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Spatial variation of satellite peaks in the Hanle curve induced by dynamic nuclear spin polarization in lateral all-semiconductor spin injection devices

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Electrical spin injection from a ferromagnet into a non-magnetic semiconductor makes it possible to dynamically polarize lattice nuclear spins in a channel through a hyperfine interaction between electron and nuclear spin systems. Dynamic nuclear spin polarization (DNP) has been intensively studied in quantum Hall regimes[1,2] or by optical means[3]. Since (Ga,Mn)As / *n*-GaAs spin Esaki junction induces high spin injection efficiency[4], all-electrical initialization and manipulation of nuclear spins, which is possibly useful for future quantum computing, could be easily implemented by the electrical spin injection at relatively small external magnetic field[5]. Under the DNP condition, injected electron spins are depolarized by Hanle type precession and relaxation due to nuclear spin magnetic field. Therefore, it is important to investigate spatial distribution of nuclear spin polarization along the pure spin current flowing in the non-local regime. In this talk, we will describe satellite peaks appearing in the Hanle measurement resulting from cancellation of nuclear and external magnetic field, which allows direct evaluation of nuclear spin polarization.

A spin injection device was fabricated from an epitaxial wafer, grown by molecular beam epitaxy, consisting of semi-insulating GaAs, 300 nm GaAs buffer layer, 500 nm AlGaAs / GaAs superlattice, and 0.8-μm-thick *n*-GaAs with $n = 2.5 \times 10^{16}$ cm^3, followed by 0.2-μm-thick n^+-GaAs, 15 nm GaAs with linearly graded doping $n^+ \rightarrow n^{++}$ with $n^+ = 5.0 \times 10^{16}$ cm^3 and $n^{++} = 6.0 \times 10^{18}$ cm^3, 8 nm n^{++}-GaAs, 2.2 nm AlGaAs diffusion barrier and finally 50 nm (Ga,Mn)As. A 10-μm-wide mesa of *n*-GaAs layer, oriented along the [110] GaAs direction, is used as a transport channel where six (Ga,Mn)As / *n*-GaAs spin Esaki junctions, defined by electron beam lithography and wet chemical etching, constitute spin-injection and detection contacts. The distances between injector and detectors defined as *L* vary from 5 to 20 μm by 5 μm increment.

Figure 1 shows a typical non-local spin-valve signal (NLSV) reflecting parallel and anti-parallel alignments of magnetizations for injector and detector under in-plane magnetic fields B_x along the contacts swept from a positive to a negative saturation field (blue dots in Fig. 1) and the Hanle signal in out-of-plane magnetic fields B_z swept from zero to either a positive or a negative field (magenta dots in Fig. 1). Both sets of data clearly indicate spin injection and transport in non-local region of the channel and dephasing due to the perpendicular magnetic field. The same Hanle measurement with a small in-plane magnetic field is displayed also in Fig. 1 (green dots). In the present of DNP, nuclear magnetic field acting on electron spin is expressed as

$$\boldsymbol{B}_{\mathrm{N}} = b_N \frac{\boldsymbol{S}\cdot\boldsymbol{B}_{ex}}{B_{ex}^2}\boldsymbol{B}_{ex},$$

where $\boldsymbol{S}$ and $\boldsymbol{B}_{\mathrm{ex}}$ indicate the electron spin and the external magnetic field. $|S|$ equals 1/2 when the electron spin is fully polarized. b_{N} is a constant in the unit of magnetic field, which depends on the strength of hyperfine coupling. When a nuclear magnetic field points opposite to the external magnetic field and large enough to cancel with it, a total magnetic field acting on the electron spin vanishes and the Hanle type precession is strongly suppressed, meaning that electron spin polarization recovers when $\boldsymbol{B}_{\mathrm{N}} = -\boldsymbol{B}_{\mathrm{ex}}$. Therefore, the satellite peaks of the Hanle curve are a direct measure of nuclear magnetic field.

Figure 2 shows the Hanle curves with satellite peaks obtained by different detectors. It is clearly seen that magnetic fields of the satellite peaks decrease with *L* becoming longer. This implies the strength of nuclear magnetic field decays with distance depending on electron spin polarization. In the talk, further quantitative evaluation of nuclear spin polarization will be discussed.

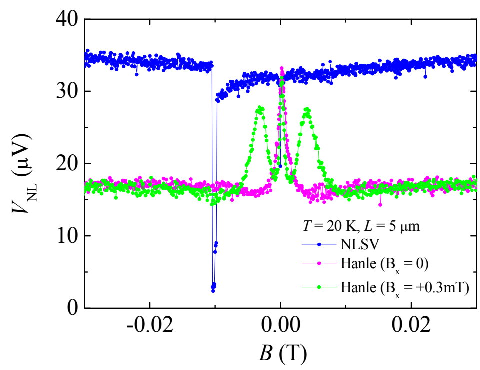

Figure 1. Non-local spin-valve (blue) and the Hanle curves with / without in-plane magnetic field (green / magenta) obtained at $T = 20$ K and $L = 5$ μm.

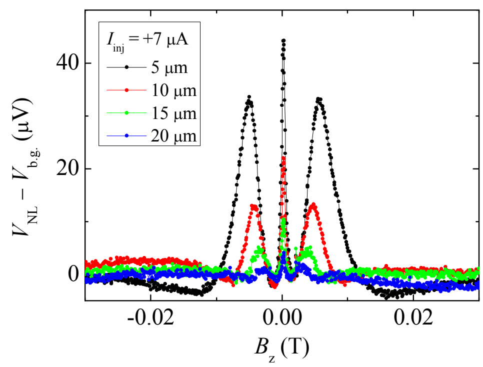

Figure 2. The Hanle curves with $B_x = 0.3$ mT obtained by different ferromagnetic contacts at $L = 5$, 10, 15, 20 μm. Measurement conditions are identical to that in Fig. 1.

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