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Temperature and Bias Voltage Dependencies of Spin Injection Signals for $Co_2FeAl_{0.5}Si_{0.5}$/*n*-GaAs Schottky Tunnel Junction

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We investigated the temperature and bias voltage dependencies of spin injection signals for $Co_2FeAl_{0.5}Si_{0.5}$ (CFAS)/*n*-GaAs schottky tunnel junction. Clear voltage change was observed at 10 K for the junction by 3 Terminal Hanle measurements. The maximum voltage change, ΔV_{MAX}, was decreased with increasing temperature and observed up to 100 K. The estimated spin relaxation time, τ, was 290 ps at 10 K and was also decreased with increasing temperature. In addition, temperature dependency of τ was lower than that of ΔV_{MAX}. The ΔV_{MAX} was increased with increasing bias voltage, and the sign of ΔV_{MAX} was reversed by opposite bias voltage direction. Moreover, bias dependency of ΔV_{MAX} became insensitive with increasing temperature. [doi:10.2320/matertrans.MBW201113]

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1. Introduction

Development of ferromagnet (FM)/semiconductor (SC) hybrid devices such as spin MOSFET is expected for higher performance integrated circuit. To realize such devices, high efficient spin injection into semiconductor from ferromagnet is required. Many researchers have challenged to achieve high efficient spin injection with various approaches,[1–4] however, we have to increase spin injection efficiency more. For high spin injection efficiency, using highly spin polarized material as ferromagnet and inserting tunnel barrier between FM/SC interface are effective in theoretical.[5,6] $Co_2FeAl_{0.5}$-$Si_{0.5}$ (CFAS) full-Heusler alloys is one of the candidates of spin injector because CFAS showed high spin polarization in magnetic tunnel junctions (MTJs).[7,8] Generally, the spin polarization of full-Heusler alloys depends on the order of the crystal structure, hence, highly ordered structure is required. In addition, formation of schottky tunnel barrier is expected between CFAS and SC interface.

It was reported that minority spin injection was observed for the Fe/*n*-GaAs schottky tunnel junctions, though Fe should have positive spin polarization.[9] One of the reasons of this unusual spin injection is changing band structure of Fe at the Fe/*n*-GaAs interface and band structure change also effected to temperature dependency of spin signals.

Recently, we reported the electrical transport properties for the $L2_1$-ordered CFAS/*n*-GaAs schottky tunnel junctions and achieved to detect spin injection signals.[10,11] However, the temperature and bias voltage dependencies of spin injection signals for the CFAS/*n*-GaAs schottky tunnel junction have not been revealed yet.

Consequently, the purpose of this study is to investigate temperature and bias voltage dependencies of spin injection signals for the CFAS/*n*-GaAs schottky tunnel junction.

2. Experimental Procedure

The *n*-GaAs and CFAS layer were prepared by molecular beam epitaxy (MBE) under a base pressure of 1×10^{-7} Pa.

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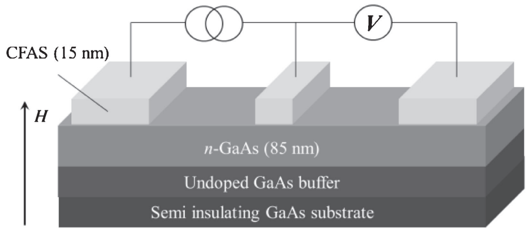

Fig. 1 Device geometry for 3 Terminal Hanle measurements. The cell size of center electrode was $10\,\mu m^2$. Magnetic field, *H*, was applied to perpendicular to plane.

Before the growth of the CFAS layer, the semi insulating GaAs (001) substrate was annealed at 700°C for removal native oxidize, and then undoped GaAs layer was deposited at 680°C for buffer layer. An 85-nm-thick *n*-GaAs layer was deposited at 520°C and doped at Si K-cell temperature (T_{Si}) of 1160°C. The doped density of *n*-GaAs layer was over $1 \times 10^{19}\,cm^{-3}$ and 2×4 reconstructed surface was obtained. After the system was pumped enough for removal of As completely, a 15-nm-thick CFAS layer was deposited at $T_S = 300$°C. The films were then transferred to a sputtering system and capped with a 3-nm-thick layer of Ta.

