Exploiting the echoes of special relativity in condensed matter:
new paradigms in spin-charge coupled physics

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Research fueled by:
Exploiting the echoes of special relativity in condensed matter: new paradigms in spin-charge coupled physics

I. Introduction: using the dual personality of the electron
   • Electronics, ferromagnetism, and spintronics
   • Internal coupling of charge and spin: origin and present use
   • Motivation: ICT, energy consumption, roadblocks

II. Control of material and transport properties through spin-orbit coupling:
   • Ferromagnetic semiconductors: magnetic anisotropy control
   • Anomalous Hall effect and spin-dependent Hall effects

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
   • New experimental results, further checks, outlook
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
  - \( E = \frac{p^2}{2m} \)
  - \( E \rightarrow i\hbar \frac{d}{dt} \)
  - \( p \rightarrow -i\hbar \frac{d}{dr} \)

- Special relativity
  - \( \frac{E^2}{c^2} = \frac{p^2}{c^2} + m^2 c^2 \)

- Dirac equation
  - \( i\hbar \frac{\partial}{\partial t} \Psi(x, t) = (\not{c} \cdot \vec{p} + \beta mc^2) \Psi(x, t) \)

"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

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

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

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

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

What about the internal communication between charge & spin? (spintronics)

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
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 \( V(r) \) \( \rightarrow \) Produces
  an electric field
  \[ \vec{E} = -\frac{1}{e} \nabla V(\vec{r}) \]

- Motion of an electron \( \rightarrow \) In the rest frame of an electron
  the electric field generates an
  effective magnetic field
  \[ \vec{B}_{\text{eff}} = -\frac{\hbar k}{cm} \times \vec{E} \]

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

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

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Consequence #1

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

\[ \vec{B}_{eff} = -\frac{\hbar \vec{k}}{cm} \times \vec{E} \]
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  In the rest frame of an electron the electric field generates an effective magnetic field
  \[
  \vec{B}_{\text{eff}} = -\frac{\hbar \vec{k}}{cm} \times \vec{E}
  \]
  This gives an effective interaction with the electron’s magnetic moment
  \[
  H_{\text{SO}} = -\vec{\mu}_B \cdot \vec{B}_{\text{eff}}
  \]

Consequence #2
Mott scattering

\[
\vec{B}_{\text{eff}} = -\frac{\hbar \vec{k}}{cm} \times \vec{E}
\]
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%
\(\uparrow\uparrow\) and \(\uparrow\downarrow\) are almost on and off states:
“1” and “0” & magnetic \(\rightarrow\) memory bit

Nobel Price 2007
Fert and Grünberg
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.

What next? The need for basic research

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

Relative electricity consumption of ICT equipment

- 2006: 95% rest, 5% ICT
- 2025: 80% rest, 20% ICT

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

- 2006: 637 Gbps
- 2025: 121 Tbps

Power consumption (billion kWh)

- Japan: 5.2 times
- World: 9.4 times

(Source) METI / Green IT Promotion Council (2008)
The need for basic research in technology development

International Technology Roadmap for Semiconductors

New materials systems
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
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Nanoelectronics, spintronics, and materials control by spin-orbit coupling

- Control of materials and transport properties via spin-orbit coupling
- New magnetic materials
- Effects of spin-orbit coupling in multiband systems
- Spintronic Hall effects
- Topological transport effects
- Caloritronics
- Magnetotransport

Nano-transport
Control of materials and transport properties via spin-orbit coupling

Ferromagnetic Semiconductors

Need true FSs not FM inclusions in SCs

GaAs - standard III-V semiconductor
+ Group-II Mn - dilute magnetic moments & holes
(Ga,Mn)As - ferromagnetic semiconductor

Magnetotransport

Caloritronics

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

Transition to a ferromagnet when Mn concentration > 1.5-2%

DOS

valence band As-p-like holes

ferromagnetism onset near MIT when localization length is longer than Mn-Mn spacing. Zener type model

Jungwirth, Sinova, et al RMP 06

Magnetotransport

Caloritronics
Control of materials and transport properties via spin-orbit coupling

Ferromagnetic Ga$_{1-x}$Mn$_x$As $x>1.5$

Magnetic materials

Nano-transport

Spintronic Hall effects

Magneto-transport

Caloritronics

Effects of spin-orbit coupling in multiband systems

Transition to a ferromagnet when Mn concentration increases

DOS spin↓ spin↑

valence band As-p-like holes

Ferromagnetism mediated by delocalized band states:

• polarized carriers with large spin-orbit coupling

Many useful properties

• FM dependence on doping

• Low saturation magnetization

What are the consequences of the strong spin-orbit coupling of the carriers “gluing” the localized Mn moments?
Effects of spin-orbit coupling in multiband systems

Nanoelectronics, spintronics, and materials control by spin-orbit coupling

Ferromagnetic Ga$_{1-x}$Mn$_x$As $x>1.5$

Ferromagnetism mediated by delocalized band states:
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Many useful properties
- FM dependence on doping
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What are the consequences of the strong spin-orbit coupling of the carriers “gluing” the localized Mn moments?

Control of magnetic anisotropy

Strain & SO

$\nabla$V

Piezoelectric stressor

$e_{xy} = 0.1\%$

$e_{xy} = 0\%$

Strain induces changes in the band structure and, in turn, changes the ferromagnetic easy axis. Piezoelectric devices: fast magnetization switching

Wunderlich, JS, et al PRB 06

M dependence on doping

Tensile strain

Compressive strain

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

***Anomalous Hall effects***

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

Spin dependent “force” deflects like-spin particles

\[ \rho_H = R_0 B \perp + 4\pi R_s M_\perp \]

\[ R_0 \ll R_s \]

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!!!

