Comparison of non-local and three-terminal detection of spin accumulation in (Ga,Mn)As/GaAs spin Esaki diode devices

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Electrical detection of spin accumulation generated by spin injection in ferromagnet/non-magnetic semiconductor heterojunctions is typically realized by four-terminal (4T) measurement in non-local (NL) configuration, *i.e.*, with spin injector and detector circuits separated from each other. An alternative method of spin detection involves three-terminal (3T) measurement (see e.g. [1]) in which both spin injection and detection are performed with a single ferromagnetic contact. The 3T-method is particularly useful in cases when no NL signal can be observed. This technique was successfully employed for many materials, especially Si and Ge [2, 3]. There has been, however, a lot of controversies related to this method, mainly because the amplitude of the measured signal often exceeds by orders of magnitude the prediction of the standard spin drift-diffusion model of the spin injection. In the present work we compare 3T and NL spin signals observed in spin injection devices with (Ga,Mn)As/GaAs spin Esaki diode structures [4].

A spin injection sample is patterned into a 50-μm-wide mesa from a wafer consisting of 50 nm (Ga,Mn)As, 2.2 nm (Al,Ga)As, 8.0 nm n^{++}-GaAs, 15 nm $n^{++} \rightarrow n^{+}$-GaAs, 0.2 μm n^{+}-GaAs, and 0.8 μm n-GaAs grown on semi-insulating GaAs substrate. Ferromagnetic spin injecting and detecting contacts were defined by electron beam lithography, wet chemical etching, and Au / Ti evaporation.

When the external magnetic field is swept along the contacts, spin-valve effect and tunneling anisotropic magnetoresistance (TAMR) effect are observed in NL and 3T voltage, respectively. Out-of-plane field sweeps result in clear Hanle-type depolarization of the spin signal observed in both configurations, thus allowing their direct comparison. We particularly focus on the signal's dependence on bias voltage/current applied to the injector. With increasing bias the NL-signal drops monotonically as spin injection efficiency is lower for higher bias voltages [4]. The 3T signal, on the other hand, increases with increasing bias up to the voltage corresponding to the Esaki dip in the current-voltage characteristic, reaches maximum and decreases upon further increase of the bias. While comparable at low bias, the 3T signal is at the maximum by a factor of ~100 larger than the NL one. A behavior of the 3T-Hanle signal will be discussed in terms of spin accumulation in localized states [1] and also taking into account the effect of electric field on the sensitivity of the spin detection [5].

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