Spins under strain

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Spins under Strain

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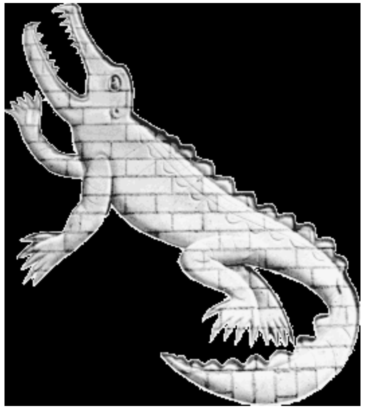

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Outline

- Spins, spintronics
- Strain: a tool to rotate spins

  -Team effort: experiment-theory

  LANL-Cambridge
- Predictions/speculations based on the analogy of strain to SU(2) gauge potential
  – My own, work in progress

Spins are fun,…

Operator algebra

$$[S_i, S_j] = i\epsilon_{ijk}S_k$$

Particle on a sphere in the field of the Dirac monopole; accumulating Berry phase

$$S[\mathbf{n}(t)] = \frac{1}{2}\int dt(\dot{\mathbf{n}}\cdot\mathbf{A} + \mathbf{n}\cdot\mathbf{B})$$

…and (potentially) useful: Spintronics

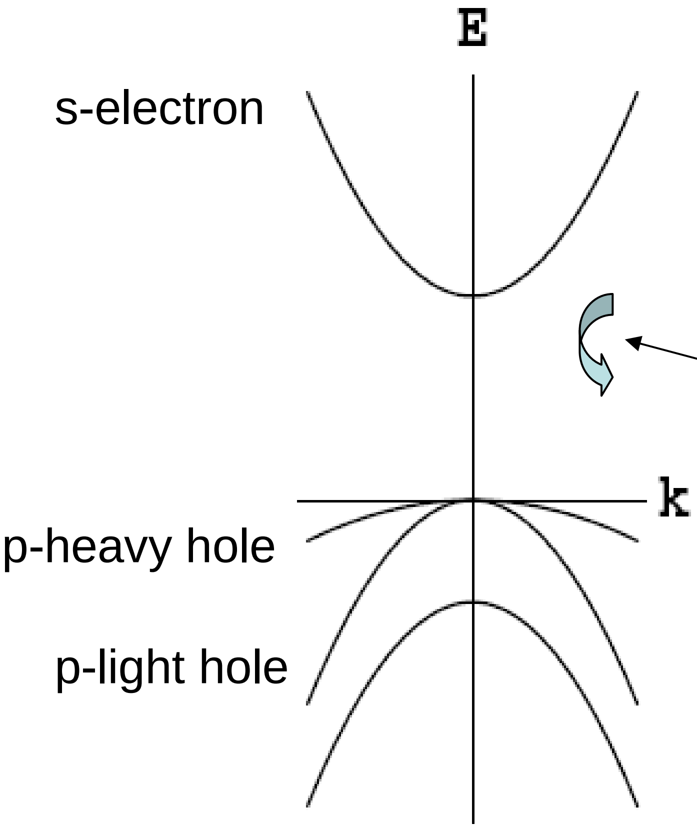
- Use spin as well as charge of electrons in semiconductor devices
  - another information channel
  - lower power consumption
  - higher speed
- 4 tasks: 1.Inject, 2.transport, 3.**rotate**, 4.detect

↑ Main focus

First describe the remaining three tasks (not a history overview)

1.Injection: (a)optical

- From **spin-orbit** coupling in the band structure—theme throughout



$$
\begin{aligned}
e:|1/2,1/2\rangle &= |s\rangle|\uparrow\rangle; \quad |1/2,-1/2\rangle = |s\rangle|\downarrow\rangle \\
hh:|3/2,3/2\rangle &= \frac{|p_x+ip_y\rangle}{\sqrt{2}}|\uparrow\rangle \\
lh:|3/2,1/2\rangle &= \sqrt{\frac{1}{3}}\frac{|p_x+ip_y\rangle}{\sqrt{2}}|\downarrow\rangle+\sqrt{\frac{2}{3}}|p_z\rangle|\uparrow\rangle
\end{aligned}
$$

circularly polarized light:

