FRIDAY AFTERNOON, 8 NOVEMBER 2013 PLAZA BALLROOM F, 1:30 TO 4:30

Session HB
SPIN INJECTION INTO SEMICONDUCTORS
Georg Schmidt, Chair

INVITED PAPER

1:30

HB-01. Spin-pumping-induced spin transport in p-Si and graphene at room temperature. *M. Shiraishi*[1] *1. Osaka Univ., Toyonaka, Japan*

Spin transport in Si is one of the quite significant research target in semiconductor spintronics, since Si is expected to possess long spin coherence because of its lattice inversion symmetry and spin transistors using Si can be a potential device as a beyond CMOS device. By now, much effort has been paid to realize room temperature spin transport in n-type and p-type Si, however there was no report on it in p-type Si. Here, our recent success on spin transport in p-type Si at room temperature by using spin pumping is presented [1]. Spin pumping is well known as a potential method for spin injection into materials with a large spin-orbit coupling, resulting in successful conversion from a pure spin current to a charge current [2]. Simultaneously, spin pumping is also potential for generating spin-wave spin current in YIG [3]. Now, we used this attractive method for generating a conventional pure spin current and for transporting spin angular momentum in solids at room temperature [1,4,5]. A number of control experiments for p-Si spin devices corroborated our claim, and the spin coherence was estimated to be ca. 120 ps in the simplest model. This method can be also used in graphene [4] and Al [5], and they will be also introduced in the presentation.

[1] E. Shikoh, M. Shiraishi et al., Phys. Rev. Lett. 110, 127201 (2013). [2] E. Saitoh et al., Appl. Phys. Lett. 88, 182509 (2006). [3] Y. Kajiwara, E. Saitoh et al., Nature 464, 262 (2010). [4] Z. Tang, M. Shiraishi et al., Phys. Rev. B87, 140401(R) (2013). [5] Y. Kitamura, M. Shiraishi et al., Sci. Reports 3, 1739 (2013).

CONTRIBUTED PAPERS

2:06

HB-02. Quantitative Investigation of Spin-drift Velocity in Highly-doped n-type Si. *M. Kameno*[1], Y. Ando[1], T. Shinjo[1], H. Koike[2], T. Sasaki[2], T. Oikawa[2], T. Suzuki[3] and M. Shiraishi[1] *1. Engineering Science, Osaka University, Toyonaka, Osaka, Japan; 2. SQ Research Center, TDK Corporation, Saku, Nagano, Japan; 3. AIT, Akita, Akita, Japan*

An effect of spin drift plays an important role for modulating spin signals also in Si spintronics. Spin drift is induced by an electric field in a spin transport channel, and in fact, it is theoretically reported that spin transport length scale can be modified [1]. Experimentally, we have reported modulation of a spin transport length scale [2,3]. Although a non-local 3-terminal method (NL-3T) has been used for discussing the spin drift effect, a previous study shows that spurious signals can be detected in the NL-3T [4], and thus, verification of successful spin transport in the same device is indispensable by using a non-local 4-terminal method (NL-4T). Here, a new approach to confirm successful spin transport and investigate the spin drift effect in highly-doped n-type Si is introduced, where we use a two-terminal method (2T) in order to measure the spin accumulation in Si with a current flow from a ferromagnetic electrode to a nonmagnetic electrode. Since an electric field is applied in the entire Si channel, this method enables to investigate spin drift velocity quantitatively. The spin valve device consisted of a phosphorus-doped (~5×10^19 cm^-3) n-type Si channel on a Si-on-Insulator (SOI) substrate, equipped with two ferromagnetic and nonmagnetic electrodes. We quantitatively studied the spin drift velocity in highly-doped Si by using the fitting function obtained from the spin drift-diffusion equation [1], and the results are strongly supported from the relationship of the carrier mobility and the electric field [5].

[1]Z.G. Yu and M.E. Flatte, Phys. Rev. B 66, 201202(R) (2002). [2]M. Kameno et al., Appl. Phys. Lett. 101, 122413 (2012). [3]M. Kameno et al., J. Appl. Phys. 111, 07C322 (2012). [4]Y. Aoki et al., Phys. Rev. B 86, 081201(R) (2012) [5]M. Kameno et al., in preparation.

