Experimental observation of the spin-Hall effect in a two dimensional spin-orbit coupled semiconductor system

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- Motivation

- Detection method:
  - Co-planar light emitting
  - $p$-$n$ junction

- Experiment and comparison on recent microscopic Calculations

- Electrical spin-generation apart from SHE

- Outlook
Generation of spin polarization, e.g.:

- Electrical spin injection
- External magnetic field
  e.g. from R. M. Potok et al., Phys. Rev. Lett. 89, 266602 (2002).

- Circular polarized light sources:

- Electrically induced ordering based on SO interaction, e.g. SHE
  - Can be applied locally, no LASER or magnet needed
  - May rely on low-dissipation processes

Caution: Even in case of the intrinsic SHE: a dissipationless transverse spin-current is accompanied by a dissipative longitudinal charge current

Spin-Hall effect utilizes spin-orbit coupling

**Ingredients:**
- gradient of potential $V(r)$
- motion of an electron

**Produces**
- an electric field

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

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

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

**gives an effective interaction with the electron’s magnetic moment:**

\[ H_{SO} = -\vec{\mu} \cdot \vec{B}_{eff} \]
Skew scattering at impurity potential (Extrinsic SHE/AHE)

\[ H_{SO} = -\left( \frac{\hbar^2 \tilde{s}}{m^2 c^2} \right) \cdot [\vec{k} \times \vec{\nabla} V_{imp}(r)] \]

Skew scattering at impurity potential (Extrinsic SHE/AHE)

Skew scattering

[Smit, Physica 24, 39 (1958)]

scattered amplitude modulated wave

\[ |k', s_z \rangle \]

\[ e^{ik'r} \]

\[ f(\theta) \]

\[ \frac{r}{\delta} \]

\[ \theta \]

\[ \theta' \]

\[ \delta \]

\[ k \]

\[ k' \]

\[ s_z \]

\[ s_z' \]

Incident wave

\[ e^{ikr} \]

\[ \delta \]

\[ \delta = \lambda_{SO} (\sigma \times k) \]

\[ |k, s_z \rangle \]

| \[ r - \delta \] |

\[ \frac{e^{ik|r - \delta|}}{r - \delta} \]

Scattered phase-shifted wave

Side-jump scattering

[Luttinger, Phys. Rev. B 112, 739 (1958)]
SHE also possible **without** anisotropic scattering by impurities:

**via SO-coupling from host atoms** (Intrinsic SHE)

\[
H_{SO} = -\vec{\mu} \cdot \vec{B}_{eff} = -\left( \frac{e\vec{s}}{mc} \right) \cdot \left[ \frac{\hbar \vec{k}}{mc} \times \vec{r} \left( \frac{1}{e\vec{r}} \frac{dV(r)}{dr} \right) \right] = \alpha \vec{s} \cdot \vec{l}
\]

\( l=0 \) for electrons \( \rightarrow \) weak SO

\( l=1 \) for holes \( \rightarrow \) strong SO
Enhanced in asymmetric QW

- E-field in QW is perpendicular to heterostructure plane –
  - B field in-plane and perpendicular to v
  - spin precesses around B (Datta-Das-device)
**Heuristic picture:**

$z$-component of spin due to precession in effective "internal" $k$-dependent magn. field

[Sinova et al. PRL 92 p126603 (2004)]

Classical dynamics in $k$-dependent (Rashba) field:

LLG equation for small drift $\rightarrow$ adiabatic solution:

$$n_x(t) = \frac{\Delta_x(t)}{\Delta_y}$$

$$\Delta_y n_z = \hbar \frac{d n_x}{dt} = \frac{\hbar}{\Delta_y} \frac{d \Delta_x}{dt}$$

$$\Delta = \lambda (\bar{z} \times \bar{k}), \frac{dk_y}{dt} = -eE_y$$

$\rightarrow$ net spin polarization vanishes, but spin current in x-direction
Boltzmann equation for current:
transverse anomalous velocity in the equilibrium band structure due to
combined E and SO effects


\[
-e^2 \frac{\mathbf{E} \times \int d^3 k \sum_n f_n \Omega_n (\mathbf{k}) - e}{\hbar} \int d^3 k \sum_n \delta f_n (\mathbf{k}) \frac{\partial \varepsilon_n}{\partial k}
\]

\[
\Omega_n (\mathbf{k}) = - \text{Im} \langle \nabla_{\mathbf{k}} u_{n\mathbf{k}} | \times | \nabla_{\mathbf{k}} u_{n\mathbf{k}} \rangle
\]

A complete quantum mechanical description: Kubo formula:

Sinitsyn et al., PRB 70, 081312 (2004)
Nomura et al. cond-mat/0407279

\[
\text{Re} [\sigma_{xy}] = - \frac{e^2}{V} \sum_{\mathbf{k} \neq \mathbf{k}'} \left( f_{n'n\mathbf{k}} - f_{n\mathbf{k}} \right) \frac{\text{Im} \langle n'\mathbf{k}' | \hat{j}_x | n\mathbf{k} \rangle \langle n\mathbf{k} | \hat{\nu}_y | n'\mathbf{k}' \rangle}{(E_{n\mathbf{k}} - E_{n'n\mathbf{k}'} + i \eta)^2}
\]
Net-spin polarization present: **Anomalous Hall effect**