$$\langle S|A_-|X+iY\rangle$$

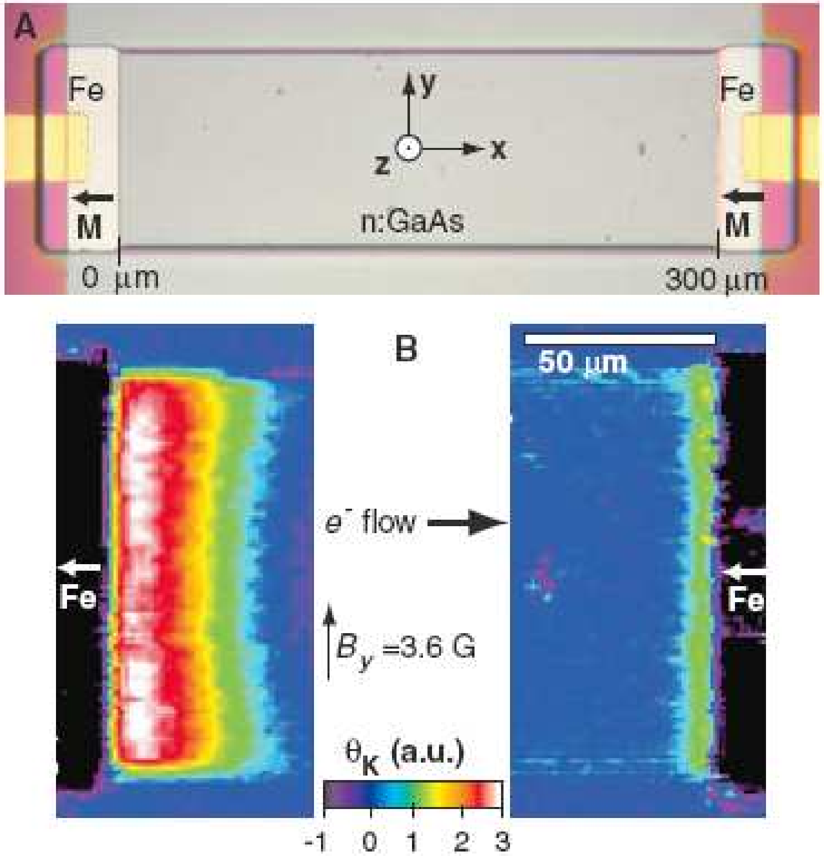
Output: mainly spin up

n doping (electrons) everywhere in this talk

1. Injection: (b)electric

Iron on top of GaAs:

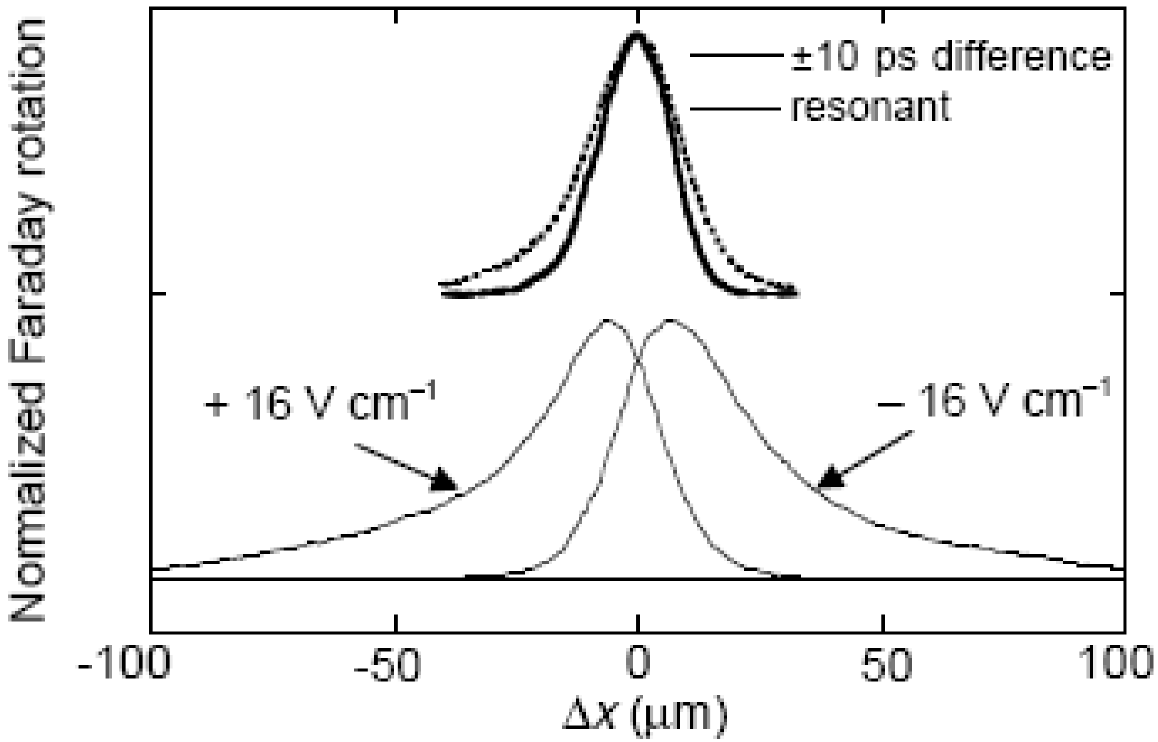
Injected spins:



Crooker et al., Science **309**, 2191 (2005)

