Simulation and Analysis of a Refracting-Facet Spin-Photodiode

°R. C. Roca, N. Nishizawa, and H. Munekata
FIRST, Tokyo Institute of Technology
E-mail: ronel.roca@isl.titech.ac.jp

Spin-photodiodes (spin-PDs) are candidate monolithic devices for the detection of circularly polarized light (CPL). Recently, our group has reported a lateral-type spin-PD with a refracting facet and demonstrated a figure of merit F as high as ≈ 0.4% [1]. This F value is four times higher than the previously reported values [2].

In order to fully understand the physical mechanism in the spin-PD, we have developed charge-spin transport model based on (1) the drift-diffusion equations for charge and spin combined with (2) spin-dependent quantum tunneling. Improved points compared to previous model [3] is that we take into account the hot spin injection into a ferromagnetic electrode (Fig. 1) and the influence of non-radiative recombination centers near the AlO_x/InGaAs interface with the effective carrier lifetime $\tau_{rec}{}^*$. Drift-diffusion equations are expressed by Eqs. (1) and (2) [4] in which $\tau_{rec}{}^*$ is the effective electron recombination lifetime $\tau_{rec}{}^* = (1/\tau_{rec} + 1/\tau_{nr})^{-1}$ with τ_{nr} the non-radiative recombination lifetime, and $\tau_{spin}{}^* = \left(1/\tau_{spin} + 1/\tau_{rec}{}^*\right)^{-1}$ with the bulk, spin lifetime τ_{spin}. The spin-dependent quantum tunneling are described in Eqs. (3) and (4) [5], in which spin-independent component J_0 is separated from spin-dependent component J_σ. We determine self-consistently a solution by imposing the equality between the drift current at AlO_x/InGaAs interface and the tunneling current.

Shown in Fig. 2 are the results of simulation plotted in the form J as a fuction of the tunneling probability T for two $\tau_{rec}{}^*$ values. J is redued with both $\tau_{rec}{}^*$ and T. Referring the experimental J value (the dashed, horizontal line) and expected T value of T = 0.04 - 0.14, the effective chrage lifetime can be determined to be $\tau_{rec}{}^*$ ~1.2×10^{-12} s in our device. Using this value and the experimental J_σ value (= 0.2 mA/cm^2), we are able to determine from a plot shown in Fig. 3 the quantity $\Delta D = D_m{}^{\uparrow} - D_m{}^{\downarrow}$, the difference in the spin-polarized density of states (DOS) at the energy level in the Fe electrode into which spin-polarized electrons are injected from a semiconductor. The ΔD is extracted to be around 5×10^{20} cm^{-3} eV^{-1} for T = 0.09, which suggests that the spin polarization of Fe in the relatively high energy region is not as large as that at the Fermi level. In order to improve the value of figure of merit F, one has to consider spin polarization not at the Fermi level, but at higher energy level in which spin-injection takes place. This result paves the way for further studies on novel magnetic contact materials for more efficient spin-PDs.

$$\frac{\partial \Delta n}{\partial t} = D\frac{\partial^2}{\partial z^2}\Delta n + \mu E_{dp}\frac{\partial}{\partial z}\Delta n - \frac{\Delta n}{\tau_{rec}{}^*} + G, \quad (1)$$

$$\frac{\partial \Delta s(P)}{\partial t} = D\frac{\partial^2}{\partial z^2}\Delta s(P) + \mu E\frac{\partial}{\partial z}\Delta s(P) - \frac{\Delta s(P)}{\tau_{spin}{}^*} + G_{spin}(P). \quad (2)$$

$$J^{\uparrow\downarrow} \approx AD_m{}^{\uparrow\downarrow}T\int\{D_{sc}f_{sc}(E - E_F{}^{*\uparrow\downarrow})dE \approx AD_m{}^{\uparrow\downarrow}T\Delta n^{\uparrow\downarrow}, \quad (3)$$

$$J = J^{\uparrow} + J^{\downarrow} = \left[AT\frac{(D_m{}^{\uparrow}+D_m{}^{\downarrow})}{2}\Delta n\right] + \left[AT\frac{(D_m{}^{\uparrow}-D_m{}^{\downarrow})}{2}\Delta s\right] = J_0 + J_\sigma. \quad (4)$$

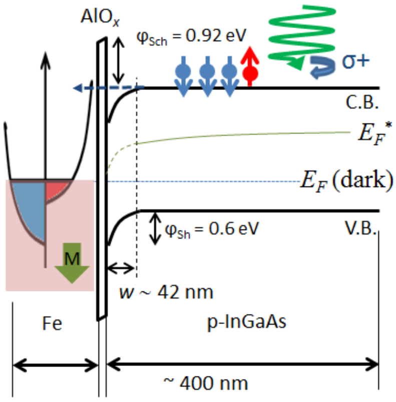

Fig. 1: Energy band diagram of the InGaAs active region of the refracting-facet spin-PD. Photogenerated spin-polarized carriers diffuse toward the p-depletion region. The built-in field inside the depletion region ballistically transports the electrons to the Fe/AlO_x junction where the electrons undergo spin-dependent tunneling.

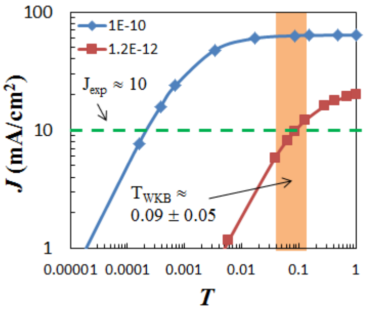

Fig. 2: Self-consistent solutions for the current J as function of T for $\tau_{rec}{}^*$ = 1×10^{-10} and 1.2×10^{-12} s.

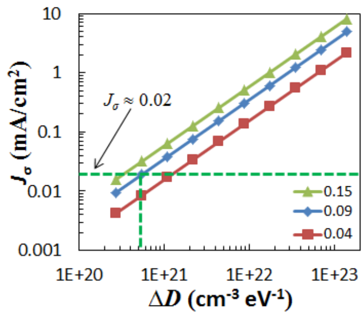

Fig. 3: Self-consistent solutions for J_σ as function of ΔD for $\tau_{rec}{}^*$ = 1.2×10^{-12} s and T = 0.15, 0.09, and 0.04.

[1] R. Roca, *et al.*, Proc. SPIE **10357**, 10357C (2017).
[2] H. Ikeda, *et al.*, J. Magn. Soc. Jpn. **38**, 151 (2014).
[3] R. Roca, *et al.*, JSAP 64th Spring Meeting, 15a-501-10 (2017).
[4] J. Fabian, *et al.*, ACTA Phys. Slovaca **57**, 565 (2007).
[5] Sze and Lee, *Semiconductor Devices Physics and Technology* (John Wiley & Sons Singapore, 2013), Ch. 2, pp. 56-68.