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Microarticle

Epitaxial growth and surface reconstruction of CrSb(0001)

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ABSTRACT

Smooth CrSb(0001) films have been grown by molecular beam epitaxy on MnSb(0001) – GaAs(111) substrates. CrSb(0001) shows (2 × 2), triple domain (1 × 4) and (√3 × √3)R30° reconstructed surfaces as well as a (1 × 1) phase. The dependence of reconstruction on substrate temperature and incident fluxes is very similar to MnSb(0001).

Introduction

The family of transition metal monopnictides (MX, where M = Ni, Cr, Mn…, X = P, As, Sb…) offers a wide range of magnetic, magneto-optical and electrical transport properties and is epitaxially compatible with standard semiconductor materials. The MnSb – NiSb – CrSb system provides respectively a set of ferromagnetic (T_C = 589 K), paramagnetic and anti-ferromagnetic (T_N = 718 K) materials. These can be grown by molecular beam epitaxy (MBE) [1–4] and the (0001) in-plane lattice mismatch between CrSb and MnSb is only 0.17%. A new application area with enormous potential is antiferromagnetic (AF) spintronics [5]. Here, an AF material is the active component, whose spin orientation is electrically manipulated. Such manipulation depends on the overall crystal symmetry and that of the AF spin sublattices, and can even avoid polarising ferromagnetic contacts to achieve electrical switching of AF spin orientation [6]. Interfaces are often crucial in controlling spintronic device performance, and in the case of epitaxial heterostructures their atomic ordering can be influenced by surface reconstruction during MBE growth. TMP materials show a range of surface reconstructions and, in common with III-Vs, TMP surface reconstructions can be altered by changing the incident fluxes in MBE, as well as the surface temperature [7]. CrSb has been grown by MBE on GaAs [5] and InGaAs [6]. On (111) surfaces, the (0001) orientation of double-hexagonal close-packed TMPs is expected and we are not aware of any previous studies of CrSb with this epitaxy. In the present work we show that smooth, reconstructed CrSb(0001) films can be grown by molecular beam epitaxy (MBE) on MnSb(0001) epilayers on GaAs(111). A range of surface reconstructions similar to those found on MnSb(0001) is observed.

Experimental details

MBE growth was performed in a custom-built vacuum system [1,2] equipped with Sb_4, Mn and Cr effusion cells, and reflection high energy electron diffraction (RHEED). MnSb epilayers ~100 nm thick were grown on GaAs(111) before depositing CrSb on to the MnSb (0001)-(2 × 2) surface. For CrSb growth, the substrate temperature was 400 °C, the beam pressure ratio of Sb_4:Cr was around 7:1 and the CrSb growth rate was 0.15 nm min^{-1}. RHEED patterns were monitored during growth of films ≤10 nm thick. After each film was grown, Cr and Sb_4 fluxes and the substrate temperature were adjusted to observe surface reconstruction changes. Samples were then removed from vacuum and imaged by ambient atomic force microscopy (AFM) in tapping mode.

Results and discussion

The AFM images showed rather featureless surface morphology with root-mean-square surface roughness < 1 nm on 1 µm image sizes. This is equal to the roughness of the underlying MnSb buffer layers, suggesting that the CrSb films are smooth and planar. This is supported

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by RHEED measurements, which consistently showed sharp and streaky patterns. The integer order streak spacings are consistent with the CrSb in-plane lattice parameter a = 0.4121 nm. The rotational symmetry is also consistent with the (0001) face of CrSb. We observed three well-defined surface reconstructions, (2 × 2), (1 × 4) and (√3 × √3)R30°, as shown in Fig. 1. Unreconstructed (1 × 1) surfaces could also be obtained (not shown).