2. Transport

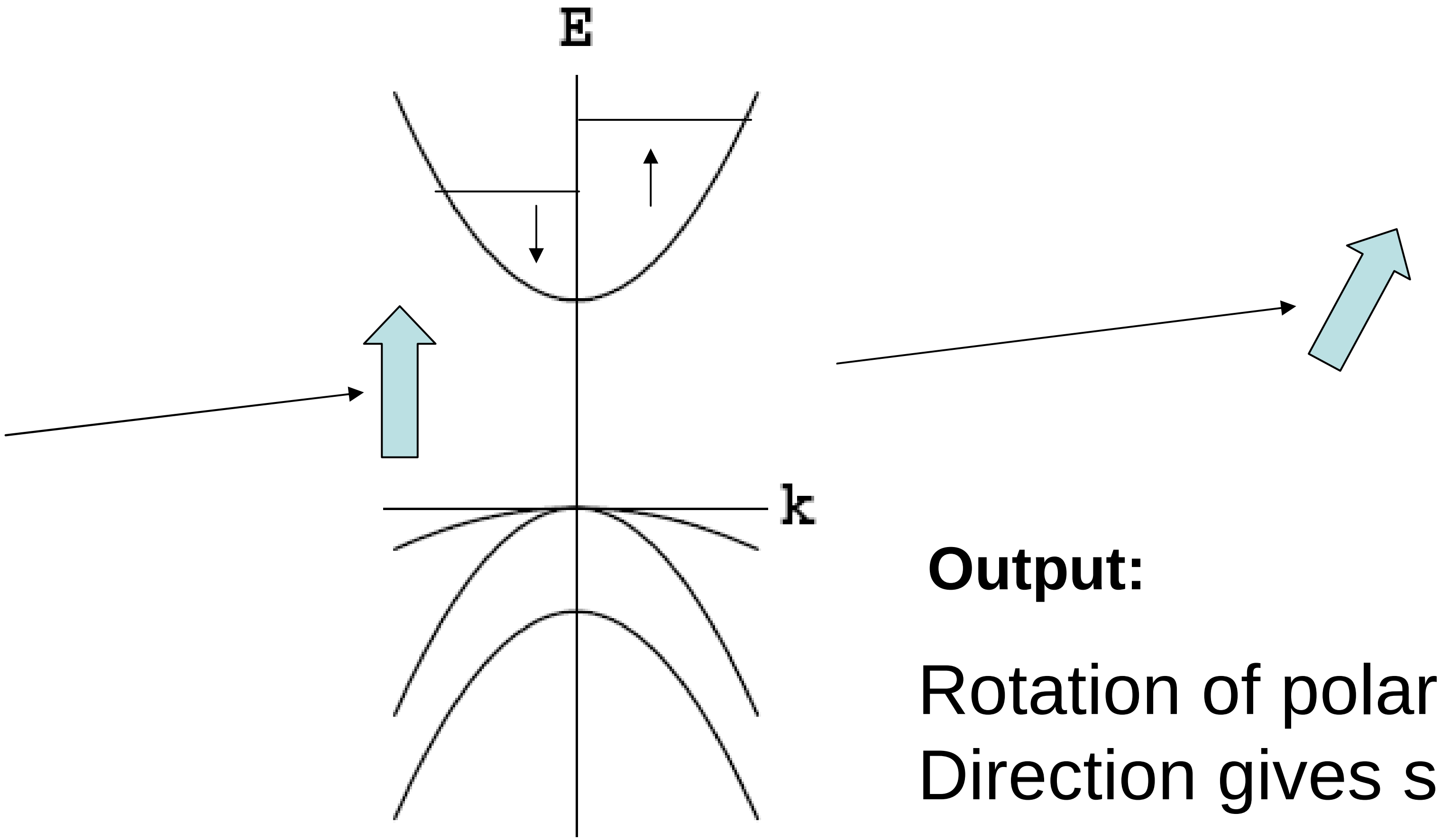
- Long spin lifetime (100 ns)…drift by electric field



J.M. Kikkawa, D.D. Awschalom, *Nature*, vol. 397, p. 139 (1999)

4. Detection: optical

- **Kerr/Faraday rotation** of the polarization direction of **linearly polarized light**



Output:

Rotation of polarization
Direction gives spin

3. Rotation

- By magnetic field—spin precession
- By strain—from spin-orbit coupling
  - Transport over longer distances—Main result

    Hruska, Kos et al. PRB **73**, 075306 (2006)

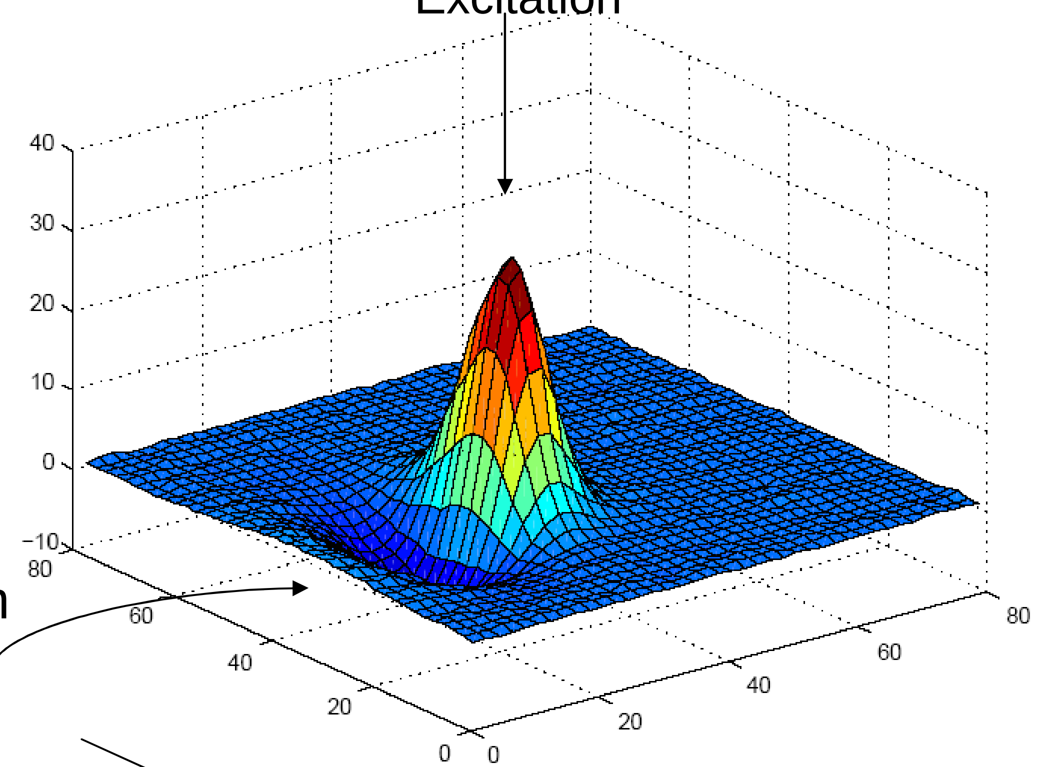
How did we think of it?

