Tetragonal zinc-blende MnGa ultra-thin films with high magnetization directly grown on epi-ready GaAs(111) substrates


Citation: Appl. Phys. Lett. 102, 102408 (2013); doi: 10.1063/1.4794951
View online: https://doi.org/10.1063/1.4794951
View Table of Contents: http://aip.scitation.org/toc/apl/102/10
Published by the American Institute of Physics

Articles you may be interested in

Tailoring magnetism of multifunctional Mn_xGa films with giant perpendicular anisotropy

Substrate-modified ferrimagnetism in MnGa films

Magnetic Tetragonal $\delta$ Phase in the Mn–Ga Binary
Journal of Applied Physics 36, 1501 (1965); 10.1063/1.1714349

Magnetoresistance effect in L10-MnGa/MgO/CoFeB perpendicular magnetic tunnel junctions with Co interlayer

Annealing temperature and thickness dependence of magnetic properties in epitaxial L10-Mn_{1.4}Ga films

Heteroepitaxial growth and surface structure of L10-MnGa(111) ultra-thin films on GaN(0001)
Manganese-gallium alloys grown on GaAs semiconductors by molecular beam epitaxy (MBE) are interesting candidates for applications in spintronics as spin injectors due to their thermodynamic stability, large spin polarization, square-like hysteresis loops, and large magnetic anisotropy.1–7 Due to dates for applications in spintronics as spin injectors due to tors by molecular beam epitaxy (MBE) are interesting candidates for producing materials suitable to replace some expensive rare-earth-based magnets in MnGa alloys are also good candidates for producing materials for thickness between 5 and 20 nm with a net magnetic moment of 3.2 $\mu_B$ per Mn atom. These epilayers are potentially suited for semiconductor spintronics applications due to the reversal of its magnetization in relatively low magnetic fields. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4794951]

Manganese-gallium alloys grown on GaAs semiconductors directly grown on GaAs(111)-(1×1) reconstructed surface. MnGa layers are characterized by the stacking of (111) planes of tetragonal zinc-blende structure, which are rotated by 11° with respect to the underlying (111) planes of the GaAs lattice. These ultra-thin MnGa epilayers with lattice parameters $a = 0.55$ nm and $c = 0.61$ nm are stabilized for thickness between 5 and 20 nm with a net magnetic moment of 3.2 $\mu_B$ per Mn atom. These epilayers are potentially suited for semiconductor spintronics applications due to the reversal of its magnetization in relatively low magnetic fields.© 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4794951]
(111) interplanar spacing of GaAs centered at 2θ = 27.4° exhibit an adjacent Bragg peak assigned to (111) plane of MnGa with d = 0.327 nm. Figure 1(g) shows a φ scan obtained by turning the sample around the [111] direction of the GaAs substrate at 70.5° from the film normal in order to evidence three diffraction peaks of the (111) family of directions. The Bragg diffraction peaks corresponding to GaAs(111) planes are observed spaced by 120°. Diffraction peaks assigned to MnGa layer are also spaced by 120° but rotated by 71° (or 49°) relatively to diffraction peaks of GaAs. From the evaluation of both RHEED and XRD patterns is inferred an epitaxial relationship GaAs(111) // MnGa (111) along the normal to the films with each direction [011], [211], and [321] of MnGa rotated by 11° with respect to the directions [011], [211], and [321] of GaAs. These findings are consistent with a tetragonal zinc-blende (TZB) cell with \( c = 0.61 \) nm and \( a = 0.55 \) nm, which three-dimensional (3D) model is described below.

Figure 2(a) shows a body-centered cubic tetragonal (bct) cell for MnGa with lattice parameters \( a' = 0.28 \) nm and \( c' = 0.31 \) nm, as previously reported. The bct cell is derived from two juxtaposed face-centered tetragonal (fct) cells of MnGa which preserves geometrical rules of a stable L1_0-type structure. RHEED and XRD analyses are consistent with MnGa layer adopting TZB cell with \( c = 0.61 \) nm and \( a = 0.55 \) nm, as shown in Figure 2(b). Such TZB cell can be formed by assuming \( c \approx 2c' \) and \( a \approx 2a' \), which results from the stacking of bct(111) planes onto GaAs(111)B-(1 × 1) reconstructed surface. The overlaid model showing the epitaxial relationship between crystalline structures of TZB MnGa(111) and ZB GaAs(111) is illustrated in Figure 2(c).

