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as of 17-Nov-2021

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Begin Performance Period: 17-Aug-2016 **End Performance Period:** 16-Aug-2017
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:**

Major Goals: Quantum Hall edges offer extremely promising prospects for exploring topological superconductivity. In the integer regime one expects to be able to generate chiral Majorana modes and localized Majorana excitations with non Abelian braiding statistics. There are however several key challenges in exploring this physics experimentally using the traditional materials exhibiting the quantum Hall effect. First, at filling factor one the ground state consists of spin polarized electrons and hence inducing superconductivity requires a p-type superconductor. Additionally, the large field needed to reach the quantum Hall regime limits the types of superconductors that one might be able to explore. To circumvent some of these challenges, we propose to explore the coupling of superconductivity to the quantum anomalous Hall effect.
The quantum anomalous Hall effect occurs at zero magnetic field in thin topological insulators that are magnetically doped. The coupling between the top and bottom surface sates when the thickness is small leads to the gapping of the surface states leaving only edge conduction. The magnetic doping removes one of the chiral edge states resulting in a quantum anomalous Hall state. Such state occurs at zero magnetic field and hence alleviates much of the difficulty associated with coupling superconductivity to quantum Hall edges. Thus far studies of the anomalous quantized Hall effect were done in millimeter size hall bars with normal contacts that are unsuitable for exploring Josephson coupling.
In this proposal we will develop micron size normal and superconducting contacts as well as optical and ebeam fabrication schemes that would pave the way towards exploring this phase in mesoscopic devices and the coupling of superconductivity and the quantum anomalous Hall effect. We will work on V doped and Cr doped (Bi, Sb)2 Te3 layers that have been shown to produce the strongest quantization of the quantized anomalous Hall state.

Accomplishments: During this seed funding period we explored fabrication and transport measurement of micron size devices to understand the key limitations in utilizing the quantum anomalous Hall effect as a hybrid component in realizing topological superconductivity (TSC). Our goals in this proposal were to establish micron size contacts to the quantum anomalous Hall edge states. While this goal has been achieved, it has become clear that the underlying bulk disorder in these systems provides a fundamental road block for their use for TSC.
During this study we unraveled several interesting transport phenomena that could be attributed to the interplay between surface and bulk transport and electro-electron interaction.
Magnetotransport measurements in Hallbar devices on magnetically doped (Bi,Sb)2Te3 films grown by molecular beam epitaxy show logarithmic dependence of transport coefficients in temperature and bias voltage which can be understood to arise from corrections to the conductivity due to electron - electron interaction. Submicron scale devices exhibit intriguing quantum oscillations at high magnetic fields with dependence on bias voltage. The observed quantum oscillations were attributed to bulk and surface transport.
In an ultrathin topological insulator film made of (BixSb1?x)2Te3 with x = 0.2, a hybridization gap opens in the TI

surface states, and the system is expected to become either a trivial insulator or a quantum spin Hall insulator when the chemical potential is within the hybridization gap. However, we found that these insulating states are destroyed by the presence of a large and long-range-correlated disorder potential, which converts the expected insulator into a metal. We perform transport measurements in ultrathin, dual-gated topological insulator films as a function of temperature, gate voltage, and magnetic field, and we observe a metallic-like, non-quantized conductivity, which exhibits a weak antilocalization like cusp at low magnetic field and gives way to a non-saturating linear magnetoresistance at large
field. We explain these results by considering the disordered network of electron- and hole-type puddles induced by charged impurities. We argue theoretically that such disorder can produce an insulator-to-metal transition as a function of increasing disorder strength, and we derive a condition on the band gap and the impurity concentration necessary to observe the insulating state. We also explain the linear magnetoresistance in terms of strong spatial fluctuations of the local conductivity, using both numerical simulations and a theoretical scaling argument.

Training Opportunities: During this project students and postdocs were exposed to state of the art fabrication, low temperature measurement apparatus and low noise measurement schemes. Students and postdocs were also trained in presenting their work to both specialized and general audiences.

Results Dissemination: This work has been incorporated into numerous talks at conferences, seminars and colloquia.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Debaleena Nandi
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Lucas Augustin Orona
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Kevin Alexander Shain
Person Months Worked: 4.00 **Funding Support:**
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Article Title: Signatures of long-range-correlated disorder in the magnetotransport of ultrathin topological insulators
Authors: D. Nandi, B. Skinner, G. H. Lee, K.-F. Huang, K. Shain, Cui-Zu Chang, Y. Ou, S.-P. Lee, J. Ward, J. S. I
Keywords: topology
Abstract: In an ultrathin topological insulator (TI) film, a hybridization gap opens in the TI surface states, and the system is expected to become either a trivial insulator or a quantum spin Hall insulator when the chemical potential is within the hybridization gap. Here we show, however, that these insulating states are destroyed by the presence of a large and long-range-correlated disorder potential, which converts the expected insulator into a metal. We perform transport measurements in ultrathin dual-gated topological insulator films as a function of temperature, gate voltage, and magnetic field, and we observe a metallic like non-quantized conductivity, which exhibits a weak anti localizationlike cusp at low magnetic fields and gives way to a non-saturating linear magnetoresistance at large fields. We explain these results by considering the disordered network of electron- and hole-type puddles induced by charged impurities. We argue theoretically that such disorder can produce an
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Article Title: Logarithmic singularities and quantum oscillations in magnetically doped topological insulators
Authors: D. Nandi, Inti Sodemann, K. Shain, G. H. Lee, K.-F. Huang, Cui-Zu Chang, Yunbo Ou, S. P. Lee, J. Wa
Keywords: topology
Abstract: We report magnetotransport measurements on magnetically doped (Bi,Sb)2Te3 films grown by molecular beam epitaxy. In Hall bar devices, we observe logarithmic dependence of transport coefficients in temperature and bias voltage which can be understood to arise from electron-electron interaction corrections to the conductivity and self-heating. Submicron scale devices exhibit intriguing quantum oscillations at high magnetic fields with dependence on bias voltage. The observed quantum oscillations can be attributed to bulk and surface transport.
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as of 17-Nov-2021