**Initial spin polarization in ferromagnetic system**

*Spin-orbit coupling “force” deflects like-spin particles*

Charge accumulation (and Spin accumulation)

\[
\rho_{xy} = R_0 B_z + 4\pi R_s M_z
\]

Smit, Physica 24, 39 (1958)
Luttinger, Phys. Rev. B 112, 739 (1958)
No net-polarization: **Spin Hall effect**

No Net spin polarization in **non-magnetic system**

*Spin-orbit coupling “force” deflects like-spin particles*

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**Spin accumulation** without charge accumulation excludes simple electrical detection

M.I. D’yakonov and V.I. Perel, Phys. Lett. 35 A 459 (1971)
Detection of the SHE

Conductance measurements by attaching ferromagnetic electrode

Detection of photon circular polarization emitted from a LED

Local MOKE

Merit of optical approaches:
Angular resolved spin detection possible

Fig. 3. Experimental setups for the detection of spin current induced by an electric field. (A) Detection by attaching a ferromagnetic electrode. The dependence of current $I$ flowing into the electrode on the direction of the magnetization $M$ is to be measured. (B) Detection by measuring the polarization of the emitted light in the quantum well of (In,Ga)As. The emitted light with circular polarization is shown as an open arrow. Right and left circular polarization will be switched when the direction of the external electric field is reversed.

[Murakami et. al., Science 301, 1348, 2003]

[Silov et. al., APL 85, 5929, 2004]
Conventional vertical spin-LED

not practical for studying transport in low-dimensional systems

require lateral arrangement of low-dimensional channel and optically active region

Spin polarization detected through circular polarization of emitted light
Conventional vertical spin-LED

R. Wang et al.: APL 86, 052901 (2005)

Co-planar spin-LED

- No hetero-interface along the LED current
- Spin detection directly in the 2DHG
- Light emission near edge of the 2DHG
- 2DHG with strong and tunable SO

Spin polarization detected through circular polarization of emitted light
Wafer design based on Schrödinger-Poisson simulations

Fabrication:
- selectively etching vertical p-i-n structure
- 2DEG depleted, 2DHG at upper i-GaAs interface
Removing p-AlGaAs lowers conduction band energy
-> Quasi lateral junction
Wafer design based on Schrödinger-Poisson simulations

- EL confined to junction step edge
- Current dominated by electrons moving from n- to p- type region
- Minority electrons injected into hole reservoir

⇒ Radiative recombination only in p –region at the junction
Sub GaAs gap spectra analysis: PL vs EL

X: bulk GaAs excitons

I: recombination with impurity states

PL

GaAs/AlGaAs superlattice and GaAs substrate

2DHG

2DEG

p-AlGaAs

I-GaAs

n-δ-doped AlGaAs

X: bulk GaAs excitons

I: recombination with impurity states

PL

GaAs/AlGaAs superlattice and GaAs substrate

2DHG

2DEG

p-AlGaAs

I-GaAs

n-δ-doped AlGaAs

Wafer 1

Wafer 2
$\chi$: bulk GaAs excitons

$I$: recombination with impurity states

Excitonic peaks visible in EL as well but indep. of bias
Sub GaAs gap spectra analysis: PL vs EL

B (A,C):
3D electron – 2D hole recombination

Wafer 1 and 2 differ in Al content of p-AlGaAs layer -> influence B (A,C)

Impurity related recombination would show different bias behaviour
Sub GaAs gap spectra analysis: PL vs EL

$\chi$: bulk GaAs excitons

$I$: recombination with impurity states

$B(A, C)$: 3D electron – 2D hole recombination

Bias dependent emission wavelength for 3D electron – 2D hole recombination

[A. Y. Silov et al., APL 85, 5929 (2004)]
- 2DHG in plane
- LED current drives EL at the edge of hole stripe
- Channel current $I_p$ induces edge spin accumulation
- Red and blue area indicate expected spin accumulation
Co-planar spin LED in GaAs 2D hole gas: ~1% polarization

1.5 µm channel

LED 1

LED 2

n
p

I_p

I_{LED 1}

-x

y

z
Opposite perpendicular polarization for opposite $I_p$ currents or opposite edges
$\Rightarrow$ SPIN HALL EFFECT
Intrinsic SHE plausible in our system?

