Literature Review

Matthew Gebert

February 14, 2020

Topological insulators surface states with ferroics

1 Topological Insualtors

1.1 Introduction

1.2 Spin-Orbit Coupling

Doesn't break time-reversal symmetry like magentic field for QHE, but can lead to **quantum spin hall effect**, or QSHE, where electrons differentiated by their spin move in opposite directions. No conserved spin current to test in a material.

1.3 Material Growths

2 Magnetic Materials

2.1 Classifications

2.1.1 Ferromagnetic

2.1.2 Anti-ferromagnetic

2.1.3 Paramagnetic

2.1.4 Diamagnetic

2.2 Ferromagnetic Insualtors

3 TI & FI Heterostructures

3.1 Theory

3.2 Experiments

https://www-nature-com.ezproxy.lib.monash.edu.au/articles/nature13534 https://advances.sciencemag.org/content/5/8/
https://tms16.sciencesconf.org/data/pages/TI_lecture2.pdf https://arxiv.org/pdf/1401.0848.pdf

4 Experimental Methods

4.1 Synthesis, Growth and Fabrication

4.1.1 MBE Growths

4.2 Metrological Methods

4.2.1 ARPES

For material characterisation, angle resolved photo-emission spectroscopy (ARPES) is a method of resolving the ejection of electrons from a material by high energy photons. Analysis of the momentum of the incident and emission resolve the electronic band structure.

5

6 Knowledge & Concepts

6.1 Symmetry

Apparently ssymmetry is very important in all physical systems. For example, the order exhibited in crystals can be described through the breaking of the continuous (rotational & translational) symmetry of space. This is due to the electrostatic interactions that cause a periodic lattice. In Magnets, spin space and time reversal symmetry are broken.

6.2 Spintronics

6.2.1 Ahrimhov Bohm Effect

6.3 Fine Structure Constant

The fine structure constant, also known as Sommerfields constant, is the coupleing constant "α" that measures the strength of the EM force interacting with light.

Two methods it has been measured by include the anomalous magnetic moment of the electron, a_e, as well as appearing in the Quantum Hall Effect (QHE).

It was originally introduced by Summerfieldas a theoretical correction to the Bohr model, explaining fine structure through elliptical orbits and relitivistic mass-velocity.

6.4 Hamiltonians of Crystal Lattices

Turns out that you can describe the hamiltonian of the electrons in a crystal lattice. For this, there exists first quantisation, second quantisation hamiltonian.

- First quantisation - The classical particles are assigned wave amplitudes. This is "semi-classical" where only the particles or objects are treated using quantum wavefunctions, but environment is classical.
- Second quantisation (Canonical Quantisation, occupation number representation) - The wave fields are "quantized" to describe the problem in terms of "quanta" or particles. This usually means referring to a wavefunction of a state, described the the vacuum state with a series of creation operators to create the current state. Fields are now treated as field operators, similar to how physical quantities (momentum, position) are thought of as operators in first quantisation.

6.4.1 Graphene

7 Review Article Notes

7.1 J. Moore - The Birth[1]

7.1.1 Lessons from the past

- Quantum Hall Effect can occur in 2D systems (condined) in the presence of a magentic field. It is a consequence of topological properties of the electronic wavefunctions.
- Question - Can this effect arise without a large external magnetic field?
- In the 1980s, Predicted that forces from motion through crystal lattice could provide the same hall state[2]
- The mechanism which this recently has occured through is **spin-orbit coupling** or SOC. Spin and orbital angular momentum degrees of freedom are coupled. This coupling causes electrons to feel a spin dependent force.
- QSHE predicted in 2003. Unclear how to measure or if realistic or not.[3;4]
- Kane & Mele in 2005 produced a key theory advance, using realistic models. Showed that QSHE can survive by the use of invariants and could compute if the 2D material has an edge state or not. 2D Insulators that have 1D wires that conduct perfectly at low temps, similar to QHE.[5]
- (Hg,Cd)Te quantum wells predicted to have quantized charge conductance[6]. These were then picked up in 2007[7].

7.1.2 Going 3D

- 2006 gave the revelation that while QHE doesn't go 2D to 3D, the TI does, subtly.[8;9;10]
- "Weak 3D TI" given through stacking of multiple 2D TIs. Not stable to disorder. A dislocation will always conains a quantum wire at the edge.
- "Strong 3D TI", connects ordinary insulators and topological insualtors by breaking time-reversal symmetry.[9] This is the focus result for experimental physics at the moment.
- SOC is also required, but mixes all spins, unlike the 2D case. Spin direction dictates the momentum along the surface. Scattering also occurs, but metallic surface cannot vanish.
- First 3D TI was Bi_xSb_{1-x}. Surfaces mapped using ARPES experiment. The surface was complex, but launched a search for other TIs.[11;12].
- Heavy metal, small bandgap semiconductors are meant to be the best candidates (this sounds like TMDs haha but not implied) for two reasons.
  - SOC is relativistic, and only strong for heavy elements.
  - Large bandgaps, relative to the scale of SOC, will not allow SOC to change the phase. This is because bands either need to invert or be able to cross or change properties by local deformation (I think).
- The discovery of Bismuth Selenide Bi_2Se_3 and Bismuth Telluride Bi_2Te_3. They exhibit TI behaviour to higher temperatures, bulk bandgaps of > 0.1 eV[13;14;15].