Scott Crooker, LANL: measured spin drift and precession in the presence of electric and magnetic fields

Spin polarization

1 µm thick layer of n:GaAs

a.u.



µm

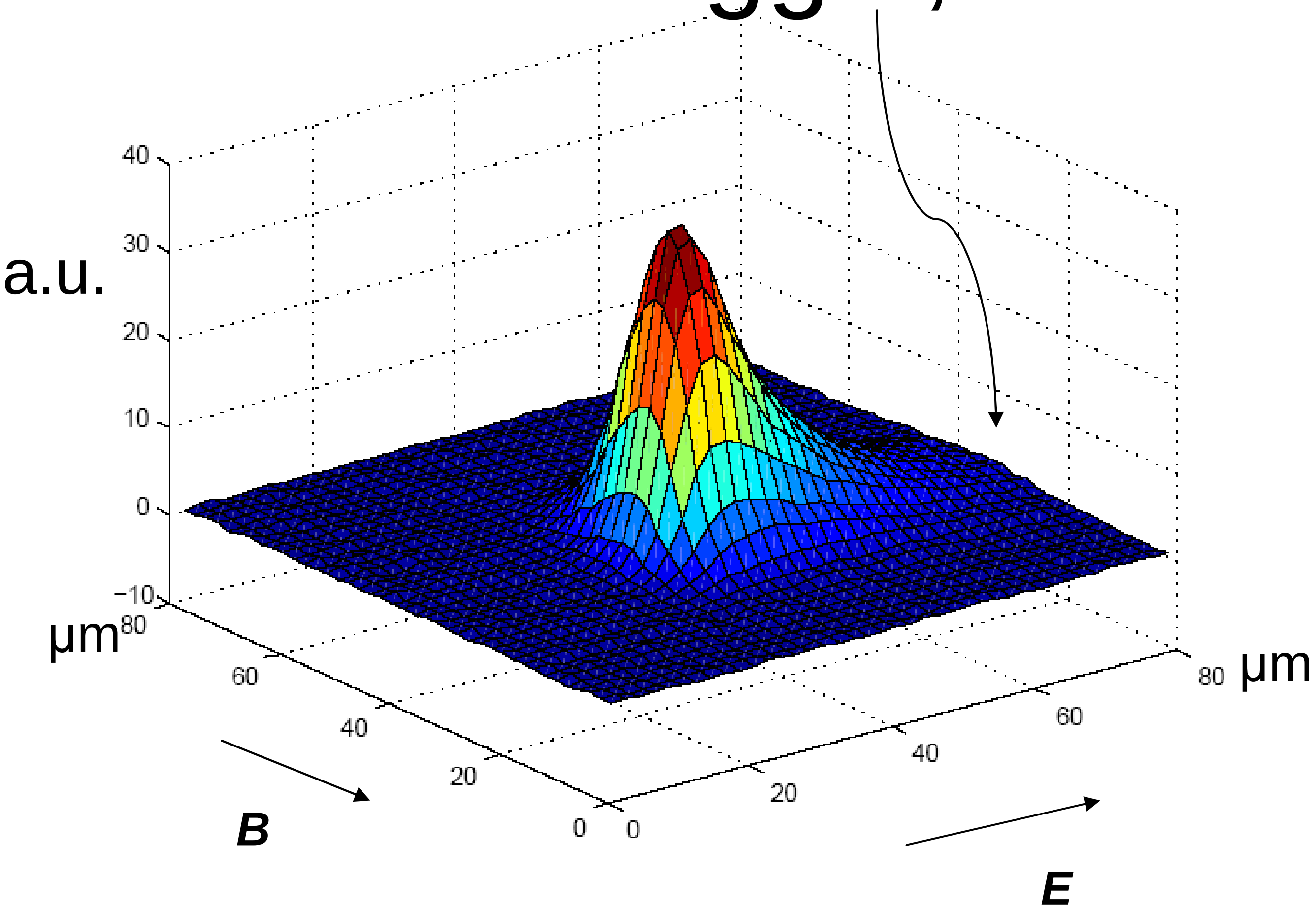
µm

Wiggle, but…

B

E

No wiggle,



when ***E*** was reversed

Resolution of the puzzle:

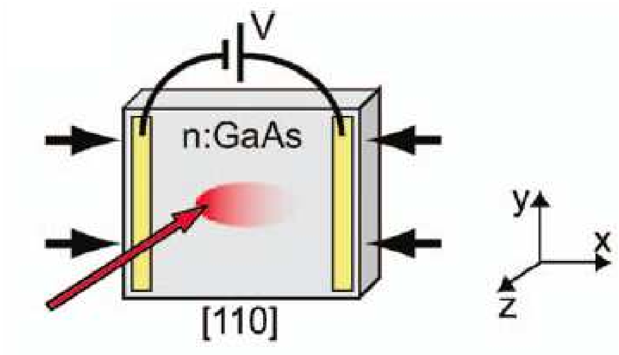
the sample was clamped!

Precession Hamiltonian $$H_{precess} = -g\mu_B \mathbf{B} \cdot \frac{\hbar}{2}\sigma$$

Strain: $$g\mu_B \mathbf{B} \rightarrow g\mu_B \mathbf{B} + C_3 \epsilon_{xy} \hat{\mathbf{z}} \times \mathbf{k}$$

From spin-orbit

axes:



Independent of ***E***

Changes sign with ***E***

Additon or subtraction

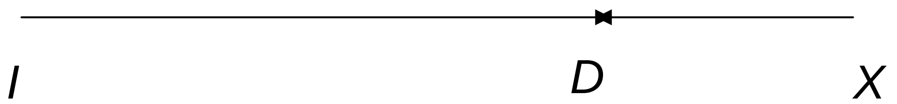
Turning a problem into a tool!

