Magnetic properties of MBE grown Mn$_4$N on MgO, SiC, GaN and Al$_2$O$_3$ substrates

ABSTRACT

Mn$_4$N is a compound magnetic material that can be grown using MBE while exhibiting several desirable magnetic properties such as strong perpendicular magnetic anisotropy, low saturation magnetization, large domain size, and record high domain wall velocities. In addition to its potential for spintronic applications involving spin orbit torque with epitaxial topological insulator/ferromagnet bilayers, the possibility of integrating Mn$_4$N seamlessly with the wide bandgap semiconductors GaN and SiC provides a pathway to merge logic, memory and communication components. We report a comparative study of MBE grown Mn$_4$N thin films on four crystalline substrates: cubic MgO, and hexagonal GaN, SiC and sapphire. Under similar growth conditions, the Mn$_4$N film is found to grow single crystalline on MgO and SiC, polycrystalline on GaN, and amorphous on sapphire. The magnetic properties vary on the substrates and correlate to the structural properties. Interestingly, the field dependent anomalous Hall resistance of Mn$_4$N on GaN shows different behavior from other substrates such as a flipped sign of the anomalous Hall resistance.

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I. INTRODUCTION

Epitaxial growth of ferromagnets by molecular beam epitaxy (MBE) is of high technical interest for spintronic applications such as devices exploiting spin orbit torque (SOT). Recently, spin orbit switching in MBE grown ferromagnet/topological insulator bilayers with a critical current as low as 1.5 MA/cm$^2$ has been demonstrated. The Mn$_4$N, which is a room temperature ferromagnet, has been successfully grown by MBE by a few groups. These MBE grown Mn$_4$N films show strong perpendicular magnetic anisotropy ($K_u = 1.1 \times 10^7$ J/m$^3$), low saturation magnetization ($M_s = 6.6 \times 10^4$ A/m), large domain size (~millimeter size on STO), and record high domain wall velocities driven by spin transfer torque (up to 900 m/s). This makes Mn$_4$N attractive for spintronic devices. Meanwhile, the successful growth of Mn$_4$N on SiC indicates a strong potential for the seamless integration of Mn$_4$N with wide bandgap semiconductors of the hexagonal crystal family such as SiC, GaN, AlN, and Sapphire. Such integration may bring spintronic functionality into the burgeoning electronics and photonics applications that these wide-bandgap semiconductor platforms are enabling today.

Most reports on the epitaxial growth of Mn$_4$N are on oxide substrates such as MgO and SrTiO$_3$ (STO). Detailed study of the magnetotransport properties such as the anomalous Hall effect of MBE Mn$_4$N films grown on other substrates are still lacking. In this work, we report the successful MBE growth of Mn$_4$N films on four substrates: cubic MgO, and wide bandgap semiconductors (SiC and GaN) and Sapphire, the last three of which are hexagonal. A comparative study of the crystalline, structural, electronic, magnetic, and
The additional peak at 40.4 degree might be due to the inclusion of Mn$^4$ spectrum shown in Fig. S1(a) corroborates that the Mn$^4$ one minute. This indicates a smooth surface, and single crystallinity changes to bright, streaky pattern as shown in Fig. 2(a) in less than one minute. This RHEED pattern implies the existence of twin domains, that are expected since a three-fold symmetric cubic Mn$^4$ nitride is being grown on a six-fold symmetric hexagonal GaN substrate, similar to a recent observation of the growth of cubic ScN on GaN. The RHEED pattern gradually becomes dimmer, and develops into a polycrystalline ring by the end of the one-hour growth as shown in Fig. 2(c). The Mn$^4$ thin film deposited directly on GaN is found to be polycrystalline (Fig. S1(b)), evidenced by both (111) and (002) peaks of the crystal. XRD peaks from Al$_2$O$_3$ and AlN originate from GaN (on sapphire) templates which were used as substrates for growths in this study.

A strong dependence of the resulting manganese nitride phases on the growth temperature is observed. A secondary phase of Mn$_2$N$_{0.88}$ is found to form as evidenced by the XRD peak marked with the addition of Mn$_2$N$_{0.88}$ in Fig. S1(c), when grown at 600 °C directly on GaN substrates. A possible reason is the thermal stability of the manganese nitride compounds: Mn$^4$N is the thermally stable phase at higher temperature than Mn$_2$N$_{0.88}$. The resulting Mn$_4$N is rather rough, with a surface rms of 34 nm for a 10x10 micron$^2$ scan as shown in Fig. S2(b).

For the growth on SiC, the initial RHEED shows a similar spotty pattern during nucleation as seen on GaN (Fig. 2(d)). As can be seen in Fig. S1(d), the epitaxial Mn$_4$N on SiC is a single-phase crystal with twinning, showing only the (111) XRD peak, as expected from the symmetry of substrates. The surface morphology is quite rough, characterized by a rms of 38 nm for a 10x10 micron$^2$ scan as seen in Fig. S2(c). The XRD spectra of single crystalline Mn$_4$N is consistent with the spotty RHEED pattern maintained throughout the growth, unlike on the GaN substrate where it becomes polycrystalline.

