Spin-injection Hall effect: a new member of the spintronics Hall family and its implications in nano-spintronics

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Spin-helix-Hall transistors and topological thermoelectrics

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University of Nottingham
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Hamburg University
May 25th, 2011

Research fueled by:
I. Introduction: using the dual personality of the electron
   • Internal coupling of charge and spin: origin and present use
   • Control of material and transport properties through spin-orbit coupling
   • Overview of program
II. Anomalous Hall effect:
   • Anomalous Hall effect basics
III. Spin injection Hall effect: a new paradigm in exploiting SO coupling
   • Spin based FET: old and new paradigm in charge-spin transport
   • Theory expectations and modeling
   • Experimental results
IV. Topological thermoelectrics:
   • Thermoelectric figure of merit
   • Increase of ZT in topological insulators.
The electron: the key character with dual personalities

**Charge**
Easy to manipulate: Coulomb interaction

**Spin 1/2**
Makes the electron antisocial: a fermion

Quantum mechanics + special relativity = particles/antiparticles & spin

\[ E = \frac{p^2}{2m} \]
\[ E \rightarrow i\hbar \frac{d}{dt} \]
\[ p \rightarrow -i\hbar \frac{d}{dr} \]

\[ E^2/c^2 = p^2 + m^2c^2 \]
(E = mc^2 for p = 0)

"Classical" external manipulation of charge & spin

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Using charge and spin in information technology

Using charge to create a field effect transistor: work horse of information processing

Using spin: Pauli exclusion principle and Coulomb repulsion → ferromagnetism work horse of information storage

total \psi = \text{orbital \psi (antisymmetric)} \times \text{spin \psi (symmetric)} (aligned)

• Robust (can be as strong as bonding in solids)
• Strong coupling to magnetic field (weak fields = anisotropy fields needed only to reorient macroscopic moment)

HIGH tunability of electronic transport properties the key to FET success in processing technology

What about the internal communication between charge & spin? (spintronics)
Internal communication between spin and charge: 
spin-orbit coupling interaction

(one of the few echoes of relativistic physics in the solid state)

Classical explanation (in reality it arises from a second order expansion of 
Dirac equation around the non-relativistic limit)

- "Impurity" potential $V(r)$
  Produces an electric field

\[ \vec{E} = -\frac{1}{e} \nabla V(\vec{r}) \]

- Motion of an electron
  In the rest frame of an electron
  the electric field generates an 
effective magnetic field

This gives an effective interaction with the electron’s magnetic moment

\[ H_{SO} = -\vec{\mu}_B \cdot \vec{B}_{eff} \]
Internal communication between spin and charge: spin-orbit coupling interaction

(classical explanation (in reality it arises from a second order expansion of Dirac equation around the non-relativistic limit))

- "Impurity" potential \( V(r) \) produces an electric field
  \[ \vec{E} = -\frac{1}{e} \nabla V(\vec{r}) \]

- Motion of an electron
  1. Motion of an electron produces an effective magnetic field
  2. In the rest frame of an electron, the electric field generates an effective magnetic field
  \[ \vec{B}_{eff} = -\frac{\hbar \vec{k}}{cm} \times \vec{E} \]
  3. Consequence #1: Spin or the band-structure Bloch states are linked to the momentum
  \[ H_{SO} = -\mu_B \cdot \vec{B}_{eff} \]

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Internal communication between spin and charge: spin-orbit coupling interaction

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- "Impurity" potential \( V(r) \) produces an electric field \( \vec{E} = -\frac{1}{e} \nabla V(\vec{r}) \)

- Motion of an electron: the electric field generates an effective magnetic field \( \vec{B}_{eff} = -\frac{\hbar \vec{k}}{cm} \times \vec{E} \)

This gives an effective interaction with the electron’s magnetic moment

\[
H_{SO} = -\vec{\mu}_B \cdot \vec{B}_{eff}
\]

Consequence #2: Mott scattering

\[
\vec{B}_{eff} = -\frac{\hbar \vec{k}}{cm} \times \vec{E}
\]
How spintronics has impacted your life: Metallic spintronics

1992 - dawn of (metallic) spintronics

• Anisotropic magnetoresistance (AMR): In ferromagnets the current is sensitive to the relative direction of magnetization and current direction.

