Nuclear spin spectroscopy for semiconductor hetero and nano structures

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cm$^3$, mm$^3$

$\mu$m$^2$ x nm

nm$^3$
· Introduction
· Electron and nuclear spin interactions and resistively detected NMR
· Possibility of nuclear spin control in nanoscale
· Nuclear-spin-based measurements as a powerful tool to study electron spin physics in 2DEG

· Novel NMR: Electric field induced NMR
· Summary
· Introduction
· Electron and nuclear spin interactions and resistively detected NMR
· Possibility of nuclear spin control in nanoscale
· Nuclear-spin-based measurements as a powerful tool to study electron spin physics in 2DEG
  · Skyrmion
  · Spin degree of freedom
  · Canted spin states
  · Spin orbit interaction
· Novel NMR: Electric field induced NMR
· Summary
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Standard NMR

Spectrum is sensitive to the conditions where nuclear spins are placed.

Effect of surrounding nuclei ---- structure analysis
Knight shift ---- electron spin information
Quadrupolar splitting ---- strain around the nucleus

NMR is widely used in the physical, chemical and biological sciences.
Disadvantages:

Weak signal
Necessity of a large volume sample (more than $10^{11}$ nuclei)
Not suitable for $I \geq 3/2$ like Ga, As, -----

NMR studies for semiconductor systems
Bell, CNRS (1995-)

100 layers of quantum wells

Standard NMR is not suitable for semiconductor single-layer-systems and nanosystems, where characteristics are controlled by gate bias.
To overcome limitations of the standard NMR, a novel NMR technique has been developed. The technique is based on direct detection of $M_z$ by using conductive electron and nuclear spin interactions.
Electron and nuclear spin interactions and resistively detected NMR

- Nuclear spin / electron spin interactions
- Nuclear spin polarization
- Detection of nuclear spin polarization
Conventional situation

Energy and angular momentum transfers are not possible. Negligible interaction between electron and nuclear spins.

Degeneration of different electron-spin states

Energy and angular momentum transfers are now possible. Interesting interactions between electron and nuclear spins.
Nuclear-spin polarization and detection

Nuclear spin polarization induces resistance change if resistance is sensitive to the effective Zeeman energy

- Transition region in the FQHE
- Transition between localized and extended states in QHE

Circularly polarized light illumination

- e.g., Awschalom group

\( \nu = \frac{2}{3} \) Fractional QHE regime

Spin polarized \( \nu = \frac{2}{3} \)
Spin unpolarized \( \nu = \frac{2}{3} \)

Electron flow

von Klitzing group
Hirayama group

Edge channel or breakdown in integer QHE regime

Coupled quantum dot

- Tarucha group

Machida group

Nuclear-spin polarization and detection

- e.g., Awschalom group
- YKIS2007

\( E_z \)
Nuclear-spin polarization and detection

Nuclear spin polarization induces resistance change if resistance is sensitive to the effective Zeeman energy.

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Circularly polarized light illumination
e.g., Awschalom group
\( \nu = \frac{2}{3} \) transition point and nuclear spin polarization
Nuclear spin polarization and detection at $\nu=2/3$

Fractional quantum Hall effect
($\nu=2/3$, domain?)

Kronmüller et al. PRL (1998)

Nuclear spins can be polarized by current flow.

Vertical nuclear-spin magnetization ($M_z$) is directly measured by resistance value.

$$M_z = \alpha R_{xx}$$
NMR spectrum measurement

- RF pulse
- State
  - ν = 2/3 (degenerate)
  - ν = ?
  - ν = 2/3 (degenerate)
- Polarization
- Temporal setting
- Resistence measurement
- Frequency: \( f \)
- Time: \( t_{pol} \) and \( t_{pulse} \)
- Resistance: \( \Delta R \)
- NMR spectrum

- \( t_{pulse} > T_2 \)
- \( t_{temp} < T_1 \)

State:
- ν = 2/3 (degenerate)
- ν = ?
- ν = 2/3 (degenerate)

Polarization:
- Temporal setting:
  - \( t_{temp} \)

Resistence measurement:
- Frequency: \( \Delta R \)

NMR spectrum:
- Frequency: \( \Delta R \)
Nuclear spin relaxation measurement

- NMR spectrum and $T_1$ time can be measured for any states.
- We can monitor electron spin states, especially electron spin correlation, from $T_1$ time.
Nuclear spin relaxation measurement

- NMR spectrum and $T_1$ time can be measured for any states.
- We can monitor electron spin states, especially electron spin correlation, from $T_1$ time
Possibility of nuclear spin control in nanoscale

- Point-contact-device with integrated antenna gate
- Full coherent control of $I=3/2$ quantum four level system
- NMR measurements of nanoscale region
Nuclear spins are polarized only in the point contact channel.

