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Study of Basic Characteristics of Spin - Photodiode Consisting of III – V *p-n* Heterojunction

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1. Introduction

An optical system composed of circular polarization emitters and detectors would be interesting in that it could be used in applications in which circular dichroism provides valuable information. Such information is very important in the fields of pharmaceutics, electronics, and materials engineering.

p-n heterojunction may yield photocurrent component which depends on circular polarization of light. As shown in Fig.1, $g_c = 0$ and $g_c \neq 0$ for *n*-and *p*-type layers, respectively, in which Zeeman splitting occurs only in the conduction band of the *p*-side when an external magnetic field is applied. At forward bias condition, spin-polarized electrons are injected from the *n*-side across the heterojunction, and they break away the spin population of electrons in the *p*-layer, causing a spin-dependent diffusive flow.

We present theoretical and experimental investigations of circularly-polarized-light dependent photocurrent $\Delta I = I_{\sigma+} - I_{\sigma-}$ in the n-$Al_xGa_{1-x}As$/p-$In_yGa_{1-y}As$ system. Both model calculation and transport measurement reveal that detection of ΔI through a spin-dependent diffusive flow is possible in the actual structures. Influence of bias and temperature on ΔI is also discussed.

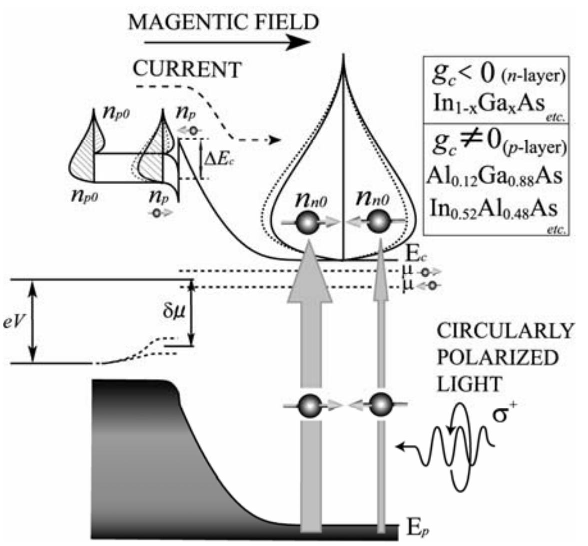

Fig.1 Schematic illustration showing the concept of the spin voltaic effect in a *p-n* heterojunction with spin split in *p*-side. Circularly polarized light is illuminated on n-side.

2 .Model Calculation

The model calculation was carried out on the basis of spin voltaic effect (SVE) [1], heterojunction transport [2], and solar cells [3]. The SVE is the electromotive force produced by the injection of spin polarized carriers, which was found theoretically in the *p-n* homo- or graded- junction. In case of heterojunction, the effect of thermionic emission, in particular the spin-dependent backward flow, should be taken into account for quantitative treatment. Consequently, ΔI can be expressed in the form of eq.(1); here, ΔE is the Zeeman splitting energy in *p*-layer, and P_n is the polarization of injected electrons across the heterointerface. β is the parameter that is introduced to take into account the magnitude of backward flow; $\beta \sim 0$ when the band discontinuity ΔE_{eff} is large, and $\beta \sim 1$ when ΔE_{eff} is zero or negative. It is worth noting that $\Delta I_{SVE} \propto I_{dark}(V)$. A circularly-polarized-light dependent photocurrent is also generated by the magnetic circular dichroism (MCD) of each constituent layer. In order to quantitatively evaluate the contribution of MCD, the solar cell model, as represented by eq.(2), is used in the model calculation. The net ΔI is given by the sum of both SVE and MCD components.

$$\Delta I_{SVE} = -I_{dark}(V) \cdot \beta P_n \cdot \sinh\left(\frac{\Delta E(H)}{k_B \cdot T}\right) \quad (1)$$

$$\Delta I_{MCD} = -2 \cdot \sum_{i=1}^{3} \frac{dI_{photo}(E_\lambda)}{d\alpha_i(E_\lambda)} \cdot \frac{B}{2 \cdot \sqrt{E_\lambda - E_{g,i}}} \cdot \left(\frac{1}{4}\left|g_{c,i}\right| - \frac{5}{4}\left|g_{v,i}\right|\right) \cdot \mu_B \cdot H \quad (2)$$

Detailed model calculations were carried out for the n-$Al_{0.12}Ga_{0.88}As$(1μm)/p-$In_{0.15}Ga_{0.85}As$(200nm)/p-GaAs structure in which $g \approx 0$ and $g \approx -1.2$ for *n*- and *p*-layers, respectively. Doping concentrations are $N_D = 5 \times 10^{17}\ cm^{-3}$ and $N_A = 8 \times 10^{18}\ cm^{-3}$ for *n*- and *p*-layers, respectively. As discussed later, this structure was actually prepared by molecular beam epitaxy and processed into mesa structures with an optical access window of $\phi = 240$μm [4].

$\Delta I - H$ curves obtained by the model calculation at 4 K for three different P_n values (0.15・0.25・0.7%) are shown in Fig. 2. The forward dark current of $I_{dark} = 5$ μA is assumed. For $P_n = 0.15\%$, ΔI exhibits negative H dependence due to the MCD effect. With increasing the P_n value, the slope is reversed and becomes positive. At P_n = 0.7%, a non-linear increase, reflecting the exponentially increasing contribution of ΔI_{SVE}, becomes visible. The results suggest that ΔI_{SVE} is detectable in the non-magnetic heterostructures having moderate *g* values when an appropriate forward current is applied at low temperature.