Appreciable sensitivity, simple design, cheap BUT only a 2-8% effect.

Giant magnetoresistance (GMR) read head - 1997

Fert, Grünberg et al. 1998

High sensitivity, very large effect 30-100%.

↑↑ and ↑↓ are almost on and off states:

“1” and “0” & magnetic → memory bit.

Nobel Price 2007
Fert and Grünberg

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
What next? The need for basic research

Industry has been successful in doubling of transistor numbers on a chip approximately every 18 months (Moore’s law). Although expected to continue for several decades several major challenges will need to be faced.

Circuit heat generation is one key limiting factor for scaling device speed
Information and communication technology power consumption HAS consequences

Estimated Amount of Data Circulating within the Internet in Japan (2006-2025)

Relative electricity consumption of ICT equipment

2006
95%
5%

2025
80%
20%

rest
ICT

Japan
5.2 times

World
9.4 times

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
The need for basic research in technology development

International Technology Roadmap for Semiconductors

- New materials
- Strongly correlated systems
- 1D systems
- Single electron systems (FETs)
- Spin dependent physics
- Molecular systems
- Ferromagnetic transport

Nanoelectronics Research Initiative

- MIND
- NRI
- SWAN

INDEX
WIN

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Control of materials and transport properties via spin-orbit coupling

- **Nano-transport**
- **Magnetotransport**
- **Caloritronics**
- **Effects of spin-orbit coupling in multiband systems**
- **New magnetic materials**
- **Spintronic Hall effects**
- **Topological transport effects**

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Control of materials and transport properties via spin-orbit coupling

Nagaosa, Sinova, Onoda, MacDonald, Ong, RMP 10
Anomalous Hall Effect: the basics

Spin dependent “force” deflects like-spin particles

Simple electrical measurement of out of plane magnetization (or spin polarization \( n_\uparrow - n_\downarrow \))

\[
\rho_{xy} = -\frac{\sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2} \approx -\frac{\sigma_{xy}}{\sigma_{xx}^2} \approx -\sigma_{xy}\rho_{xx}^2 \approx -A\rho_{xx} - B\rho_{xx}^2 \\
\sigma_{xy}^{AH} \approx B + A\sigma_{xx}
\]

\( \rho_{H} = R_0 B_{\perp} + 4\pi R_s M_{\perp} \)

\( R_0 \ll R_s \)

AHE is does NOT originate from any internal magnetic field created by \( M_{\perp} \); the field would have to be of the order of 100T!!!
Anomalous Hall effect (scaling with ρ for metals)

\[ \rho_{xy} = -A \rho_{xx} - B \rho_{xx}^2 \]

\[ \sigma_{xy} \approx B + A \sigma_{xx} \]

\[ \sigma_{xx} > 10^6 (\Omega \text{cm})^{-1} \]

\[ \sigma_{xx} \sim 10^4-10^6 (\Omega \text{cm})^{-1} \]

Material with dominant skew scattering mechanism
Material with dominant scattering-independent mechanism

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Cartoon of the mechanisms contributing to AHE $\sigma_{xy}^{AH} \approx B + A\sigma_{xx}$

**Skew scattering**

$A \sim \sigma / n_i$

Asymmetric scattering due to the spin-orbit coupling of the electron or the impurity. Known as Mott scattering.

**Intrinsic deflection**

Electrons deflect to the right or to the left as they are accelerated by an electric field ONLY because of the spin-orbit coupling in the periodic potential (electronics structure)

$\dot{x}_c = \frac{\partial \varepsilon(k)}{\hbar \partial k} + \frac{e}{\hbar} \vec{E} \times \vec{\Omega}$

SO coupled quasiparticles

Electrons have an “anomalous” velocity perpendicular to the electric field related to their Berry’s phase curvature which is nonzero when they have spin-orbit coupling.

**Side jump scattering**

Independent of impurity density

Electrons deflect first to one side due to the field created by the impurity and deflect back when they leave the impurity since the field is opposite resulting in a side step. They however come out in a different band so this gives rise to an anomalous velocity through scattering rates times side jump.

