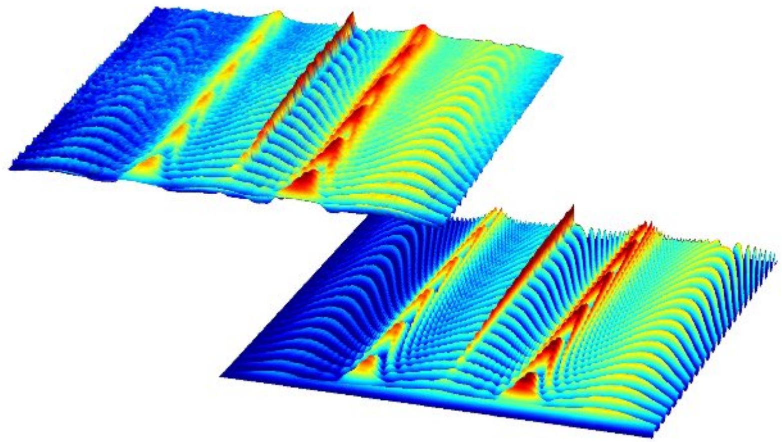
The 4th symposium of Tohoku University
The 21st Century COE Program

東北大学

Controlled Multiple Quantum Coherences of Nuclear Spins in a Nanoscale Device



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3. **<u>NTT Basic Research Labs. (This work was performed at NTT)</u>**

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Quantum Computers using Coherence of Nuclear Spins

Quantum computation based on NMR

Experimental realization of **D-J algorithm**

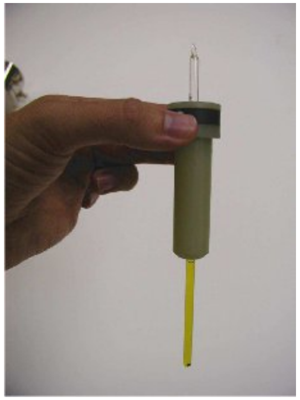
I. L. Chuang *et al*., Nature (1998).

Experimental realization of **Shor's factoring algorithm**

L. M. Vandersypen *et al*., Nature (2001).

A typical NMR sample

L. M. K. Vandersypen
quant-ph/0205193v1



PROBLEM

Liquid-state NMR is not suitable for a scalable device

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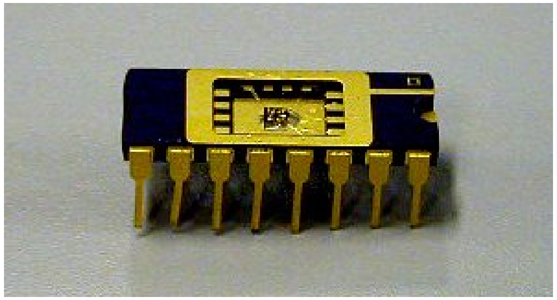
Quantum computers based on

all-electrical solid-state NMR

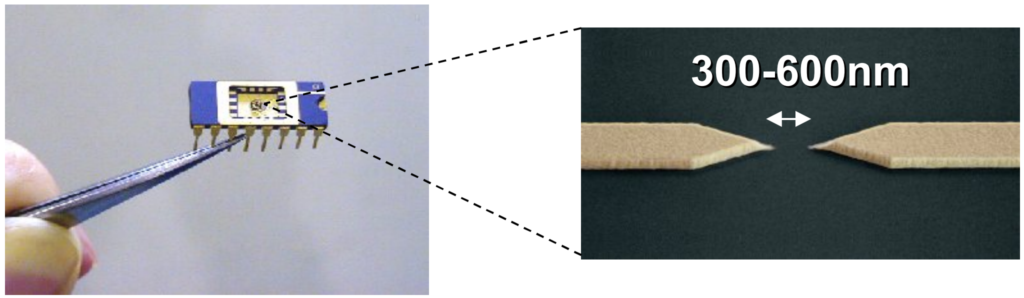
Electronics + **NMR**

Our NMR chip



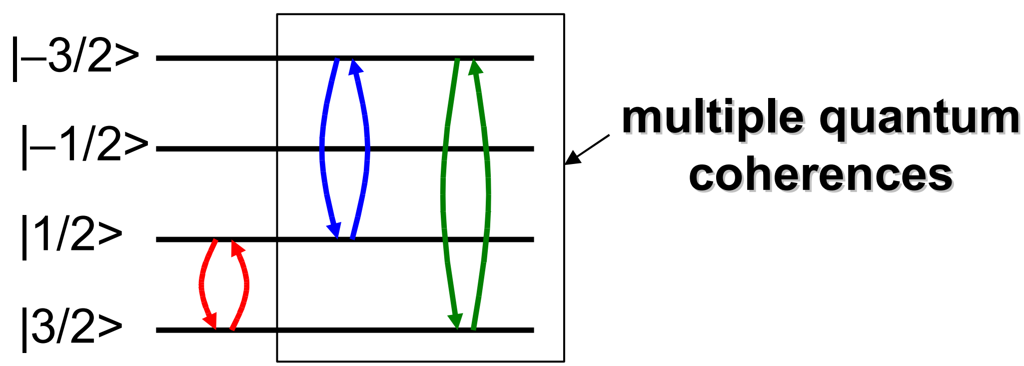
Outline

A self-contained semiconductor chip that can access nuclear spins in a nanoscale region



New NMR: **Direct detection of multiple quantum coherences**, which are invisible by conventional NMR

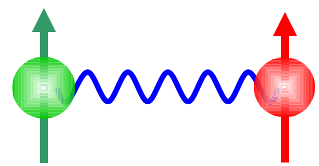
Nuclei often possess total spin angular momentum greater than a half and multiple spin levels are formed.



