Simulation of an edged-illuminated refracting-facet spin photodiode

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Recent advances in the development of spin photodiodes (spin-PD), as exemplified by the helicity-dependent photocurrent ratio ΔI_{spin} / I_{ph} ≈ 5% at room temperature, have mostly been limited to surface-illuminated devices [1]. We propose, on the basis of the first-generation edge-illuminated spin-PD [2], a novel design that utilizes a refracting facet [3]. Unique points of the design are, firstly, a thin active layer (with a thickness less than the spin relaxation length of electrons), and secondly, a refracting facet that guides the light from the facet of the device into the active layer.

The structure of the proposed device is shown in Fig. 1. We assume an operating wavelength of 900 nm ($h\nu$ = 1.38 eV), at which GaAs (E_g = 1.42 eV) is transparent. On a p-GaAs substrate, a p-$In_{0.5}G_{0.95}As$ (E_g = 1.35 eV) active layer of thickness d is used along with a Fe/γ-AlO_x top contact. A Schottky junction is formed in the semiconductor side of the γ-AlO_x/p-InGaAs interface, in which the depletion region yields an electric field that collects photo-generated spin-polarized electrons. We assume that the edge of the device is slanted at an angle θ_{facet} with respect to the sample surface, thus forming the refracting facet.

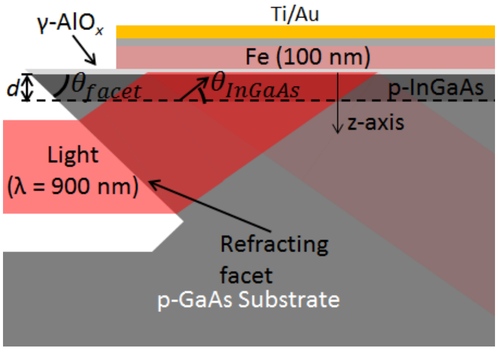

Fig. 1: Diagram of proposed refracting-facet spin-PD with an InGaAs active layer.

For the simulation, we have extended a mathematical model that has been developed for the first-generation edge-illuminated spin-PD [4] incorporating the optical irradiance profile inside the active region and the spin relaxation length [5]. Inside the InGaAs active layer, the light is exponentially attenuated due to absorption. Consequently, photo-generated electrons are collected in the Fe/γ-AlO_x tunnel contact owing to the built-in electric field in the Schottky depletion region. The total photocurrent I_{ph} collected at the top contact is expressed by Eq. (1), whereas the spin photocurrent I_s and helicity-dependent photocurrent ratio ΔI_{spin} / I_{ph} are described by Eqs. (2) and (3), respectively. Note that $\Delta I_{spin} \sim I_s(\sigma+) - I_s(\sigma-)$ [2], and e is the electron charge, E the irradiance of the light in W/cm^2, η the quantum efficiency, A the area of initial spot size of the light, T the transmittance of the refracting facet, f the bias-dependent fraction of the photo-generated electrons that contribute to the photocurrent, $\delta_{eff} = \delta \sin(\theta_{InGaAs})$, the effective attenuation length along z-axis, δ (≈ 1 μm) the optical attenuation length in the active layer, θ_{InGaAs} the angle of the light propagation direction with respect to the InGaAs/GaAs interface, P_0 (= ±0.5 for σ±) the factor that accounts for the optical selection rules, R the reflectance of the top metal layers from the active layer, λ_{spin} (≈ 1.2 μm) the spin relaxation length, and P_{Fe} (≈ 0.42) is the spin polarization of Fe. Since the thickness of the active layer is much shorter than the carrier diffusion length (≈ 21 μm), instead of calculating the carrier and spin density profiles [2], we simply consider the carrier photo-generation profile and the associated transport lengths, and then introduce the net efficiency $\eta \cdot f$ to account for losses [5]. We also account for the effect of θ_{InGaAs} to the spin orientation as well as to the optical attenuation.

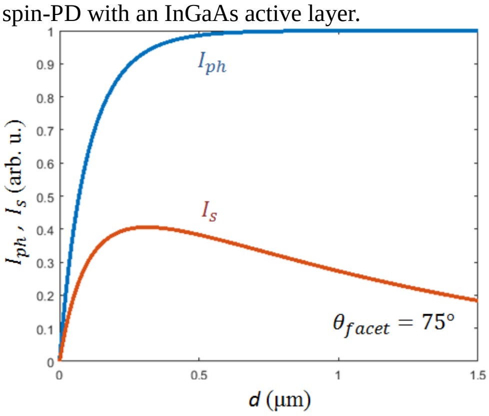

Fig. 2: I_{ph} and I_s simulation results as a function of active layer thickness d with θ_{facet} = 75°.

We find an interesting case at θ_{facet} = 75° in the sense that the facet transmittance T is high and δ_{eff} is short. Shown in the Fig. 2 are the simulation results for the normalized I_{ph} and I_s as functions of the InGaAs thickness d. It can be seen that as d is initially increased both I_{ph} and I_s increase, as more photons are absorbed in a thick active layer. As d is increased further, I_{ph} saturates, as most of the available photons are absorbed, whereas I_s reaches a maximum at d ≈ 0.4 μm and then is reduced. This reduction is due to the spin relaxation experienced by the electrons as the transport length is increased. At d ≈ 0.4 μm, a helicity-dependent photocurrent ΔI_{spin} / I_{ph} ≈ 19% is expected. This value is higher than that of the current best reported in the literature [1], which would open up various applications.

$$I_{ph} = \frac{E e \eta A T f}{h\nu}\left[\int_0^d exp\left(\frac{-z}{\delta_{eff}}\right)dx + \int_0^d R\, exp\left(\frac{-(z+d)}{\delta_{eff}}\right)dx\right] \quad (1)$$

$$I_s(\sigma) = \frac{E e \eta A T f P_0 \cos(\theta_{InGaAs})}{h\nu}\left[\begin{array}{c}\int_0^d exp\left(\frac{-z}{\delta_{eff}}\right) exp\left(\frac{-z}{\lambda_{spin}}\right)dx \\ +\int_0^d R\, exp\left(\frac{-(z+d)}{\delta_{eff}}\right) exp\left(\frac{-z}{\lambda_{spin}}\right)dx\end{array}\right] \quad (2)$$

$$\Delta I_{spin}/I_{ph} \approx \frac{\frac{1}{2}P_{Fe}[I_s(\sigma+)-I_s(\sigma-)]/I_{ph}}{1-\frac{1}{2}P_{Fe}[I_s(\sigma+)-I_s(\sigma-)]/I_{ph}} \quad (3)$$

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