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Efficient spin injection in GaAs-based spin-LEDs through crystalline aluminum oxide layers

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Abstract

We show that an ultra-thin, oxidized aluminum epilayer grown on the GaAs surface works as a high-quality tunneling barrier for spin injection from a ferromagnetic metal to a non-magnetic semiconductor. A key point of the present oxidation method is to oxidize the Al epilayer of appropriate thickness without oxidizing the Al/GaAs interface. The oxidized Al epilayer is not amorphous but preserves crystalline feature which is reminiscent of spinel structure of γ –Al_2O_3. A spin-LED incorporating the Fe/AlO_x/*n*-AlGaAs structure has exhibited circularly polarized electroluminescence (EL) with circular polarization P_{EL} ~ 0.145, suggesting an efficient spin injection with injection efficiency of ε = 0.63.

1. Introduction

Formation of an ultra-thin oxide layer such as AlO_x or MgO between a ferromagnetic metal and a semiconductor is indispensable for sufficient spin transport across the two materials. However, in the system consisting of AlO_x on GaAs-based structure, the prominent spin injection endurable for device applications has not been achieved so far because of high density of interface-state due to the dangling-bonds at the interface. Therefore, a high –quality oxide layer is required for efficient spin injection. We discuss, in this paper, a method to prepare an ultra-thin, crystalline aluminum oxide layer for spin injection from Fe into GaAs-based structure. Spin injection efficiency has been improved significantly, as observed in the tested spin light emitting diode (spin-LED).

2. Preparation of Fe-AlO_x-LED structure

Molecular beam epitaxy (MBE) was utilized to prepare both a LED structure and an AlO_x layer. The LED structure consists of an AlGaAs/InGaAs double heterostructure (DH) incorporating a 500-nm thick $In_{0.03}Ga_{0.97}As$ active layer. A 1.0-nm thick AlO_x layer was formed by the post-oxidation method described in the next paragraph on the DH. This is followed by the deposition of a 100-nm thick Fe layer and 1.5-nm Ti layer using an e-beam evaporator.

Formation of a 1.0-nm thick AlO_x barrier layer on a LED surface consists of four stages: (i) epitaxial growth of a 5.5-Å thick Al layer at room temperature, (ii) exposure to the dry air at atmospheric pressure for over 10 hours, (iii) re-deposition of a 2.3-Å Al, and (iv) final oxidation with the same condition as the step (ii). We believed that an ultra-thin aluminum epilayer protects the GaAs surface through the formation of Al-As bonds without generating interface traps, and the oxidation at room temperature would not give extra kinetic energy that allows migration of Al atoms to generate dangling bonds.

3. Results and discussion

During the preparation of AlO_x layer, surface condition was studied with *in-situ* reflection high energy electron diffraction (RHEED) As shown in figure 1(a), the As-stabilized *c*(4×4) surface of a top AlGaAs layer of DH has been changed into the (1×1) streak pattern when an Al layer was deposited on the AlGaAs surface. The observed change is consistent with the early work [1] in sense that an fcc Al layer grows on a GaAs (001) surface with 45-deg. in-plane rotation. Streaky patterns remains throughout the entire oxidation process, which indicates that the resultant AlO_x layer possesses the crystalline feature with an atomically flat surface. The separation of streaky patterns was converted into the spacing of lattice planes parallel to GaAs [1-10] (Fig. 1(b)). After first oxidation, the value of lattice spacing becomes close to the distance between nearest neighbor Al atoms in the crystalline γ-Al_2O_3 which is about 0.67 nm.

Figure 2(a) shows a cross-sectional transmission electron microscopy (TEM) image around the Fe/AlO_x/AlGaAs interface. Note that the interface is atomically flat, and we can see an ultra-thin, uniform AlO_x layer as a bright region between single-crystalline AlGaAs and poly-crystalline Fe layers. A magnified lattice images is shown in Fig. 2(b), from which a triangular lattice image due to γ -Al_2O_3 has clearly been observed. These results strongly suggest that post oxidation of an Al epilayer at room temperature yields a crystalline AlO_x layer.

The overall spin polarization was evaluated by measuring circular polarization P_{EL} of electroluminescence (EL) emitted from a cleaved side-wall of a spin-LED. A magnetic field of 5 kOe was applied prior to the measurement in order to magnetize a Fe spin-injection layer along the easy-axis, EL from the sample with an AlO_x layer shows elliptically polarized emission with P_{EL} ~ 0.145 at 10 K, which corresponds to spin polarization P_{spin} ~ 0.29. EL spectra are shown in Fig. 3(a). Knowing that the value of spin polarization has been P_{Fe} ~ 0.46 for a pure Fe layer [2], the overall spin injection efficiency ε is estimated to be ε = 0.63, which is the highest value among spin-LEDs incorporating Fe-AlO_x junction. The sample without an

AlO_x layer exhibits almost no circular polarization (Fig.3 (b)). These results strongly suggest that an oxidized Al epilayer works as the layer which helps efficient spin injection.

4. Conclusion

Aiming at improving electrical spin injection efficiency into semiconductors, a method for the preparation of tunneling barrier aluminum oxide has been developed. Crystallographic evaluation has showed that the resultant AlO_x layer has crystalline feature close to γ -Al_2O_3. A spin-LED with a crystalline AlO_x layer has exhibited circularly polarized EL with high spin polarization of P_{EL} ~ 0.145.