Control and Detection of Coherence of Nuclear Spins

Contact Hyperfine Interaction

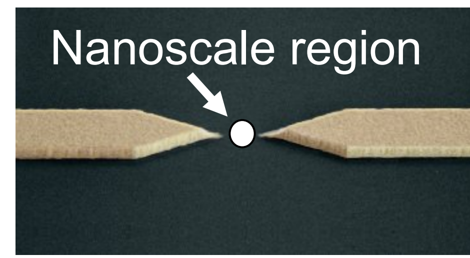
Nuclear Spins
Long coherence time



Electron Spins
Electrical accessibility

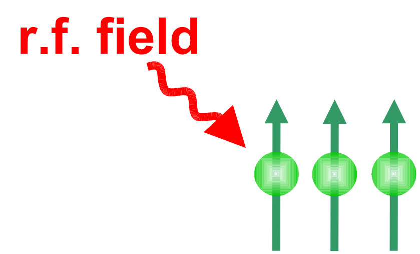
① Initialization (Polarization)

- Electron-nuclear spin coupling (flip-flop process).
  ->Polarization only in the nanoscale region .



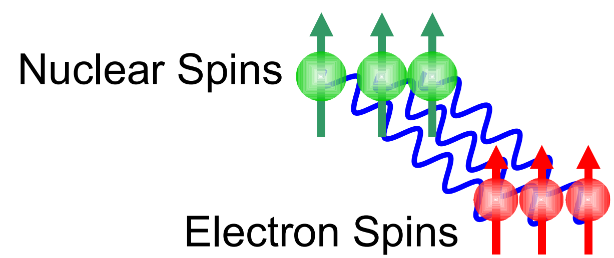
② Creation of quantum mechanical superpositions of states

- Nuclear magnetic resonance (NMR) on a self-contained semiconductor chip



③ Readout

- Electron-nuclear spin coupling.
- Measurement of polarization by resistance



Polarization of Nuclear Spins

Electron-nuclear spin coupling in 2D system in the **fractional quantum Hall regime** (ν=2/3)

- **Long-time-scale resistance enhancement (~10 min)**
  - Due to long longitudinal (spin-lattice) relaxation time T_1
- **Current dependence**
  - Large current is required to polarize nuclear spins
- **Resistively detected CW-NMR**

- Kronmuller *et al*., PRL **81**, 2526 (1998).
- Smet et al., PRL **86**, 2412 (2001).
- Hashimoto et al., PRL **88**, 176601 (2002).
- Smet et al., Nature **415**, 281 (2002).
- Kumada et al., PRL **89**, 116802 (2002).
- Kraus et al., PRL **89**, 266801 (2002).

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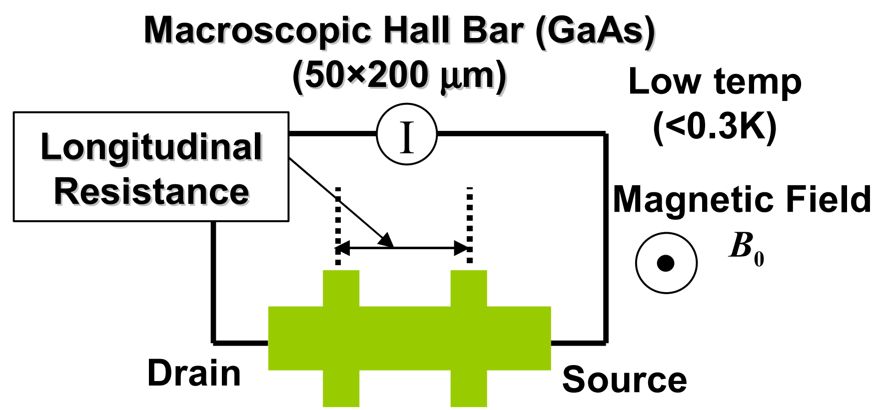
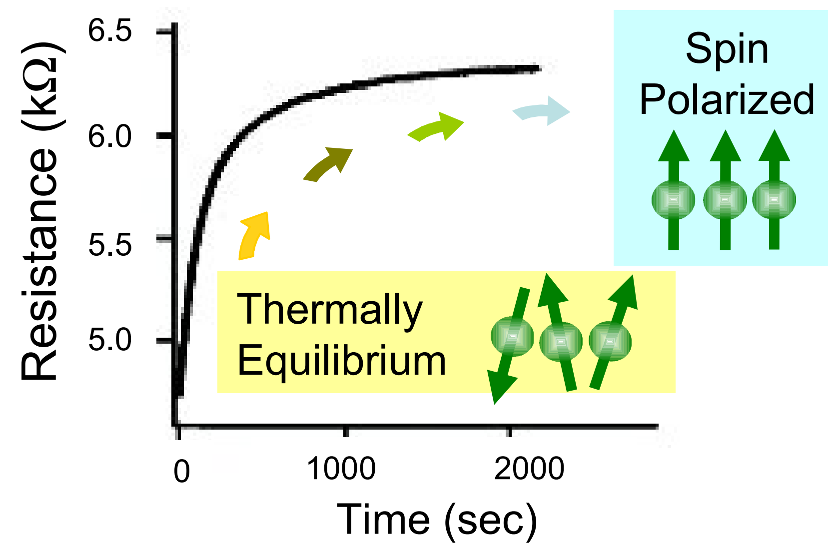