Inset shows calculated temperature dependence of ΔI with I_{dark} = 10 μA and P_n = 0.7%. ΔI decreases steeply with increasing temperature, reflecting reduced population difference between up- and down-spin electrons in a *p*-layer; ΔI drops three orders of magnitude from 4 to 77 K. It is worth noting that ΔI can be enhanced significantly by increasing the forward bias because of steep *I-V* characteristics. Using a pair of semiconductors with larger difference in *g*-factors, *e.g.*, *n*-InAlAs/*p*-InGaAs and III-Sb based alloys, would be another solution to increase ΔI.

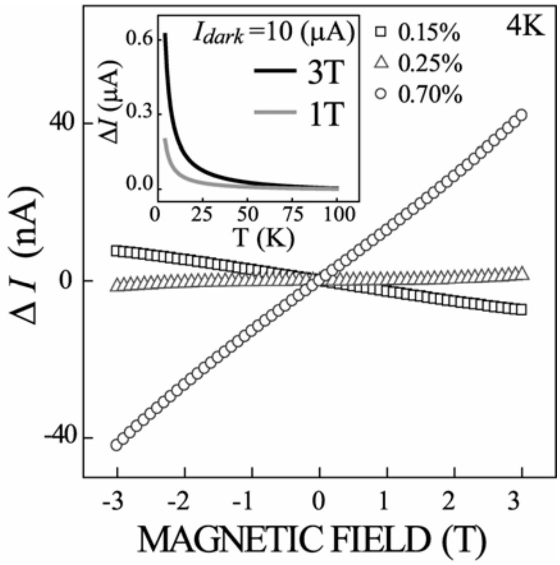

Fig2: Calculated Δ*I*-*H* curves at 4 K with three different P_n values. Inset shows temperature dependence of Δ*I* with two different *H*.

4. Experimental Results

The tested diode exhibited standard rectifying *I-V* characteristics with sound photocurrent of I_{Photo} = 1 × 10^{-5} A at 4 K under the illumination with λ = 685 nm and *P* = 15mW/cm^2 (not shown). Figure 3 shows ΔI – *H* characteristics at *T* = 4K with various bias conditions. ΔI ($\equiv I_{\sigma+} - I_{\sigma-}$) was measured by using lock-in technique combined with a stress modulated quarter wave plate which generated right (σ^+) and left (σ^-) polarization alternatively at the frequency of 42 kHz. For *V* = -1.4 V and 0V , the ΔI - *H* curves show linear behavior with negative slope, indicating that parasitic ΔI_{MCD} is the dominant component. Experimentally, we obtain the relation ΔI_{MCD} / I_{Photo} = -7 × 10^{-4} (1/Tesla). In contrast, for the forward bias condition, the slope of ΔI-*H* curves turns positive at *V* = 1.5V, and ΔI increases exponentially with increasing *V* (see the curve at *V* = 1.6 V in Fig.3). Solid lines in the figures are the curves obtained by the model calculation with a constant P_n value of P_n = 0.7%, which matches fairly well with experimental data. With both experiments and calculations, we arrive at the conclusion that the photocurrent component due to SVE exists in the *p-n* heterojunction. The magnitude of SVE is tunable with bias condition.

5. Summary

Basic performance of a *p-n* heterojunction spin-PD based on the SVE and MCD was examined theoretically and experimentally at 4 K. The results indicate that circularly-polarized-light dependent photocurrent due to SVE can become larger than that due to the ordinary MCD with increasing applied forward bias. High temperature operation of spin-PD has also been discussed on the basis of model calculation.

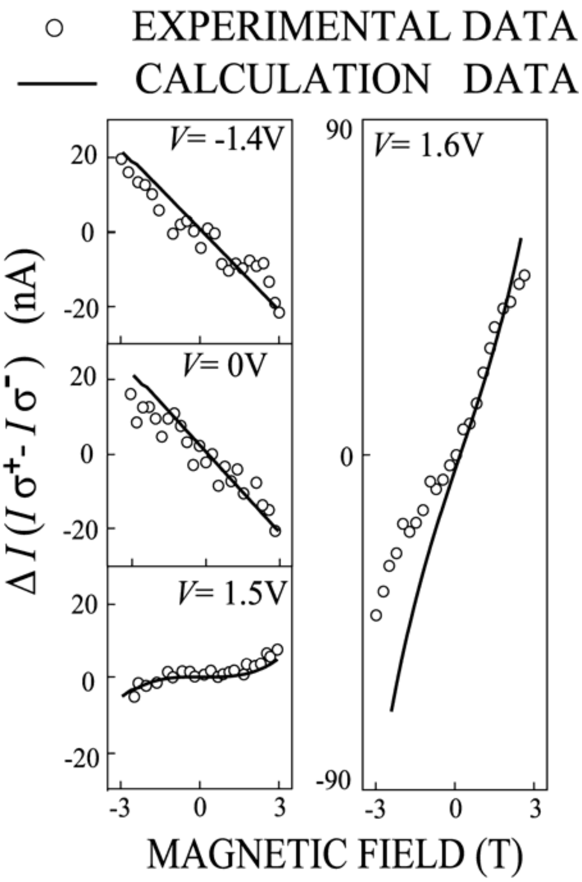

Fig3: Δ*I* - *H* characteristics at 4 K with various bias voltage (*V*=-1.4, 0, 1.5, and 1.6 V).

References

[1] I. Žutić, J. Fabian, and S. Das Sarma, Phys. Rev. Lett. **88** (2002) 066603.

[2] A. A. Grinberg and S.Luryi, IEEE Trans. Electron Devices **40** (1993) 859.

[3] S. M. Sze, *Physics of Semiconductor Devices 2nd edition*, (John Wiley & Sons, New York, 1981), Chap.14.

[4] J. Hayafuji, T. Kondo, and H. Munekata, IOP Conference Proceeding Series **184** (2005), 127.