The MBE growth of Mn$_4$N on SiC and GaN with a presumably smoother surface has been reported in Ref. 4. At this stage, we are unable to explain the difference in surface morphology observed earlier and this study. The possible reasons could be different surface treatments or nucleation conditions before growth, or the major difference could stem from the fact that the instead of the plasma source for nitrogen used here, the MBE growths in the previous study was performed using a NH$_3$ source.

When grown directly on sapphire, the RHEED pattern of manganese nitride develops into very dim and diffusive pattern less than five minutes into the growth. No peaks other than from substrate are seen in the XRD spectrum for the film grown on sapphire, indicating an amorphous nature of the film. From the magnetic characterization shown latter, ferromagnetism is still observed, likely due to nanocrystalline Mn$_4$N, the only ferromagnetic phase of manganese nitride at room temperature. The surface morphology is rough with a rms of 66 nm for a 10x10 micron$^2$ scan as shown in Fig. S2(d).

Since the surface of sapphire was not nitridized prior to the deposition, this is likely due to the large lattice mismatch between Mn$_4$N and sapphire.

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**III. RESULTS AND DISCUSSIONS**

**A. Crystal quality**

Manganese nitride is known to crystallize in several bulk phases such as MnN, Mn$_2$N$_2$, Mn$_2$N$_3$ and Mn$_3$N. Among them, only Mn$_4$N is ferrimagnetic. As shown in inset of Fig. 1(a), Mn$_4$N has an antiperovskite crystal structure with a nitrogen (N) atom located at the body center, and two inequivalent manganese sites (Mn$_A$ and Mn$_B$) with magnetic moments of 3.85 $\mu_B$/f.u. and 0.9 $\mu_B$/f.u. occupying the corner and face-centered positions, respectively. The crystal structure of Mn$_4$N belongs to the space group P4$_3$m, with the {111} planes of Mn$_4$N exhibiting trigonal symmetry. Fig. 1(a) shows the energy bandgap and lattice constants of the four substrates chosen for nitrogen used here, the MBE growths in the previous study was monitored by in situ reflection-energy electron diffraction (RHEED). A detailed description of sample preparation and characterization methods are provided in the supplementary section.

**FIG. 1.** (a) Bandgap and lattice constant of different substrates (inset) Crystal structure of Mn$_4$N (b) Schematic of MBE growth of Mn$_4$N on different substrates.
Therefore, Mn$_4$N grows single crystalline on MgO with smooth surface. On GaN, the Mn$_4$N film is rough and polycrystalline, with both (002) and (111) orientations out of plane. It is single crystalline on SiC, though the surface is rough. On sapphire, the film is very rough and amorphous. Table S1 summarizes the crystalline qualities of Mn$_4$N films deposited directly on these substrates without nucleation layers.

**B. Magnetic properties**

The film grown on MgO exhibits a square hysteresis loop with almost full remanence at zero field (Fig. 3 (a)). The sharp switching of the magnetization for this sample and comparison with in plane M vs H loop (Fig. S3 (a)) indicate a strong perpendicular magnetic anisotropy (PMA).

The out of plane M vs H loop of Mn$_4$N on GaN shown in Fig. 3(b) is significantly different from that grown on SiC (Fig. 3(c)). Considering the similarity between SiC and GaN, this sharp contrast in magnetic properties is quite surprising. Though the saturation magnetization on GaN at 5 K is similar to Mn$_4$N on SiC, the saturation magnetization drops significantly towards 300 K, reaching only about 50 emu/cc. A similar large drop of the saturation magnetization of Mn$_4$N with increase in temperature was also reported in Mn$_4$N grown on Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$–PbTiO$_3$ (PMN-PT) substrates.

It is worth mentioning that magnetic properties of manganese nitride films grown on GaN depend critically on growth temperature, for example there is a large difference in coercive field between the film grown at 700 °C and the film grown at 600 °C with clear evidence of Mn$_2$N$_{0.36}$ inclusion.

The saturation magnetization and coercive field of Mn$_4$N on SiC seen in Fig. 3(c) are both comparable to an earlier report. The switching of magnetization is not as sharp as Mn$_4$N on MgO, possibly due to more structural defects, or weaker PMA on SiC (Fig. S3 (c)). Because strain is believed to be the origin of strong PMA in Mn$_4$N, the PMA strength is likely to be weaker on strain-relaxed Mn$_4$N on SiC.
Though Mn$_4$N-related XRD peaks were not observed for the film grown on sapphire, Fig. 3(d) nevertheless shows a weak hysteresis loop. Since Mn$_4$N as the only ferrimagnetic phase at room temperature, it is reasonable to attribute the film grown on sapphire to have Mn$_4$N inclusions, though the crystal quality is poor, and the surface is rough.