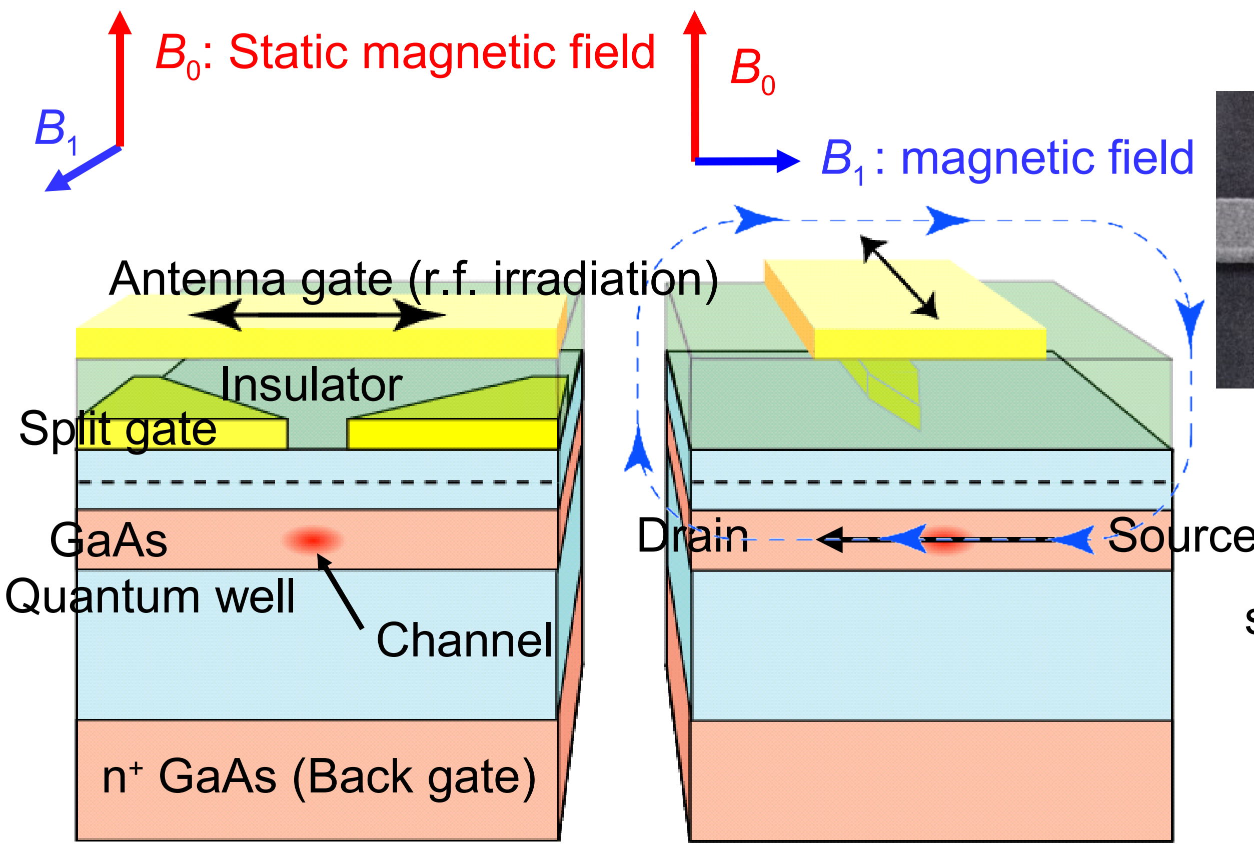


Hashimoto *et al*., PRL (2002).

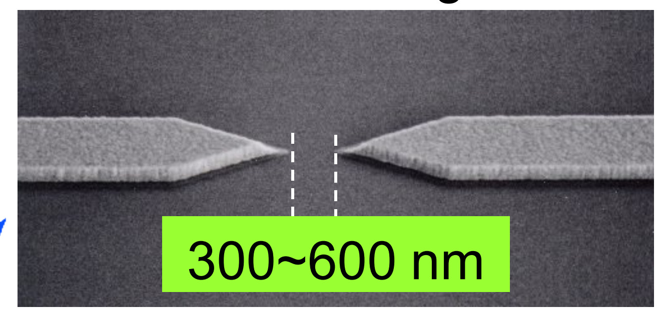
Self-contained NMR Device

Three gate electrodes

1. **Back gate**: to control electron density.
2. **Split gate**: to define nanoscale region
3. **Antenna gate**: for r.f. irradiation



