# Quantitative analysis of the nuclear spin dynamics in GaAs with irradiation by RF magnetic field

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## 1. Introduction

Nuclear spin (NS) system is a key technology for implementing quantum bits in solid-state quantum information memories. We observed interesting behaviors for NS dynamics throughout the oblique Hanle effect measurement, using a spin injection device with $Co_2MnSi$/CoFe/n-GaAs Schottky tunnel junction, with and without irradiation by rf magnetic field (RF), see Fig. 1 [1, 2]. Furthermore, we simulated the transient response of the nuclear spins by incorporating the concept of the time dependence of the nuclear spin temperature for the case without RF [3]. The subject of this attempt is to quantitatively analyze the transient response of NSs with RF. These analyses lay the fundamental basis of the nuclear spin dynamics for the quantum information applications.

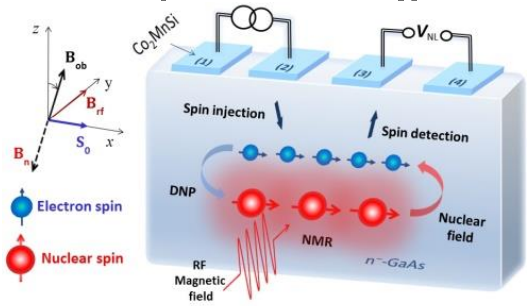


*Figure 1: Schematic structure of a four-terminal nonlocal device used for oblique Hanle effect measurements.*

## 2. Simulation Model

The time dependence of nuclear spin temperature ($\theta_\alpha$) under the dynamic nuclear polarization (DNP) is given by [4]:

$$\frac{d}{dt}\left(\frac{1}{\theta_\alpha}\right) = -\frac{1}{T}\left(\frac{1}{\theta_\alpha} - \frac{1}{\theta_{0\alpha}}\right) \qquad (1)$$

where $T$ is the required time for the DNP which can be as long as several hundred seconds, and $\theta_{0\alpha}$ is the steady-state nuclear spin temperature, which is given by [4]:

$$\frac{1}{k_B\theta_{0\alpha}} = \beta\frac{\mathbf{B}_{ob}\cdot\mathbf{S}}{\mathbf{B}_{ob}{}^2+\xi \boldsymbol{B}_L{}^2} \qquad (2)$$

here $\beta$ is a constant depending on the loss of polarization, $\mathbf{B}_{ob}$ is the applied field, $\mathbf{S}$ is the average electron spin, $\xi$ is a numerical coefficient which depends on the nature of the spin-spin interactions and, $\boldsymbol{B}_L$ is the local dipolar field experienced by the nuclei. Furthermore, to introduce the nuclear magnetic resonance (NMR) into our simulation, we reset the reciprocal nuclear spin temperature, $\theta_\alpha^{-1}$, to zero at the time the nuclear magnetic resonance condition, $\gamma_\alpha|\mathbf{B}_{ob}| = \omega$ (3), is satisfied, where $\gamma_\alpha$ is the gyromagnetic ratio of all nuclei types contained in GaAs, and $\omega$ is the angular frequency of the RF. Since the electron spin precession is induced by $\mathbf{B}_{ob}+\mathbf{B}_n$, the nonlocal voltage $V_{NL}$ between contact 3 and 4 was approximately calculated by using the conventional spin diffusion model [5].

## 3. Results and Discussion

Fig. 2 shows (a) transient oblique Hanle signals without (***black curve***) and with (***red curve***) irradiation by RF, and (b) their simulation result [6]. Experimental results showed that 1) without irradiation by RF, two clear side-peaks were observed, whilst 2) irradiation by RF leads to appearance of step-dip structure, in the place of the right-side peak, along with disappearance of the left-side peak. Appearance of the right-side peak could be directly explained in terms of a steady state model [2]. However, the rest behaviors were qualitatively explained.

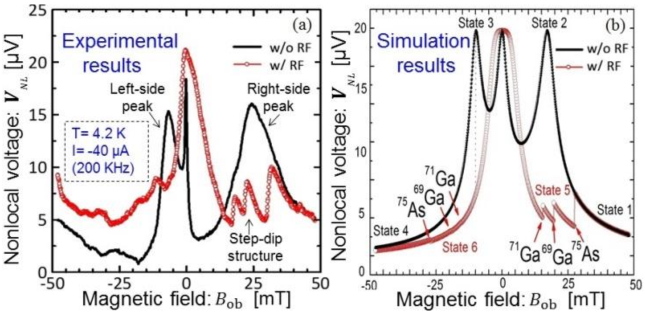


*Figure 2: (a) Experimental and (b) simulation results of oblique Hanle signals observed in GaAs with a $Co_2MnSi$ spin source.*

Since our simulation well reproduced these behaviors [state 3 and state 5 in Fig. 2(b)], the origin of these behaviors can be explained as follows. Without irradiation by RF, a transient state of NS polarization [state 3, Fig 2 (b)] was due to a delay of time response of the nuclear spin temperature to a change in the magnetic field. This explained the presence of the left-side peak. On the other hand, with irradiation by RF, the disappearance of this peak [state 6, Fig 2 (b)] together with appearance of a step-dip structure [state 5, Fig 2 (b)] was due to the NMR occurring at the resonant fields of $^{71}$Ga and $^{69}$Ga and $^{75}$As.

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**References:**

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