Partners

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I certify that the information in the report is complete and accurate:
Signature: Amir Yacoby
Signature Date: 10/29/21 4:51PM

W911NF1610491 : 6.1.2 (ARO): Contacting the Quantum Anomalous Hall State

Reporting Period: AUG 17, 2016 to AUG 16, 2017

Date Received:

Submitter: Amir Yacoby

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Major Goals

Quantum Hall edges offer extremely promising prospects for exploring topological superconductivity. In the integer regime one expects to be able to generate chiral Majorana modes and localized Majorana excitations with non Abelian braiding statistics. There are however several key challenges in exploring this physics experimentally using the traditional materials exhibiting the quantum Hall effect. First, at filling factor one the ground state consists of spin polarized electrons and hence inducing superconductivity requires a p-type superconductor. Additionally, the large field needed to reach the quantum Hall regime limits the types of superconductors that one might be able to explore. To circumvent some of these challenges, we propose to explore the coupling of superconductivity to the quantum anomalous Hall effect. The quantum anomalous Hall effect occurs at zero magnetic field in thin topological insulators that are magnetically doped. The coupling between the top and bottom surface sates when the thickness is small leads to the gapping of the surface states leaving only edge conduction. The magnetic doping removes one of the chiral edge states resulting in a quantum anomalous Hall state. Such state occurs at zero magnetic field and hence alleviates much of the difficulty associated with coupling superconductivity to quantum Hall edges. Thus far studies of the anomalous quantized Hall effect were done in millimeter size hall bars with normal contacts that are unsuitable for exploring Josephson coupling. In this proposal we will develop micron size normal and superconducting contacts as well as optical and ebeam fabrication schemes that would pave the way towards exploring this phase in mesoscopic devices and the coupling of superconductivity and the quantum anomalous Hall effect. We will work on V doped and Cr doped (Bi, Sb)2 Te3 layers that have been shown to produce the strongest quantization of the quantized anomalous Hall state.

Accomplishments Under Goals

During this seed funding period we explored fabrication and transport measurement of micron size devices to understand the key limitations in utilizing the quantum anomalous Hall effect as a hybrid component in realizing topological superconductivity (TSC). Our goals in this proposal were to establish micron size contacts to the quantum anomalous Hall edge states. While this goal has been achieved, it has become clear that the underlying bulk disorder in these systems provides a fundamental road block for their use for TSC. During this study we unraveled several interesting transport phenomena that could be attributed to the interplay between surface and bulk transport and electro-electron interaction. Magnetotransport measurements in Hallbar devices on magnetically doped (Bi,Sb)2Te3 films grown by molecular beam epitaxy show logarithmic dependence of transport coefficients in temperature and bias voltage which can be understood to arise from corrections to the conductivity due to electron - electron interaction. Submicron scale devices exhibit intriguing quantum oscillations at high magnetic fields with dependence on bias voltage. The observed quantum oscillations were attributed to bulk and surface transport. In an ultrathin topological insulator film made of (BixSb1?x)2Te3 with x = 0.2, a hybridization gap opens in the

TI surface states, and the system is expected to become either a trivial insulator or a quantum spin Hall insulator when the chemical potential is within the hybridization gap. However, we found that these insulating states are destroyed by the presence of a large and long-range-correlated disorder potential, which converts the expected insulator into a metal. We perform transport measurements in ultrathin, dual-gated topological insulator films as a function of temperature, gate voltage, and magnetic field, and we observe a metallic-like, non-quantized conductivity, which exhibits a weak antilocalization like cusp at low magnetic field and gives way to a non-saturating linear magnetoresistance at large field. We explain these results by considering the disordered network of electron- and hole-type puddles induced by charged impurities. We argue theoretically that such disorder can produce an insulator-to-metal transition as a function of increasing disorder strength, and we derive a condition on the band gap and the impurity concentration necessary to observe the insulating state. We also explain the linear magnetoresistance in terms of strong spatial fluctuations of the local conductivity, using both numerical simulations and a theoretical scaling argument.

Plans Next Period

Results Dissemination

This work has been incorporated into numerous talks at conferences, seminars and colloquia.

Honors and Awards

Nothing to Report

Training Opportunities

During this project students and postdocs were exposed to state of the art fabrication, low temperature measurement apparatus and low noise measurement schemes. Students and postdocs were also trained in presenting their work to both specialized and general audiences.

Technology Transfer

Nothing to Report

Participants

Name	Role	Person Months
Orona, Lucas	Graduate Student (research assistant)	1
Shain, Kevin	Graduate Student (research assistant)	4
Nandi, Debaleena	Postdoctoral (scholar, fellow or other postdoctoral position)	6