SEM Image



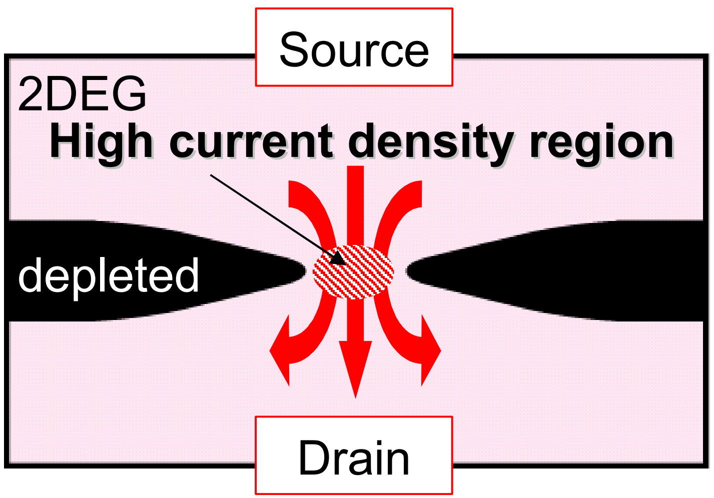
Number of Nuclei <~10^8

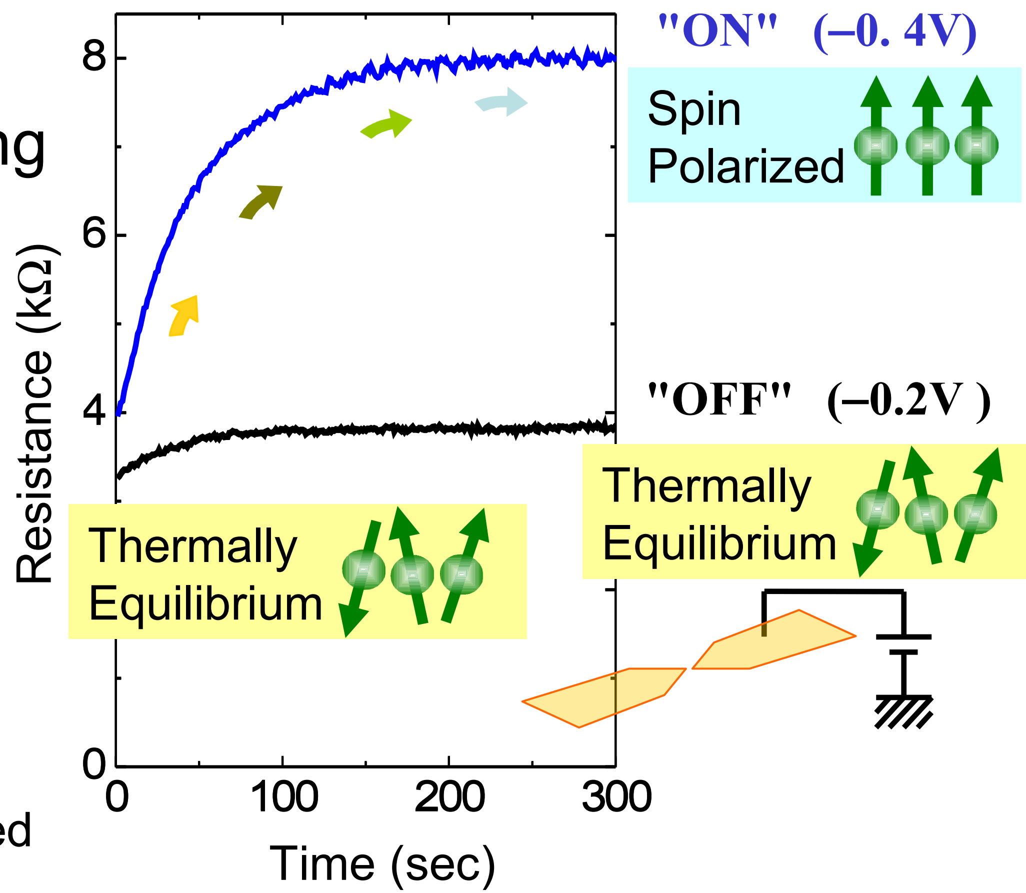
This is much smaller than the **detection limit** of standard NMR (**~10^{11}-10^{13}**).

Polarization of Nuclear spins in a Nanoscale Region

Temperature ~0.1 K

Current dependence of electron-nuclear spin coupling





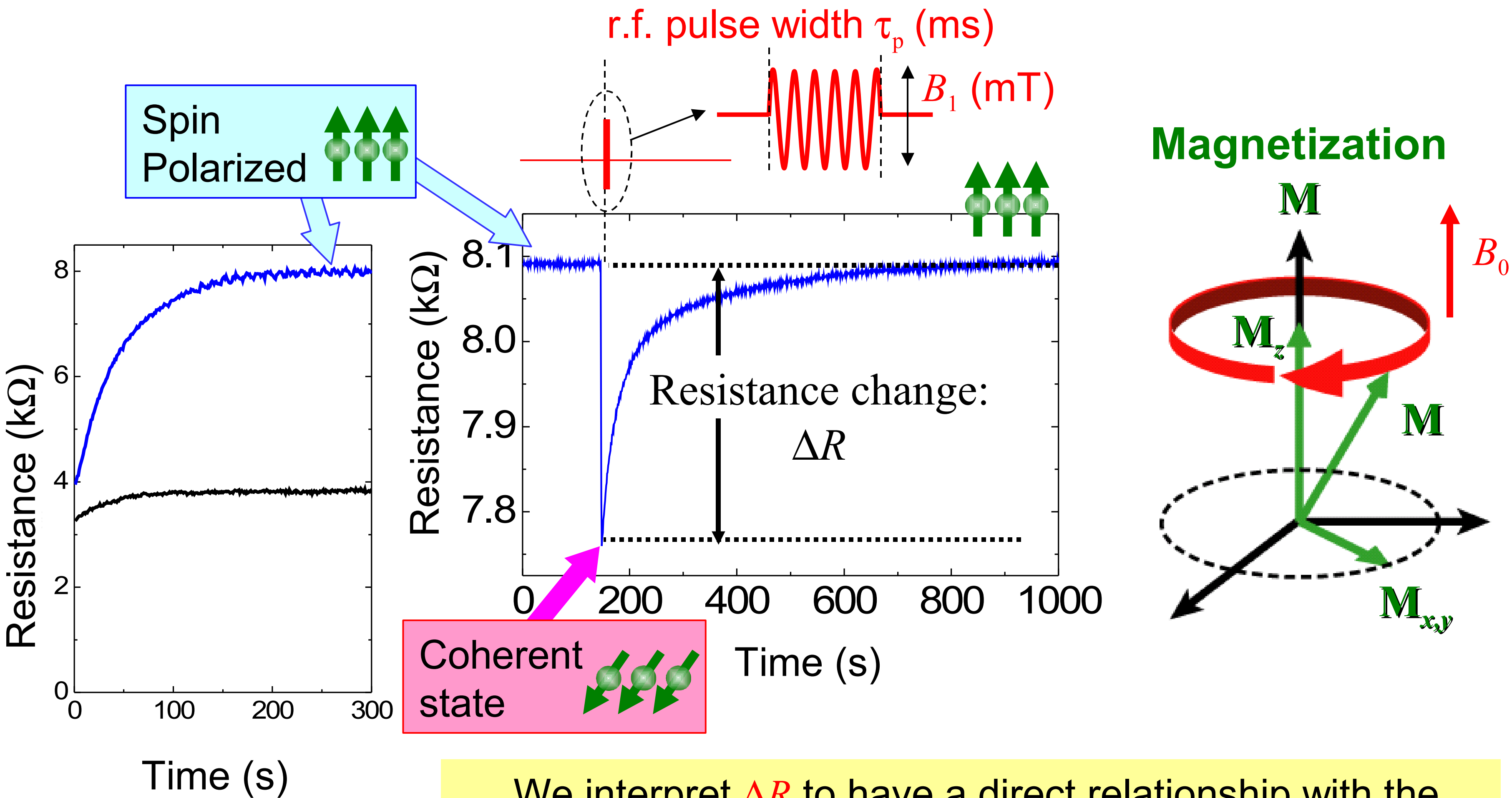
By producing high current density region, nuclear spins can be polarized only in the nanoscale region.

