量子反常霍尔效应研究进展

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2019-12-05 收稿, 2020-01-20 修回, 2020-01-20 接受, 2020-01-21 网络版发表

国家重点基础研究发展计划(2018YFA0307100, 2017YFA0303303)和国家自然科学基金(51661135024)资助

摘要 量子反常霍尔效应是一种不需要外加磁场的量子霍尔效应. 它不但为手征量子霍尔态的理解和应用提供了一个理想的研究平台, 还可以用于构建多种新奇拓扑量子物态. 本文回顾了近年来量子反常霍尔效应实验方面的研究进展, 包括对磁性掺杂拓扑绝缘体中量子反常霍尔效应相关机理的深入研究、基于量子反常霍尔绝缘体的各种异质结构的制备及性质研究, 以及可能具有更高工作温度的量子反常霍尔效应材料体系的探索等. 这些研究进展对量子反常霍尔效应的未来发展方向和凝聚态物理的发展具有重要的启示作用.

关键词 量子反常霍尔效应, 拓扑绝缘体, 磁性掺杂, 异质结构, 内禀磁性

1 量子反常霍尔效应的原理及其实现

20世纪80年代, 整数和分数量子霍尔效应的发现开启了一扇通往奇异的拓扑量子物态世界的大门^[1,2]. 此后30多年里, 物理学家构想出很多新奇的拓扑量子物态, 这不但大大推动了凝聚态物理领域的发展, 还为低能耗电子器件和量子计算的发展提供了新思路. 2016年诺贝尔物理学奖授予了在拓扑相变和拓扑物态方面做出杰出贡献的3位理论物理学家, 这是此领域近年来蓬勃发展的一个标志. 但拓扑物态领域存在一个很大的问题: 只有很少数的新奇拓扑物态能够在实验中获得实现. 很长一段时间里, 实验上寻找新拓扑物态的几乎唯一的途径是在极低温度、极强磁场环境中研究具有极高载流子迁移率的量子霍尔系统. 这类研究高度依赖于各种尖端实验技术的发展水平, 进展较为缓慢, 更难以实现拓扑物态的应用. 1988年, 美国理论物理学家F. D. M. Haldane构想出一个基于石墨烯晶格的简单模型, 其能带结构具有和 $\nu=1$ 的整数量子霍尔系

统类似的拓扑不变量(ν 是整数), 在不需要外加磁场形成朗道能级的情况下就可以产生整数量子霍尔效应, 即具有量子化的霍尔电阻(h/e^2)和零纵向电阻(h 是普朗克常数, e 是电子电荷). 这种不需要外加磁场的量子霍尔效应后来被称为量子反常霍尔效应^[3]. Haldane的这项研究表明, 人们可以通过调控材料的能带结构获得拓扑物态, 指出了通往拓扑物态世界的一条更简单的道路. 2005年前后, 在一定程度上受到Haldane模型的启发, 人们发现了一类新的拓扑物态: 时间反演不变拓扑绝缘体(简称拓扑绝缘体)^[4-8]. 由于可以基于能带理论去设计材料, 人们很快就发现了多种属于拓扑绝缘体的材料, 这大大加快了拓扑物态的研究步伐.

通过进一步在拓扑绝缘体薄膜中引入磁有序破坏时间反演对称性, 则有可能实现量子反常霍尔效应. 例如, 在三维拓扑绝缘体薄膜中通过磁性掺杂, 能够获得垂直于膜面方向的磁化, 薄膜的上下表面因此会打开能隙并形成具有不同拓扑性质的表面态. 同时, 薄膜侧面作为两个不同拓扑相的边界将出现手征量子霍尔边

引用格式: 冯硝, 何珂, 王亚愚, 等. 量子反常霍尔效应研究进展. 科学通报, 2020, 65: 800-809

Feng X, He K, Wang Y Y, et al. Recent progress in the research of quantum anomalous Hall effect (in Chinese). Chin Sci Bull, 2020, 65: 800-809, doi: 10.1360/TB-2019-0801

缘态, 从而实现量子反常霍尔效应. 因此, 要实现量子反常霍尔效应, 需要获得拓扑绝缘体薄膜, 需要在保持拓扑性质不变的情况下引入具有垂直易磁化轴的长程铁磁序, 还需要将体系的费米能级同时调节到上下表面态的磁能隙中以使输运性质完全由边缘态贡献.