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HB-03. Spin Injection and Diffusion in Silicon Based Devices from a Space Charge Layer. *J. Ghosh*[1], V. Sverdlov[1], T. Windbacher[1] and S. Selberherr[1] *1. Institute for Microelectronics, Technical University of Vienna, Vienna, Austria*

The scaling of CMOS devices will reach fundamental limits in the near future, which necessitates the development of new technologies in semiconductor industry. Spin-based electronics (spintronics) is a promising successor technology which facilitates spin as a degree of freedom. Silicon, due to its long spin lifetime and well established processes and technology, is an ideal material for spintronics [1]. In this paper we study the electron spin and charge transport in an n-doped silicon bar with spin-dependent conductivity. Our investigations can reproduce the analytical solution of the classical spin drift-diffusion model without presence of a space-charge at the boundary under arbitrary external electric field [2]. Additionally our research is not restricted to charge neutrality and simulations were carried out considering charge accumulation and depletion at the boundaries. Injection of charge causes obviously a non-zero charge current in the device. A significant spin and charge accumulation can thereby also be introduced and in addition to the charge current, spin current can diffuse out of this region. This spin current can be tuned by varying the spin and the charge accumulation. In addition, the charge current can be compensated by applying an external voltage. In such a case, the spin current decreases compared to the uncompensated case and the existence of an upper threshold spin current can be confirmed [3]. The non-zero charge current is also present in the case of depletion and the corresponding spin current is found to be smaller compared to the one in case of accumulation. The presence of charge accumulation as well as depletion has a significant influence on the spin signal, thereby providing additional means for designing efficient spintronic devices. This research is supported by the European Research Council through the Grant #247056 MOSILSPIN.

[1] R. Jansen, Nat. Mater. 11, 400–408 (2012). [2] Z. G. Yu and M. E. Flatte, Phys. Rev. B 66, 235302 (2002). [3] V. Zayets, Phys. Rev. B 66, 174415 (2012).

2:30

HB-04. Local magnetoresistance through Si at room temperature and its bias voltage dependence in ferromagnet/MgO/SOI lateral spin valves.

Y. Saito[1], M. Ishikawa[1], T. Tanamoto[1], T. Inokuchi[1], H. Sugiyama[1], K. Hamaya[2] and N. Tezuka[3] *1. Corporate R&D Center, Toshiba Corporation, Kawasaki, Japan; 2. Department of Electronics, Kyushu University, Fukuoka, Japan; 3. Department of Materials Science, Tohoku University, Sendai, Japan*

Efficient spin injection and detection are essential for spintronics. For this purpose, spin transport has been intensively studied in various kinds of materials. Recently, we have been observing spin accumulation signals in silicon (Si) with relatively long spin relaxation time by measuring three-terminal and four-terminal Hanle signals for epitaxially grown CoFe/MgO/Si(100) devices. [1] Here we experimentally and theoretically investigate a local magneto-resistance (MR) through Si and its bias voltage (V_{bias}) dependence in ferromagnet (FM)/MgO/Silicon-on-insulator (SOI) devices. To our knowledge, there is no report for the V_{bias} dependences on local-MR for FM/MgO/SOI devices. Our device (Fig. 1) is based on the lateral spin valve structure where a nonmagnetic Si wire is bridged by two FM/MgO wires. The SOI contains phosphorus at the density of $2*10^{19}$ cm^{-3} at 300 K. We have observed local-MR signals up to room temperature for FM (CoFe or Heusler Co_2FeSi)/MgO/SOI lateral spin valves with center-to-center FM distance L=2.25 μm. Figure 2 shows V_{bias} dependences on MR ratio for lateral spin valves at 20 K and 77 K with various FM/MgO structures. In the case of the V_{bias} dependence on tunnel MR ratio in the magnetic tunnel junctions, tunnel MR ratio decreases with increasing V_{bias}. However, V_{bias} dependence on MR ratio through Si has a unique curve as shown in Fig. 2. This anomalous behavior can be understood by considering the standard drift-diffusion theory [2] improved by taking into account the difference in the interface resistances between FM/MgO/Si and Si/MgO/FM interfaces and V_{bias} dependences on interface resistances. In the case of semiconductor materials, the interface resistances between both interfaces are usually different from each other, because of the existence of a depletion layer. These results indicate that observed local-MR is related to the spin signal through Si bulk band. These results are consistent with the observation of non-local MR and Hanle signals. This work was partly supported by Grant-in-Aid for Scientific Research from JSPS.

[1] M. Ishikawa et al., Appl. Phys. Lett. 100, 252404 (2012).; Y. Saito et al., IEEE Trans. Magn. 48, 2739 (2012). [2] A. Fert and H. Jaffr'es, Phys. Rev., B 64, 184420 (2001).