-use strain for precession with an extra benefit

Diffusive transport: random walks

Spin decay from spin flip processes
Additional decay from precession

1d:



Trajectories:1=*ID; 2=IXD*

Precession angles along *DX* and *XD*
add for magnetic field; subtract for strain

→ Spin is transported further with strain than with magnetic field

Technique: Boltzmann equation

Density of the
i-th spin component

$$\frac{\mathbf{p}}{m} \cdot \partial_{\mathbf{r}} \rho_i - e\mathbf{E} \cdot \partial_{\mathbf{p}} \rho_i + [\mathbf{Q} \times \rho]_i = -\frac{\rho_i - n_i f_o}{\tau} - \frac{\rho_i}{\tau_s} + J\delta_{z,i}$$

3 new terms:

1.Precession

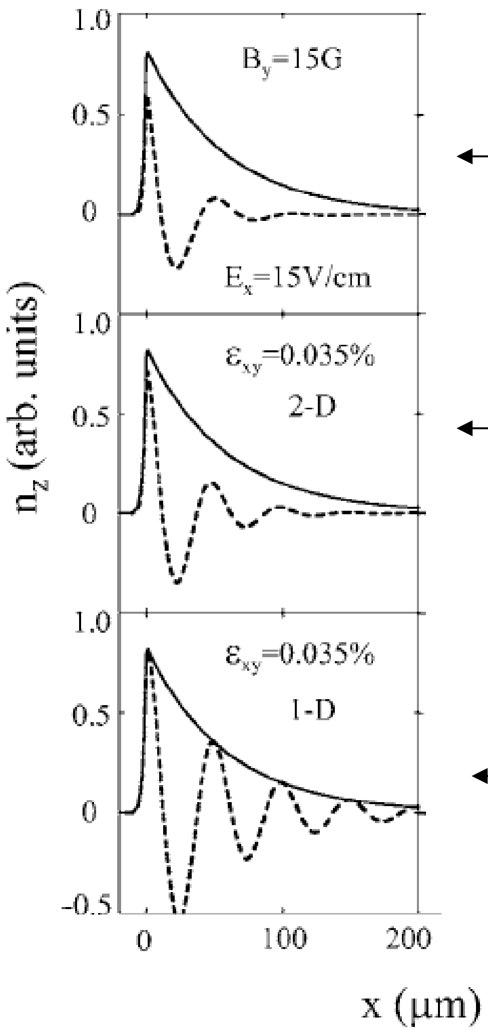
$$\mathbf{Q} = g\mu_B \mathbf{B} + C_3 \epsilon_{xy} \hat{\mathbf{z}} \times \mathbf{k}$$

2.Spin flip

3.Spin injection

- Separation of time scales τ/τ_s <<1
- Integrate over momenta to get the continuity equation; keep the lowest order in τ

Numerical results



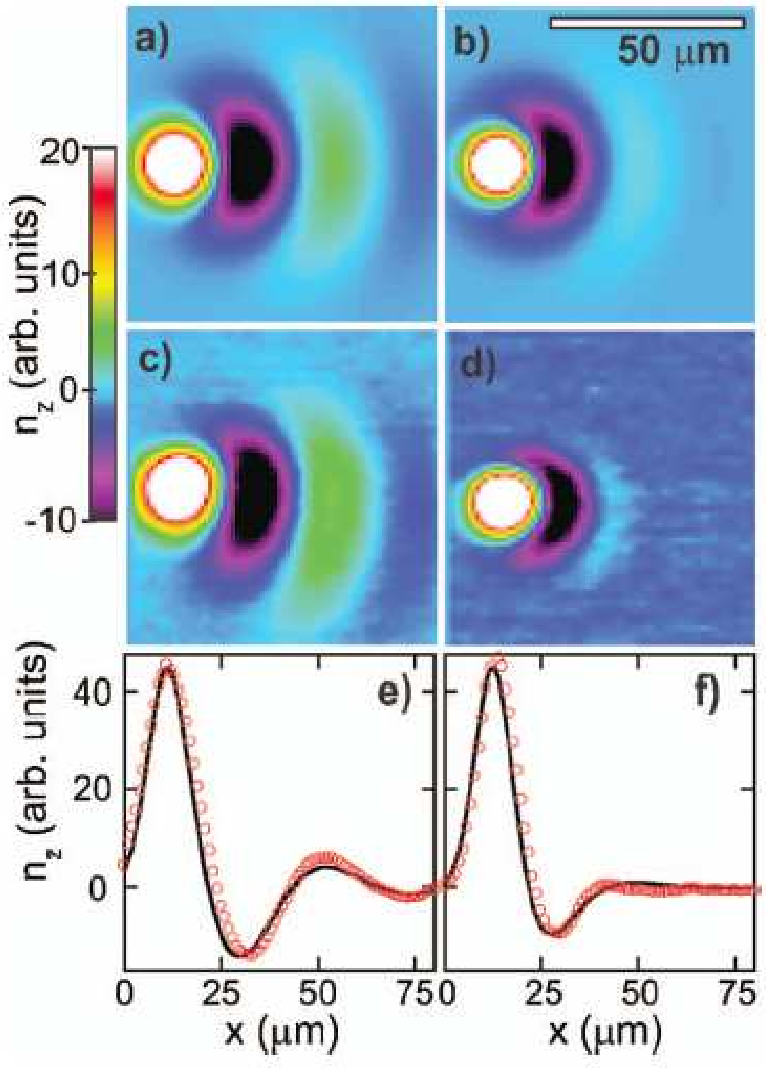
Magnetic field: extra decay

Strain in 2D: partial effect

Strain in 1D: no extra decay

Comparison to experiment

Strain   Magnetic field



Theory

Experiment

Comparison

Hruska, Kos et al.
PRB **73**, 075306 (2006)