本研究组及其合作者^[9~11]使用分子束外延生长设备制备出了高质量、层厚精确可控的拓扑绝缘体薄膜, 在 $(\text{Bi}, \text{Sb})_2\text{Te}_3$ 薄膜中通过精确控制Bi/Sb束流比例减少了体载流子浓度^[12], 并利用碳酸镱衬底低温下的巨大介电常数实现了对薄膜费米能级的精确场效应调控. 在此基础上, 通过掺杂磁性元素Cr成功在薄膜中引入具有垂直易磁化轴的长程铁磁性^[13]. 最终, 于2012年底在5层Cr掺杂的 $(\text{Bi}, \text{Sb})_2\text{Te}_3$ 拓扑绝缘体薄膜中首次实验观测到了量子反常霍尔效应^[14](图1), 为探索新奇量子现象开辟了新的方向.

2 量子反常霍尔效应实现温度的提高

量子反常霍尔效应不依赖于朗道能级, 理论上可以在比实现量子霍尔效应更高的温度下实现. 然而, 在Cr掺杂的 $(\text{Bi}, \text{Sb})_2\text{Te}_3$ 拓扑绝缘体薄膜中量子反常霍尔

效应的实现温度仅为30 mK, 这大大限制了进一步的研究和应用. 针对这个问题, 本研究组^[15]系统研究了Cr掺杂的 $(\text{Bi}, \text{Sb})_2\text{Te}_3$ 拓扑绝缘体薄膜中量子反常霍尔效应随层厚的变化. 当薄膜厚度较小时(<4 quintuple layer, QL), 会发生量子反常霍尔相到普通绝缘体相的转变; 当厚度较大时(>6 QL), 会由于其他导电通道的引入而使其霍尔电阻逐渐偏离量子化; 厚度为4 QL的薄膜在零磁场下霍尔电阻偏离量子化数值, 但是强磁场下可以实现完全量子化(图2(a)). 此项工作描绘了磁性拓扑绝缘体薄膜中量子反常霍尔相的相图, 并说明在磁性掺杂拓扑绝缘体中, 磁无序可能对于量子反常霍尔效应的实现温度起着重要作用. 在扫描隧道显微镜^[16]、纳米-超导量子干涉仪^[17]和输运^[18,19]等研究中, 人们也的确观测到了磁性掺杂拓扑绝缘体中高度不均匀的磁结构.

因此, 通过改善体系中的磁有序度有可能提高量子反常霍尔效应的观测温度^[20~31]. 美国麻省理工学院Moodera研究组^[21,22]在V掺杂的 $(\text{Bi}, \text{Sb})_2\text{Te}_3$ 薄膜中也观察到了量子反常霍尔效应. 该体系具有更大的矫顽场, 也就意味着更强的磁各向异性, 在零磁场附近铁磁

图 1 磁性掺杂拓扑绝缘体薄膜中量子反常霍尔效应的实验发现. (a) 磁性掺杂拓扑绝缘体薄膜中量子反常霍尔效应测量示意图; (b) 零磁场下霍尔电阻和纵向电阻随背栅极电压变化曲线; 不同栅极电压下霍尔电阻(c)和纵向电阻随磁场变化曲线(d). Reprinted with permission from Ref. [14], Copyright © 2013 AAAS

Figure 1 Experimental realization of quantum anomalous Hall (QAH) effect in magnetically doped topological insulator (TI) thin films. (a) Sketch for QAH measurement in magnetic-doped TI; (b) back gate dependence of $\rho_{yx}(0)$ and $\rho_{xx}(0)$ curves; magnetic field dependence of $\rho_{yx}(0)$ (c) and $\rho_{xx}(0)$ curves (d) with different back gate voltage^[14]. Reprinted with permission from Ref. [14], Copyright © 2013 AAAS

