Effects of Electron-Electron Interaction on the Transport in Spintronic Devices

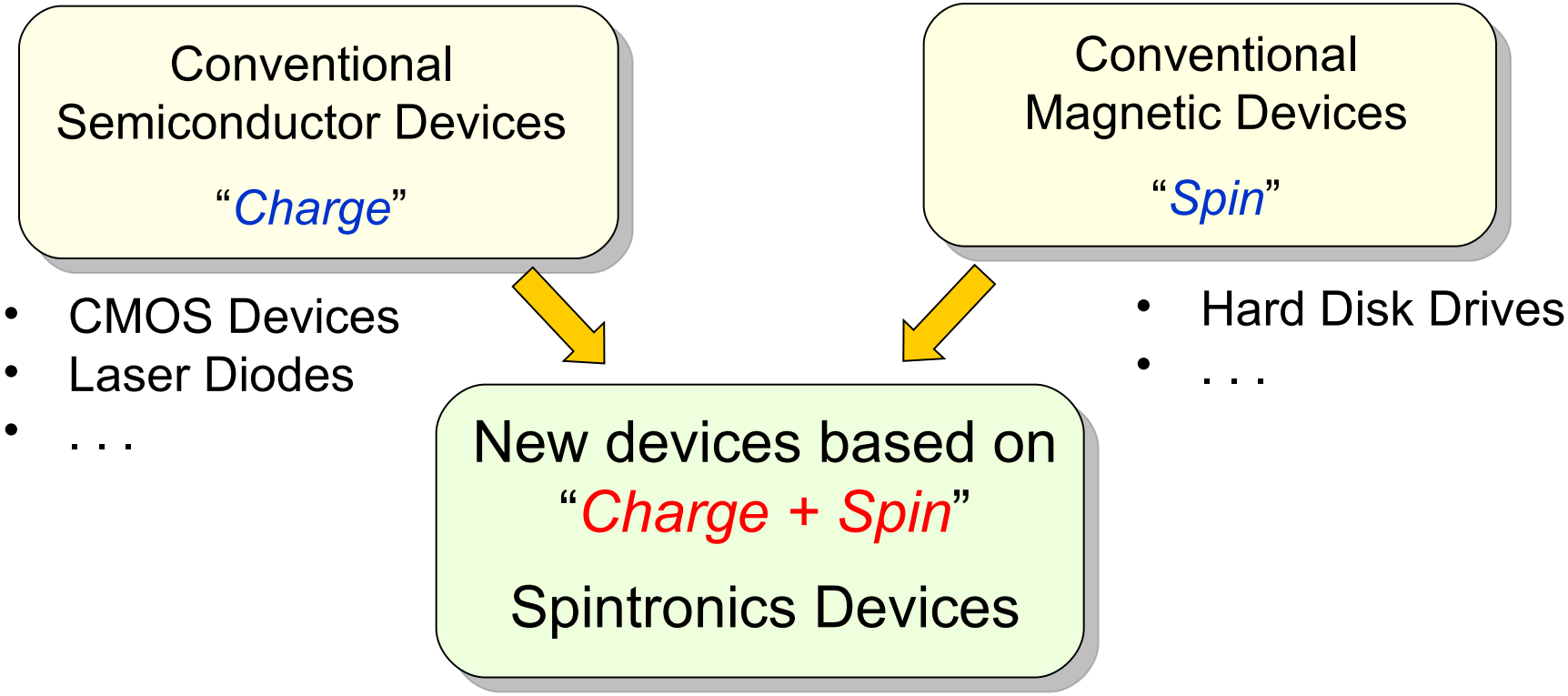
Yutaka Takahashi

Nobuyuki Inaba

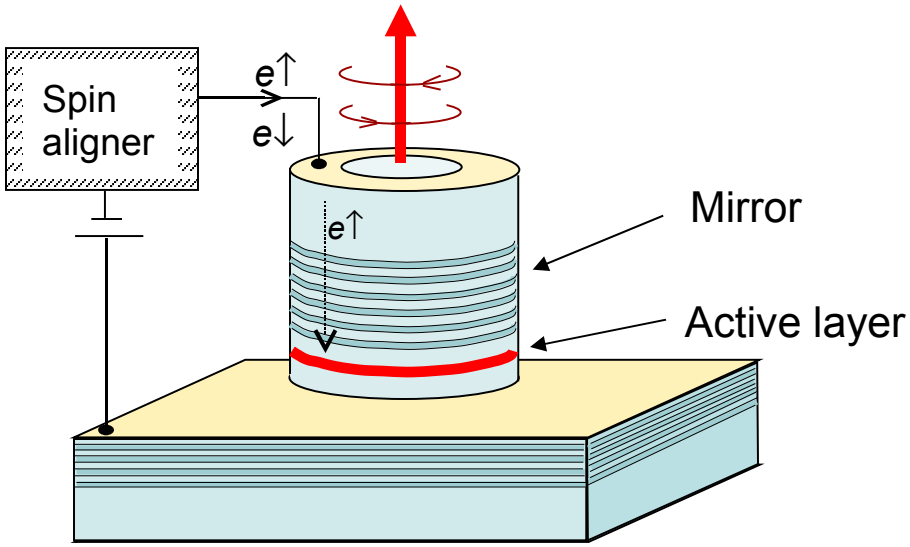
Fumihiko Hirose

Department of Electrical Engineering
Yamagata University

Electronics Devices Work on Electrons



Spin LD : Vertical-Cavity Surface-Emitting Laser



Band Structure (III-V group)

⇩

Injection e↑,↓ ⇒ Photon emission
Helicity ±

Symmetry of Cavity

⇩

can support
Circularly Polarized Modes

Binary information
can be transmitted by
left or right-circular polarizations

Transport Mechanism of *Spin-Polarized* Electrons in Devices

Transport in Unpolarized vs. Polarized system

Does the Carrier Transport Depend on Electron-Electron Scattering ?

