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# Spin transport across indirect gap barriers in GaAs-AlGaAs heterostructures

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## 1. Introduction

In order to realize spin-photonic devices [1] with semiconductor heterostructures, it is indispensable to quantitatively understand to what extent carriers retain their spin polarization when they pass across a *p-n* depletion region and multi-barriers. We have tested the efficiency of spin transport with the optical spin injection/detection technique for various GaAs-AlGaAs heterostructures incorporating an abrupt energy barrier and a depletion region. Illumination with circular polarized light (CPL) yields electron spins in a 3μm-thick AlGaAs layer [2], whereas light emission from a GaAs/InGaAs/GaAs QW reflects spin polarization $P_{spin}$ of electrons that recombine with un-polarized holes. An AlGaAs barrier and a *p-n* depletion region are inserted in between the light absorption and spin detection regions. These processes are illustrated schematically in Fig.1, together with the band edge profiles.

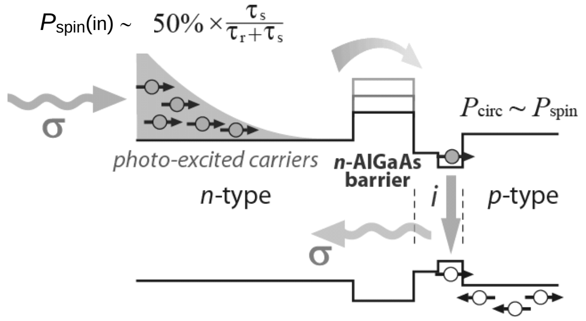


Fig.1: Schematic illustration of a GaAs-based heterostructure with a abrupt energy barrier. Bending of band edge profile due to a built-in electric field is ignored in the figure.

We have found that $P_{spin}$ did not degrade or rather became higher in samples having barriers with indirect band gaps (Al ≥ 0.4) [3]. Influences of applied bias and temperature on the $P_{spin}$ value apparently became weaker in the samples with indirect-gap barriers.

## 2. Experimental

Sample wafers were prepared by molecular beam epitaxy, and consisted of, from the top, 15-nm $n^+$-GaAs ($5\times10^{18}$ cm$^3$)/ 2.97-μm $n$-$Al_{0.03}Ga_{0.97}As$ ($1\times10^{17}$cm$^3$)/ 60-nm $n$-$Al_xGa_{1-x}As$ ($1\times10^{17}$cm$^3$)/ 30-nm $i$-GaAs/ 30-nm $i$-$In_{0.06}Ga_{0.94}As$/ 550-nm $p$-$Al_{0.1}Ga_{0.9}As$ ($6\times10^{18}$cm$^3$)/ 500-nm $p$-GaAs buffer ($1\times10^{18}$cm$^3$)/ $p^+$-GaAs(001) substrate. The substrate temperature during the growth was $T_s$ = 505 °C. Al content $x$ of the $n$-$Al_xGa_{1-x}As$ barrier was varied $x$ = 0.03 (no barrier), 0.1, 0.2, 0.35, 0.5, and 0.8. The barrier was doped with Sn and constituted a part of a *p-n* depletion region whose width was approximately 250 nm. The thickness of the light absorption (spin generation) $n$-$Al_{0.03}Ga_{0.97}As$ layer was determined on the basis of absorption coefficient of AlGaAs [4]. That no emission from a QW detector occurred under the forward bias of $V_f \leq 1$ V verified no direct optical excitation of the detector.

Wafers thus prepared were processed into mesa structures by metal deposition, photolithography, and wet chemical etching. The metal contact had an optical access window of 240-μm diameter on top of the mesa. Electroluminescence (EL) emitted through the optical window was analyzed by the standard spectrophotometry system. Double lock-in technique was used to extract the sum ($\sigma^+ + \sigma^-$) and difference ($\sigma^+ - \sigma^-$) of the EL intensity, from which we obtained circular polarization $P_{circ} = (\sigma^+ - \sigma^-) / (\sigma^+ + \sigma^-)$. We assume $P_{circ} \sim P_{spin}$, since heavy- and light-hole subbands are not degenerated in a 30-nm thick InGaAs layer.

Control experiment *without* a AlGaAs barrier has exhibited $P_{circ}$ = 22 % at 4 K with $V_f$ = 1.2 V. This fact suggests that the transport across a *p-n* depletion region does not result in severe reduction of spin polarization at least in the diffusion-limited carrier transport [5].

## 3. Results and discussions

In Fig.2, we show various experimental results obtained from the sample having a direct-gap energy barrier with $x$ = 0.2. The minimum of the conduction band is present at the $\Gamma$ point, as shown schematically in Fig.2(a). Current-voltage (*I-V*) curves at 4 K without and with illumination are shown in Fig.2(b). A sound rectification characteristics is noticeable. The reduction in the onset voltage of the forward current upon the illumination with light indicates the effective generation and transport of photo-generated electrons without the direct excitation of a InGaAs QW, as expected. The photoluminescence spectrum taken at 4 K at $V_f$ = 0 V does not show the emission from the QW [Fig.2(c)], which is consistent with the results shown in Fig.2(b). The emission band from the QW, which peaks at around 1.45 eV, becomes visible at $V_f \sim 1.5$ V and develops with increasing $V_f$, as shown in Fig.2(c). Figure 2(d) depicts the bias dependence of $P_{circ}$ at the emission peak, which shows that $P_{circ}$ first increases with $V_f$ up to 1.6 V, reaching at the saturation value of $P_{circ} \sim 22$ % at $V_f$ = 1.6 – 1.8 V, and decreases rapidly in the region of $V_f > 1.8$ V. An increase in $P_{circ}$ at relatively low $V_f$ region indicates the enhanced spin transport efficiency, whereas a decrease in $P_{circ}$ at relatively high $V_f$ region is presumably due to enhanced injection of unpolarized carriers from a non-magnetic metal electrode. As a whole, the bias window that yields high spin injection efficiency is narrow. Similar trend was obtained from the sample with $x$ = 0.1.