图2 磁性掺杂拓扑绝缘体中的磁无序。(a) 不同层厚磁性拓扑绝缘体薄膜中霍尔电阻和纵向电阻随磁场的变化曲线, Reprinted with permission from Ref. [15], Copyright © 2016 John Wiley and Sons. (b) 扫描隧道显微镜观测到的磁性掺杂拓扑绝缘体中不均匀的磁结构^[16]
Figure 2 Magnetic disorder in magnetically doped TIs. (a) Thickness dependence of the QAH effect at high magnetic field^[15], reprinted with permission from Ref. [15], Copyright © 2016 John Wiley and Sons; (b) atomic-scale measurement of non-uniform magnetic structure in magnetically doped TI by scanning tunneling microscope (STM)^[16]

序会更好,使得这个系统的纵向电阻在零磁场下可以严格降至零。然而,此系统的量子反常霍尔的实现温度仍然很低。研究发现,该体系的狄拉克点低于价带顶^[23],体导电通道的参与可能是此系统无法在更高温度实现量子反常霍尔效应的原因。日本RIKEN研究所Tokura研究组^[24]通过调制掺杂的方式制备了类似“拓扑绝缘体/重磁性掺杂绝缘体/拓扑绝缘体/重磁性掺杂绝缘体/拓扑绝缘体”的5层结构,他们在He₃制冷机的温度(~300 mK)就可以实现很好的量子化,然而其机理尚不清楚(图3(a~c))。在稀磁半导体中,通过磁性元素共掺杂的方式可以增强磁有序。本研究组^[26]制备出了Cr与V共掺杂的(Bi, Sb)₂Te₃薄膜,获得了比单一磁性元素掺杂更高的量子反常霍尔效应实现温度(图3(d~f)),与Tokura研究组的研究结果相仿。磁力显微镜研究显示,这种磁性共掺杂的拓扑绝缘体薄膜确实比Cr或V单独掺杂的薄膜具有更高的磁有序度。通过选择不同的磁性共掺杂组合,或许能进一步提高量子反常霍尔效应的实现温度。

为了进一步提高量子反常霍尔效应的观测温度,人们从理论上也提出了多种设想^[27~31]。其中一个可能的途径就是利用由两个铁磁绝缘体层和夹在中间的拓扑绝缘体层组成的三明治结构。铁磁绝缘体一般具有更高的磁有序度,其居里温度可能高于磁性掺杂的拓扑绝缘体,因此有希望实现更高温度的量子反常霍尔效应。然而,尽管有很多铁磁绝缘体-拓扑绝缘体异质结构的研究工作报道了拓扑绝缘体中的近邻铁磁性,但所获得的反常霍尔电阻都远低于量子化数值^[33]。最近,日本Tokura研究组^[32]制备了(Zn,Cr)/(Bi,Sb)₂Te₃/

(Zn,Cr)Te的三明治结构并成功观测到了量子反常霍尔效应,但是实现温度仍旧很低。可能的一个原因是铁磁绝缘体会将拓扑绝缘体表面态推离界面,导致其与铁磁绝缘体层的相互作用很弱。在拓扑绝缘体的亚表面区域插入铁磁绝缘体薄层可能可以解决这个问题,从而提高量子反常霍尔效应的实现温度,这也可能是前面介绍的调制掺杂结构能够提高量子反常霍尔效应观测温度的原因之一^[24]。而近期备受关注的层状磁性材料^[34,35],也可以作为拓扑绝缘体的插层来实现更高温度的量子反常霍尔效应。