Initialization completed

G. Yusa *et al*. Phys. Rev. B **69** 161302(R) (2004)

r.f.-Pulse Irradiation

to create a quantum mechanical superposition of states

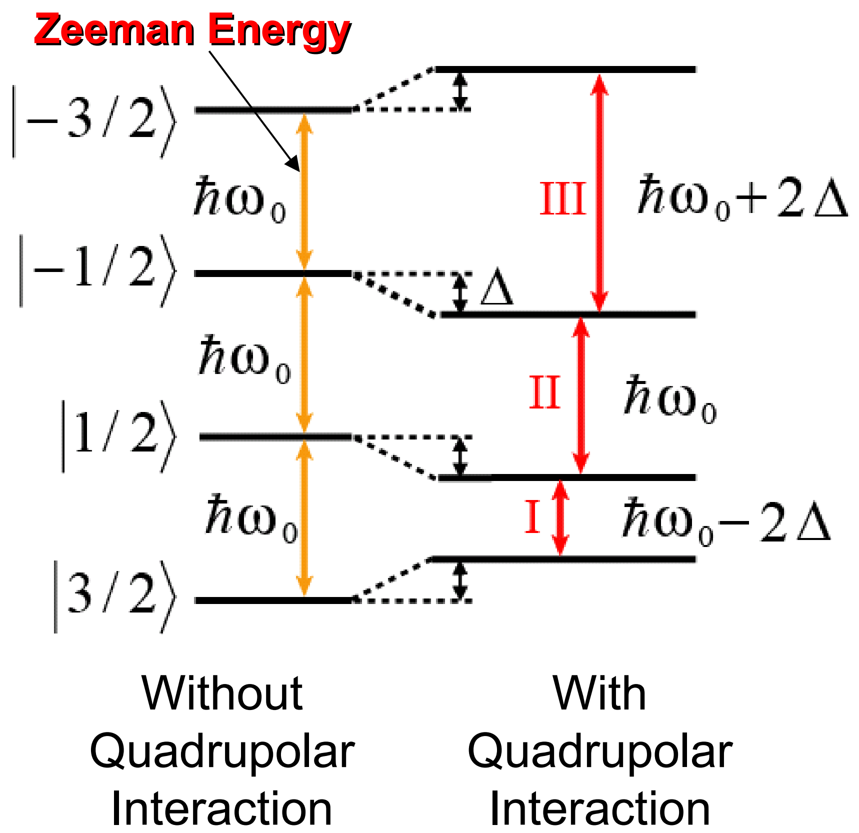


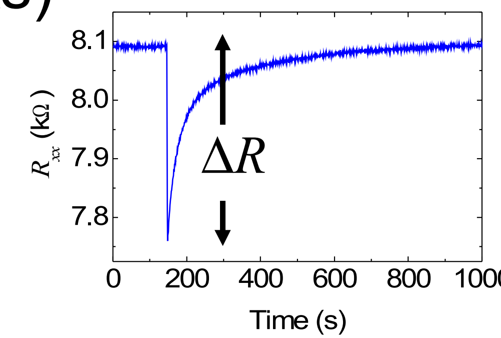
We interpret ΔR to have a direct relationship with the change in the ***z* component of the magnetization, M_z** induced by the altered population by the r.f. pulse.

Quadrupolar Interaction

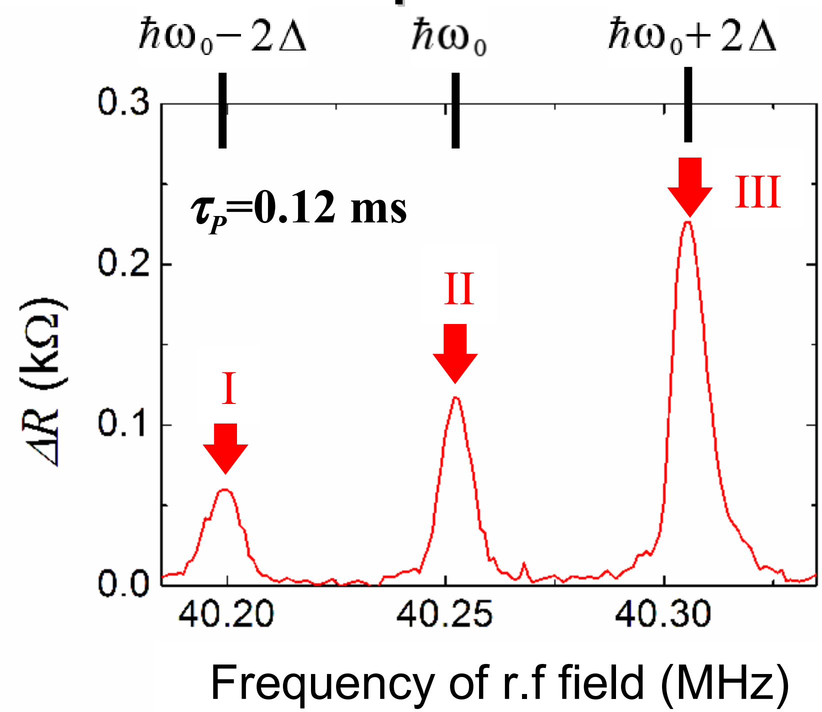
Nuclear spin I=3/2 (^{69}Ga, ^{71}Ga, ^{75}As)