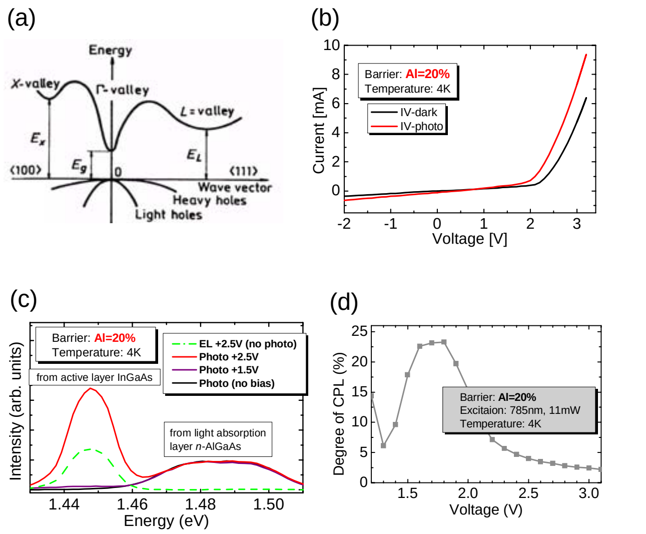


Fig.2: (a) Schematic band structure of $Al_{0.2}Ga_{0.8}As$, (b) I-V characteristics at 4 K of a tested diode incorporating a $Al_{0.2}Ga_{0.8}As$ barrier, (c) PL and EL spectra at 4 K under four different conditions, and (d) dependence of forward bias on $P_{circ}$ of EL from the same diode.

We now turn eyes on the data taken for the sample having a indirect-gap energy barrier with $x$ = 0.8. The minimum of the conduction band is now near the $X$ point, as shown schematically in Fig.3(a). Current-voltage (*I-V*) curves at 4 K without and with illumination are shown in Fig.3(b). Irrespective of with- or without-illumination, the onset voltage of a forward current is obviously higher than that of the $x$ = 0.2 sample, reflecting a higher energy barrier. Consistently, the development of the EL emission from a QW detector occurs at relatively high forward bias region, as shown in Fig.3(c). It is worth noting, however, that the emission of low-to-moderate intensity is detectable already at $V_f$ ~ 1.4 V in the sample with an indirect gap barrier. This fact suggests that the indirect $X$ point works as a leaky channel for the charge transport. Figure 3(d) depicts the bias dependence of $P_{circ}$ at the emission peak of $h\nu$ ~ 1.45 eV, showing the presence of relatively wide bias region ($V_f$ = 1.4 – 2.8 V) characterized by $P_{circ} \geq 20$ %. This is interesting in that the leaky $X$ channel works as the spin transport channel that is more robust than the direct $\Gamma$ channel. In the region of $V_f > 2.5$ V, $P_{circ}$ starts decreasing. This may be understood in terms of the contribution of unpolarized carrier injection from a non-magnetic metal electrode. Consequently, we found that samples with $x \geq 0.35$ exhibits behaviors similar to those shown in Fig.3.

Another interesting feature of the $x$ = 0.8 sample is its relatively weak temperature dependence. The maximum $P_{circ}$ value is 27 % at 4 K,  and it only drops for a few per-

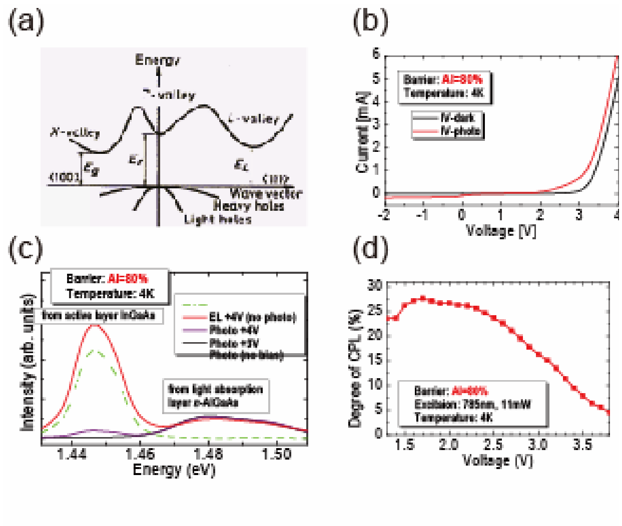


Fig.3: (a) Schematic band structure of $Al_{0.8}Ga_{0.2}As$, (b) *I-V* characteristics at 4 K of a tested diode incorporating a $Al_{0.8}Ga_{0.2}As$ barrier, (c) PL and EL spectra at 4 K under four different conditions, and (d) dependence of forward bias on $P_{circ}$ of EL from the same diode.

cent at 70 K (data not shown).

## 4. Conclusions

Spin transport across a single $n$-$Al_xGa_{1-x}As$ barrier was studied in GaAs-based heterostructures by the optical spin injection/detection technique. We have found that spin polarization did not degrade or rather became higher in samples having barriers with indirect band gaps (Al ≥ 0.4). There are a few candidate mechanisms to account for the robust spin transport through the indirect gap channel: relatively weak phonon-electron interaction and difference in the relativistic effective field between $\Gamma$ and $X$ valleys. If spin polarization of carriers varies as a function of their kinetic energy, barriers may serve the role of a energy-dependent spin filter. We only note these points as speculations at the point of writing this abstract.


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## References


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