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Anomalous Hall effect: more than meets the eye

Anomalous Hall Effect

Spin Hall Effect

Topological Insulators

Kane and Mele
PRL 05

Valenzuela et al
Nature 06

Wunderlich, Kaestner, Sinova,
Jungwirth PRL 04

Brune, Roth, Hankiewicz,
Sinova, Molenkamp, et al
Nature Physics 2010

Wunderlich, Irvine, Sinova,
Jungwirth, et al, Nature Physics 09

Inverse SHE

Mesoscopic Spin Hall Effect

Intrinsic

Kato et al
Science 03

Extrinsic

Spin-injection Hall Effect

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Towards a realistic spin-based non-magnetic FET device

Can we achieve direct spin polarization injection, detection, and manipulation by electrical means in an all paramagnetic semiconductor system?

**Long standing paradigm: Datta-Das FET (1990)**

Exploiting the large Rashba spin-orbit coupling in InAs

Electrons are confined in the z-direction in the first quantum state of the asymmetric trap and free to move in the x-y plane.

**Rashba effective magnetic field**

$$\vec{B}_{eff} = -\frac{\hbar k}{cm} \times \vec{E}$$
Towards a realistic spin-based non-magnetic FET device

Can we achieve direct spin polarization injection, detection, and manipulation by electrical means in an all paramagnetic semiconductor system?

Long standing paradigm: Datta-Das FET (1990)
Exploiting the large Rashba spin-orbit coupling in InAs

\[ \vec{B}_{\text{eff}} = -\frac{\hbar \vec{k}}{cm} \times \vec{E} \]

\[ \text{BUT } I_{\text{MF}} \ll L_{S-D} \text{ at room temperature} \]
Dephasing of the spin through the Dyakonov-Perel mechanism

\[ \vec{B}_{\text{eff}} = -\frac{\hbar \vec{k}}{cm} \times \vec{E} \]

\[ L_{SD} \sim \mu m \]

\[ l_{MF} \sim 10 \text{ nm} \]
New paradigm using SO coupling: SO not so bad for dephasing

\[ \vec{B}_{\text{eff}} = -\frac{\hbar k}{cm} \times \vec{E} \]

**Problem:** Rashba SO coupling in the Datta-Das SFET is used for manipulation of spin (precession) BUT it dephases the spin too quickly

1) Can we use SO coupling to manipulate spin **AND** increase spin-coherence?

2) Can we detect the spin in a non-destructive way electrically?
Spin-dynamics in 2D electron gas with Rashba and Dresselhauss spin-orbit coupling

1) Can we use SO coupling to manipulate spin AND increase spin-coherence?

A 2DEG is well described by the effective Hamiltonian:

\[
H_{\text{2DEG}} = \frac{\hbar^2 k^2}{2m} + \alpha (k_y \sigma_x - k_x \sigma_y) + \beta (k_x \sigma_x - k_y \sigma_y) + \lambda^* \vec{\sigma} \times (\vec{k} \times \nabla V_{\text{dis}}(\vec{r}))
\]

\[
\lambda^* = \frac{P^2}{3} \left( \frac{1}{E_g^2} - \frac{1}{(E_g + \Delta_{\text{so}})^2} \right) \approx 5.3 \text{Å}^2 \text{ for GaAs}
\]

\[
\beta = -B \langle k_z^2 \rangle \quad B = 10 \text{ eV Å}^3
\]

\[
\alpha = \lambda^* E_z
\]

Rashba: from the asymmetry of the confinement in the z-direction

\[\alpha > 0, \quad \beta = 0\]

Dresselhauss: from the broken inversion symmetry of the material, a bulk property

\[\alpha = 0, \quad \beta < 0\]
Spin-dynamics in 2D electron gas with Rashba and Dresselhauss spin-orbit coupling

Something interesting occurs when $\alpha \sim -\beta$

$$H_{2\text{DEG}} \approx \frac{\hbar^2 k^2}{2m} + \alpha(k_y - k_x)(\sigma_x + \sigma_y)$$

- spin along the [110] direction is conserved
- long lived precessing spin wave for spin perpendicular to [110]