Transport in
Unpolarized System

Mobility is determined by
- *e*-impurity (low temp.)
- *e*-phonon (higher temp.)

but
* *e-e* interaction does not affect,
[to the lowest order]

Transport in
Spin-Polarized System

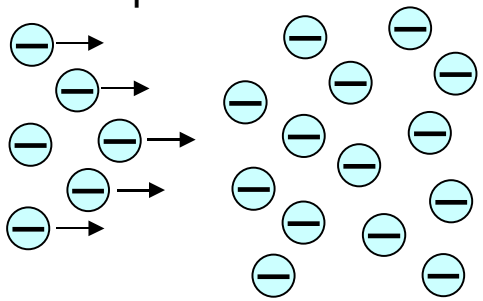
Spin transport is determined by
- *e*-impurity (low temp.)
- *e*-phonon (higher temp.)

also by
* *e-e* interaction

Effect 1: Spin Drag by Electron-Electron Collisions

Transport in Unpol. system

No spin discrimination



e-e scattering conserves momentum

▪

Total momentum does not change

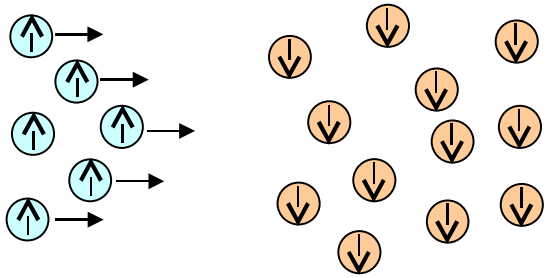
$$J = e \sum_{i=1}^{N} v_i$$

Total current is independent of *e-e* scattering

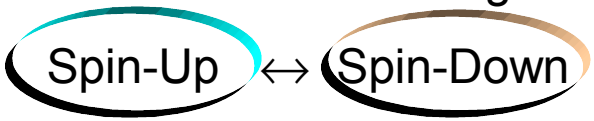
e-e affects the transport in higher order

- Modified distribution functions, f(k)
- Umklapp process

Transport in Pol. system



Momentum exchange



Spin-Up current depends on *e-e* scattering

Spin-Down electrons are dragged by the flow of Spin-Up electrons

▪

Spin Drag effect

(I. D'Amico, G. Vignale *Phys. Rev.* B**62** 4853 (2000))

Effect2: caused by Bandgap Renormalization

Many-particle Effects

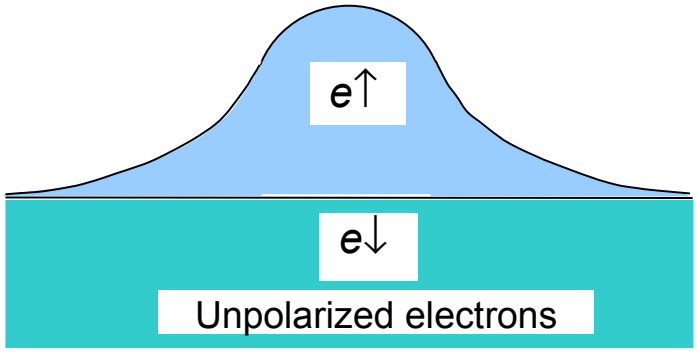
▪

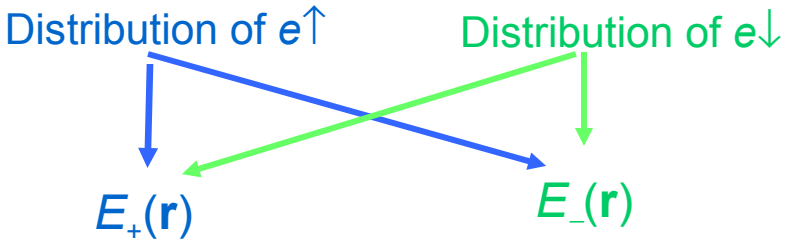
Modified Energy Dispersion

▪

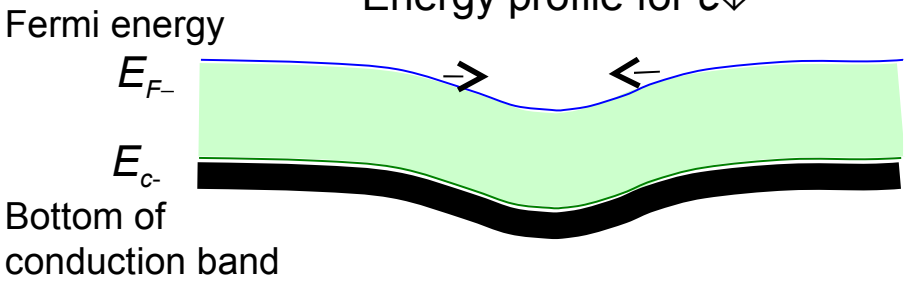
Bandgap Renormalization (density dependent)