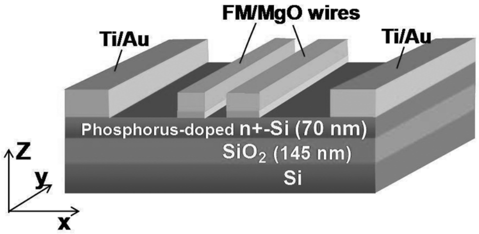

Figure 1 Schematic diagram of a lateral spin valve device used in this study

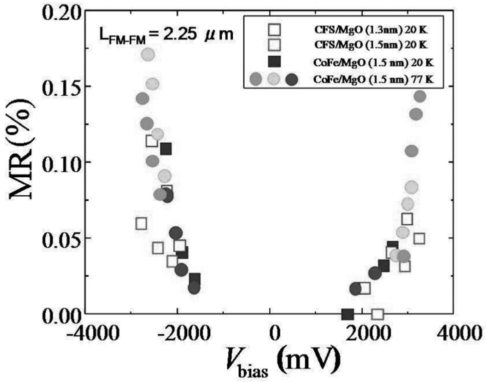

Figure 2 Bias voltage dependence on local-MR in FM/MgO/SOI lateral spin valve

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HB-05. Spin Accumulation Induced in Ge using an Epitaxial Mn_5Ge_3 Schottky Contact.

A.M. Spiesser[1], *H. Saito*[1], R. Jansen[1], S. Yuasa[1] and K. Ando[1] *1. Spintronics Research Center, National Institute of Advanced Industrial Science and Technology AIST, Tsukuba, Ibaraki, Japan*

The considerable progress in the creation of spin accumulation in group-IV semiconductors(SC) has strengthened the field of semiconductor spintronics. One promising approach is to inject spins directly from a ferromagnet(FM)/SC Schottky contact using a specific FM alloy. This avoids the use of an insulator as the tunnel barrier and may reduce the contact resistance of the junction, which is a crucial issue for continued CMOS scaling. In this context, the Mn_5Ge_3 compound is an attractive spin injector for Ge since epitaxial Mn_5Ge_3 films having high crystalline quality can be easily grown on Ge [1,2]. In addition, the FM shows a reasonable Curie temperature (~300 K) that can be greatly enhanced by carbon doping [3]. Also, the possibility to fabricate perpendicular magnetized films by tuning the film thickness could lead to the development of spin transfer torque devices [4]. Here, we demonstrate electrical spin creation in Ge using an epitaxial Mn_5Ge_3 Schottky contact in a three-terminal configuration [5]. The Mn_5Ge_3 film was fabricated on an n-type Ge(111) substrate (carrier concentration $\sim 1\times10^{18}$ cm^{-3} at 300 K) by solid phase epitaxy [1,2]. Typical Hanle and inverted Hanle effects were observed up to 200 K, proving that spin polarization was induced in the Ge. The magnitude of the spin signal is as large as that reported in FM/oxide/Ge tunnel junctions [5], although two-step tunneling via interface states related to the oxide cannot occur in a Schottky contact. This result will be discussed in terms of different transport mechanisms. A new feature is the presence of a hysteresis in the inverted Hanle curve that reflects the variation of the local stray field during the magnetization reversal. **Acknowledgments:** This work was supported by the JSPS Postdoctoral Fellowship for Foreign Researchers (A. S.) and the Funding Program for Next Generation World-Leading Researchers.

[1] C. Zeng *et al.*, Appl. Phys. Lett. **83** (2003) 5002. [2] S. Olive-Mendez *et al.*, Thin Solid Films **517** (2008) 191. [3] A. Spiesser *et al.*, Phys. Rev. B **84** (2011) 165203. [4] A. Spiesser *et al.*, Phys. Rev. B **86** (2012) 035211. [5] R. Jansen *et al.*, Semicond. Sci. Technol. **27** (2012) 083001.

2:54

HB-06. Surface Enhancement of Spin Injection in GaAs Detected with X-ray Magnetic Circular Dichroism.

S. Zohar[1], P.J. Ryan[1], J. Kim[1] and D.J. Keavney[1] *1. Advanced Photon Source, Argonne National Laboratory, Argonne, IL*

The generation, detection, and transport of spin in condensed electronic systems continues to attract considerable attention due the potential for exciting