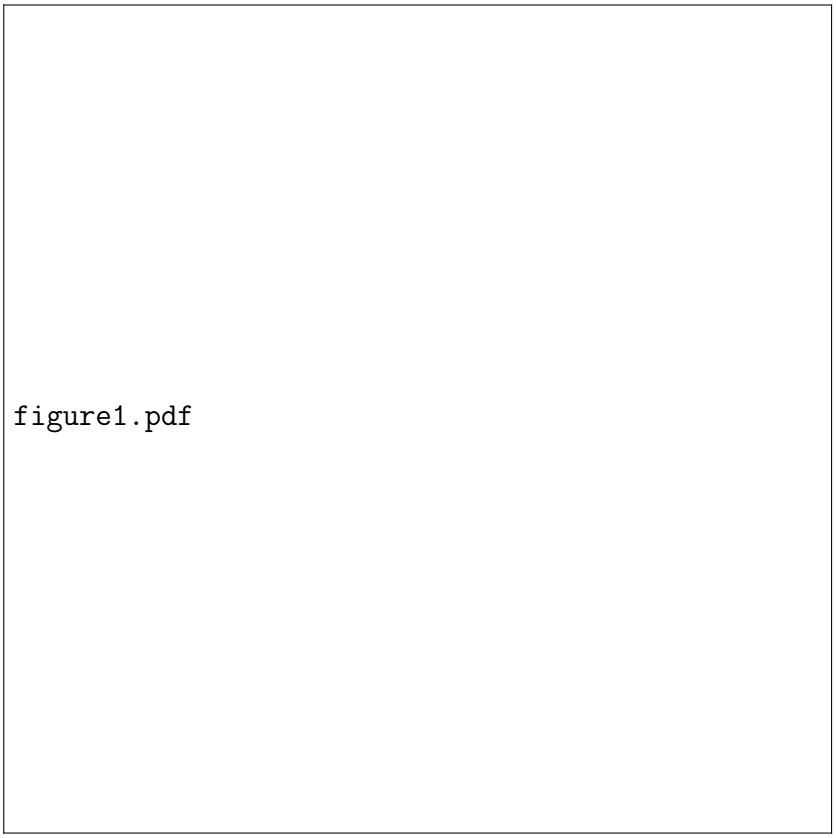

Figure 1: Caption for Figure 1.

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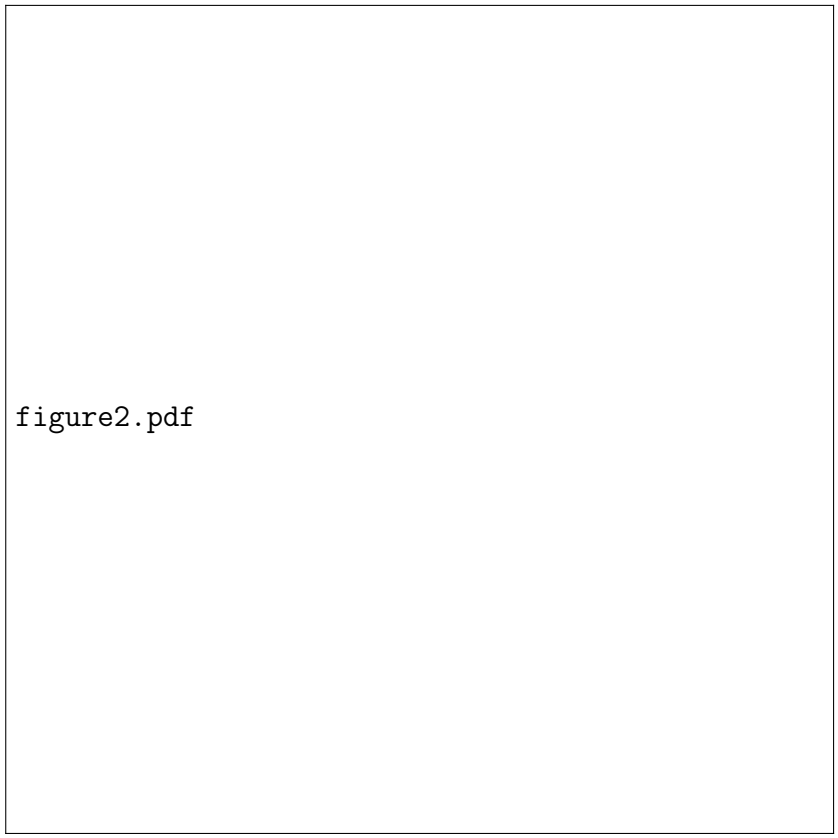

Figure 2: Caption for Figure 2.