Electrical injection and detection of spin-polarized electrons in lateral (Ga,Mn)As/GaAs Esaki diode devices

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Outline

- Motivation
- Experimental device
- Spin injection and detection experiments
  - spin-valve effect
  - Hanle effect
- Bias dependence of spin injection efficiency
- Tunneling Anisotropic Magnetoresistance (TAMR) and Tunneling Anisotropic Spin Polarization (TASP) effects
- Summary and outlook
Motivation: Datta – Das spin FET transistor

Spin injection

spin manipulation

spin detection

source

Vg

drain

InGaAs

InAlAs

FM

FM

**Electrical spin injection**

- **From ferromagnetic metals (FM)**
  - A tunnel barrier (e.g. tailored Schottky barrier, oxide layer) between FM and semiconductor solves conducting mismatch problem
  - Spin polarization $P \sim 30\%$ achieved in Fe/(Al,Ga)As structures

- **From diluted magnetic semiconductors (DMS)**
  - Paramagnetic II-VI materials, e.g. BeZnMnSe, $P \sim 90\%$
  - Ferromagnetic III-V materials, e.g. (Ga,Mn)As in spin Esaki diode structure, $P \sim 80\%$
Electrical spin detection

- Most of the experiments employ optical detection through LED.

- Only recently all-electrical injection detection scheme in hybrid FM/semiconductor lateral devices
  
  van't Erve et al., Appl. Phys. Lett. 91, 212109 (2007)

- Up-to-date no report on successful all-electrical, all-semiconductor spin injection-detection device.
Sample preparation - device layout

- Ferromagnetic (Ga,Mn)As contacts
- Non-magnetic PdGe contacts
- n-GaAs channel
Sample preparation - spin Esaki diode structure

125 nm Ti/Au
20 nm (Ga,Mn)As, 5%
2.2 nm (Al,Ga)As, 0.36
8 nm $n^+$-GaAs
15 nm $n^+ \rightarrow n$-GaAs
250 nm $n$-GaAs

$n=6 \times 10^{16} \text{cm}^{-3}$
$n^+=6 \times 10^{18} \text{cm}^{-3}$

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Sample preparation - SEM picture
Non-local detection of spin accumulation $\mu_s$

\[ V_{nl}^s = \pm \frac{P_{inj} P_{det} l \lambda_{sf} \rho_N}{2S} \exp\left(-\frac{L}{\lambda_{sf}}\right) \]

Spin-charge coupling

\[ V_{nl}^s = -P_{det} \mu_s(L) \]

\[ \mu_s(x) = \mu_s(0) \exp\left(-\frac{x}{\lambda_{sf}}\right) \]

Spin injection efficiency

\[ P_{inj} = \frac{j_{\uparrow} - j_{\downarrow}}{j_{\uparrow} + j_{\downarrow}} \]

M. Johnson & R.H. Silsbee PRL 55, 1790 (1985)

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Non-local spin valve

\[ V_{nl}^s = \pm \frac{P_{inj} P_{det} I \lambda_{sf} \rho_N}{2S} \exp\left(-\frac{L}{\lambda_{sf}}\right) \]

\[ \Delta V = 2V_{nl}^s \]
Non-local spin valve measurements

\[ \Delta V \sim \exp\left(-L / \lambda_{sf}\right) \]

\[ \lambda_{sf} \approx 2.8 \mu m \]
Spin precession in transverse magnetic field – Hanle effect

\[ L = 2\lambda_{sf}, \nu_d = 0 \]

\[ V_{||}(x_1, x_2, B) = V_0 \int_{0}^{\infty} \frac{1}{\sqrt{4\pi Dt}} e^{-\left(x_2 - x_1 - \nu_d t\right)^2 / 4Dt} \times \cos(\omega_L t)e^{-t/\tau_s} dt \]

\[ V_0 = \pm \frac{P_{inj}P_{det}\lambda_{sf} \rho_N}{2S} \]

\[ \nu_d \text{– drift velocity} \]
\[ D \text{– diffusion constant} \]
\[ \tau_s \text{– relaxation time} \]

F. Jedema et al., Nature 410, 345 (2001)

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Hanle effect measurements

$V_{36}$
$L=5\mu m$

$V_{46}$
$L=10\mu m$

$V_{56}$
$L=15\mu m$

$I=-50\mu A$  $T=4.2K$

$B_z(T)$  $V(\mu V)$

$V$  $V$  $V$

$B_z$  $B_z$  $B_z$
Hanle effect measurements - model curves

Model:

\[
V_{\parallel}(x_1, x_2, B) = V_0 \int_0^\infty \frac{1}{\sqrt{4\pi Dt}} e^{-(x_2-x_1-v_d t)^2 / 4Dt} \times \cos(\omega_L t)e^{-t/\tau_s} dt
\]

integrated over widths of injector and detector

\[
V_0 = \pm \frac{P_{\text{inj}} P_{\text{det}} I \lambda_{sf} P_N}{2S}
\]

assuming \( P_{\text{inj}} \approx P_{\text{det}} = P, \ v_d = 0 \)

free parameters: \( P, \ \tau_s, \ \lambda_{sf} \)
Hanle effect measurements - temperature dependence