除了铁磁绝缘体,反铁磁绝缘体的铁磁表面也可以用来打开拓扑绝缘体的表面能隙。在自然界中,相比铁磁绝缘体材料,反铁磁绝缘体材料更为丰富,如MnSe和MnTe族材料,它们具有与Bi₂Se₃族拓扑绝缘体相近的晶格结构,(111)表面具有垂直方向易磁化轴^[36]。由于量子反常霍尔效应的实现需要上下两个表面态在具有相同磁化方向的磁矩下形成能隙,如何控制上下两个反铁磁绝缘体与拓扑绝缘体界面的磁化方向一致是一个很重要且又很有挑战性的难题。

3 零电导平台现象

既然量子反常霍尔效应是由材料的磁化所致,那么在磁化反转过程中两个量子反常霍尔平台之间的相变如何进行,是否和量子霍尔平台间相变具有类似的规律?目前,有两个研究组分别独立发现了在Cr掺杂的(Bi, Sb)₂Te₃磁性拓扑绝缘体薄膜矫顽场附近出现的零霍尔电导平台现象,表明在两个量子反常霍尔平台之间的相变要经过一个普通绝缘体相,从而呈现一个

图 3 可以提高量子反常霍尔效应实现温度的3种结构设想。“拓扑绝缘体/重磁性掺杂绝缘体/拓扑绝缘体/重磁性掺杂绝缘体/拓扑绝缘体”的5层结构的结构示意图(a)、霍尔电阻(b)和纵向电阻(c)随温度的变化曲线^[24]。Copyright © 2015 AIP Publishing; 磁性共掺杂拓扑绝缘体的结构示意图(d)、零磁场霍尔电阻和纵向电阻随温度(e)及栅极电压(f)的变化曲线。其中红色箭头表示磁化矢量方向^[26]。Copyright © 2017 John Wiley and Sons. 三明治结构的结构示意图(g)、霍尔电阻和纵向电阻随磁场(h)及温度(i)的变化曲线^[32]。Copyright © 2019 AIP Publishing

Figure 3 The structural schematic diagram for QAH system. (a) Penta-layer structure which has the heavily magnetically doped (HMD) layer as sub-surface layer; temperature dependence of R_{yx} (b) and R_{xx} (c)^[24], Copyright © 2015 AIP Publishing; (d) magnetic co-doped TI for QAH; (e) temperature and (f) back gate voltage dependence of ρ_{yx}^0 (0) and ρ_{xx}^0 (0)^[26], Copyright © 2017 John Wiley and Sons. The red arrow indicates the direction of magnetic moment; (g) sandwich heterostructure for QAH; (h) magnetic field and (i) temperature dependence of R_{yx} and R_{xx} ^[32], Copyright © 2019 AIP Publishing

零霍尔电导和零纵向电导的平台^[37,38](图4(a, b))。系统的研究发现, 量子反常霍尔效应平台间相变的规律与传统量子霍尔效应不同, 不能用网状模型描述, 有可能是来自磁化过程中磁畴运动对电子态的影响(图4(c))。

在异质的磁性拓扑绝缘体薄膜中可以观察到另一种有趣的零电导平台现象。前面提到, 在磁性三维拓扑绝缘体薄膜中, 当上下两个表面的垂直方向的磁化矢量指向相同时, 会呈现量子反常霍尔效应; 但如果磁化矢量指向相反, 上下两个表面会具有相同的拓扑性质, 此时量子反常霍尔边缘态将会消失, 直流输运测量中系统会显示出普通绝缘体的行为, 即呈现霍尔电导和纵向电导均为零的平台(图4(d))。但在交流输运测量中, 系统则会呈现拓扑磁电效应。与平常的磁电效应不同, 拓扑磁电效应中电场和磁场共线耦合, 且耦合常数是

与精细结构常数有关的量子化值。这种绝缘体可以看作作为粒子物理中的轴子在固体物理中的版本, 因此被称为轴子绝缘体^[4,5]。已有几个实验工作通过量子反常霍尔薄膜异质结构实现轴子绝缘体结构。这些薄膜的上下两个表面附近含有不同的磁性掺杂浓度或者元素, 因此具有不同的矫顽场; 而在中间区域不掺杂磁性元素, 使两个表面层没有磁耦合, 这样可以通过调控外磁场使其上下表面具有相反的磁化方向。在这些异质结构中, 清楚的零电导平台已经在直流输运测量中被观测到, 但是拓扑磁电效应的实验观测仍旧是一个巨大的挑战^[39-41]。