Comparisons between in plane and out of plane M vs H loops of Mn$_4$N on different substrates are shown Fig. S3. Mn$_4$N epitaxial layers are found to exhibit PMA on all the four substrates.

The longitudinal resistivity $R_{xx}$ of the Mn$_4$N epitaxial layer is 143 $\mu\Omega$ cm on MgO, slightly lower than the reported value of 187 $\mu\Omega$ cm in Refs. 5 and 6. The longitudinal resistance on GaN is similar to Mn$_4$N on MgO. However, layers grown on SiC and sapphire are almost twice as resistive, as summarized in Table. S2. Fig. 4 shows that the anomalous Hall resistance of all the films resemble the shape of the M vs H hysteresis curves. However, the Hall resistance is almost two orders smaller for Mn$_4$N grown on GaN, than on the other substrates [note the different scales in Fig. 4 (b)]. The Hall angle $\theta_{H}$=$R_{xy}/R_{xx}$ is as large as 0.01 for Mn$_4$N grown on MgO, consistent with earlier reports, while being smaller (0.007 and 0.005) when grown on SiC and sapphire respectively. This is the first report on the magneto transport properties of MBE grown Mn$_4$N films on substrates other than MgO or STO.

Apart from the extremely small Hall angle (0.002) when grown on GaN, the most interesting feature is the sign reversal of the Hall resistance, seen in Fig. 4 and Fig. S4 (a). Such sign reversal of Hall resistance has been reported in other material system such as epitaxial NiCo (002) films and Co/Pd multilayers. However, in these reports, the sign of the anomalous Hall resistance depends on either the thickness of the layer, the temperature, or the composition ratio of multilayers. These are different from the substrate dependence we observe here. The different strain conditions in Mn$_4$N films might be a reason, since strain modifies the band structure, resulting in the difference in band filling of Mn$_4$N films grown on different substrates. However, it is difficult at this stage to explain the difference between films grown on SiC and GaN considering the similar lattice constant and symmetry of the substrates. On the other hand, for manganese nitride grown on GaN at lower temperatures, where clear XRD peaks from Mn$_2$N$_{0.86}$ can be seen (Fig. S1 (c)), n-type like anomalous Hall resistance is observed (not shown), indicating that the spin states of Mn$_4$N can vary significantly due to exchange interaction with other magnetic inclusions such as Mn$_2$N$_{0.86}$.

The sign reversal of anomalous Hall resistance of Mn$_4$N film grown on GaN (Fig. S4 (a)) might be a result of the interaction between Mn$_4$N and other magnetic inclusions, even though these inclusions are not observed in XRD. This is very likely to happen because of the rich magnetic properties of different phases in (gallium) manganese nitride material system, if we also consider the possibility of inter-diffusion between GaN and Mn$_4$N. Furthermore, the observation of the shift in M vs H hysteresis loop (Fig. S4 (b)) when field cooling to low temperatures to measure the exchange bias further supports the hypothesis of inclusion of other magnetic phases. Future electron microscopy and chemical analysis is necessary to help unravel the surprising behavior observed in the magnetotransport properties of Mn$_4$N grown on GaN. Table. S2 summarizes the measured magnetic properties of the samples in this study.

**IV. CONCLUSIONS**

In summary, ferrimagnetic Mn$_4$N films were grown directly on four substrates: MgO, GaN, SiC and sapphire under identical growth conditions. No secondary phases are identified from XRD. Based on RHEED and XRD, Mn$_4$N grown single crystalline on MgO and SiC, polycrystalline on GaN, and amorphous on sapphire. The magnetic properties are found to have a strong correlation with the crystal quality. Mn$_4$N grown on MgO shows the sharpest switching behavior indicating strong PMA and low density of structural defects. On other substrates, the M vs H curves are not as sharp. The anomalous Hall effect shows n-type like behavior when grown on MgO, SiC, and Sapphire. When grown on GaN at a low substrate temperature, the AHE is n-type like behavior, which switches to p-type like behavior when grown at a higher substrate temperature of 700 $^\circ$C. The sign reversal of the anomalous Hall effect, together with the observation of exchange bias indicates possible inclusion of other
magnetic phases in Mn$_4$N films grown on GaN. To exploit the integration of Mn$_4$N with wide bandgap semiconductors such as GaN and SiC by MBE, it is essential that methods of nucleation that lead to much smoother surface morphologies be developed soon. Then, the rich magnetic properties that can already be observed in the current samples can be improved significantly, and the use of epitaxially integrated magnets can enable new applications that take advantage of the wide bandgap semiconductor electronics and photonics platform.

SUPPLEMENTARY MATERIAL

The supplementary material provides the details of growth and characterization methods, X-Ray Diffraction (XRD) spectra, atomic force microscopy (AFM) images, additional magnetic characterization data and summary of crystal quality and magnetic properties of Mn$_4$N films deposited on 4 different substrates.

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