Taking topological insulators for a spin

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Chapter 1

Introduction
1.1 Topology: Exploring new states of matter

The establishment of quantum mechanics in the 1920s yielded a framework towards understanding the physical properties of atomic, molecular, and solid-state systems. Following that, Bloch focused on the behavior of metals and their electrical resistance [1]. In his doctoral thesis, he developed a model where electrons are subject to a periodic crystal potential, leading to states extended over the crystal that electrons can occupy. These electronic states can be represented as (un)occupied bands that can be used to explain many physical properties of crystals and formed the basis to understand the behavior of solid-state matter that we use in our daily life.

However, Bloch’s framework could not explain phenomena that were observed in systems at lower dimensions that are subject to low temperatures. In order to explain these features, the concept of topology was introduced. This concept, as developed by Thouless and Kosterlitz in the early 1970s [2], led to the understanding that in such systems ordering is present that cannot be destroyed by thermal fluctuations. The ordering is realized due to the presence of vortices, which cannot be removed to yield the ultimate ground state since they are topologically distinct. This topological distinction is a powerful property that is difficult to change, unless the system’s temperature is raised above the critical value of the system. To visualize this distinction more, I refer to the commonly used example of the orange and the doughnut that are topologically different based on the number of holes at the two-dimensional surface [3]. These objects can only be made topologically equivalent when one drills a hole into the orange.

Such topologically distinct phases can also be found in solid-state systems where the topology can be related to the band structure of a crystal. Here, the phase of the Bloch wave functions gives rise to different topologies in materials. The quantity defining the topology of an electronic band structure is topologically protected, which means that it cannot be changed unless the band gap is closed. Therefore, such an integer is a very strong and secure property of a band structure. In order to connect two materials with a different topology, one can imagine that a crossover state is required to meet the topology difference. Such a crossover state thus originates from the concept of topology and provides interesting physical phenomena.

The first discovered, topologically distinct state is the quantum Hall state in which the conductivity perpendicular to the bias direction was found to change in quantized steps [4]. This observation has been theoretically explained by Thouless et al. to be connected to the state’s topology, being different from that of its environment (say vacuum or air) [5]. Therefore, a crossover state at the edge of the quantum Hall state can be expected to match the difference in topology. The classical explanation of electrons traveling via skipping orbits along this edge thus fits to the ‘bigger’ picture of topological classification that predicts such an edge state to be present. The abrupt change in conductivity by exactly one conductance quantum and the possibility to exactly determine the value of this physical constant are manifestations of topology, emphasizing the power of this theoretical concept. Afterwards, Haldane realized that distinct phases as in the quantum Hall state can also be present in sys-

1Later, he gained interest in experimental studies on nuclear magnetic resistance for which he was awarded the Nobel Prize for Physics in 1952.
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tems where an applied magnetic field is not required [6]. About 20 years later, several theoretical groups realized that topological band structures can be found in ordinary three-dimensional systems too, paving the way towards topological insulators.

The realization of topological phases of matter as established by Thouless, Kosterlitz, and Haldane have provided many new possibilities to engineer systems with novel properties adding to those found from the settled band theory by Bloch. These new systems not only provide opportunities for novel applications, but are interesting from a fundamental point of view too. Therefore, it is not surprising that these three physicists were awarded the Nobel Prize for Physics 2016.

1.2 Topological insulators and their high potential

The quest for new topological states of matter sparked when theoreticians realized that spin–orbit coupling in graphene gives rise to a topologically distinct band structure. Nevertheless, such effects in graphene were still estimated to be rather small in order to experimentally observe them. Therefore, it was a logical step to explore the periodic system to find elements and corresponding multi-element compounds where spin–orbit coupling is more prominent and could give rise to a more ‘stable’ system that can be experimentally accessed. This search led to the proposal of distinct phases in HgTe quantum wells [7]. Such quantum wells were already investigated because of their large spin–orbit coupling and large Zeeman splitting. Recent developments on increasing the mobility of these quantum wells led to a fast experimental realization of topological states in this two-dimensional system [8]. In this system, it was found that edge states were present which do not carry a charge current, but do carry a net spin current. These edge states are found to originate from required crossover states at the interface of the topologically distinct phases. The spin and momentum of the carriers in these states are directly related and the generated currents were found to flow dissipationless. The quantized version of the spin Hall effect was realized [9,10], opening up new opportunities for spintronic applications.

Afterwards, it was theoretically proposed that binary compounds with heavy elements Bi, Sb, Se, and Te could give rise to three-dimensional topological insulators where the one-dimensional edge states are transformed into two-dimensional surface states. Such surface states have been experimentally observed in the alloy Bi$_x$Sb$_{1-x}$ and the binary compounds Bi$_2$Se$_3$, Bi$_2$Te$_3$, and Sb$_2$Te$_3$ [11–16] by angular-resolved photoemission spectroscopy. For the binary compounds, the topological surface states can be addressed independently from the bulk since these states are located inside the bulk band gap. Furthermore, the charge carriers have their momentum connected to their spin similar to the quantum spin Hall state, which is known as ‘spin–momentum locking’. This property is protected by topology and thus cannot be destroyed by any perturbation that still preserves time-reversal symmetry. However, breaking of time-reversal symmetry can lead to other interesting phenomena, including the quantized version of the anomalous Hall effect that was realized in 2013 [17], completing the quantum Hall trio [18].