The crystalline structures of CFAS film were analyzed by *in situ* reflection high energy electron diffraction (RHEED). The CFAS/*n*-GaAs junctions which have the area of $10\,\mu m^2$ in size were fabricated by EB lithography and Ar ion milling. The current density–voltage (*J*–*V*) measurements were carried out by DC four probe method. In this study, positive voltage means that electron was flowing from the *n*-GaAs into the CFAS film, and the *J*–*V* measurements were performed at room temperature (RT). For detecting the spin injection, we performed 3 Terminal (3T) Hanle measurements with same junction for the *J*–*V* measurements. Device geometry is shown in Fig. 1.

3. Results and Discussion

From *in-situ* RHEED patterns of the CFAS thin film on the *n*-GaAs layer (Fig. 2), streak patterns and additional half

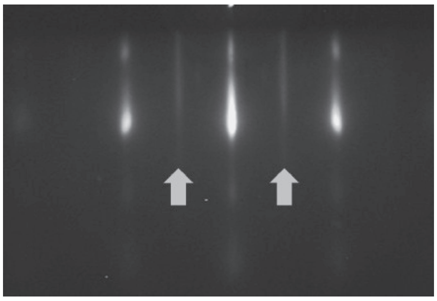

Fig. 2 RHEED patterns for 15-nm-thick $Co_2FeAl_{0.5}Si_{0.5}$ thin film on n-GaAs layer. The first half-order streaks marked by arrows are (11) and $(\bar{1}\bar{1})$.

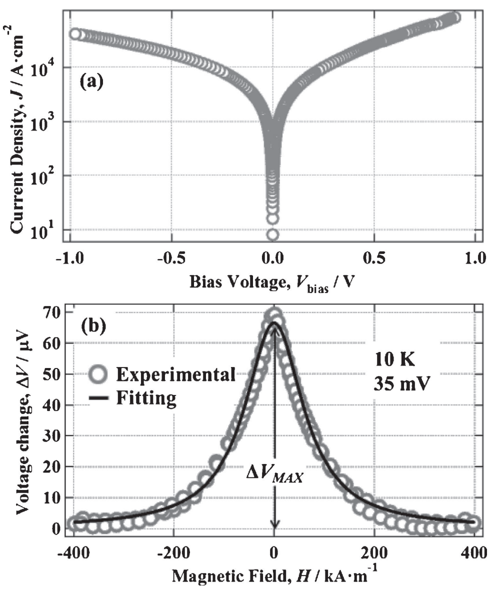

Fig. 3 (a) Typical J–V characteristic for the $Co_2FeAl_{0.5}Si_{0.5}$/n-GaAs schottky tunnel junction. Measurement was performed at room temperature. (b) 3-Terminal Hanle signals for the $Co_2FeAl_{0.5}Si_{0.5}$/n-GaAs junction. Measurement was performed at 10 K with a bias voltage of about 35 mV. The open circles are experimental data, and the solid line is the result of the fitting from eq. (2).

ordered patterns which indicate existence of $L2_1$ structure were observed. Hence, this CFAS thin film was grown on n-GaAs layer epitaxially and crystallized into the $L2_1$ structure. From transmission electron microscopy observation, any interface compounds could not be confirmed and an abrupt interface was obtained. The detail of the results of structure and magnetic properties was reported in Ref. 10).

Figure 3(a) shows the typical J–V characteristic for the CFAS/n-GaAs junction measured at RT. The little rectifying characteristic was obtained because of high doped density. The schottky barrier height Φ_B was estimated from the thermionic emission electron transport mechanism according to equations,[12]

$$J = J_S[\exp(qV/kT) - 1]$$
$$J_S = A^* T^2 \exp(-q\Phi_B/kT), \quad (1)$$

where J_S and A^* are saturation current density and Richardson constant of the n-GaAs. A value of $8\,A/K^2{\cdot}cm^2$ was used for the Richardson constant.[12] $J_S \approx 2.23 \times 10^2$ A/cm^2 was obtained from J–V characteristic and estimated value of Φ_B was 0.3×10^{-19} J (0.2 eV). The work function of CFAS has not been investigated, therefore, identical value of Φ_B between the CFAS/n-GaAs is unknown. However, this Φ_B value is almost the same as that of the Fe/n-GaAs schottky tunnel junctions.[13]