4 量子反常霍尔系统的多层结构

现有的量子反常霍尔效应体系的陈数 $C=1$, 即只有

图4 零电导平台现象。(a), (b) 磁性掺杂拓扑绝缘体薄膜中的零霍尔电导平台现象^[37,38], Copyright © 2015 AIP Publishing. (c) 磁化反转过程中的磁畴模型示意图^[37]。黄色和绿色箭头分别标记了磁化矢量向上和向下的磁畴; (d) 上下表面磁化矢量方向相反的轴子绝缘体零电导平台现象(上图)和相同的(下图) $C=1$ 的量子反常霍尔效应^[39]及相应的(e, f)三明治结构示意图, 其中红色箭头表示磁化矢量方向。Copyright © 2017 AAAS. Reprinted/modified from Ref. [39]. © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) <http://creativecommons.org/licenses/by-nc/4.0/>
Figure 4 Zero Hall conductance plateau. (a), (b) Zero Hall conductance plateau in magnetically doped TI^[37,38], Copyright © 2015 AIP Publishing; (c) schematic representation of the multi-domain formed during the magnetization reversal process^[37]. Yellow and green arrow denote the up and down magnetic domain respectively; (d) axion insulator (upper) and $C=1$ QAH insulator (lower) respectively with the magnetization of top and bottom surface in anti-parallel and parallel configuration^[39]; (e), (f) their sandwich structure respectively. Red arrow indicates the direction of magnetic moment. Copyright © 2017 AAAS. Reprinted/modified from Ref. [39]. © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) <http://creativecommons.org/licenses/by-nc/4.0/>

一条手性边缘通道。将两层相同的量子反常霍尔薄膜堆叠在一起, 中间由普通绝缘体层隔开, 可能构成具有两条平行手性边缘通道的量子反常霍尔系统, 具有等效的陈数 $C=2$ 。如果这两层量子反常霍尔薄膜有相反的磁化矢量, 则两个手性边缘态有相反的动量和自旋方向, 则可以形成类似量子自旋霍尔绝缘体的螺旋边缘态, 但不同的是两支边缘态在空间上是分离的。当所涉及的物理问题的尺度(比如超导相干长度、自旋弛豫平均自由程)远大于两支边缘态的间距时, 这种量子反常霍尔双层结构可以表现出和量子自旋霍尔系统类似的行为。堆叠多层量子反常霍尔效应薄膜, 以普通绝缘体层间隔, 可以得到等效的高陈数量子反常霍尔系统; 通过减小量子反常霍尔薄膜和普通绝缘体的厚度使量

子反常霍尔层间的电子态杂化, 可以获得仅有一对外尔点的磁性外尔半金属^[42]; 库伦相互作用可能在量子反常霍尔双层和多层结构中引起更多有趣的现象, 正如量子霍尔双层膜中所发现的库伦拖曳、激子凝聚等。

本研究组^[43]使用分子束外延生长方法制备了磁性掺杂的 $(\text{Bi}, \text{Sb})_2\text{Te}_3$ 量子反常霍尔薄膜和 $\text{CdSe}(0001)$ 普通绝缘体薄膜的超晶格结构(CVBST/ CdSe), 实现了最大为4层的量子反常霍尔多层结构, 并在实验中测量到 h/Ne^2 的等效高阶量子反常霍尔效应(图5(d), N 为层数), 这为寻找新的拓扑态铺平了道路。由于导电通道并联导致的“热点”处电阻的减小, 这种量子反常霍尔多层结构的两端电阻随层数增加明显降低, 这对量子反常霍尔手征边缘态应用于低能耗电学器件具有重要指导