Density profile





Energy profile for e↓



- Bottom of conduction band
- Fermi level

} drops for e↓

▪

e↓ flows toward low energy region

Competition of Spin Drag and Bandgap Renormalization

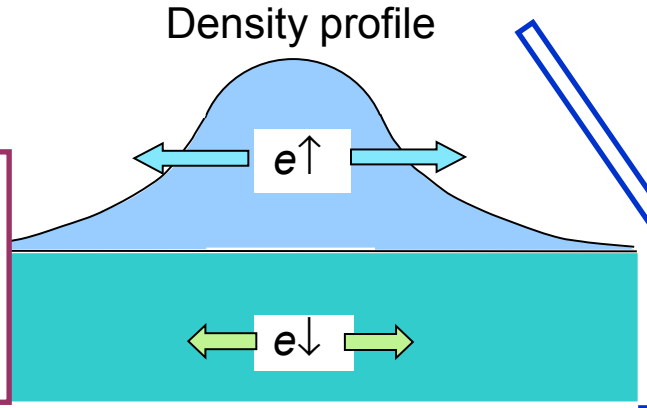
Spatial distribution of $e\uparrow$

Spin Drag

$e\uparrow$ flow outward by diffusion

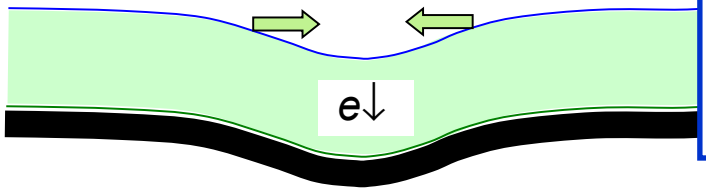
▪

$e\downarrow$ flow <u>outward</u>
by *Spin Drag*



Bandgap Renormalization

Energy profile for $e\downarrow$



Spatial distribution of E_F *for* $e\downarrow$

▪

$e\downarrow$ flow <u>inward</u>
toward low energy region

$$\mathbf{J}_{ee-} = -qD'_{ee-}\frac{\partial n_+}{\partial \mathbf{r}}$$

Positive contribution from ⇒ Spin Drag

D'_{ee-}

⇐ Negative contribution from Bandgap Renormalization

Full quantum mechanical transport equation

Quantum transport eq. from *nonequilibrium Green's functions*

- Distribution functions 2 x 2 in spinor space
  - Electron spin is treated exactly in quantum mechanics
- Many-particle effects included in the RPA order
  - Band dispersions are modified differently for $e\uparrow$ and $e\downarrow$ when $n_+ \neq n_-$

- G.D. Mahan *Many-Particle Physics* (3rd ed.) (§8-5)
- H. Haug, A. Jauho *Quantum Kinetics in Transport and Optics of Semicondnuctors*
- Y. Takahashi *et al*., Phys. Rev. B **60** (7) 4856 (1999)

Transport equation

$$\nabla\bar{\mu}_{+} = -\mathbf{j}_{+}\frac{m}{n_{+}}\left(\frac{1}{\tau_{+}}+\frac{1}{\tau_{ex+}}\right)+\mathbf{j}_{-}\frac{m}{n_{+}\tau_{-}}$$

$$\nabla\bar{\mu}_{-} = -\mathbf{j}_{-}\frac{m}{n_{-}}\left(\frac{1}{\tau_{-}}+\frac{1}{\tau_{ex-}}\right)+\mathbf{j}_{+}\frac{m}{n_{-}\tau_{+}}$$

$\bar{\mu}_{\gamma}(\mathbf{r}) = \mu_{\gamma}(\mathbf{r}) + q\phi(\mathbf{r})$: electrochemical potential ($\mu_{\pm}(\mathbf{r})$: chemical potential)

q : charge

m : band effective mass

$\phi(\mathbf{r})$: electrical potential

$\mathbf{j}_{\pm} = \mathbf{J}_{\pm}/q$: current of spin-up/down electrons ($\mathbf{J}_{+}+\mathbf{J}_{-}$: total charge current)

$n_{\pm}(\mathbf{r})$: distribution function for spin-up/down electrons

$\tau_{ex\pm} = (1/\tau_{ion\pm} + 1/\tau_{ph\pm})^{-1}$

$\tau_{\pm}$: relaxation time for *e-e* scattering

$\tau_{imp\pm}$: relaxation time for *electron-impurity* scattering

$\tau_{ph\pm}$: relaxation time for *electron-phonon* scattering

Case 1

Drift transport driven by electric field (Mobilities)

- Electrons are driven by external field
- Homogeneous electron distributions

No effect from Bandgap Renormalization

$$\mathbf{J}_\gamma = n_\gamma q \mu_{nee\gamma} \mathbf{E}$$

$\mu_{nee\pm} = \mu_{n\pm}$ x (Correction Factor for *e*-*e* scattering)

mobility without *e*-*e* $\quad \mu_{n\gamma} = \dfrac{q\tau_{ex\gamma}}{m}$

Spin Drag modifies mobilities:

$$\mu_{n\pm} \Rightarrow \mu_{nee\pm}$$

Case 2

Diffusion transport driven by density gradient

- Electron density depends on position
- Currents are driven by density gradient

affected by both Spin Drag and Band Renormalization

2. Driving term : $$\frac{\partial \mu_\gamma}{\partial \mathbf{r}} = \frac{\partial \mu_\gamma}{\partial n_\gamma}\frac{\partial n_\gamma}{\partial \mathbf{r}} + \frac{\partial \mu_\gamma}{\partial n_{\mp}}\frac{\partial n_{\mp}}{\partial \mathbf{r}}$$