Energy Diagram of I=3/2 system

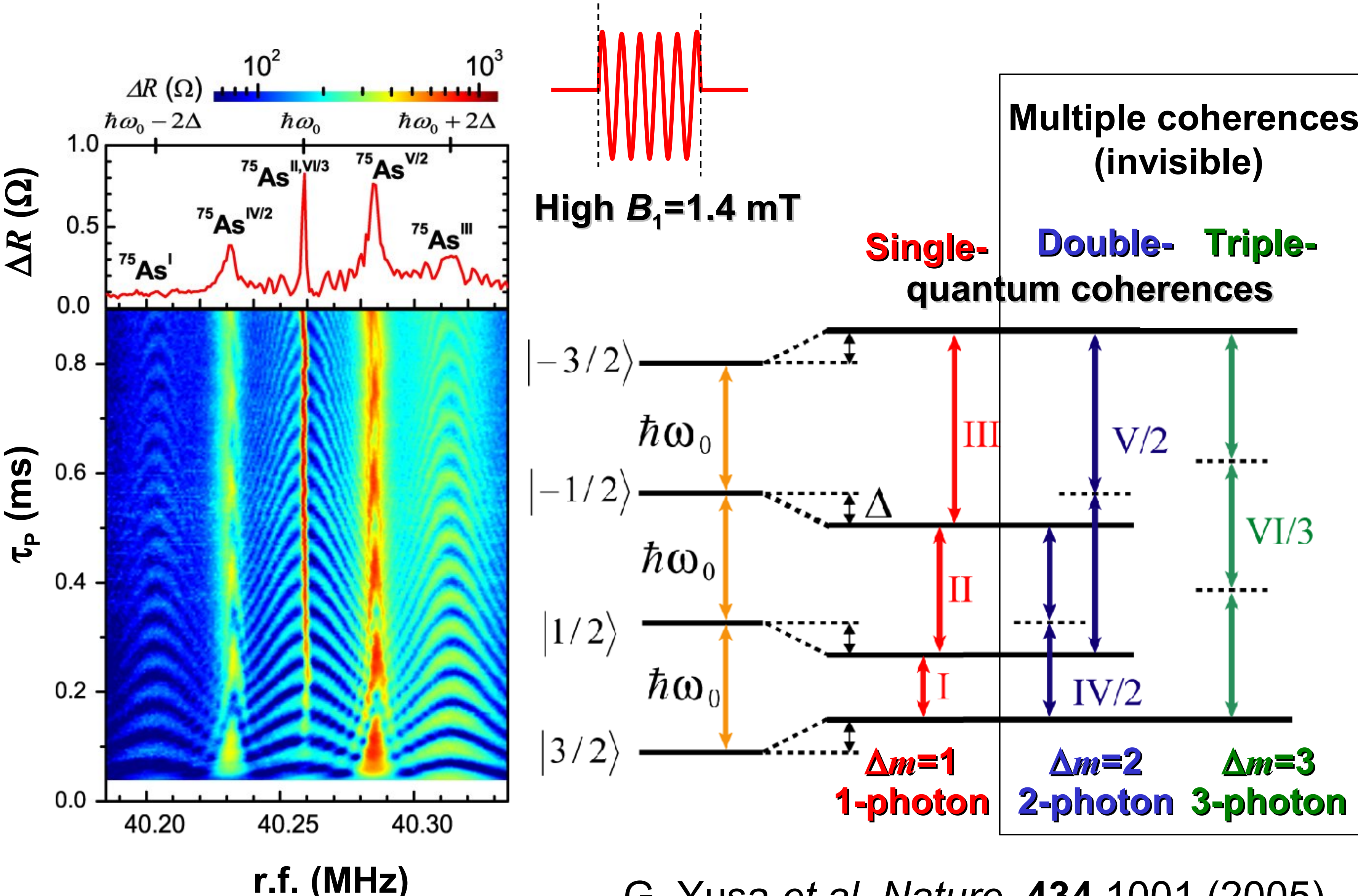




NMR Spectrum of ^{75}As



Time Evolutional Spectra



G. Yusa *et al*. *Nature*, **434** 1001 (2005)

Quantitative Discussion

ASSUMPTION:

The change in the resistance (*ΔR*) is proportional to the change in the magnetization $\mathbf{M}_z$ induced by altered population: $\Delta R \propto \Delta \mathrm{M}_z$

Simulation of M_z using rotating-frame approximation

$$i\hbar \frac{d}{dt}\left|\Psi(t)\right\rangle = H\left|\Psi(t)\right\rangle$$

Zeeman — Quadrupolar — r.f. field

$$H = -\gamma\hbar B_0 I_z + \Delta/3[3I_z^2 - I(I+1)] + \gamma\hbar B_1 \cos(\omega t) I_x$$