图5 量子反常霍尔系统的多层结构。(a) CVBST/CdSe超晶格结构示意图; 该结构的扫描电子显微镜截面图(b)和区域放大图(c); (d) $N=1\sim 4$ 层超晶格结构中霍尔电阻和纵向电阻随磁场变化曲线^[43]

Figure 5 Multilayer structure of the QAH system. (a) Schematic structure of CVBST/CdSe superlattice; cross-sectional transmission electron microscope (TEM) image (b) and zoom-in image (c); (d) magnetic field dependence of R_{yx} and R_{xx} curves in $N=1\sim 4$ samples^[43]

意义。

5 手性拓扑超导体系

量子反常霍尔绝缘体与S波超导体的近邻效应可以表现出手性拓扑超导体的性质^[5]。在这种拓扑超导体的磁性涡旋中有可能出现Majorana束缚态。这种束缚态可以用于构成具有较强抗退相干能力的拓扑量子比特。在手性拓扑超导体和量子反常霍尔绝缘体的边界处, 存在具有能量-动量色散的手性Majorana边缘态, 可以认为是手性量子反常霍尔边缘态的一半^[44]。利用手性Majorana边缘态的干涉效应可以用来探测Majorana束缚态和读取拓扑量子比特^[45,46]。手性Majorana边缘态存在的一个特征是具有 $1/2$ 量子化数值的两端电导平台^[47,48]。这方面最近已有实验报道, 但尚待确认^[49]。为了避免界面无序产生的干扰, 探索及制备更加干净、可控的量子反常霍尔-超导体界面对这一方向的进一步研究至关重要。近期发现, 只有几个原子层的 α -Sn薄膜具有超导电性, 而且可以通过PbTe缓冲层外延生长在 Bi_2Te_3 族拓扑绝缘体上。因此 α -Sn薄膜或许可以用来构成理想的量子反常霍尔-超导体界面^[50]。

6 探索新的量子反常霍尔效应材料体系

在磁性掺杂拓扑绝缘体中, 磁性杂质导致的电子结构和磁性的不均匀是量子反常霍尔效应实现温度极

低的主要成因之一, 也大大增加了手性Majorana相关研究的难度。理想的磁性拓扑绝缘体应当是内禀的, 即具有确定的化学配比、磁性元素排列有序的化合物。在Mn掺杂的 Bi_2Se_3 (Bi_2Te_3)及 MnSe (MnTe)与 Bi_2Se_3 (Bi_2Te_3)的异质结构中, 人们观察到了 MnBi_2Te_4 (MnBi_2Te_4)相的存在。这是一种层状材料, 每个“七层”(septuple layer, SL)按照Te-Bi-Te-Mn-Te-Bi-Te的顺序由7个单原子层堆垛而成^[51~54]。如果这类材料低温下具有铁磁序, 居里温度以上是拓扑绝缘体, 则是一种内禀的磁性拓扑绝缘体, 有可能在更高温度下实现量子反常霍尔效应。有理论工作发现将1 SL厚的 MnBi_2Te_4 生长于 Bi_2Te_3 上时, 会使拓扑绝缘体表面态“拓展”到 MnBi_2Te_4 层, 从而与铁磁层形成较强的相互作用, 能够获得最大为77 meV的磁能隙^[31], 但并未解释其原因。本研究组使用分子束外延生长方法, 通过交替制备单层 Bi_2Te_3 和 MnTe 以及控制随后退火的过程, 可以一个SL接一个SL制备出 MnBi_2Te_4 薄膜^[55]。利用角分辨光电子能谱可以观测到厚度在2 SL及以上的薄膜中存在狄拉克型无能隙表面态(图6(a)), 表明这是一个三维拓扑绝缘体。这很自然地解释了为何它与 Bi_2Te_3 的异质结构会使拓扑表面态“拓展”到其表面。结合磁性测量结果和第一性原理计算, 他们发现这种材料的体相是一种反铁磁拓扑绝缘体: Mn原子的磁矩在每个SL内为铁磁排列, 在SL之间为反铁磁排列。进一步的理论计算结果发现, 这种独特