Predictions/Speculations

- Strain analogous to SU(2) gauge field
  - Equilibrium spin current; edge spin currents
    - In analogy to Landau diamagnetism
  - Structural instability
  - Non-equilibrium magnetization
  - A new mode

E&M

Coupling to field $\mathbf{p} \to \mathbf{p} - \frac{e}{c}\mathbf{A}$

Classical physics: $Z = \int dpdq \exp - \left(\sum \frac{p^2}{2m} + V(q) \right)$

Static field ***A***: shift of variable ***p*** ⇨ zero current!

Equivalently: cancellation of the paramagnetic and diamagnetic term

$$\mathbf{v} \equiv \frac{\partial H}{\partial \mathbf{p}} = \frac{\mathbf{p}}{m} - \frac{e}{mc}\mathbf{A}$$

Quantum physics: incomplete cancellation due to Landau levels

⇨ Landau diamagnetism, edge currents

Related to: de Haas-van Alphen effect, Shubnikov-de Haas effect, quantum Hall effect

Analogue for strain

$$H = \frac{p^2}{2m} + \epsilon(\sigma_x p_y - \sigma_y p_x)$$

SU(2) gauge field

$$v_x = \frac{\partial H}{\partial p_x} = \frac{p_x}{m} - \epsilon\sigma_y$$

"paramg" "diamg"

v breaks *T* symmetry (unlike s-o) but ***vσ*** does not

Spin current

We need Quantum Mechanics,

i.e., something non-commuting!

SU(2) even for constant ϵ ⟺ constant non-Abelian potential is not a pure gauge

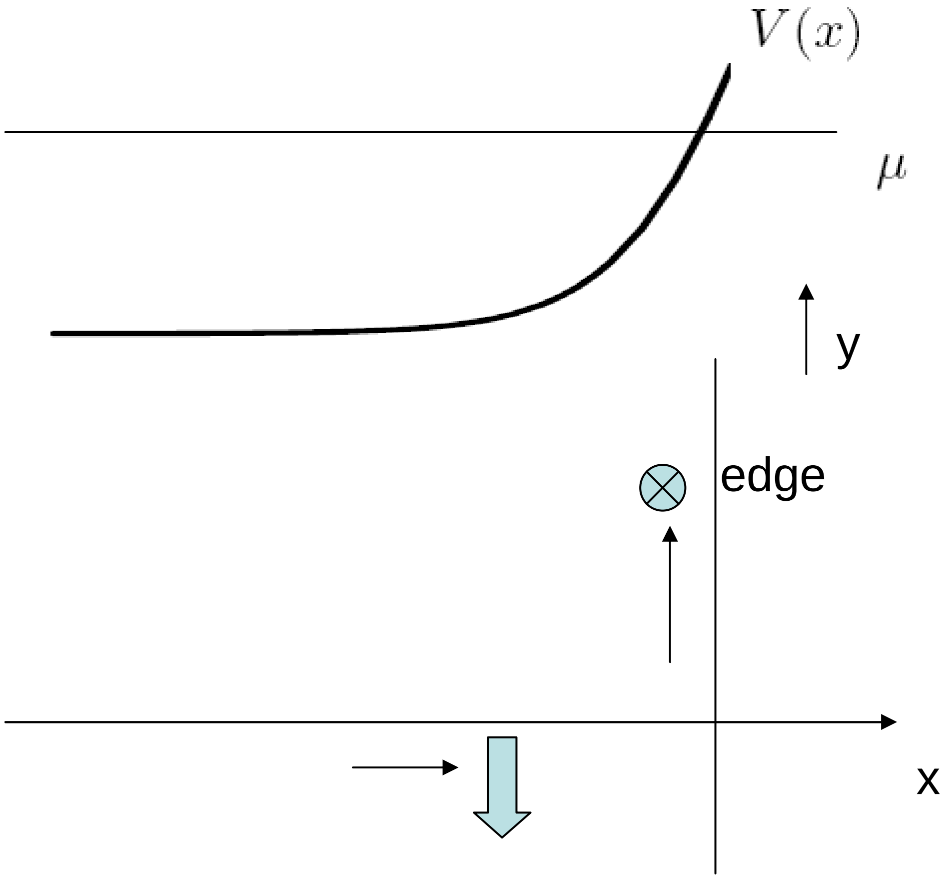
$$v_x \sigma_y \equiv j_x^y = -\epsilon^3 \frac{m^2}{3\pi}$$ Rashba, 2003

Third order…possibly beyond the validity of the original *H*

Rashba: this current needs to be eliminated!

Nuisance or a real thing?

Edge: spin accumulation prohibited by *T*; circumvented by edge currents from the source term



$$\partial_x j_x^y = -2m\epsilon j_y^z$$

But how to measure spin current?