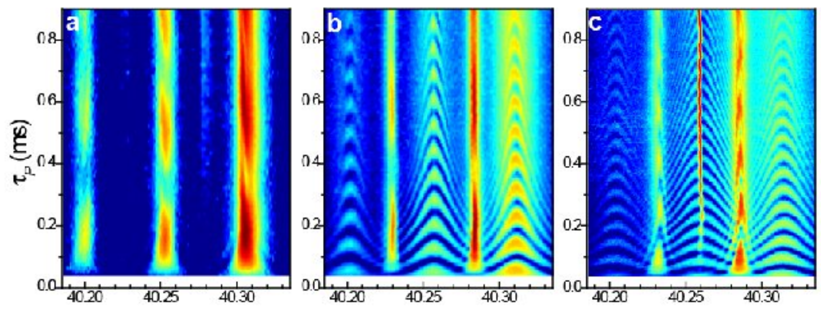
γ: gyromagnetic ratio

Δ: quadrupolar constant

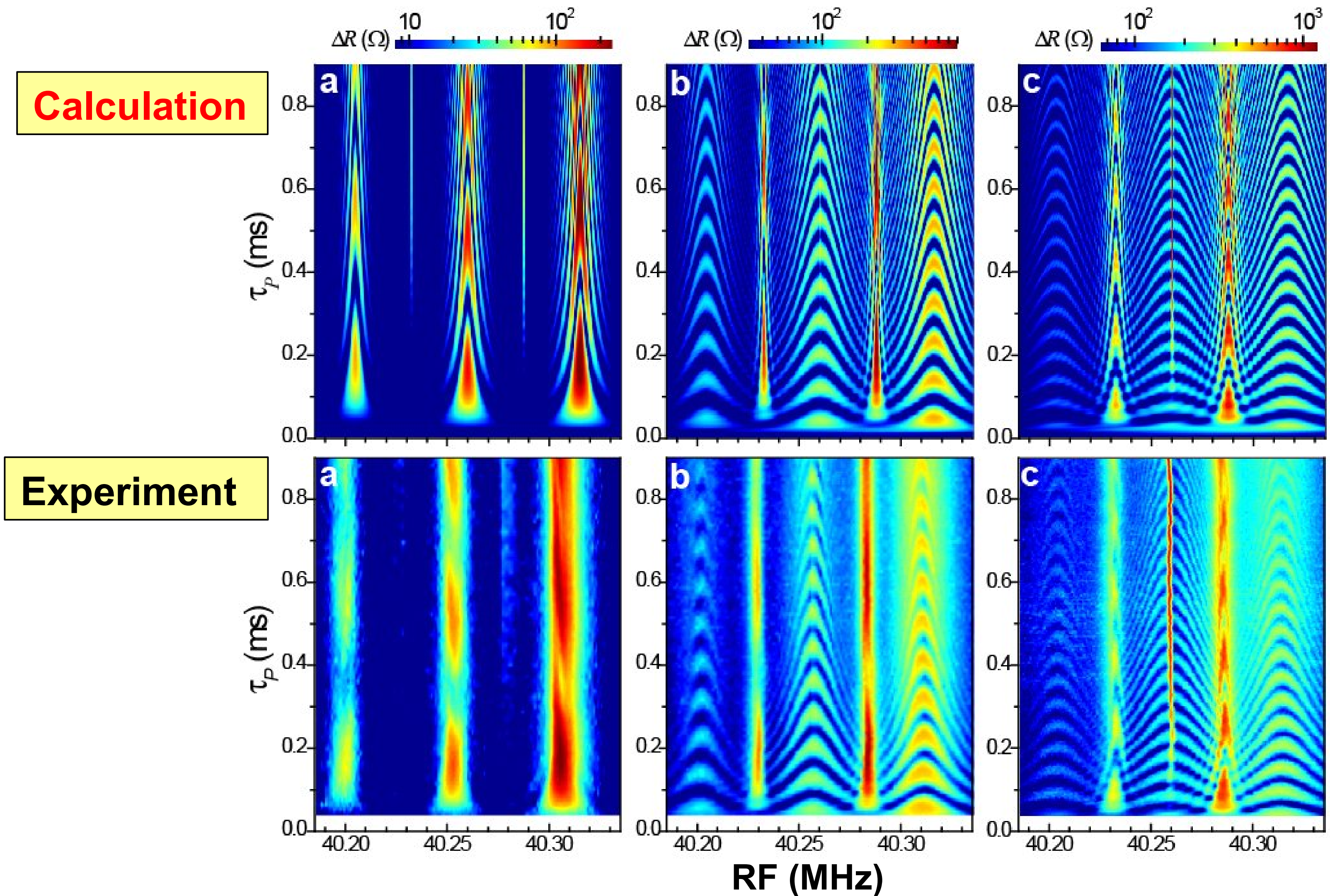
The initial population is the same for all three panels.