3. Current :

> without *e*-*e* $\mathbf{J}_\gamma = -qD_\gamma \frac{\partial n_\gamma}{\partial \mathbf{r}}$ (Fick's law) ($D_\pm$: Diffusion coefficient)

> *e*-*e* included $\mathbf{J}_{ee\gamma} = -qD_{ee\gamma}\frac{\partial n_\gamma}{\partial \mathbf{r}} - qD'_{ee\gamma}\frac{\partial n_{\mp}}{\partial \mathbf{r}}$ ($D_{ee\pm}$: modified Dif. coefficient)

Spin-Down current is modified by the distribution of Spin-Up electrons.

Numerical calculations: conditions

Modulation-doped 2D Electron Gas in GaAs/AlGaAs heterostructures

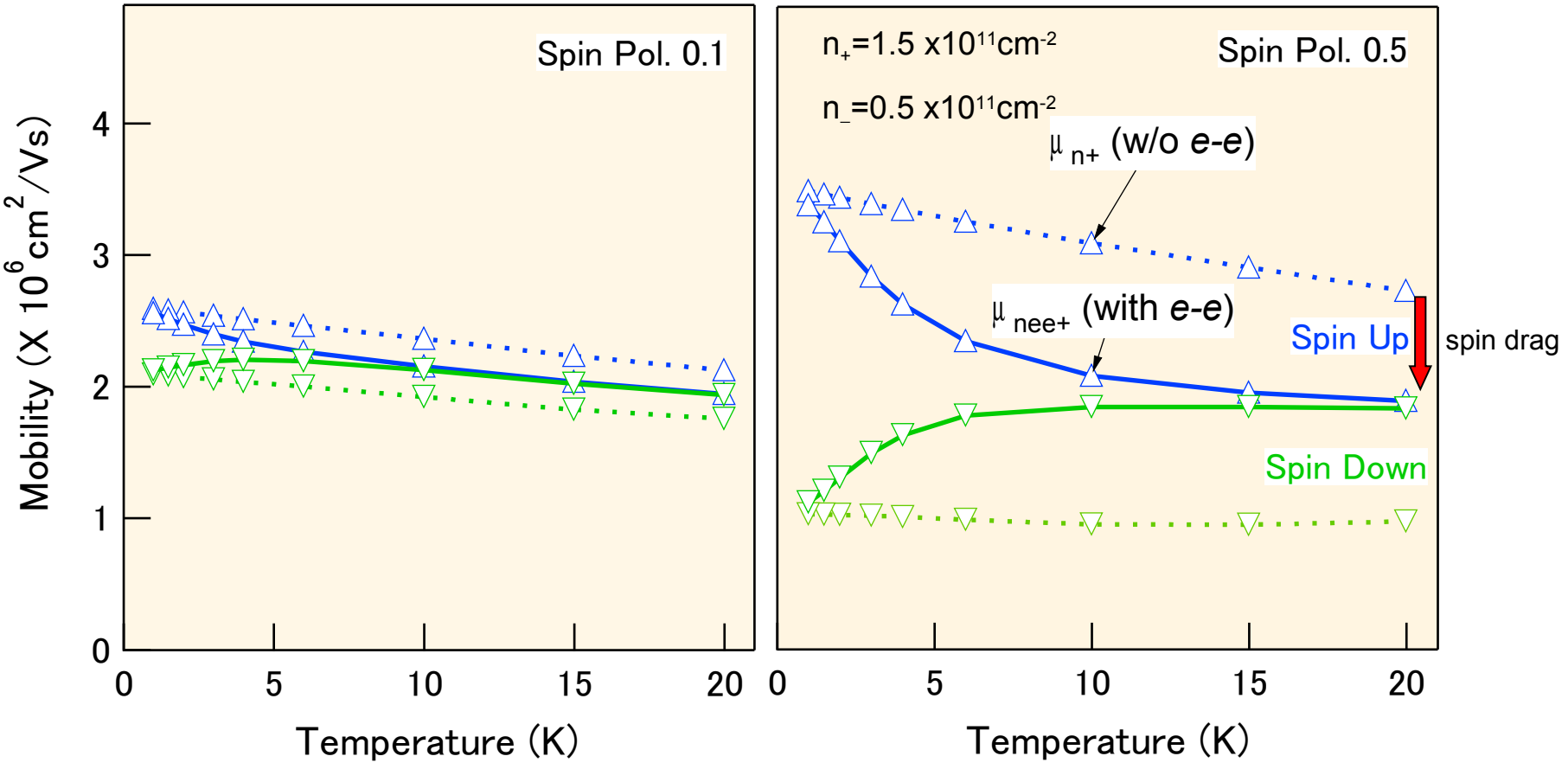
- Carrier density ($n_+ + n_-$) : 2×10^{11} cm^{-2}
- Spin polarization ($P = \frac{n_+ - n_-}{n_+ + n_-}$) : 0.0 ~ 0.5
- Temperature : 1 K ~ 20 K (<< T_F) *Electrons are degenerate*