The property of spin–momentum locking in the surface states is interesting from a fundamental perspective and because it can serve as an interesting platform for novel
device applications. From the fundamental perspective, topological insulators can host effects such as the topological magnetoelectric effect (which is supposed to induce quantized Faraday rotation and giant Kerr effects) and the creation of Majorana fermions when the topological insulator is in contact with a superconductor [3, 19]. For device applications, topological insulators that host spin-textured surface states are currently considered mainly as a platform for spintronic applications where the electron’s spin is used as information carrier. Spintronics opens up possibilities to lower the power consumption, to further miniaturize device components, to enhance the data processing speed, and to have nonvolatile devices [20]. The design of such a spintronic device has been proposed by Datta and Das and is the spin-analogue of a charge-based field-effect transistor [21]. Realizing such a transistor requires the availability of efficient spin injectors and detectors, transport channels with a long spin lifetime, and means to control and manipulate the spin in such channels. One can think of employing topological insulators here as spin injectors (detectors) since a spin accumulation with a relatively high polarization can be easily created (detected) by sourcing (probing) a charge-current bias due to spin–momentum locking. In contrast to proximity-effect-limited ferromagnetic contacts, topological insulators can be easily downscaled as spin injector or detector contacts, enabling low-dimensional spin transistor geometries. Furthermore, the large band gap relative to $k_B T$ of some topological insulators allows for applications at room temperature. Such current-induced spin accumulations make topological insulators further interesting as components in spin-torque-based memory. In this type of memory, a spin accumulation switches the magnetization of the ferromagnetic memory. A combination of these properties makes this class of materials thus attractive for spintronic applications.

1.3 Thesis outline

Although topological insulators are potentially very interesting, their properties are not yet fully understood. The complexity of the system, where bulk and surface states often compete, gives rise to additional side effects that mask the novel properties of the topological surface states.

This thesis describes the efforts to identify the surface states in topological insulators through investigation of spin and charge transport. This will provide an understanding of the applicability of topological insulators for aforementioned device applications and it provides a more fundamental understanding of effects occurring in this rather unknown system. This thesis consists of the following chapters:

Chapter 2 provides a more in-depth discussion on the principles of topological band theory without going into any mathematical details. Subsequently, these concepts are applied to systems where topology plays a role, ending with a treatment on three-dimensional topological insulators. Here, the topological properties as well as the basic band structure properties of the studied systems in this thesis are discussed. In the last part of the chapter, I will discuss the different growth techniques of these topological insulators and how these growth types affect the electrical properties of the material. These properties are qualified by the relative bulk and surface contributions to the total charge transport. Additional theoretical concepts to support the experimental
work will be given in every chapter separately. Chapter 3 reports on the efforts to characterize and understand the properties of the interface between metals and topological insulators where the topological insulator is being treated as a semiconductor. In the first part, I will give an overview on the current understanding of such interfaces. Theoretical studies indicate that such interfaces yield generally charge-accumulation layers and thus no interface barriers are expected. We have employed several techniques to probe the interface, but we have not observed any clear signatures of a barrier present at the interface. This finding is in agreement with theory, but is partially hindered by technical issues at the same time.

Chapter 4 comprises of studies towards optical excitation of helicity-dependent photocurrents originating from the topological surface states. In the first part of the chapter, I will discuss the earlier findings from optical experiments. This ranges from an experimental understanding of the band structure to charge-relaxation dynamics upon optical excitation where the dynamics are of importance for our photocurrent studies. Subsequently, I will discuss the mechanisms that could lead to the generation of a photocurrent and other mechanisms that could mimic such an effect. Thereafter, I report on our findings from experiments where we have photoexcited charge carriers at IR wavelengths using a free-electron laser and measured the resulting potential difference by measuring the voltage between two contacts. A helicity dependence is observed, but we cannot rule out artifacts that could mimic the effect.

Chapter 5 describes the study to disentangle the different charge-transport channels in a topological insulator by performing high-field magnetotransport measurements. I will discuss our efforts to probe the different transport channels by analysis and comparison of the magnetoresistance features and Shubnikov–de Haas oscillations observed at high fields. In the metallic samples of Bi$_2$Se$_3$, it is found that a strong contribution from the bulk is present that is Zeeman-split at higher magnetic fields. Besides the interfering bulk channel, a second low-mobility channel is present which hints at the topological surface state. Signatures of a third channel have been observed but identification of its origin is limited by the resolution of our measurements.

Chapter 6 covers our work on detecting charge-current-induced spin polarization from topological surface states by using ferromagnetic contacts to detect the spin voltage. I will first provide an overview of related work and give a more detailed explanation on the detection of spin polarization, which is useful for detection of such polarizations in other materials, too. In the main part of the chapter, I will discuss the results of spin detection in topological insulators where we have used a geometry that enables us to investigate additional magnetoresistance effects. We find an isotropic switching of the spin voltage that is independent of the relative magnetization and charge-current directions. This isotropy is attributed to artifacts that are induced by fringe fields originating from the ferromagnetic detector. Because of the uncertainty of the origin of the spin voltage, I will provide an outlook with novel device schemes to distinguish different effects and a section with additional measurements that we have performed to improve the understanding of the observed effects.

Chapter 7 contains a feasibility study on the applicability of topological insulators for real device applications. In the first part, I will look into the production of topological insulator materials by looking at the mining and refining of the elements
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needed as well as the growth on an industrial scale. I will further discuss the impact on the environment and the costs associated with the production process. In the second part, I will discuss the possibilities of using topological insulators for spintronic, electronic, thermoelectric, and optoelectronic applications. Findings from the work described in this thesis as well as from literature serve as a basis for the last part of this thesis.

I hope you will enjoy reading the work presented in this thesis!

1.4 References