The nesting property of the Fermi surface:

$$E_{\downarrow}(\vec{k}) = E_{\uparrow}(\vec{k} + \vec{Q})$$

$$Q = \frac{4m\alpha}{\hbar^2}$$

Bernevig et al PRL 06, Weber et al. PRL 07
\[ H_{2\text{DEG}} = \frac{\hbar^2 k^2}{2m} + \alpha (k_y \sigma_x - k_x \sigma_y) + \beta (k_x \sigma_x - k_y \sigma_y) \]
Spin-dynamics in 2D systems with Rashba and Dresselhauss SO coupling

For the same distance traveled along [1-10], the spin precesses by exactly the same angle.
Persistent state spin helix verified by pump-probe experiments

Nondiffusive Spin Dynamics in a Two-Dimensional Electron Gas


PRL 98, 076604 (2007) PHYSICAL REVIEW LETTERS week ending 16 FEBRUARY 2007

Similar wafer parameters to ours

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Spin-helix state when $\alpha \neq \beta$

\[ S_{z/x} - (x_{1\bar{1}0}) = S_{z/x}^0 \exp[qx_{1\bar{1}0}] \]

\[ |q| = \left( \tilde{L}_1^2 \tilde{L}_2^2 + \tilde{L}_4^4 \right)^{1/4} \quad \text{and} \quad \theta = \frac{1}{2} \arctan \left( \frac{\sqrt{2\tilde{L}_1^2 \tilde{L}_2^2 - \tilde{L}_4^4/4}}{\tilde{L}_2^2 - \tilde{L}_1^2/2} \right) \]

\[ \tilde{L}_{1/2} = 2m|\alpha \pm \beta|/\hbar^2 \]

For Rashba or Dresselhaus by themselves NO oscillations are present; only and over damped solution exists; i.e. the spin-orbit coupling destroys the phase coherence.

There must be TWO competing spin-orbit interactions for the spin to survive!!!

Wunderlich, Irvine, Sinova, Jungwirth, et al, Nature Physics 09
Problem: Rashba SO coupling in the Datta-Das SFET is used for manipulation of spin (precession) BUT it dephases the spin too quickly (DP mechanism).

1) Can we use SO coupling to manipulate spin AND increase spin-coherence? ✓

   Use the persistent spin-Helix state and control of SO coupling strength (Bernevig et al 06, Weber et al 07, Wünderlich et al 09)

2) Can we detect the spin in a non-destructive way electrically
Contributions understood in simple metallic 2D models

**Semi-classical approach:**
Gauge invariant formulation

Sinitsyn, Sinova, et al PRB 05, PRL 06, PRB 07

**Kubo microscopic approach:**
in agreement with semiclassical

Borunda, Sinova, et al PRL 07, Nunner, Sinova, et al PRB 08

\[ \sigma_{xy} = \sigma_{II}^{xy} + \sigma_{side}^{xy} + \sigma_{skew}^{xy} \]

\[ \sigma_{AH}^{xy} \approx B + A\sigma_{xx} \]

**Non-Equilibrium Green’s Function (NEGF) microscopic approach**

Kovalev, Sinova et al PRB 08, Onoda PRL 06, PRB 08

\[ G^R = G_0 + G_0 \Sigma_R G^R \]
\[ (G_0^{-1} - \Sigma_R)G^R = 1 \]

\[ \hat{\Sigma}^c = \hat{\Sigma}^R \otimes \hat{G}^- \otimes \hat{\Sigma}^A \]
\[ \left[ [G_0^A] \right] \otimes \hat{G}^- \otimes \left[ [G_0^c] \right] = \hat{\Sigma}^R \otimes \hat{G}^- \otimes \hat{\Sigma}^R + \hat{\Sigma}^c \otimes \hat{G}^A - \hat{G}^R \otimes \hat{\Sigma}^c \]

Restriction to homogeneous magnetization.
Magnetic textures lead to the so called topological AHE.
AHE contribution to Spin-injection Hall effect in a 2D gas

$$H_{2D} = \frac{\hbar^2 k^2}{2m} + \alpha(k_y \sigma_x - k_x \sigma_y) + \beta(k_x \sigma_x - k_y \sigma_y) + \lambda^* \vec{\sigma} \times (\vec{k} \times \nabla V_{dis}(r))$$