First-order effect

Inhomogeneous strain…non-commutation in space

$$\epsilon(\mathbf{r})p \rightarrow \frac{1}{2}[\epsilon(\mathbf{r}), p]_+$$

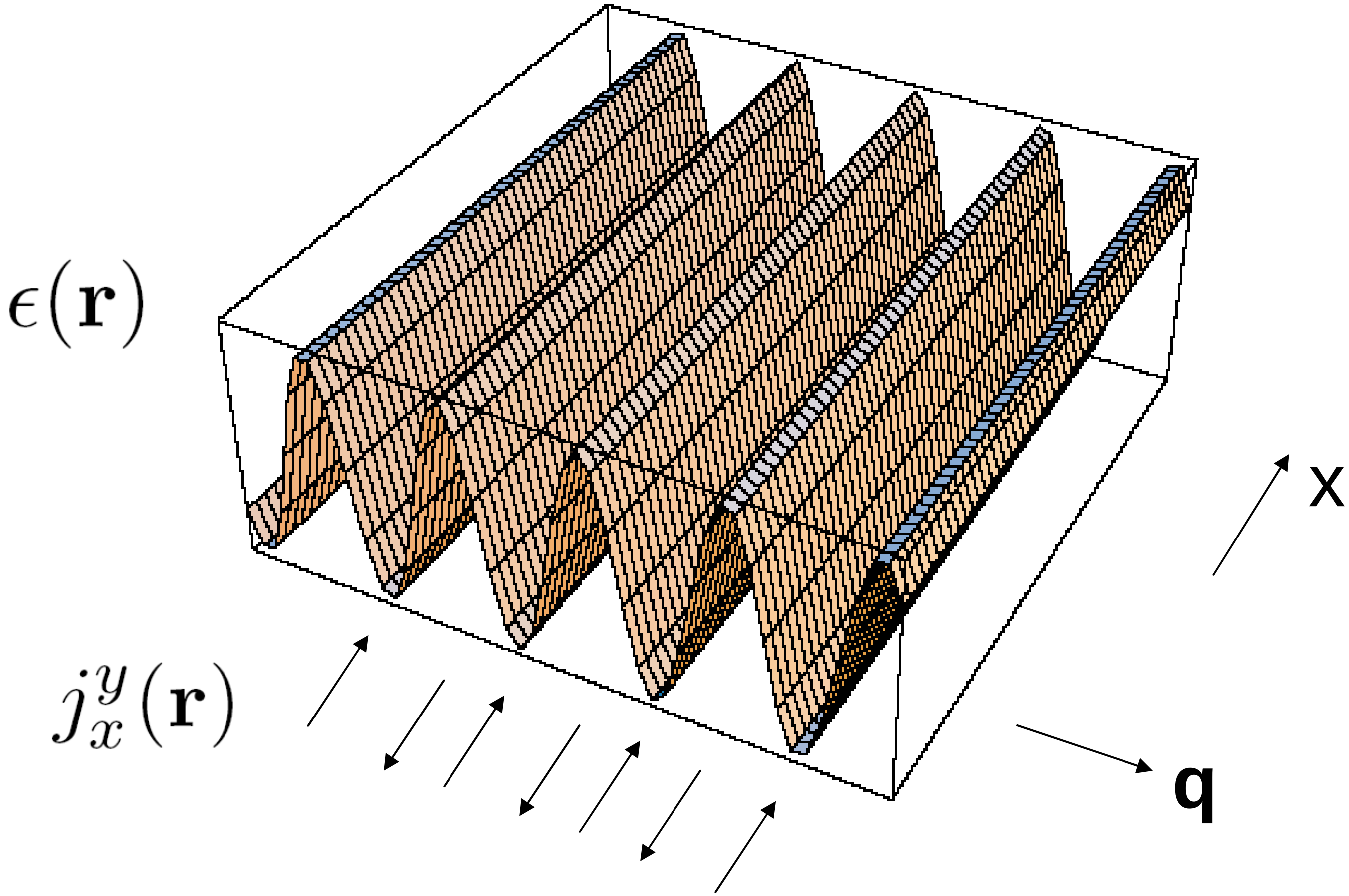
$$\begin{aligned} j_x^y(\mathbf{q}) &= -2\left(n + \int (dk)G_+G_-\, k_x^2\right)\epsilon(\mathbf{q}) \\ &\sim -n\left(\frac{q}{2k_F}\right)^2 \epsilon(\mathbf{q}) \text{ for } \mathbf{q} \perp \hat{x} \end{aligned}$$

-Zero for q=0, in agreement with Rashba

-"Diamagnetic" term wins (minus sign) like for Landau

“Edge” currents

From $\mathbf{q} \perp \hat{x}$



Decrease in energy

- In contrast to Landau diamagnetism
- Even for homogeneous strain

$$\frac{F - F_0}{V} \simeq -\epsilon^2 nm$$

I propose structural transition
driven by spin-orbit interaction

Magnetization: measurable in principle….

Breaks *T*—we need to get out of equilibrium

First order again: $M_i(\mathbf{q},\nu) = \chi_i(\mathbf{q},\nu)\epsilon(\mathbf{q},\nu)$

$$\chi(\mathbf{q},\nu) = \int (dk)\Gamma G_+ G_- k$$

Spectrum: $$\chi''(\mathbf{q},\nu) = -\frac{N_0}{2}\frac{\nu^2 Dmq}{\nu^2 + (Dq^2)^2}$$

Two differences from the diffusive density-density response:

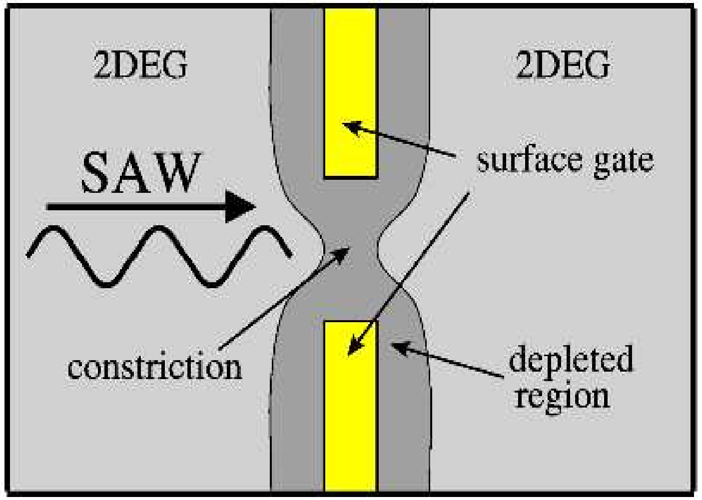
1. Even in frequency
2. Saturates above $\nu = Dq^2$ up to $\nu = 1/\tau$