图6 探索新的量子反常霍尔材料体系MnBi₂Te₄。(a) 不同层厚MnBi₂Te₄薄膜的表面电子结构；(b) MnBi₂Te₄原子结构示意图；(c) 剩余磁矩和矫顽场随层厚的变化曲线^[55]

Figure 6 MnBi₂Te₄—A new QAH system. (a) Energy band structure of MnBi₂Te₄ with different thickness; (b) schematic crystal structure of MnBi₂Te₄; (c) thickness dependence of remnant magnetization (upper panel) and coercive field (lower panel)^[55]

的磁结构使得这种材料显示出极其丰富的、性能优异的拓扑量子物态：奇数层的薄膜处于量子反常霍尔相、偶数层的薄膜处于轴子绝缘体相并呈现拓扑磁电效应，三维体相则是追寻已久的具有拓扑轴子表面态的反铁磁拓扑绝缘体，在外加磁场下又可转变为最简单(只有一对外尔点)的磁性外尔半金属^[56–58]。近期，复旦大学张远波研究组^[59]在单晶解理的5 SL奇数层MnBi₂Te₄薄膜中，观察到了量化的霍尔电阻和零纵向电阻($T=1.6$ K, $\mu_0 H>6$ T)，分析发现，这是由于材料的层间反铁磁性及材料缺陷带来的磁交换能隙涨落，因此需要外加强磁场来实现量子反常霍尔效应。清华大学王亚愚研究组^[60]则在6 SL的MnBi₂Te₄薄膜中观察到了轴子绝缘体相，并在外加强磁场的作用下实现了轴子绝缘体相到Chern绝缘体相的相变，进一步确认了材料的层间反铁磁性质。北京大学王健研究组^[61]在7 SL和9 SL解理薄膜中分别观察到了 $C=1$ 和 $C=2$ Chern绝缘体相，在温度近60 K时，还能观测到数值为 $0.784h/e^2$ 的霍尔电阻平台。理论预言，这种材料的拓扑表面态上可能存在大于38 meV的磁能隙，意味着可以在更高温度下实现量子反常霍尔效应及其他量子效应。

MnBi₂Te₄中有序的磁性原子排列、巨大的磁能隙，以及所蕴含的丰富的拓扑相使其成为一个理想的磁性拓扑绝缘体系统，为量子反常霍尔效应实现温度的提高指出了一条新的道路，并可以作为研究多种拓扑物态和量子效应的平台，用于探索维度、磁性、对称性

与拓扑之间的相互作用以及由此衍生出的新物理与新应用。而且与Bi₂Te₃或MnTe能够形成异质超晶格，如MnBi₄Te₇和MnBi₆Te₁₀^[62,63]，为实现量子反常霍尔效应等新奇量子现象提供了更为广阔的材料平台。

除磁性拓扑绝缘体之外，人们也在探索其他体系中的量子反常霍尔效应。2014年，苏黎世联邦理工学院的Esslinger研究组^[64]在冷原子系统中模拟出了Haldane^[3]提出的零磁场量子霍尔效应模型。最近，美国两个研究组在双层和三层魔角石墨烯体系中分别观测到了陈数为1和陈数为2的量子反常霍尔效应，前者可以在1.5 K以上的温度实现完全量子化^[65,66]。这些进展进一步拓展了量子反常霍尔效应的研究范围。

7 总结和展望

量子反常霍尔效应实验的实现不仅是拓扑量子物态领域的一个标志性实验进展，更为探索各种新奇量子现象和应用开辟了新的道路。量子反常霍尔效应的无耗散的一维边缘导电通道有可能在未来低耗散电子学和量子计算领域发挥重要作用。目前该领域的主要研究目标是继续提高量子反常霍尔效应的实现温度，寻找更容易制备的量子反常霍尔效应体系，通过各种异质结构实现新奇量子效应，并探索基于量子反常霍尔效应及相关量子效应的各种应用。这些工作将使拓扑量子物态这一基础凝聚态物理学对电子学、信息科学与技术等领域产生重大的推动。

