Tailoring magnetic anisotropy via phosphorus composition grading in $Ga_{1-x}Mn_xAs_{1-y}P_y$ films

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This study investigates the magnetic anisotropy properties of Ga1-xMnxAs1-yPy films grown via molecular beam epitaxy with a graded phosphorus concentration along the growth direction. Two sample types were analyzed: one with phosphorus content increasing (forward-graded) and the other with phosphorus content decreasing (reverse-graded). The results indicate distinct magnetic anisotropies, with the forward-graded sample exhibiting a layered structure with in-plane and out-of-plane magnetization components, while the reverse-graded sample displays uniform out-of-plane anisotropy. These findings highlight the critical influence of growth dynamics on the magnetic properties of graded ferromagnetic semiconductors.

Keywords: Ferromagnetic semiconductors; graded composition; magnetic anisotropy; Hall effect

1. Introduction

Ferromagentic semiconductors, such as $Ga_{1-x}Mn_xAs$ and $Ga_{1-x}Mn_xAs_{1-y}P_y$, [1] have been extensively studied due to their potential applications in spintronics. The magnetic properties of these materials are strongly influenced by epitaxial strain, which can be controlled through alloying with phosphorus to form $Ga_{1-x}Mn_xAs_{1-y}P_y$. When grown on GaAs, compressive strain favors in-plane magnetization, while tensile strain, achieved by incorporating phosphorus, promotes out-of-plane magnetization.[2] By grading the phosphorus concentration, strain and magnetic anisotropy can be modulated throughout the film.[3,4] This study explores how forward and reverse grading impact the resulting magnetic anisotropy and the role of initial nucleation conditions during growth. [5]

2. Results and discussion

Hall effect measurements reveal a complex magnetic anisotropy profile in the forward-graded sample, where different layers exhibit distinct easy axes. The lower portion, with lower phosphorus content, favors in-plane magnetization, while the upper phosphorus-rich region favors out-of-plane magnetization. A transition layer in between exhibits mixed anisotropy. These findings suggest that forward grading creates a multi-layered ferromagnetic structure suitable for spintronic applications, such as field-free spin-orbit torque switching. Unlike the forward-graded sample, the reverse-graded sample exhibits a single out-of-plane magnetic easy axis. The uniform anisotropy suggests that the initial conditions at the nucleation interface predominantly determine the overall magnetic behavior. The absence of in-plane magnetization throughout the film implies that magnetization dynamics are significantly influenced by phosphorus distribution during growth.

Temperature-dependent measurements indicate that the magnetic anisotropy weakens as the temperature approaches the Curie temperature (~40 K for the forward-graded sample and ~65 K for the reverse-graded sample). Notably, the reverse-graded sample shows a two-step transition at intermediate temperatures, suggesting a gradual change in anisotropy due to temperature-dependent domain formation.

The study demonstrates that graded phosphorus composition in $Ga_{1-x}Mn_xAs_{1-y}P_y$ films significantly impacts magnetic anisotropy. Forward-graded films create layered magnetic structures with varying anisotropy, while reverse-graded films exhibit uniform out-of-plane anisotropy. These results underscore the role of initial nucleation conditions in determining the final magnetic properties, offering insights for designing ferromagnetic semiconductor structures for spintronic applications.

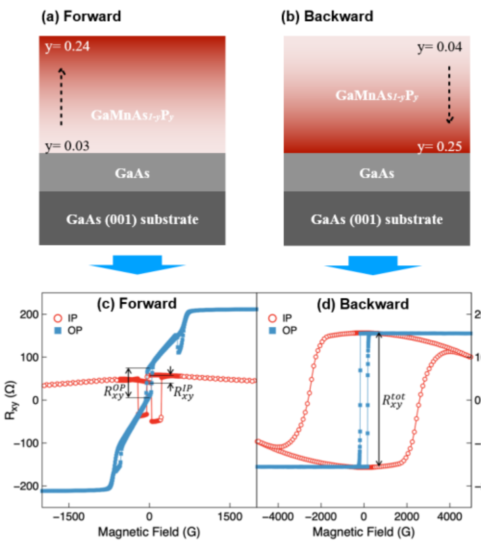

Figure 1: Sketch of the structures for (a) forward- and (b) reverse graded $Ga_{1-x}Mn_xAs_{1-y}P_y$ samples. Hall resistance R_{xy} obtained by sweeping magnetic field in-plane (open red circles) and out-of-plane (solid blue circles) for forward (c) and reverse (d) samples at 10 K.

References

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