室温円偏光スピン発光ダイオード作製に関する現状

Present status of preparing a room-temperature circular polarization spin-LED

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In 2015-2016, we have found unexpectedly the nearly pure circular polarization electroluminescence (CP-EL) at room temperature when a current of J = 100 A/cm^2 or higher was sent through the edge-emitting, GaAs/AlGaAs-based spin-LEDs that had ultra-thin (1nm), γ-Al_xO_y-like spin tunnel layers [1, 2]. Since then, we have been working on this subject aiming at development of methods for preparation of Al_xO_y layers that are robust against both electrical stress of $J \geq 100$ A/cm^2 and wet-lithography process for stripe-electrodes formation: the former spin-LEDs were usually short circuiting at the stage when CP-EL took place, and moreover, the former naturally oxidized Al epilayers tended to dissolve into an alkaline-based developer during the photolithograph process for ferromagnetic stripe electrodes.

In order to circumvent these problems, four approaches have been experimented: (1a) oxidation of atomically flat AlAs epilayers instead of Al epilayers and (1b) subsequent high-temperature post oxidation, (2) direct sputter-deposition of non-magnetic-metal/ferromagnetic-metal stripe electrode pads on thus prepared Al_xO_y tunnel layers through mechanical masks, and (3) pulse-current operation of spin-LEDs with duration Γ = 1000 μs or shorter and duty cycle D = 0.1 % (frequency $f = (\Gamma / D)^{-1}$).

The task (1a) is the one that is most difficult in sense that it demands removal of natural oxide on top of a laser quality AlGaAs/GaAs DH wafer and subsequent epitaxy of ultra-thin AlAs/n-GaAs layers. After removing natural oxide at 600 °C, deposition of 15-nm GaAs at 150 °C, annealing (re-crystallization) it at 530 °C for 10 min and the growth of 1-nm AlAs on top of it, has results in atomically very flat surface, as shown in Fig. 1. The density of pits (black dots) is $10^8 \sim 10^9$ cm^{-2}.

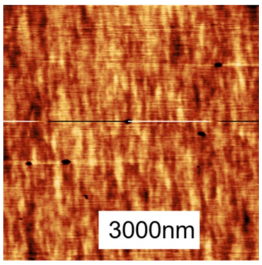

Fig. 1: AFM image of a surface obtained from a naturally oxidized AlAs layer. Difference in height is 1.8 nm.

Shown in Fig. 2 is CP-resolved EL spectra obtained from one of spin-LEDs having a 0.1 × 2 mm Pd/Fe stripe pad on top of naturally-oxidize ultra-thin AlAs. The values of Γ, f, and nominal J are 10 μs, 100 Hz, and 35 A/cm^2, respectively. The spectra clearly show the onset of CP enhancement. However, J-V and emission stability degrade by further increasing pulse voltage.

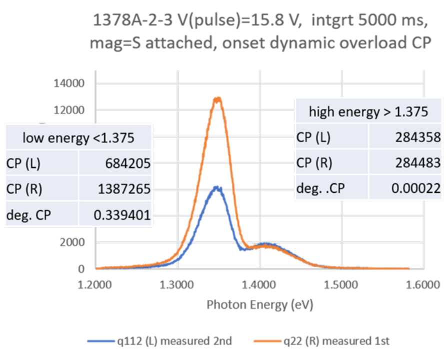

Fig. 2: CP-resolved EL spectra at the pulse voltage of 15.8 V. Magnetic pole S faces a spectrometer.

Intentional post-oxidation of AlAs layers at 400 °C for 1hr or longer in water moisture or O_2 gas has resulted in significant improvement in device operation stability up to 200A/cm^2 for both dc- and pulse-operation. However, EL with large CP value has not been unearth at the point of writing this abstract.

[1] N. Nishizawa *et al.*, PNAS **114**, 1783 (2017).

[2] N. Nishizawa and H. Munekata, Micromachines **12**, 644 (2021).