Scattering processes

6. electron-impurity scattering
   - i. Scattering by remote impurities (modulation-dopants, 50 nm from the 2DEG)
   - Scattering by inplane impurities (residual impurities: 1×10^8 cm^{-2})
7. electron-phonon scattering
   acoustic phonon scattering by deformation potential
8. electron-electron scattering
   by RPA-screened Coulomb interaction

Result

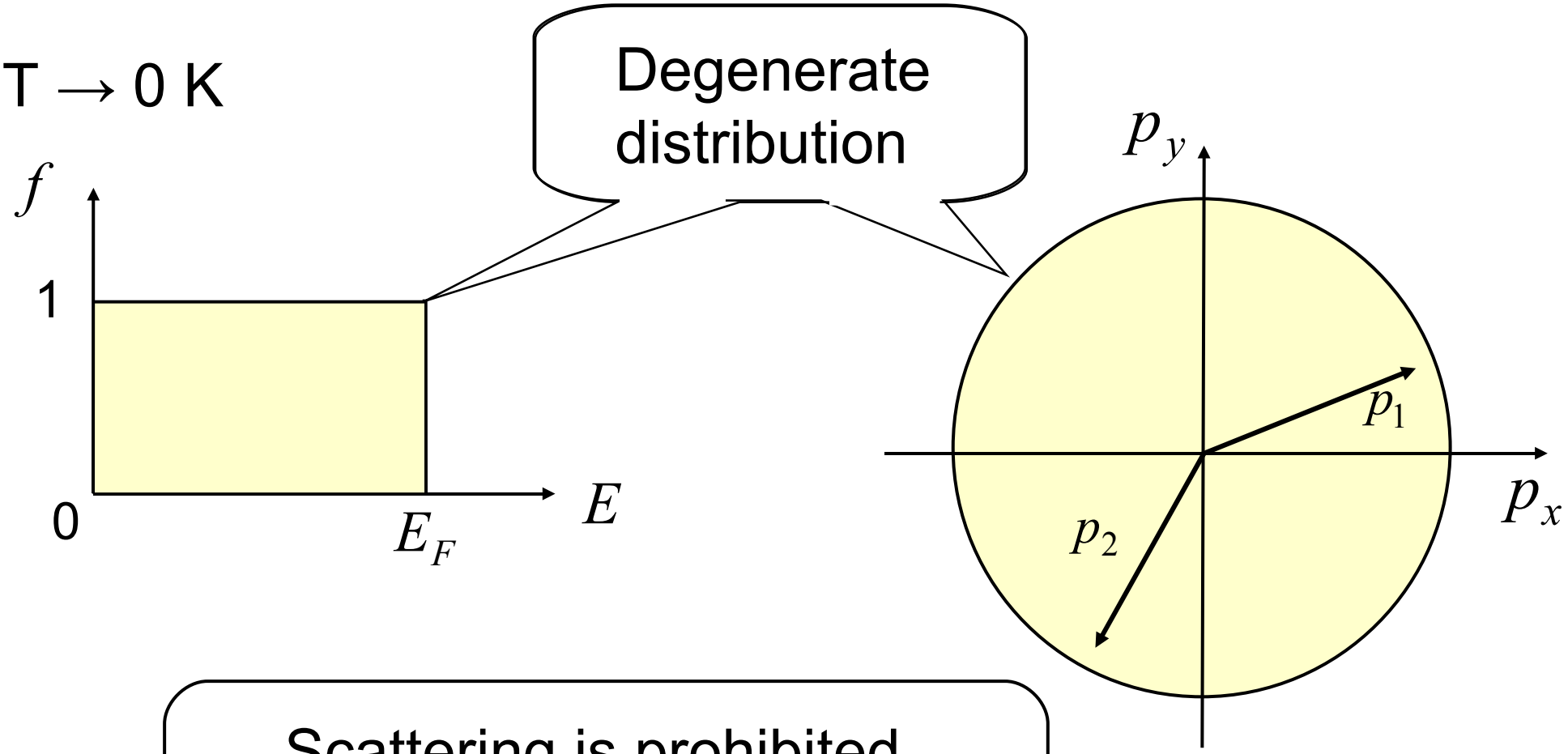
Electron mobilities $\mu_{nee\pm}$ vs. $\mu_{n\pm}$ at electron density $n_+ + n_- = 2 \times 10^{11}$ cm^{-2}