Self-consistent LDA & 6-band calculations for the [001] QW

Determine SO coupling strength:
- For unbiased QW only one HH and one LH exist
- Only HH is occupied at measured hole density of $p = 2.0 \times 10^{12} \text{ cm}^{-2}$

Measured hole mobility: $3400 \text{ cm}^2/\text{V s}$

Close to the intrinsic SHE regime
Kubo formula

for stripe width $>>$ mean free path

$$S(x) = -\frac{i\hbar E_y}{L_x L_y} \int_0^{L_y} dy \sum_{n,n'} \frac{f(E_n) - f(E_{n'})}{E_n - E_{n'}} \frac{\langle n(x,y) | s^2 | n'(x,y) \rangle \langle n'(x,y) | j_y | n(x,y) \rangle}{E_n - E_{n'} + i\eta}$$

Hamiltonian

$$H_R = \begin{pmatrix} \frac{\hbar^2 k^2}{2m} & i\lambda k_- \\ -i\lambda k_+ & \frac{\hbar^2 k^2}{2m} \end{pmatrix}$$

+ hard walls + disorder
Numerical observations for weak scattering & strong SO:

- $v_F S_{edge}^z \sim j_{bulk}^z$

- $S_{edge}^z$ increases with SO coupling strength

- independent of QP lifetime

- independent of the stripe width

- 2DHG more favorable than 2DEG
Spin Hall Effect in a symmetric Device

- 10µm channel width
- similar longitudinal electric as before

Large spin accumulation can be induced near edges of macroscopically wide channels
... generation of occupation-asymmetry

Applying an electric field, subbands become asymmetrically occupied.

Dark area corresponds to occupied states.

$x$-component of integrated spin polarization is non-zero in each subband.

$\Rightarrow$ net total spin polarization

$\Rightarrow \textit{generation of in-plane polarization for a } [001]\text{ grown GaAs quantum well}$
... generation of occupation-asymmetry

- Minority electrons injected into hole reservoir
- Electron occupation asymmetry \parallel \text{ to QW}
- Assume that voltage drop does not shift holes
- Radiative Recombination acts like spin filter

\[\text{[Mal’shukov et al., PRB 65, 241308(R) (2002)]}\]

⇒ generation of in-plane polarization for a [001] grown GaAs quantum well

⇒ Separate from SHE by angle resolved detection
Circular Polarization of EL detected at perpendicular to 2DHG plane

Energy [10^3 cm^{-1}] vs. Degree of Circular polarization [%]

- EL intensity [a.u.]
- Energy [eV]
Polarization of EL detected at different angles

- Increasing detection angle -> polarization in x-direction
- Indirect observation in-plane $B_{\text{int}}$ for E applied $||$ to QW

[investigated e.g. by Kikkawa et al. Nature 397, p139 (1999)]
Inplane Circular Polarization ($\alpha = 85^\circ$) detected at \( B = +3 \) T.
Inplane Circular Polarization ($\alpha = 85^\circ$) detected at $B = \pm 3T$. 
Compare inplane/out of plane

\[ \alpha \]

\[ x, B \]

\[ \sim 1.5 \text{T} \]

\[ B_x = -3 \text{T} \]

\[ B_x = +3 \text{T} \]

\[ B_z = -3 \text{T} \]

\[ B_z = +3 \text{T} \]

⇒ NO perp.-to-plane component of polarization at B=0

⇒ Symmetric polarization curve for perpendicular to plane

⇒ B≠0 anisotropic behavior consistent with SO-split 2DHG
Conclusion

- Presented a spin-detection method in low-dimensional systems:

- Detection of current induced Spin polarization

- Spin-Hall effect in hole system
  Detection of perpendicular-to-plane polarization inverse at opposite sides of the stripe and reversed for opposite current direction

- Spin polarization due to occupation-asymmetry
  Detection of in-plane net-spin-polarization perpendicular to current direction
Excitation with circular polarized light of tuneable wavelength

Measuring Hall signal as function of CP, distance to POG, wavelength, temperature ...

Reverse breakdown: $V_R = -11.5V \ (T = 4.2K)$

Reverse biased (only photo-current (100% spin-polarized at point of generation (POG)))
Acknowledgements

- Shoucheng Zhang and Mohammed Khalid for many useful discussions
applying higher channel current ...

- blue shift of peak B
- peak A becomes also slightly polarized (opposite polarization)
Circular polarization as a function of energy and applied magnetic field $B_x$. 

![Graph showing circular polarization as a function of energy and applied magnetic field $B_x$.]
Comparing extrinsic and intrinsic SHE contribution for our system by taking HH mass and mobility in account:

Self-consistent LDA & 6-band calculations for the [001] QW

Kubo formula calculation

Tolerance of SH conductivity to disorder as hole density (i.e. SO interaction) is varied; Within red area only weakly suppressed, where device operates

Result of:
Modulation doping → weak disorder
p-type asymmetric QW → strong SO
Sub GaAs gap spectra analysis: Temperature dep.

\( \chi: \)
Red-shift with increasing T due to gap lowering

\( B (A): \)
below T \( \sim \) 10K

Temperature dependent emission wavelengths for bulk excitons and 3D electron – 2D hole recombination

[A. Y. Silov et al. JAP 73, 7775 (1993)]
Dissipative spin-polarized currents in non-magnetic systems at B=0

Spin-current is along the applied electric field $\rightarrow$ proportional to non-equilibrium distribution function

asymmetric scattering involving spin-flip

[ Ganichev et al., cond-mat/0403641, Silov et al. APL 04]