論文の内容の要旨

論文題目　Static and dynamic spin transport in lateral spin valves（面内スピンバルブにおける静的及び動的スピン輸送）

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Generation, control and detection of spin current are key ingredients in spintronics. Pure spin current, a flow of spin angular momentum without net charge flow, bridges the conventional charge based transport phenomena and the physics in magnetism such as a spin-transfer torque, *s-d* interaction etc. and thus is the key concept in spintronics. The thesis is devoted to a series of experiment aiming at the understanding of static and dynamic properties of the spin current by means of a non-local spin injection technique in lateral spin valves (LSVs).

Non-local spin injection technique in lateral spin valves is an effective method to generate the pure spin current in non-magnetic material. The non-local spin injection was first demonstrated in 1985 using micro-scale devices which consist of a 50-µm-thick Al bar with ferromagnetic junctions [M. Johnson and R. H. Silsbee, Phys. Rev. Lett. 55, 1790 (1985)]. This experiment yielded a tiny spin accumulation signal of a few tens of pico-volts. The experiment was revisited in 2001 using nano-scaled LSVs [F. Jedema *et al*, Nature **410**, 345 (2001)]. This brought about an enhanced signal of about one micro-volt at room temperature, which spurred intensive research efforts in non-local LSVs for spintronic device applications. Further enhancement of the spin accumulation is beneficial for the understandings of transport properties of the pure spin current which is flowing along the slope of the spin accumulation.

In this thesis, the non-local spin injection properties were studied with metallic LSVs. The enhancement of the spin accumulation was realized in LSVs with ferromagnet/MgO/Ag junctions. With annealed $Ni_{80}Fe_{20}$(Py)/MgO/Ag junctions, the hundred-fold spin accumulation signal ΔV = 225 μV was realized. The results were analyzed using spin diffusion model and the underlying physics was understood as a (spin) resistance (conductance) mismatch. In addition to it, the structure of LSV was systematically optimized. The dual injection scheme was demonstrated and the effect of spin absorption was examined. Dual injector lateral spin valves (DLSVs) with Py/MgO/Ag junctions enabled 3-fold enhancement whereas a little (~1.2 times) enhancement in Py/Ag junctions due to spin absorption. LSVs with $Co_{50}Fe_{50}$/MgO/Ag junctions showed the 20% improvement of injection/detection efficiency compared with Py/MgO/Ag junctions.

Spin relaxation mechanism in non-magnetic wire was experimentally examined by characterizing spin transport properties of Ag and Mg in LSVs. For Ag, the temperature variations of the spin relaxation time τ_{sf} and the momentum relaxation time τ_e were analyzed to discuss the intrinsic spin relaxation properties in non-magnet. Spin relaxation ratio $\varepsilon \equiv \tau_e / \tau_{sf}$, the characteristic value of the Elliott-Yafet spin relaxation mechanism, of Ag nanowire was agreed with the value of bulk Ag obtained by conduction electron spin resonance. Phonon contribution of the spin relaxation was universally expressed with the material independent curve scaled by the spin-orbit interaction for monovalent metal. The surface spin scattering, which hampered quantitative analysis in previous reports, is well suppressed in Ag nanowire by an MgO capping layer. Non-local spin injection into Mg nanowire revealed that the spin diffusion length was comparable to the other non-magnet such as Cu, Ag and Al despite the fact that the light metal Mg shows small spin-orbit interaction. This is because the complex electronic structure of Mg promotes spin relaxation (spin-hot-spot), which explains the relatively short spin diffusion length of approximately 200 nm at room temperature.

Collective spin precession in LSVs, so-called Hanle effect, were studied. In ballistic spin transport, spins can coherently rotate at a Larmor frequency proportional to the applied perpendicular magnetic field. This allows us to control the direction of the spins in the channel and to manipulate the output signal of LSVs by adjusting an effective external parameter such as the Rashba field tunable via a gate voltage. This scheme realizes an active spin device such as the spin-transistor [S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990)].

In contrast, in a diffusive pure spin current in non-magnets, the precession causes dephasing, and drastically decreases the spin accumulation. Therefore the understandings of dynamic transport properties of spin current is indispensable.

The dynamic transport properties of the pure spin current in metallic LSVs with various devices were systematically studied. The effect of the spin absorption on the Hanle signal was clearly observed. We have successfully formulated the Hanle effect for the LSVs with anisotropic spin absorption for the transverse and longitudinal components of the spin polarization in the spin current relative to the detector magnetization-direction, which enables to characterize intrinsic spin transport properties even with the spin absorption effect. The velocity of diffusive spin currents and the transit-time distribution was successfully characterized by applying Fourier transform to the experimental Hanle signals, resulting in excellent agreement with the empirical model in the case of Py/MgO/Ag junctions. In contrast, we found that the transit-time distribution in LSVs with Py/Ag junctions strongly deviated from that expected in the empirical model and that the spins diffuse much faster than in LSVs with Py/MgO/Ag junctions, reflecting the spatial distribution of chemical potential affected by the type of junctions.

Moreover, we demonstrate the LSVs with dual injectors enable to detect a highly coherent spin precession over a distance of 10 μm with keeping spin accumulation vector in plane. We show the phase coherency in precession is improved with an increase of the channel length. The coherency in the spin precession shows a universal behavior as a function of the normalized separation between the injector and the detector in material-independent fashion for metals and semiconductors including graphene.

The thesis presents a systematic study on the spin dependent transport in the metallic devices. The thesis consists of three complimentary studies, the efficient non-local spin injection (the effect of the junction and the device structure), the spin relaxation mechanism (intrinsic properties: phonon contribution and the effect of the electronic structure), and the collective spin precession (the characterization of the spin transport properties and the modulation), which are deeply related each other. The in-depth understandings of lateral spin transport could be base on the future physics of spintronics and new technological applications based on pure spin current.