Spin Drag ⇒ strong temperature dependence

Electron-Electron scattering

- $T \rightarrow 0$ K

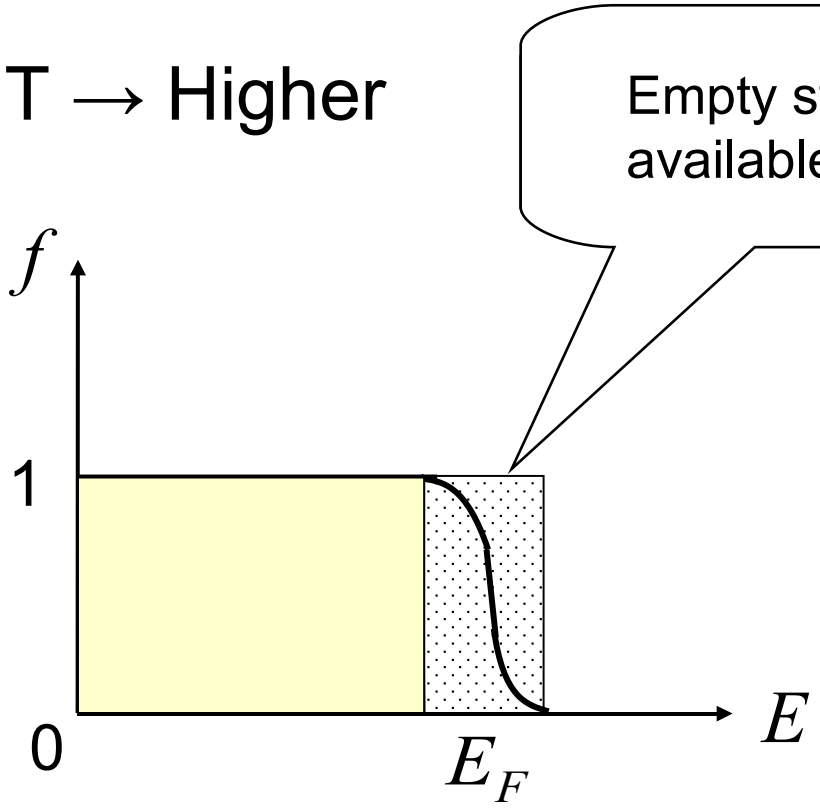


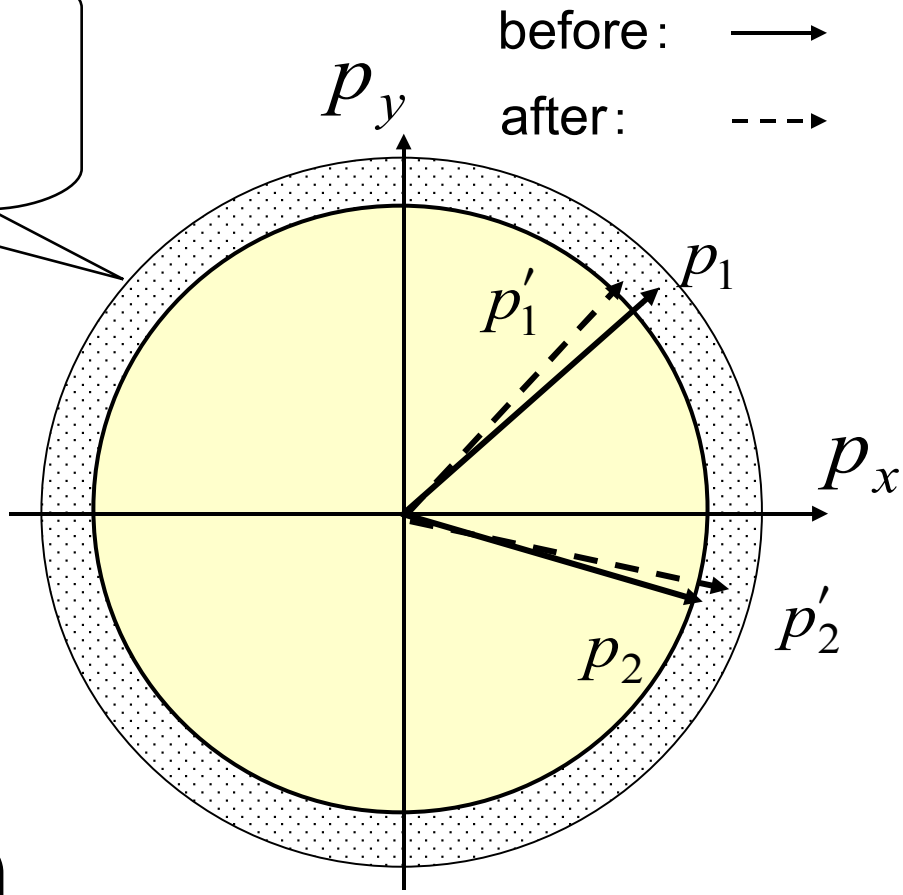
Scattering is prohibited

- Pauli blocking
- Energy-momentum conservation

Electron-Electron scattering

- T → Higher

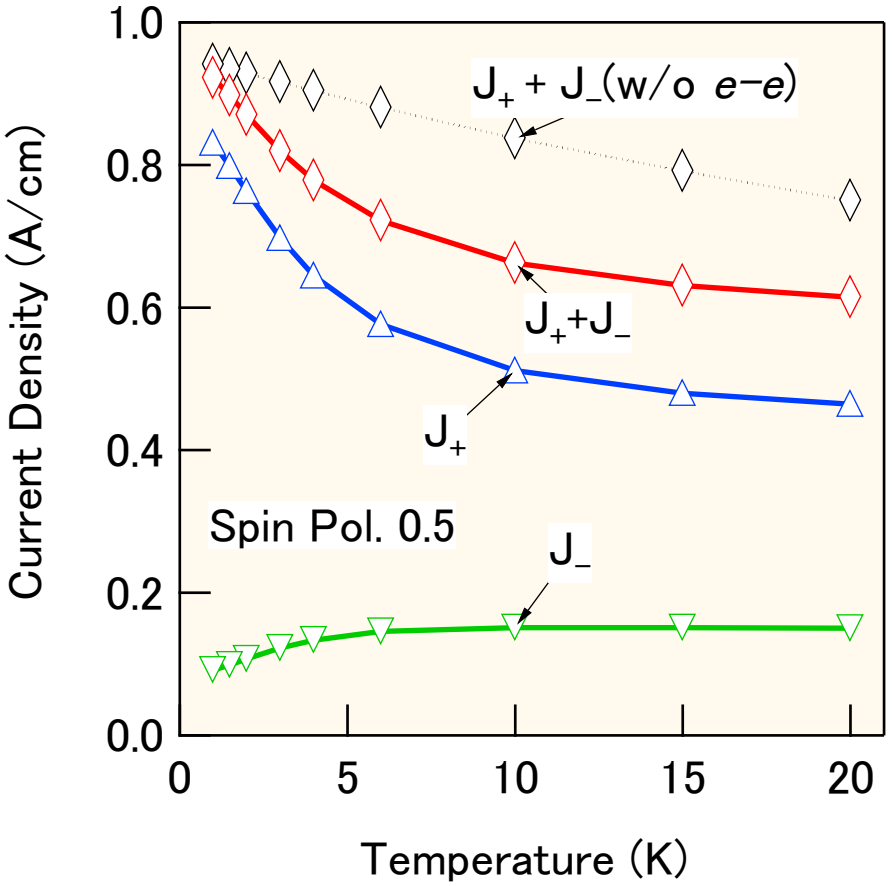




Scattering is allowed at the Fermi surface