Figure 3(b) shows the result of 3T-Hanle measurement for the CFAS/n-GaAs junction measured at 10 K. A clear voltage change was observed. Now, we defined maximum value of voltage changes as ΔV_{MAX}. Dash *et al.* reported that this signal can be expressed by equations as follows,[2]

$$\Delta\mu(B) = \Delta\mu(0)/[1 + (\omega_L \tau)^2]$$
$$\omega = g\mu_B B/\hbar$$
$$\Delta V = P \times \Delta\mu/2, \quad (2)$$

where μ, B ($= \mu_0 H$, μ_0 and H are permeability and applied magnetic field respectively), ω, τ, g, μ_B, and P are electrochemical potential, magnetic flux density, Larmor frequency, spin relaxation time, Landé g-factor, Bohr magneton and spin polarization, respectively. We have used a value of -0.44 as the g-factor of GaAs.[1] The fitting result was also shown in Fig. 3(b). From this fitting, we estimated the $\tau = 290$ ps. This value of τ is longer than other reported value of 40 ps in n-GaAs having almost the same doped density with the n-GaAs layer in this study.[14]

Spin relaxation mechanism in an n-GaAs which doped density is over $1 \times 10^{18}\,cm^{-3}$ is dominated by the D'yakanov–Perel' (DP) mechanism.[14] In DP mechanism, spin relaxation is contributed to spin–orbit scattering from precession about anisotropic internal magnetic fields and this spin relaxation is suppressed by dimensional confinement of the momentum of electrons.[15–19] The n-GaAs layer thickness which we fabricated was much thinner than other reported sample. Therefore, it is thought that dimensional confinement effect was one of the reasons of the longer τ.

Here, the 3T-Hanle spin signals can be also described as a function of applied magnetic field along the perpendicular to plane as follows,[20]

$$\frac{\Delta V(B_\perp)}{I} = \frac{P^2 \lambda_N}{2\sigma A}(1 + \omega^2\tau^2)^{-1/4} \cos\left[\frac{\tan^{-1}(\omega\tau)}{2}\right], \quad (3)$$

where I is the current, λ_N ($= \sqrt{D\tau}$, D is diffusion constant of GaAs), σ and A are the spin diffusion length, the conductivity and the cross sectional area of the nonmagnetic layer, respectively. We also fitted the 3T-Hanle spin signals for the CFAS/n-GaAs junction measured at 10 K and $I = 5\,\mu A$ with eq. (3) and roughly estimated the value of P. Here, D and σ values were referred to Ref. 12) and the value of τ was estimated from eq. (2). As a result, we obtained $P \approx 0.74$, which was almost the same as reported value for the CFAS in MTJs.[7] In addition, the obtained P value was larger than P for the Fe/n-GaAs and the CoFe/n-GaAs schottky tunnel junctions.[1,4] Consequently, it is shown that CFAS is more effective as a spin injector than other ferromagnetic materials.

The temperature dependencies of ΔV_{MAX} and τ were shown in Fig. 4. The ΔV_{MAX} was decreased with increasing temperature and observed up to 100 K. The value of τ was also decreased with increasing temperature, however, temperature dependency of τ was more insensitive than that of ΔV_{MAX}. Here, ΔV_{MAX} was described as follows,[9,12]

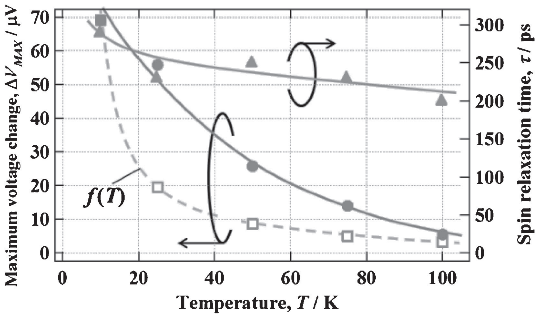

Fig. 4 Temperature dependencies of maximum voltage change ΔV_{MAX} and spin relaxation time τ. The circles are ΔV_{MAX} and the triangles are τ. The calculated $f(T)$ value [eq. (4)] from obtained τ as a function of temperature was also shown with the open square.

$$\Delta V_{\mathrm{MAX}} \propto P^2 \times \sqrt{\tau/D}$$
$$D \equiv kT\mu_{\mathrm{n}}/q, \tag{4}$$

where k, T, and μ_{n} are Boltzmann constant, temperature and mobility of electron in nonmagnetic layer. In addition, μ_{n} is proportional to $T^{3/2}$ at low temperature because impurity scattering are dominant in SC.[12)] Hence, ΔV_{MAX} should be proportional to $P^2 \times \sqrt{\tau/T^{5/2}}$. Now, we defined $f(T)$ as follows,

$$f(T) = \Delta V_{\mathrm{MAX}}(10K) \times \frac{\sqrt{\tau(T)/T^{5/2}}}{\sqrt{\tau(10K)/10^{5/2}}}, \tag{5}$$

which neglects P^2 term from ΔV_{MAX}. The calculated $f(T)$ value from obtained τ as a function of temperature is also shown in Fig. 4. The $f(T)$ decreased more rapidly than ΔV_{MAX} with increasing temperature. With increasing temperature, other electron scattering, such like piezo electrical scattering and space charge scattering,[21)] would influence more and they relax increase of μ_{n} with increasing temperature. Therefore, the $f(T)$ curve will be close to the ΔV_{MAX} curve. From this analysis, it is considered that the decrease of ΔV_{MAX} with increasing temperature was not contributed to temperature dependency of P^2 much, and was contributed to temperature dependency of electron scattering in the n-GaAs layer.