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Summary for “量子反常霍尔效应研究进展”

Recent progress in the research of quantum anomalous Hall effect

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The quantum anomalous Hall (QAH) effect is a quantum Hall effect that can occur without external magnetic field. The experimental realization of this effect in magnetically doped topological insulator thin films not only provides an ideal platform for research and application on chiral quantum Hall state, but also paves the way for constructing many other exotic topological quantum phases. But the realization temperature of QAH is quite low. The non-uniform magnetic disorder could be one of main reasons. To increase the uniformity of magnetic order, different element was doped, like V instead of Cr, or Cr-V co-doping, which enhance the magnetic anisotropy in the system. In Cr-V co-doping system, the realization temperature of the QAH was ten times enhanced. Also, a penta-layer structure with heavily doped sub-surface layer was formed to effectively increase the QAH temperature. In this structure, the modulation-doping originates from the suppression of the disorder in the surface state interacting with the rich magnetic moments. In the future, with combined element doping and modified structure, we may get much improved QAH temperature. To elevate the working temperature of the QAH effect, a TI sandwiched by two ferromagnetic insulator layers is also applied because of the more ordered structure and potentially high Curie temperature. Although several works on FMI/TI heterostructure reports the proximity ferromagnetic in TI, the QAH was observed at quite a low temperature in an all-telluride base heterostructure. A strong coupling between the surface state of TI and ferromagnetic layer could be required.

In a magnetically doped TI system, it is natural to ask how a QAH system evolves in a magnetization reversal process. Two groups observed the zero plateau of Hall conductance around the coercive field independently, indicating transition between two QAH phases occurs via an ordinary insulator phase, which could be understood in a multi-magnetic domain structure. A similar zero plateau of Hall conductance have been observed in magnetic-doped TI (MTI) sandwich structure MTI/TI/MTI but with opposite out-of-plane magnetization direction on top and bottom surface. The system behaves like a normal insulator in a *DC* transport measurement but will have topological magnetoelectric effect in *AC* measurement, which is still a challenge.

The QAH insulator is important not only as a rare topological quantum phase that has been unambiguously experimentally realized, but also as a solid and versatile building block to construct many other topological quantum states. The latter role requires a QAH system to be engineered or incorporated into various kinds of heterostructures, on which several exciting experimental progresses have been made in the past years: The QAH insulator-normal insulator heterostructures simulated high Chern number QAH insulator has been experimental reported. But it is still quite challenging because the multilayer structure acquires accurate growth parameter control; a QAH insulator acquiring proximity superconductivity from an adjacent *s* wave superconductor (SC) layer can show the properties of a chiral topological SC. Majorana bound states (MBSs) are expected to appear in the magnetic vortices of the topological SC and could be used to compose topological qubits which are presumably robust against decoherence with topological protection. A better-defined QAH-SC interface is crucial for further explorations in this direction to avoid disturbance of interface disorders; the first intrinsic anti-ferromagnetic TI material MnBi_2Te_4 with intercalation ferromagnetic layer MnTe was found. By alternating MBE growth of Bi_2Te_3 and MnTe, MnBi_2Te_4 thin film was formed and gapless Dirac surface state from ARPES in over 2 SL films indicate the “topology” of this material. Recently the quantized Hall resistance was reported in exfoliated thin flake of MnBi_2Te_4 with high magnetic field. The results establish that MnBi_2Te_4 could be an idea platform for further exploring topological phenomena.

The recent progresses on QAH show us big opportunities to reach various novel topological states of matter experimentally. The explorations call for more exquisitely designed heterostructures and higher sample quality. With these efforts, the fantastic world of topological quantum matter is getting more and more realistic.

quantum anomalous Hall effect, topological insulator, magnetic doping, heterostructure, intrinsic magnetic

doi: [10.1360/TB-2019-0801](https://doi.org/10.1360/TB-2019-0801)