The rotation angles of 49° and 71° between lattices observed in Figure 1(g) can be obtained by a tetragonal distortion of about ~2% in the ZB cell and rotation by 11° of MnGa lattice with respect to GaAs, confirmed by RHEED analyses. The schematic drawing of moiré pattern originated from the...
The saturation magnetization is \( M_S \) for TZB-MnGa, the in-plane magnetization is weakly anisotropic. The hysteresis loop exhibits low MR (about 110 Oe) for both in-plane projections. Out-of-plane saturation field. Despite of the significant differences in the remanent magnetization, respectively. Coercive fields (\( H_C \)) are about 210 Oe for both in-plane projections. Out-of-plane hysteresis loop exhibits low \( M_R \) (~6%) with \( H_C = 110 \) Oe. The saturation magnetization is \( M_S = 650 \) emu/cm\(^3\) which corresponds to 12.9 \( \mu_B \) per TZB cell or 3.2 \( \mu_B \) per Mn atom. Figure 3(b) shows the thickness dependence of the in-plane saturation magnetization. For layers containing 52.5 at. % Mn thicker than 20 nm it is observed a significant loss of magnetization. This is indicating that ordered TZB structure enables stabilize large values of saturation magnetization.

For films thinner than 20 nm the hysteresis loops measured with applied field along the directions denoted by \( H_1 \) and \( H_2 \) exhibit quite similar values of coercivity and saturation field. Despite of the significant differences in the remanent magnetization values, the in-plane anisotropy is weak, as shown in Figure 3(a). Out-of-plane magnetization saturates at fields as high as 40 kOe. This value is much higher than the shape anisotropy field estimated as 47 Ms \~ 8.2 \) kOe. The Stoner-Wohlfarth approach can tentatively be used by admitting 2 K/Ms \~ 40 \) kOe, which yields an effective value of magnetic anisotropy \( K \sim 1.3 \times 10^7 \) erg/cm\(^3\). This effective value \( K \) is close to those reported for \( \delta \)-MnGa alloys with 56–59 at. % Mn, indicating that a strong magneto-crystalline anisotropy also occurs in our films. In \( \delta \)-MnGa, the hybridization between the Mn d electrons and the delocalized Ga p electrons promotes a certain degree of itinerancy to the former, which favors an easy axis of magnetization along the crystallographic c-axis, largely affected by strain. In our TZB-MnGa, the in-plane magnetization is weakly anisotropic. The existence of equivalent epitaxial domains rotated by 120° one relative to the other should reduce the anisotropy of magnetization along a and c crystallographic axes. Due to a tetragonal distortion with \( c/a \sim 1.1 \) contributions of elastic and magnetoelastic anisotropy certainly play important roles in these TZB MnGa layers.

The estimate value of 3.2 \( \mu_B \) per Mn atom for tetragonally distorted \( ZB \) MnGa layers is higher than experimental values previously reported for bct cells of MnGa. For instance, magnetic moment values between 0.7 and 1.2 \( \mu_B \) per Mn atom were reported by Tanaka et al. and references therein, and 2.5 \( \mu_B \) per Mn atom are found by Bedoya-Pinto et al. Also, calculated values of 2.5 \( \mu_B \) per Mn atom by Sakuma and 2.8 \( \mu_B \) per Mn atom described by Yang et al. for strained bct cells are smaller than our present result. MnGa films with zinc-blend structure directly integrated on GaAs(111) certainly deserves further studies of their electronic structure in order to better understand the relation between the high magnetization and crystalline structure. Another important issue is the investigation of the possibility of matching between energy levels of TZB-MnGa and GaAs, which could favors the spin-injection efficiency for applications in spintronics devices. Our present results open approaches to explore the usage of these alloys as spin injectors in magnetic tunnel junctions.
In summary, we present results for MnGa epilayers directly grown on the \((1 \times 1)\)-reconstructed surface of GaAs(111)B substrates without GaAs buffer layer growth. We identify a heteroepitaxy between MnGa and GaAs with a well-defined epitaxial film-substrate relationship consistent with a zinc-blende lattice. Besides, noble-metal and rare-earth-free MnGa alloy films are interesting for applications in ultrahigh-density magnetic recording media. Moreover, this kind of material is also promising to be developed for economical permanent magnets as pointed by Zhu et al.\(^\text{20}\) The high saturation magnetization, together with moderate to low values of remanence and coercivity, make ZB MnAs suitable for spin injector electrodes in spintronics devices.

The authors thank Fabiano Yokaichiya (LNLS, Campinas) for excellent support and help during the XRD measurements and acknowledge financial support by CNPq, Fundação Araucária (Grant PRONEX 17386 \#118/2010), and Brazilian Synchrotron Light Laboratory (LNLS) under proposal XPD-12533. Two of us thank CAPES/PRODOC (H.F.J) and REUNI/UFPR (J.Z.) for financial support.