Two types of contributions:

i) S.O. from band structure interacting with the field (external and internal)

ii) Bloch electrons interacting with S.O. part of the disorder

Type (i) contribution much smaller in the weak SO coupled regime where the SO-coupled bands are not resolved, dominant contribution from type (ii)

$$|\sigma_{xy}|^{\text{skew}} = \frac{2\pi e^2 \lambda^*}{\hbar^2} V_0 \tau \ n(n_\uparrow - n_\downarrow)$$

$$|\sigma_{xy}|^{\text{side-jump}} = \frac{2e^2 \lambda^*}{\hbar} (n_\uparrow - n_\downarrow)$$

Crepieux et al PRB 01

Nozier et al J. Phys. 79

$$\alpha_H(x_{[1\bar{1}0]}) = 2\pi \lambda^* \sqrt{\frac{e}{\hbar n_{i\mu}}} \ n \ p_z(x_{[1\bar{1}0]}) \approx 1.1 \times 10^{-3} p_z$$

Wunderlich, Irvine, Sinova, Jungwirth, et al, Nature Physics 09

Lower bound estimate of skew scatt. contribution
Spin-injection Hall effect: theoretical expectations

Local spin-polarization → calculation of AHE signal
Weak SO coupling regime → extrinsic skew-scattering term is dominant

\[ \alpha_H(x_{[1\overline{1}0]}) = 2\pi \lambda^* \sqrt{\frac{e}{\hbar n_i \mu}} n P_z(x_{[1\overline{1}0]}) \]

Lower bound estimate

1) Can we use SO coupling to manipulate spin AND increase spin-coherence?
   Use the persistent spin-Helix state and control of SO coupling strength ✓

2) Can we detect the spin in a non-destructive way electrically?
   Use AHE to measure injected current polarization electrically ✓
Device schematic - material
Device schematic - trench

2DHG

Inset: p, n [10^18/cm^3]

Energy [eV]

z [nm]

VB

CB

E_F
Device schematic – n-etch

- Carrier concentration: $p, n [10^{18}/\text{cm}^3]$
- Energy [eV]
- $E_F$ ( Fermi Level )
- VB (Valence Band)
- CB (Conduction Band)
- 2DHEG (Two-Dimensional High Efficiency Gap)
- 2DEG (Two-Dimensional Electron Gas)

Graph showing the energy levels and concentration of carriers.
Spin-injection Hall effect device schematics

For our 2DEG system:

\[ \beta \approx -0.02 \text{ eV A} \], \quad m = 0.067m_e

\[ \alpha \approx 0.01 - 0.03 \text{ eV A} \quad (\text{for } E_Z \approx 0.01 - 0.03 \text{ eV/ Å}) \]

Hence \( \alpha \approx -\beta \)
Spin-injection Hall device measurements

\[ \sigma^- + \sigma^0 + \sigma^+ = \sigma^0 \]

Graph showing the trans. signal over time.
Spin-injection Hall device measurements

Local Hall voltage changes sign and magnitude along a channel of 6 µm
Further experimental tests of the observed SIHE
Further experimental tests of the observed SIHE
SiHE: new results


(a) and (b): Graphs showing $R_H$ and $I_{PH}$ with $\sigma^+$ and $\sigma^-$ labels.
SiHE transistor

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
SHE transistor AND gate

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Summary of spin-injection Hall effect

- Basic studies of spin-charge dynamics and Hall effect in non-magnetic systems with SO coupling

- Spin-photovoltaic cell: solid state polarimeter on a semiconductor chip requiring no magnetic elements, external magnetic field, or bias

- SIHE can be tuned electrically by external gate and combined with electrical spin-injection from a ferromagnet (e.g. Fe/Ga(Mn)As structures)
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Control of materials and transport properties via spin-orbit coupling

- **Nanoelectronics**
- **Spintronics**
- **Materials control by spin-orbit coupling**