Result

Current densities : J_+, J_- and $J_+ + J_-$ for E = 10 V/cm at $n_+ + n_- = 2 \times 10^{11}$ cm^{-2}



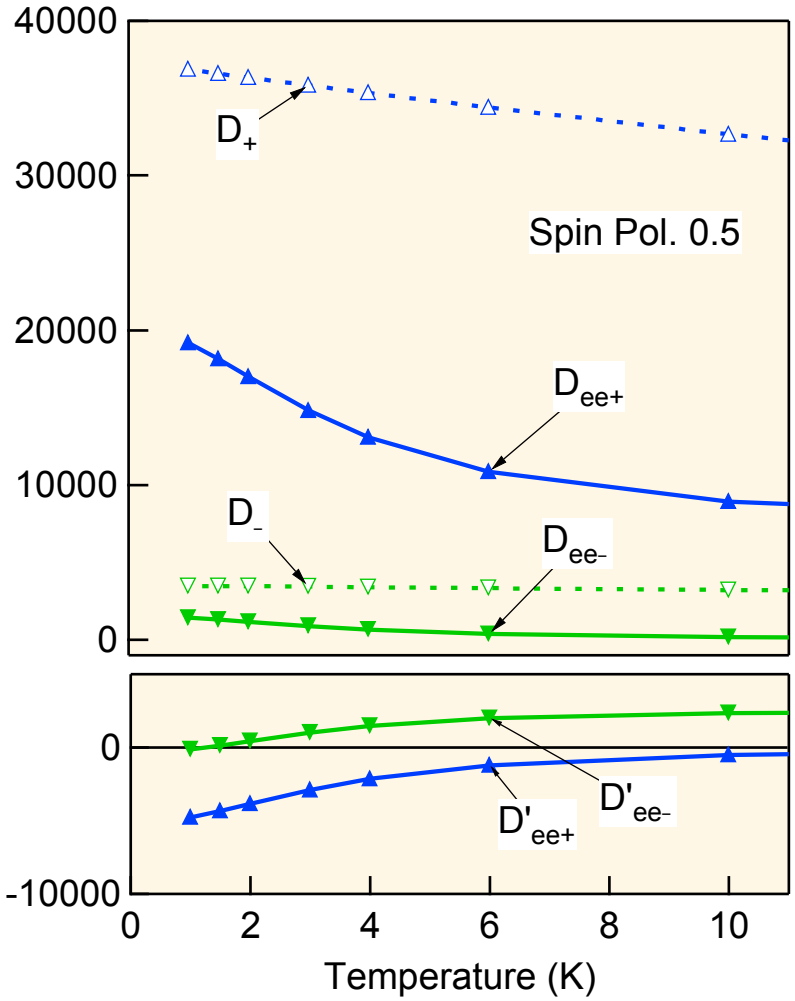
Spin drag effect appears
(Bandgap renormalization is absent because of uniform distribution)

J_+ and J_- show characteristic temperature dependence

Total current $J_+ + J_-$ also shows sublinear temperature dependence.