In addition, the P^2 had increased with increasing temperature from this analysis. It was reported that FM/GaAs structure has also tunneling conductance dependencies of the Bloch states' symmetry such like MgO tunnel barrier.[22)] Hence, there is possible that this tunneling effect through GaAs schottky tunnel barrier caused increasing of spin polarization with increasing temperature.

The bias voltage dependency of ΔV_{MAX} at 10 K was shown in Fig. 5(b). The positive and negative signals were observed at positive and negative bias voltages respectively such like Fig. 5(a) and $|\Delta V_{\mathrm{MAX}}|$ was increased with increasing bias voltage. On the other hands, it was reported that negative signals were also observed in positive bias voltage for the Fe/n-GaAs junctions.[9)] This means that minority spin was injected in positive bias voltage region and one of the reasons of this behavior is band structure change of the Fe. In the CFAS/n-GaAs junctions, such minority spin injection was not observed. Therefore, it is thought that there was not peculiar change of a band structure where spin polarization becomes negative for the CFAS thin films on

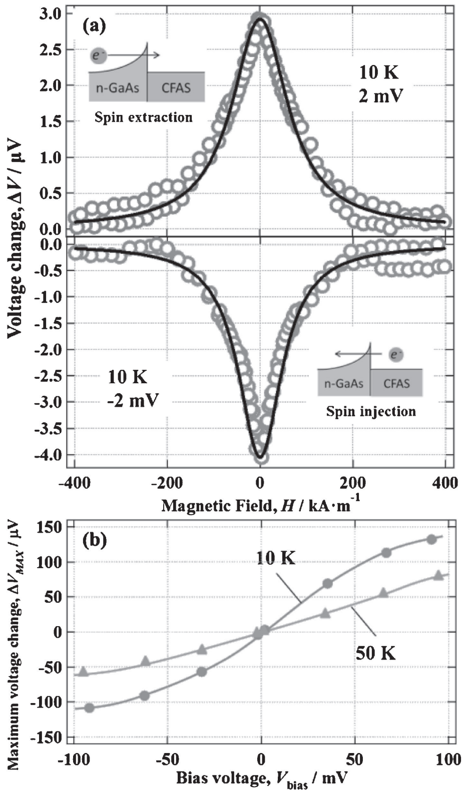

Fig. 5 (a) Results of 3 Terminal Hanle measurements at 10 K with bias voltages of 2 and −2 mV respectively. The open circles are experimental data, and the solid line is the result of the fitting from eq. (2). Insets are illustrations of electron flow direction. (b) Bias dependencies of ΔV_{MAX} at 10 and 50 K. The circles are results at 10 K and the triangles are results at 50 K.

GaAs. Figure 5(b) also shows bias voltage dependency of ΔV_{MAX} at 50 K. It was found that the bias voltage dependency at 50 K was more insensitive than that of 10 K. This tendency was also observed for other FM/SC structures.[2,9)] It was guessed that similar reason with the other FM/SC structures caused lower bias voltage dependency at higher temperature for the CFAS/n-GaAs junction.

In conclusion, we have demonstrated the temperature and bias voltage dependencies of spin injection signals for the CFAS/n-GaAs schottky tunnel junctions. By 3T-Hanle measurements, clear voltage change was observed at 10 K. This voltage change was observed up to 100 K with decreasing ΔV_{MAX}. The estimated τ was 290 ps at 10 K and the τ was also decreased with increasing temperature. Temperature dependency of τ was smaller than that of ΔV_{MAX}. From these results, it was indicated that contribution of P was small for temperature dependency of ΔV_{MAX}. The sign of ΔV_{MAX} was reversed by opposite bias voltage and $|\Delta V_{\mathrm{MAX}}|$ was increased with increasing bias voltage. Moreover, the bias dependency of ΔV_{MAX} lowered at higher temperature.

Acknowledgements

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