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

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

\[ \sigma^{\text{AH}}_{xy} \approx B + A \sigma_{xx} \]
Cartoon of the mechanisms contributing to AHE \( \sigma_{xy}^{AH} \approx B + A\sigma_{xx} \)

**Skew scattering** \( A \sim 1/n_i \)

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

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

**Intrinsic deflection** \( B \)

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)

\[ \Omega_z(k, n) = 2\text{Im} \left( \frac{\partial}{\partial y} n_k \right) \]

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** \( B \)

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
Contributions understood in simple metallic 2D models

**Kubo microscopic approach:**
in agreement with semiclassical
Borunda, Sinova, et al PRL 07, Nunner, JS, et al PRB 08

\[
\sigma_{xy} = \sigma_{xy}^{II} + g_{xy} + \gamma
\]

- intrinsic contribution
- side jump
- skew scattering

**Semi-classical approach:**
Gauge invariant formulation
Sinitsyn, Sinvoa, et al PRB 05, PRL 06, PRB 07

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

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

\[
\begin{align*}
G^R &= G_0 + G_0 \Sigma R G^R \\
(G_0^{-1} - \Sigma R) G^R &= 1 \\
\hat{\Sigma}^c &= \hat{\Sigma}^e \otimes \hat{G}^c \otimes \hat{\Sigma}^A \\
\left[G^R_0\right]^\dagger \otimes \hat{G}^e - \hat{G}^e \otimes \left[G^A_0\right]^\dagger &= \hat{\Sigma}^c \otimes \hat{G}^c - \hat{G}^e \otimes \hat{\Sigma}^R + \hat{\Sigma}^c \otimes \hat{G}^A - \hat{G}^R \otimes \hat{\Sigma}^c
\end{align*}
\]

Kovalev, Sinova et al PRB 08, Onoda PRL 06, PRB 08
Anomalous Hall effect: more than meets the eye

**Anomalous Hall Effect**

- Inverse SHE

**Spin Hall Effect**

- Wunderlich, Kaestner, Sinova, Jungwirth PRL 04
  - Intrinsic

- Kato et al Science 03
  - Extrinsic

**Mesoscopic Spin Hall Effect**

- Valenzuela et al Nature 06

**Spin-injection Hall Effect**

- Brune, Roth, Hankiewicz, Sinova, Molenkamp, et al 09

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

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
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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.

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

BUT $I_{MF} \ll L_{S-D}$ at room temperature

**Towards a realistic spin-based non-magnetic FET device**

$\vec{B}_{eff} = -\frac{\hbar k}{cm} \times \vec{E}$
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

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

Problem: Rashba SO coupling in the Datta-Das SFET is used for manipulation of spin (precession) but dephases 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:

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

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

\[ \beta = -B \langle k_z^2 \rangle \]

\[ B = 10 \text{ eV Å}^3 \]

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

\[ \beta = 0, \quad \alpha = \lambda^* E_z \]

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

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

Can we use SO coupling to manipulate spin AND increase spin-coherence?
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
Effects of Rashba and Dresselhaus SO coupling

\[ H_{2DEG} = \frac{\hbar^2 k^2}{2m} + \alpha (k_y \sigma_x - k_x \sigma_y) + \beta (k_x \sigma_x - k_y \sigma_y) \]

\( \alpha > 0, \beta = 0 \)

\( \alpha = 0, \beta < 0 \)

\( \alpha = -\beta \)
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 $\alpha \neq \beta$

$$S_z/x_-(x_{[1\bar{1}0]}) = S^0_z/\chi_\exp[qx_{[1\bar{1}0]}]$$

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

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

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).

New paradigm using SO coupling: SO not so bad for dephasing

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

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
AHE contribution to Spin-injection Hall effect in a 2D gas

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

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)

AHE contribution to Spin-injection Hall effect in a 2D gas:

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

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

Crepieux et al PRB 01
Nozier et al J. Phys. 79

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

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

Lower bound estimate of skew scatt. contribution

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Spin-injection Hall effect: theoretical expectations

Local spin-polarization $\rightarrow$ calculation of AHE signal

Weak SO coupling regime $\rightarrow$ extrinsic skew-scattering term is dominant

$$\alpha_H(x_{[1\bar{1}0]}) = 2\pi\lambda^* \sqrt{\frac{e}{\hbar n_i \mu}} n p_z(x_{[1\bar{1}0]})$$
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2) Can we detect the spin in a non-destructive way electrically? ✓

Use AHE to measure injected current polarization at the nano-scale electrically (Wünderlich, et al 09, 04)
Device schematic - material
Device schematic - trench
Device schematic – n-etch

Energy [eV]

p, n [10^{18}/cm^3]

p, n [10^{18}/cm^3]

z [nm]

2DHG

2DEG
Device schematic – Hall measurement
Spin-injection Hall effect device schematics

For our 2DEG system:
\[
\beta \approx -0.02 \text{ eV Å}, \quad m = 0.067m_e
\]
\[
\alpha \approx 0.01 - 0.03 \text{ eV Å} \quad (\text{for } E_Z \approx 0.01 - 0.03 \text{ eV/Å})
\]
Hence \( \alpha \approx -\beta \)
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
Non public slides deleted. Please contact Sinova if interested
Non public slides deleted. Please contact Sinova if interested
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)*
Control of materials and transport properties via spin-orbit coupling

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

Nanoelectronics, spintronics, and materials control by spin-orbit coupling
Sinova’s group

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and many others

Nanoelectronics, spintronics, and materials control by spin-orbit coupling