Nanoscale GaAs NMR device

*Nuclear spins are polarized in 200nm x 200nm x 20nm regime.
*Coherent control and NMR have been demonstrated in nanoscale semiconductor device.
By flowing 10nA current, nuclear spin polarization occurs only in the point contact regime.

The degree of nuclear spin polarization can be detected by $R_{xx}$.

Nuclear spins are polarized only in the point contact channel.
Coherent nuclear spin oscillation in point contact device

Fully coherent control of quantum four-level system = two-qubit operation

Yusa, Muraki, Takashina, Hashimoto, and Hirayama, Nature 434, 1001 (2005)
Coherent nuclear spin oscillation in point contact device

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Coherent nuclear spin oscillation in point contact device

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Pulse current duration (ms)</th>
<th>NMR signal</th>
<th>NMR signal (kΩ)</th>
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<tr>
<td>40.20</td>
<td></td>
<td></td>
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<td>40.25</td>
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<tr>
<td>40.40</td>
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<td>75As nuclei</td>
<td>0.8</td>
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</tbody>
</table>

Fully coherent control of quantum four-level system = two-qubit operation

Yusa, Muraki, Takashina, Hashimoto, and Hirayama, Nature 434, 1001 (2005)
Coherent nuclear spin oscillation in point contact device

- Fully coherent control of quantum four-level system = two-qubit operation

Pulse current duration (ms) | Frequency (MHz)
--- | ---

- NMR signal

Electro-magnetic wave irradiation

Yusa, Muraki, Takashina, Hashimoto, and Hirayama, Nature 434, 1001 (2005)
Coherent nuclear spin oscillation in point contact device

Fully coherent control of quantum four-level system = two-qubit operation

Yusa, Muraki, Takashina, Hashimoto, and Hirayama, Nature 434, 1001 (2005)
The value of the quadrupolar splitting is different in every device though the devices are fabricated using same material.

We speculate that this splitting probes the strain induced by sample mounting.

Nanoscale characteristics detected by novel NMR Knight shift Electron spin polarization

Quadrupolar splitting

With 2DEG

Without 2DEG
• Nuclear-spin-based measurements as a powerful tool to study electron spin physics in 2DEG

• Skyrmion
• Spin degree of freedom
• Canted spin states
• Spin orbit interaction
Filling factor dependence of $T_1$ and Skyrmion

Coexistence of spin up and down CF at $\nu=1/2$ results in a slight enhancement of nuclear spin relaxation at $\nu=1/2$. 

The bilayer $\nu=1$ state has a small, but finite, spin fluctuation.

Bilayer system with $\nu=2$

Width: 50 $\mu$m
Length between voltage probes: 100 $\mu$m
Quantum well thickness: 20 nm

$\delta = (n_f - n_b)/(n_f + n_b)$
$1+\delta = \nu_f$  $1-\delta = \nu_b$
NMR spectrum observed for bilayer $\nu=2$

**Nuclear spin relaxation observed for bilayer $\nu=2$**

Although transitions between different phases are detected by transport experiments, nuclear spin based measurements give us a very clear evidence.

Experimental confirmation of low-energy collective excitation mode

Symmetry of electronic confinement potential can be controlled keeping the electron density constant.

Effect of confinement potential

The potential inversion asymmetry enhances spin-orbit interaction. However, the effects are tiny in a conventional GaAs 2DEG system.
Control of confinement-potential-symmetry and $\nu = 2/3$ electronic-spin transition

$B_t$ as a function of $\delta n$
Nuclear spin relaxation is enhanced under asymmetric confinement.

Summary

- We have developed novel and highly sensitive NMR based on direct detection of nuclear spin magnetization by the resistance measurements.
- This NMR provides us powerful tool to study coherent control of nuclear spins in semiconductors and to characterize quantum wells and nanosystems.
- Some electron spin features, which was difficult to detect by other methods, were already clearly detected.
- We have developed fully-electrical NMR based on the domain motion.