***B_1* is the only input parameter for each panel.**

Experiment

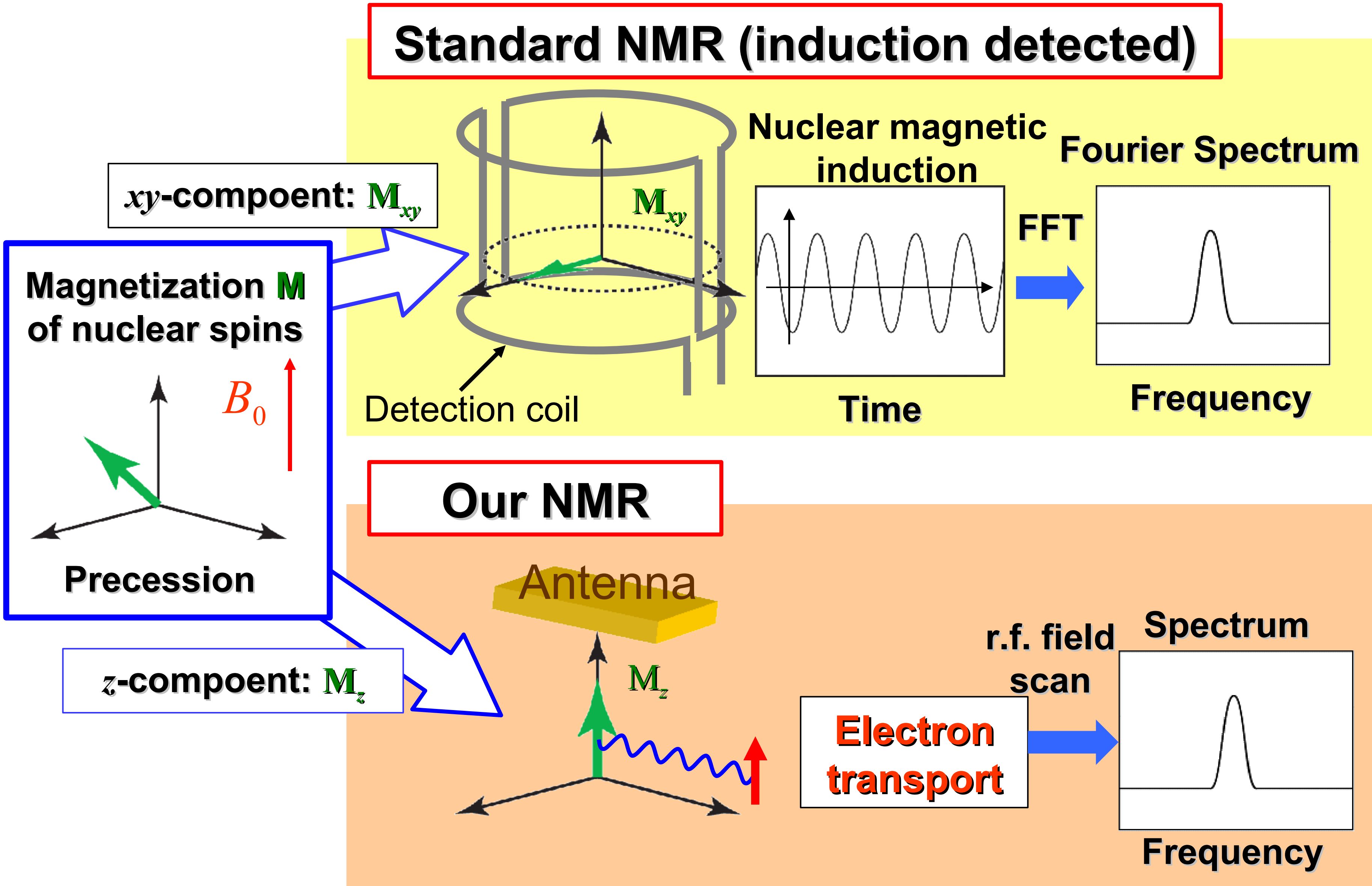


Numerical Calculations



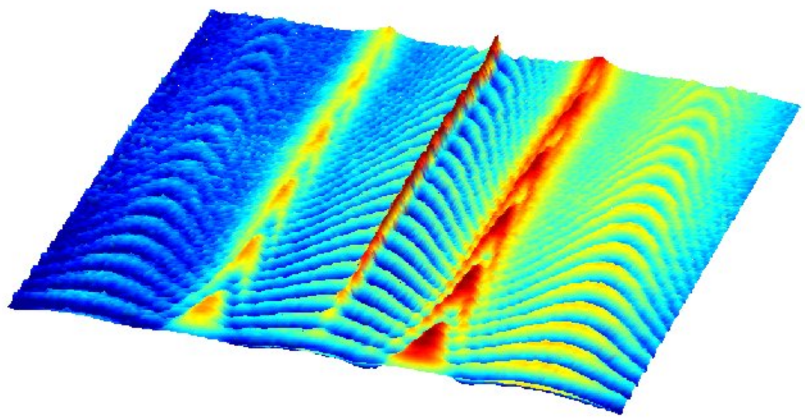
We measure the change in M_z by the resistance

Standard vs. Our NMR

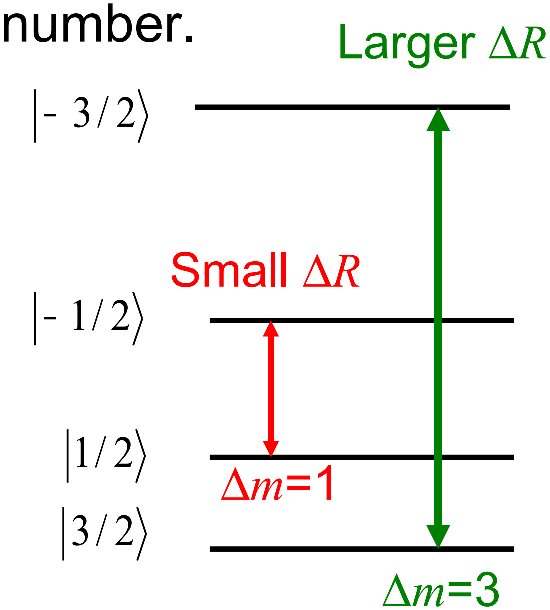


Our NMR ($\mathbf{M}_z$ detection)

- **<u>Direct detection</u> of multiple quantum coherence**
  - The oscillation amplitudes for higher order coherences are larger than those for single, reflecting greater change in spin
  - Width is scaled down by the photon number.



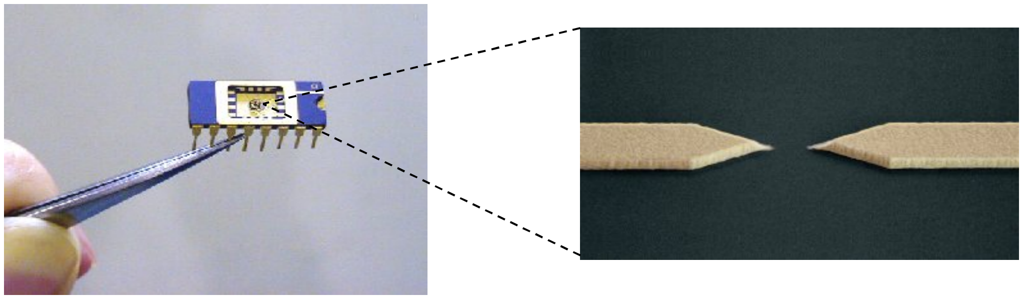
on a logarithmic scale



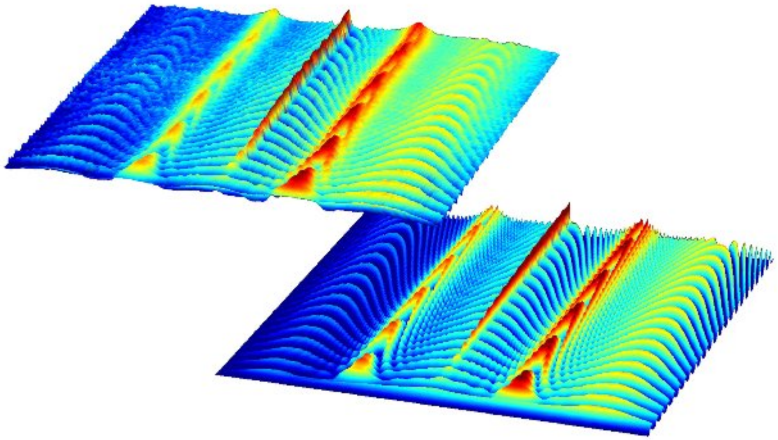
- **<u>High sensitivity</u>** (<10^8)
  - Much less than the detection limit of standard NMR (10^{11}-10^{13})

Conclusion

A self-contained semiconductor device with a novel paradigm of NMR, which accesses nuclear spins in a nanoscale region



Direct detection of multiple quantum coherences, which is invisible by conventional NMR



Three single, two double and one triple quantum coherences for one nuclide, 18 in total for three nuclides (^{69}Ga, ^{71}Ga, ^{75}As), are completely controlled by all-electrical means.