– The large bandgap is good for measurement in higher temperature
– Simple surface states to investigate heterostructures etc.
– Complication - Distinction between surface and bulk states - residual conductivity resulting from impurities.

- Bi_2Se_3

7.2 title

8 Bibliography

[1] Joel E. Moore. The birth of topological insulators, March 2010. URL `http://www.nature.com/articles/nature08916`.

[2] F. D. M. Haldane. Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the "Parity Anomaly". *Physical Review Letters*, 61(18):2015–2018, October 1988. doi: 10.1103/PhysRevLett.61.2015. URL `https://link.aps.org/doi/10.1103/PhysRevLett.61.2015`.

[3] Shuichi Murakami, Naoto Nagaosa, and Shou-Cheng Zhang. Dissipationless Quantum Spin Current at Room Temperature. *Science*, 301(5638):1348–1351, September 2003. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.1087128. URL `http://science.sciencemag.org/content/301/5638/1348`.

[4] Shuichi Murakami, Naoto Nagaosa, and Shou-Cheng Zhang. Spin-Hall Insulator. *Physical Review Letters*, 93(15):156804, October 2004. doi: 10.1103/PhysRevLett.93.156804. URL `https://link.aps.org/doi/10.1103/PhysRevLett.93.156804`.

[5] C. L. Kane and E. J. Mele. Z 2 Topological Order and the Quantum Spin Hall Effect. *Physical Review Letters*, 95(14), September 2005. ISSN 0031-9007, 1079-7114. doi: 10.1103/PhysRevLett.95.146802. URL `https://link.aps.org/doi/10.1103/PhysRevLett.95.146802`.

[6] B. Andrei Bernevig, Taylor L. Hughes, and Shou-Cheng Zhang. Quantum Spin Hall Effect and Topological Phase Transition in HgTe Quantum Wells. *Science*, 314(5806):1757–1761, December 2006. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.1133734. URL `http://science.sciencemag.org/content/314/5806/1757`.

[7] Markus König, Steffen Wiedmann, Christoph Brüne, Andreas Roth, Hartmut Buhmann, Laurens W. Molenkamp, Xiao-Liang Qi, and Shou-Cheng Zhang. Quantum Spin Hall Insulator State in HgTe Quantum Wells. *Science*, 318(5851):766–770, November 2007. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.1148047. URL `http://science.sciencemag.org/content/318/5851/766`.

[8] Liang Fu, C. L. Kane, and E. J. Mele. Topological Insulators in Three Dimensions. *Physical Review Letters*, 98(10):106803, March 2007. doi: 10.1103/PhysRevLett.98.106803. URL `https://link.aps.org/doi/10.1103/PhysRevLett.98.106803`.

[9] J. E. Moore and L. Balents. Topological invariants of time-reversal-invariant band structures. *Physical Review B*, 75(12):121306, March 2007. doi: 10.1103/PhysRevB.75.121306. URL `https://link.aps.org/doi/10.1103/PhysRevB.75.121306`.

[10] Rahul Roy. Topological phases and the quantum spin Hall effect in three dimensions. *Physical Review B*, 79(19):195322, May 2009. doi: 10.1103/PhysRevB.79.195322. URL `https://link.aps.org/doi/10.1103/PhysRevB.79.195322`.

[11] D. Hsieh, D. Qian, L. Wray, Y. Xia, Y. S. Hor, R. J. Cava, and M. Z. Hasan. A topological Dirac insulator in a quantum spin Hall phase. *Nature*, 452(7190):970–974, April 2008. ISSN 0028-0836, 1476-4687. doi: 10.1038/nature06843. URL `http://www.nature.com/articles/nature06843`.

[12] D. Hsieh, Y. Xia, L. Wray, D. Qian, A. Pal, J. H. Dil, J. Osterwalder, F. Meier, G. Bihlmayer, C. L. Kane, Y. S. Hor, R. J. Cava, and M. Z. Hasan. Observation of Unconventional Quantum Spin Textures in Topological Insulators. *Science*, 323(5916):919–922, February 2009. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.1167733. URL `http://science.sciencemag.org/content/323/5916/919`.

[13] Y. Xia, D. Qian, D. Hsieh, L. Wray, A. Pal, H. Lin, A. Bansil, D. Grauer, Y. S. Hor, R. J. Cava, and M. Z. Hasan. Observation of a large-gap topological-insulator class with a single Dirac cone on the surface. *Nature Physics*, 5(6):398–402, June 2009. ISSN 1745-2481. doi: 10.1038/nphys1274. URL `http://www.nature.com/articles/nphys1274`.

[14] Haijun Zhang, Chao-Xing Liu, Xiao-Liang Qi, Xi Dai, Zhong Fang, and Shou-Cheng Zhang. Topological insulators in Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface. *Nature Physics*, 5(6):438–442, June 2009. ISSN 1745-2481. doi: 10.1038/nphys1270. URL `http://www.nature.com/articles/nphys1270`.

[15] Y. L. Chen, J. G. Analytis, J.-H. Chu, Z. K. Liu, S.-K. Mo, X. L. Qi, H. J. Zhang, D. H. Lu, X. Dai, Z. Fang, S. C. Zhang, I. R. Fisher, Z. Hussain, and Z.-X. Shen. Experimental Realization of a Three-Dimensional Topological Insulator, Bi2Te3. *Science*, 325(5937):178–181, July 2009. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.1173034. URL `http://www.sciencemag.org/cgi/doi/10.1126/science.1173034`.