- **Nano-transport**
- **Magneto-transport**
- **New magnetic materials**
- **Effects of spin-orbit coupling in multiband systems**
- **Caloritronics**
- **Topological thermoelectrics**
- **Spintronic Hall effects**
  - **Topological transport effects**

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
ONE SEEBECK DEVICE "COUPLE" CONSISTS OF ONE N-TYPE AND ONE P-TYPE SEMICONDUCTOR PELLET

N-TYPE BISMUTH TELLURIDE

HEAT REMOVED

COLD SIDE

ELECTRON FLOW

HOT SIDE

HEAT REMOVED

P-TYPE BISMUTH TELLURIDE

HOLE FLOW

ABSORBED HEAT

STEVE J. NOLL
PELTIER-INFO.COM

LOAD

THERE MUST BE A TEMPERATURE DIFFERENCE BETWEEN THE HOT AND COLD SIDES FOR POWER TO BE GENERATED

Thermoelectric generator
Thermoelectric Cooling

Seattle Systems provides ideal solutions for cold therapy.

Courtesy of Saskia Fischer

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Thermoelectric Current Generation in Cars

BMW wins ÖkoGlobe 2008 award for thermoelectric generator

5-10% Reduction in Fuel Consumption

Courtesy of Saskia Fischer
From AHE to topological insulators to thermoelectrics

**Topological Insulators:** edge (2D) or surface states (3D) survive disorder effects when the bulk gap is produced by spin-orbit coupling

Kane, Zhang, Molenkamp, Moore, et al

Dislocations have 1D channels which also protected

Vishwanath et al Nature Physics 09

Zhang, Physics 1, 6 (2008)

QSHE in HgTe

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
From AHE to topological insulators to thermoelectrics

ZT = \frac{\sigma S^2}{\kappa_e + \kappa_l}

Seebeck coefficient

S = \frac{\pi k_B^2 T}{3e} \left[ \frac{\partial \ln \sigma(E)}{\partial E} \right]_{E_F}

Dislocations have 1D channels which also protected

Can we obtain high ZT through the topological protected states; are they related to the high ZT of these materials?
Possible large ZT through dislocation engineering

Large thermoelectric figure of merit for three-dimensional topological Anderson insulators via line dislocation engineering

O. A. Tretiakov, Ar. Abanov, Shuichi Murakami, and Jairo Sinova
(Received 23 July 2010; accepted 30 July 2010; published online 18 August 2010)

\[
\frac{1}{ZT} = \frac{(L_0^b + snL_0^{1D})(L_2^b + snL_2^{1D} + \kappa_{ph}T)}{(L_1^b + snL_1^{1D})^2} - 1
\]

where the L’s are the linear Onsager dynamic coefficients

\[
L_\alpha^{1D} = -\frac{l}{sh} \int \mathcal{T}(E)f'(E)(E - \mu)^\alpha dE
\]

\[
L_\alpha^b = -\tau \int_{E_m}^{\infty} D(E)f'(E)v^2(E - \mu)^\alpha dE
\]

\[
L_\alpha^b = \frac{2\sqrt{2m^*}}{\pi^2\hbar^3} \tau cT^\alpha + 3/2 \int_{E_m - \mu}^{\infty} dx \frac{x^\alpha(x + \mu/T)^{3/2}e^x}{(e^x + 1)^2}
\]

Bi$_{1-x}$Sb$_x$ (0.07 < x < 0.22)

Localized bulk states

Tretiakov, Abanov, Murakami, Sinova APL 2010
Possible large ZT through dislocation engineering

Remains very speculative but simple theory gives large ZT for reasonable parameters

Tretiakov, Abanov, Murakami, Sinova APL 2010
Beyond Bi$_{1-x}$Sb$_x$ (0.07 < x < 0.22)

So far only one material is believed to have protected 1D states on dislocations: how to further exploit TI properties to increase ZT?