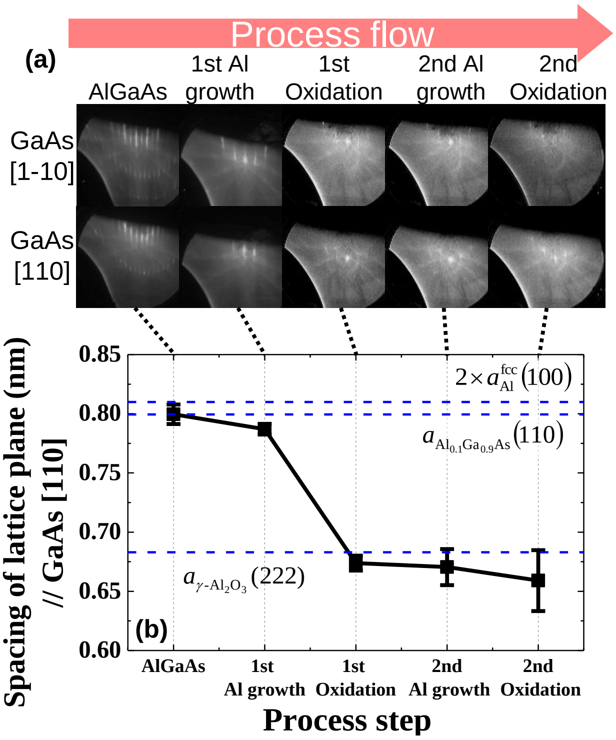

Fig.1: (a) RHEED patterns taken along two orthogonal azimuths, GaAs[1-10] and [110] in accordance with the progress of oxidation process. (b) A plot of spacing of lattice planes converted from the separation of streaky patterns shown in (a).

References

[1] A. Y. Cho and P. D. Dernier, J. Appl. Phys. **49** (1978) 3328.

[2] S. V. Karthik, *et al.*, J. Appl. Phys. **105** (2009) 07C916.

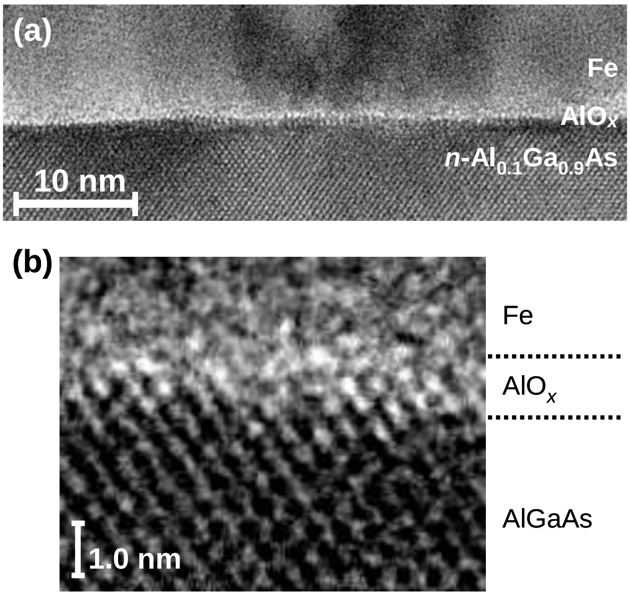

Fig.2: (a) Cross-sectional TEM image around Fe/AlO_x/AlGaAs. (b) The magnified view of the images shown in (a).

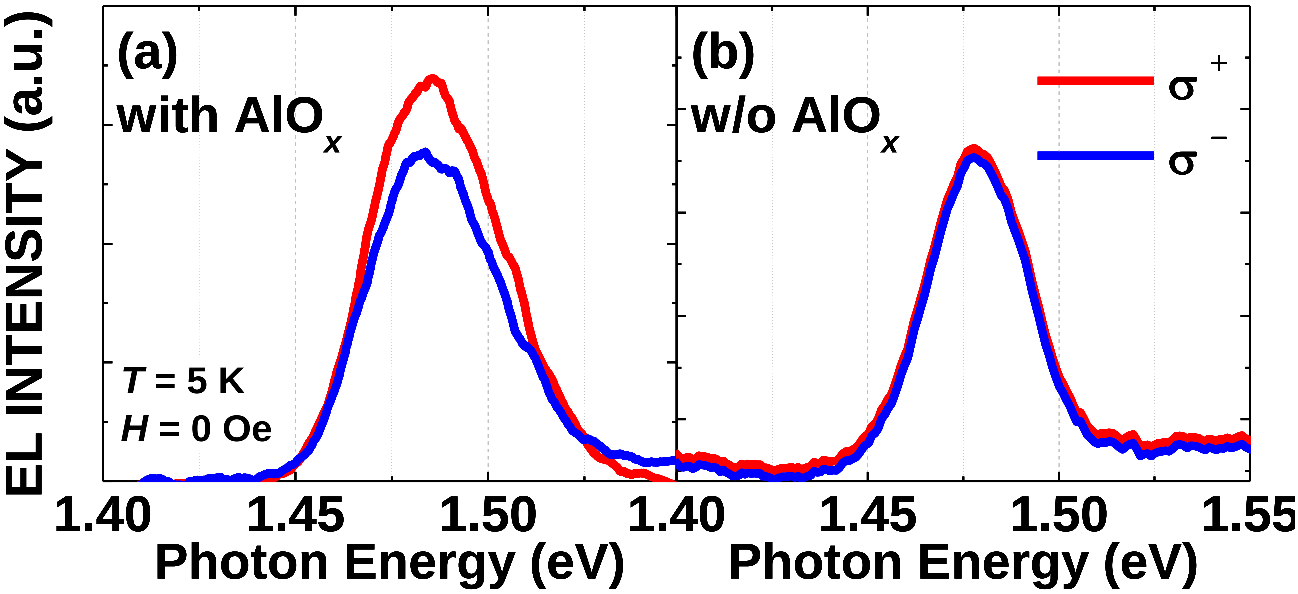

Fig.3: σ^+ and σ^- components of EL spectra obtained from side-walls of (a) with and (b) without AlO_x layer. No external magnetic field was applied during the measurements.