- Curves get wider due to decrease of the spin lifetime
- Agreement with the model improves with T

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The origin of spin-valve signal

$V(V)$

$L=5 \mu m$

$I=-5 \mu A$

$B (T)$
The origin of spin-valve signal

\[ V(I, B) \]

\[ I = \pm 5 \mu A \]

\[ L = 5 \mu m \]

\[ B_x \]

\[ I > 0, V_{nl} \]

\[ I < 0 \]

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The origin of spin-valve signal

\[ \Delta V \approx V_{nl}^s = \pm \frac{P_{ij}^s P_{det}^d \lambda_{sf} \rho_N}{2S} \exp\left(-\frac{L}{\lambda_{sf}}\right) \]

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Bias dependence of a spin signal

\[ \Delta R = \frac{\Delta V}{I} = \pm \frac{P_{\text{inj}} P_{\text{det}} \lambda_{sf} \rho_N}{2S} \exp\left(-\frac{L}{\lambda_{sf}}\right) \]

- \( I (\mu A) \)
- \( V (\mu V) \)
- \( B_x (T) \)
- \( \Delta R (\Omega) \)

- \( L=5 \mu m \)
- \( L=10 \mu m \)

\( T=4.2K \)

\( L=5 \mu m \)
Bias dependence of a spin signal

\[ \Delta R = \frac{\Delta V}{I} = \pm \frac{P_{\text{inj}} P_{\text{det}} \lambda_{sf} \rho_{N}}{2S} \exp\left(-\frac{L}{\lambda_{sf}}\right) \]

\[ T = 4.2 \text{K} \]
\[ L = 5 \mu m \]

\[ P_{\text{inj}} (|I| = 1 \mu A) \approx P_{\text{det}} \rightarrow P_{\text{inj}} \approx 50\% \]
Bias dependence of a spin injection efficiency

\[ \Delta R = \frac{\Delta V}{I} = \pm \frac{P_{\text{inj}} P_{\text{det}} \lambda_{sf} \rho_N}{2S} \exp\left(-\frac{L}{\lambda_{sf}}\right) \]

\[ P_{\text{inj}}(I = 1 \mu A) \approx P_{\text{det}} \rightarrow P_{\text{inj}} \approx 50\% \]
Bias dependence of $P_{\text{inj}}$ – reverse bias

Experiment – detection with LED

Calculations

Finite reverse bias increases the contribution of minority spins to tunneling decreasing the resulting spin polarization

P. Van Dorpe et al. PRB 72, 205322 (2005)
Bias dependence of $P_{\text{inj}}$ – forward bias

- Inelastic scattering events through the forbidden states in the bandgap
- The thermal current taking over the tunneling current
TAMR and TASP effects – in-plane

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure}
\caption{Graph showing TAMR effect in injector circuit. Resistance sensitive to change of \textbf{M} in injector contact ONLY.}
\end{figure}

\textit{C. Gould et al. PRL 93, 117203 (2004)}
TAMR and TASP effects – in-plane

TAMR and TASP effects – in-plane

P. Sankowski et al.
PRB 75, 045306 (2007)
TAMR and TASP effects – out-of-plane

$V \mu V$ vs $B_z(T)$

$L = 10 \mu m$

$I = -50 \mu A$

$T = 4.2 K$

background
TAMR and TASP effects – out-of-plane

\[ TASP_{\perp} = \frac{P_{\perp} - P_{\parallel}}{P_{\parallel}} \]

Assuming \( P_{\text{inj}} \approx P_{\text{det}} = P \)

\[ TASP_{\perp} \approx 50\% \]
Summary

- Successful realization of an *all-electrical* spin injection and detection scheme in *all-semiconductor* lateral devices.

- Bias-dependence of spin injection efficiency reflects the physics of Esaki devices.

- Observed Tunneling Anisotropic Spin Polarization (TASP) effect consistent with previous findings.
Outlook

- Control over the magnetization in (Ga,Mn)As contacts
- Classical spin–valve measurements
- 2DES as an active channel
- The effect of bias on TAMR and TASP
- The role of hyperfine effects