**Analogy to HolEy Silicon**

Tang *et al* Nano Letters 2010

Also phononic nanomesh structures (Yu, Mitrovic, et al Nature Nanotechnology 2010)
Extending the idea to the entire class of TI insulators

- The surface of the holes provide the needed anisotropic transport
- Similar theory analysis as in 1D protected states but not as robust
- Curvature of the holes can be critical for TI to remain protected (Ostrovsky et al PRL 10, Zhang and Vishwanath PRL 10)

\[
\frac{1}{ZT} = \frac{(L_0^b + NL_0^s)(L_2^b + NL_2^s + (\kappa_{ph} + N\kappa_{ph}^s)T)}{(L_1^b + NL_1^s)^2} - 1
\]

\[
L_\alpha = L_\alpha^b + NL_\alpha^s
\]

\[
ZT_{2D} = \lim_{n \to \infty} ZT = \frac{(L_1^s)^2}{L_0^s(L_2^s + \kappa_{ph}^s T) - (L_1^s)^2}
\]

\[
\kappa_{ph} \approx 0.01 \text{Wm}^{-1}\text{K}^{-1}
\]

Tretiakov, Abanov, Sinova (in preparation) 2011
Preliminary results (yesterday)
spin-helix transistors and topological thermoelectrics

Control of materials and transport properties via spin-orbit coupling

I. Anomalous Hall effect: from the metallic to the insulating regime
   • Established a consistent theory of Anomalous Hall effect for metallic regime with homogeneous magnetization

II. Spin injection Hall effect: a new paradigm in exploiting SO coupling
   • Modeled and constructed a spin FET in the diffusive regime
   • First spin AND gate with pure spin currents

III. Topological thermoelectrics:
   • Speculative theory of how to increase of ZT in topological insulators via line dislocations.

A long list of challenges: DMSs, Antiferromagnetic semiconductors, current driven magnetization dynamics, pseudo-spintronics in double layer systems, spin-caloritronics (Spin Seebeck effect)
Nanoelectronics, spintronics, and materials control by spin-orbit coupling

Sinova’s group

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Spin in Cold Atoms and CM systems

NEWSPIN 2
Spin physics and topological effects in cold atoms, condensed matter, and beyond

International Winter School and Workshop
December 12th-17th 2011
Mitchell Institute of Fundamental Physics
College Station, Texas

Organizers:
Artem Abanov
Rembert Duine
Alexander Finkel'stein
Victor Galitski
Jairo Sinova
Ian Spielman
Henk Stoof

School Lecturers
12th-14th of December
G. Bauer (Delft) 
R. Duine (Utrecht) 
V. Galitski (Maryland) 
R. Hulet (Rice) 
J. Moore (Berkeley) 
J. Orenstein (Berkeley) * 
J. Spielmann (NIST) 
J.H. Thywissen (Toronto) 
R. van Wees (Groningen) *

Workshop Speakers
15th-17th of December
G. Bauer (Delft) (L) 
I. Bloch (Mainz) * 
A. Brataas (Trondheim) * 
G.J. Conduit (Cambridge) * 
E. Cornell (JILA) * 
E. Demler (Harvard) * 
R. Duine (Utrecht) (L) 
V. Galitski (Maryland) (L) 
R. Hulet (Rice) 
G. Juzeliunas (Vilnius) 
W. Ketterle (MIT) * 
M. Klau (Konstanz) 
A.H. MacDonald (Texas) 
S. Maekawa (Sendai) 
J. Moore (Berkeley) (L) 
J. Orenstein (Berkeley) (L) * 
S. Parkin (IBM) * 
A. Rosch (Cologne) 
C. Salomon (Paris-France) * 
K. Sengstock (Hamburg) 
I. Spielmann (NIST) (L) 
J.H. Thywissen (Toronto) (L) 
Y. Tserkovnyak (UCLA) 
B. van Wees (Groningen) (L) * 
M. Zwierlein (MIT/Harvard) *

Topics
• Magnetism in cold atoms
• Spin and Anomalous Hall effect
• Spin transfer and spin pumping
• Spin motive forces
• Controlling spins by light
• Spin orbit coupling in cold-atom systems
• Spin imbalance in cold Fermi gases
• Topological insulators
• Dirac physics in cold atoms and condensed matter
• Pseudospin physics

Sponsors
http://newspin2.physics.tamu.edu

1. * Unconfirmed
† Spin image courtesy of Randy Hulet’s group
Further experimental tests of the observed SIHE