Result

Diffusion coefficients $D_{ee\pm}$ vs. $D_{\pm}$at



Both effects appears

- Spin drag
- Bandgap renormalization

$D'_{ee\pm}$

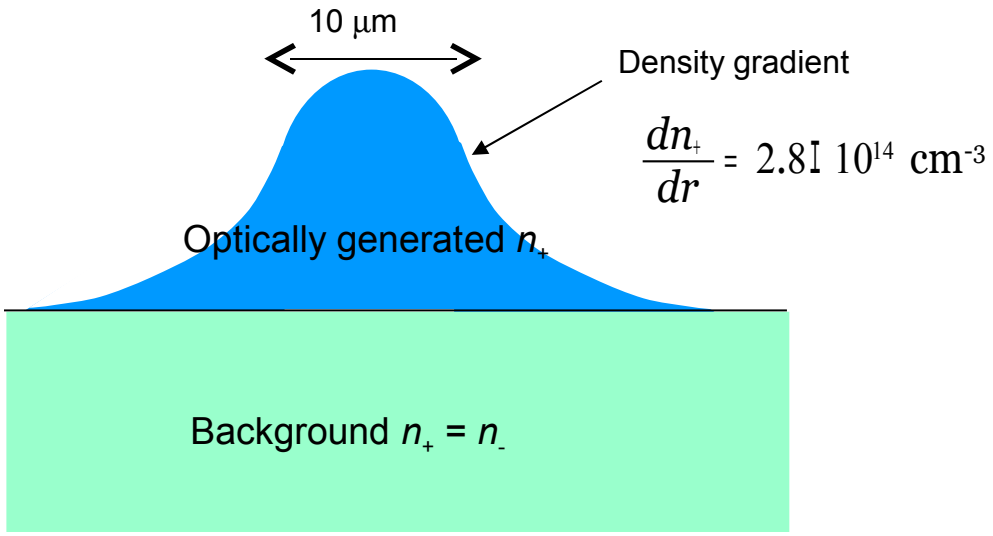
Negative contribution from Bandgap Renormalization

Positive contribution from Spin Drag

Result

Density gradient by optical excitations

Spin-up electrons are optically generated by a Gaussian-profile beam with circular polarization in a n-doped GaAs heterostructure.



No *e*-*e* interaction

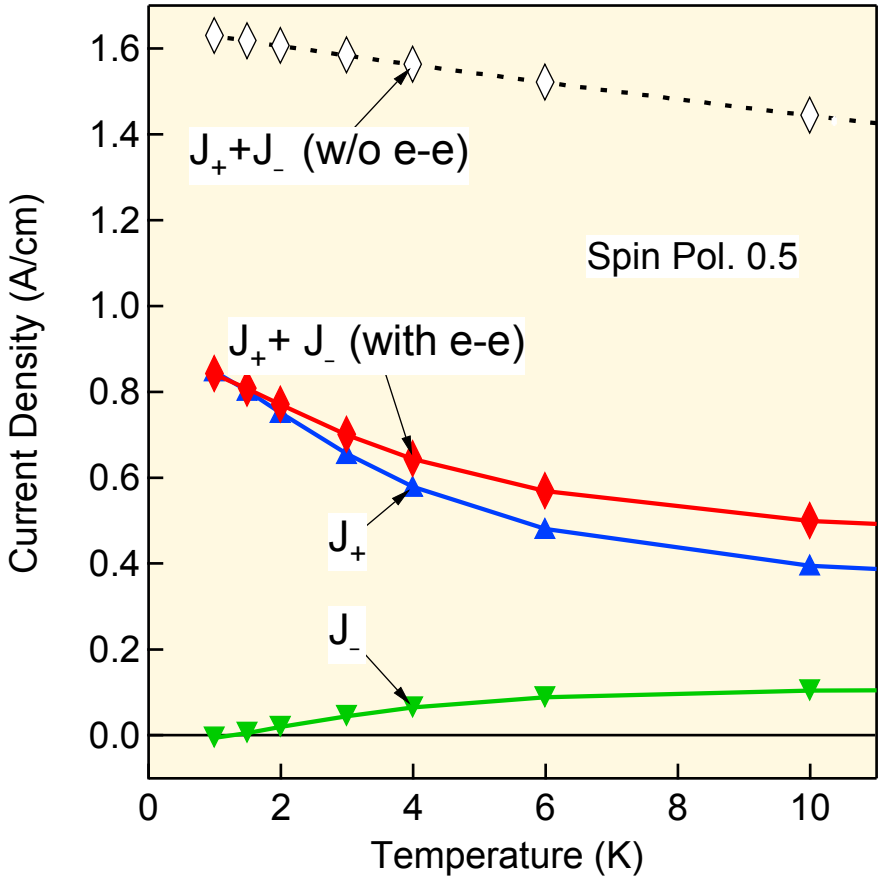
- J_+ flows outward
- $J_- = 0$

With *e*-*e* interaction

- J_+ flows outward
- J_-
  - flows outward by Spin Drag
  - flows inward by Energy renormalization

Result

Diffusion current densities : $J_{\pm}$ and $J_{ee\pm}$ at $n_+ + n_- = 2 \times 10^{11}$ cm^{-2}



w/o e-e interaction

J_+ only ($J_- = 0$)

with e-e interaction

Finite J_-

J_- is negative at the lowest temp. (inward flow)

$$\mathbf{J}_+ = -qD_{ee+}\frac{\partial n_+}{\partial \mathbf{r}}$$

$$\mathbf{J}_- = -qD'_{ee+}\frac{\partial n_+}{\partial \mathbf{r}}$$

Conclusions

Competition of Spin Drag and Bandgap Renormalization

Field-driven transport ⇒ Current is modified only by *Spin Drag* at higher temperatures

Density-driven transport ⇒ Current is modified by *both Spin Drag and Bandgap Renormalization*

Problems:

Carrier dynamics from S.O. coupling
(effective magnetic field due to BIA and SIA)
is not included