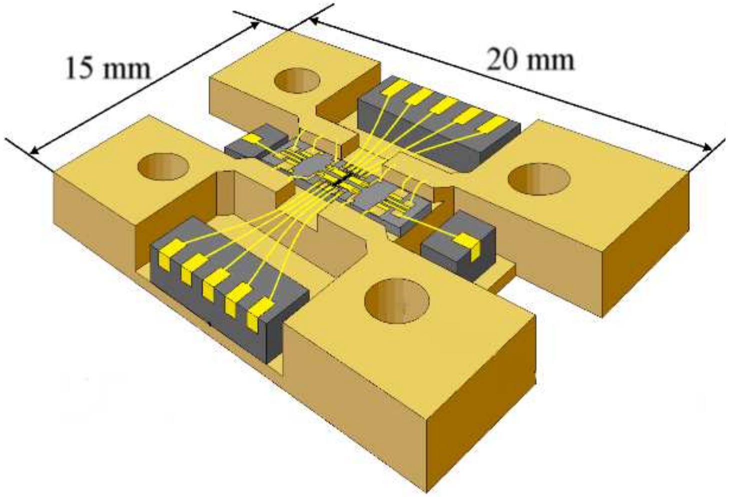
…and possibly also in practice!

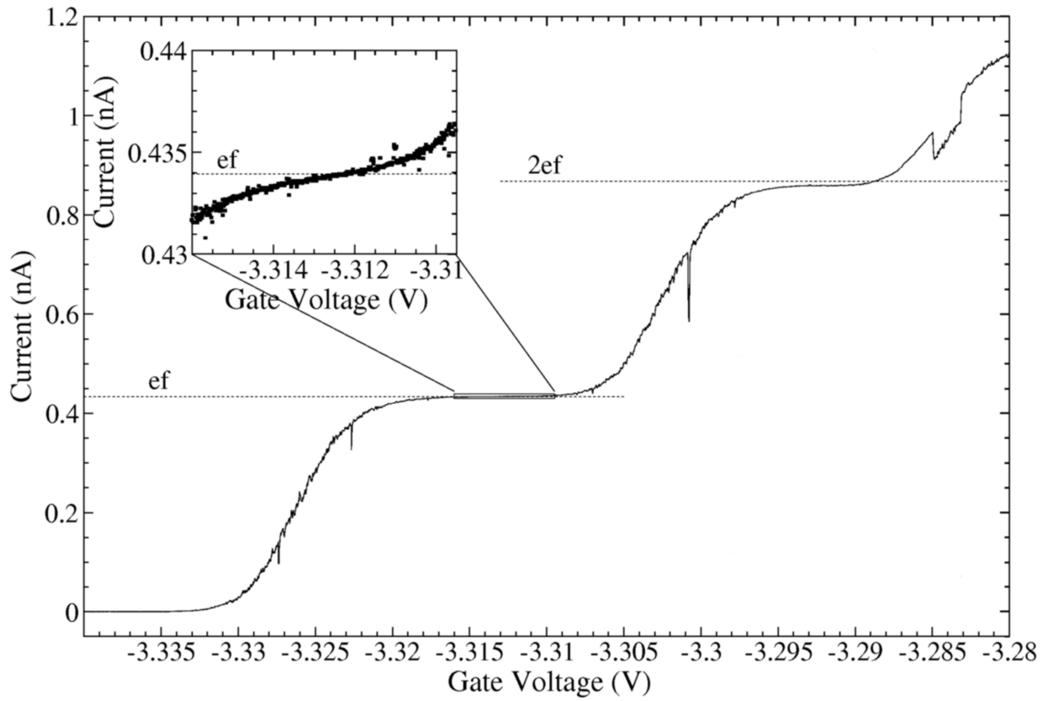
$$
\begin{aligned}
n &= 10^{16}\mathrm{cm}^{-3} \\
v_s &\simeq 5 \times 10^{5}\mathrm{cm/s} \\
D &= 10\mathrm{cm}^2/\mathrm{s} \\
\nu &= 25\mathrm{GHz} \\
q &= 5 \times 10^{4}\mathrm{cm}^{-1} \\
\epsilon &= 10^{-4}
\end{aligned}
$$

$$M \simeq n \times 5 \times 10^{-5}$$

Surface-acoustic waves in semiconductors







Semiconductor Physics Group, Cambridge

Acoustic wave→phonon

→magneto-acoustic mode

Tying it all together

Magnetization—the SU(2) analogue of charge

Corresponding potential: $-g\mu_B \mathbf{B}\cdot\frac{\hbar}{2}\sigma$

Also coupled to the U(1) electromagnetic field

Need a combined SU(2)xU(1) theory
to put together all the fragments

Presumably from the non-relativistic limit of the
Dirac equation—the common source

Conclusions

- Strain used for rotation of spins in n:GaAs
- Consequences of analogy of strain with an SU(2) gauge potential
- **Spintronics**—understanding the real world, using beautiful mathematics, and making something useful