The 0° and 30° azimuths are defined in Fig. 2 along with the RHEED pattern interpretations. The surface reconstruction was (2 × 2) during MBE growth of CrSb under the chosen conditions. Post-growth, all four surface periodicities could be produced by adjusting substrate temperature and incident fluxes, as follows. Exposure to Sb_4 flux at lower substrate temperatures (< 350 °C) produced a triple domain td(1 × 4) reconstruction. By analogy with MnSb(0001)-td(1 × 4) [7] and MnAs (0001)-td(1 × 3) [8] this is most likely based on an Sb chemisorption structure with chains of Sb atoms lying along the three <1$\bar{1}$00> (30°) directions. A (1 × 1) surface resulted when annealing in Sb_4 flux at substrate temperatures > 350 °C. Exposure to an incident Cr flux induces the (√3 × √3)R30° reconstruction over whole range of substrate temperatures used (200 °C–400 °C). It seems likely that this reconstruction is related to the Mn-stable (2√3 × 2√3)R30° found on MnSb(0001). Exposure of the (√3 × √3)R30° to Sb flux reverted it to the (2 × 2) before the appearance of either the (1 × 1) or td(1 × 4) depending on substrate temperature. Similarly, exposure of the (1 × 1) or td(1 × 4) to Cr flux would generate a (2 × 2) before the appearance of the (√3 × √3)R30° periodicity. Hence, the sequence of "Sb-rich" to "Cr-rich" phases td(1 × 4) − (1 × 1)/(2 × 2) − (√3 × √3)R30° is closely analogous to the Sb-rich to Mn-rich sequence on MnSb(0001). It is worth noting that CrSb and MnSb both differ from NiSb(0001), which has an Sb-rich td(1 × 4), an intermediate (1 × 1) but no (2 × 2), and a Ni-rich (4 × 4) [2].

Conclusions

Smooth CrSb(0001) films have been grown on epitaxial MnSb (0001) by MBE. This demonstrates the possibility of combining controlled layers of different magnetic ordering in a single fully epitaxial structure. The CrSb(0001) surface reconstruction periodicities and their behaviour under flux and temperature changes are similar to those of MnSb(0001).

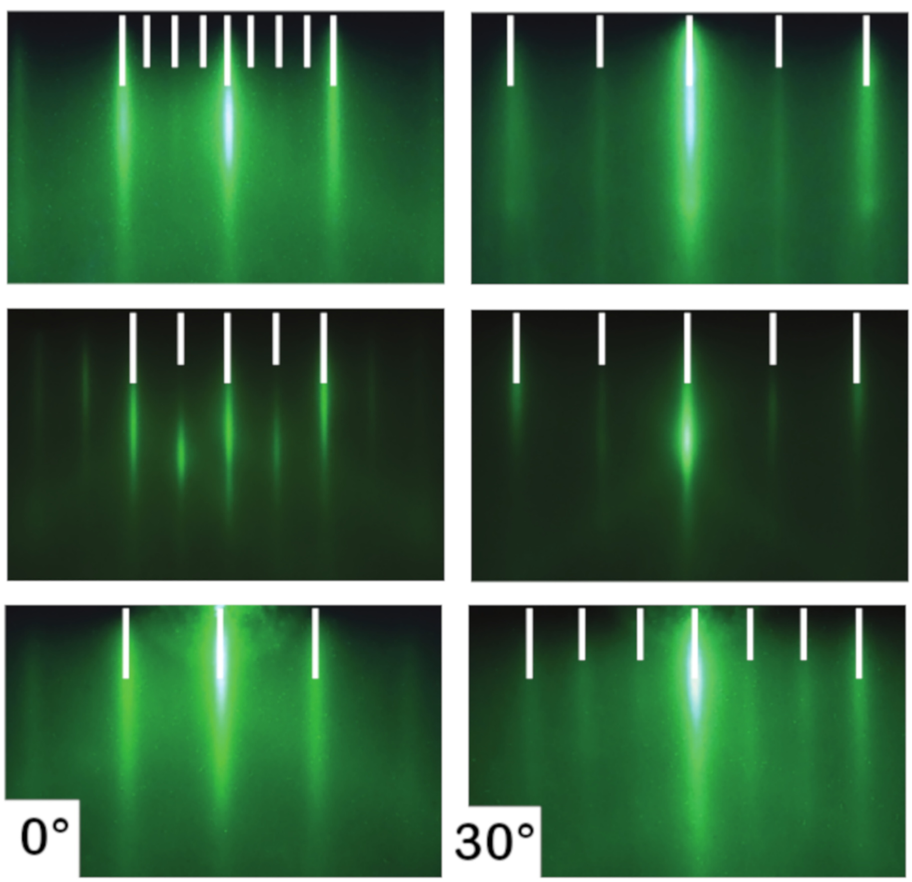

Fig. 1. RHEED patterns in two azimuths (defined in Fig. 2) for three surface reconstructions of CrSb(0001): td(1 × 4) [top], (2 × 2) [middle], and (√3 × √3)R30° [bottom]. Longer white dashes highlight integer order streaks, with fractional orders shown by shorter dashes.

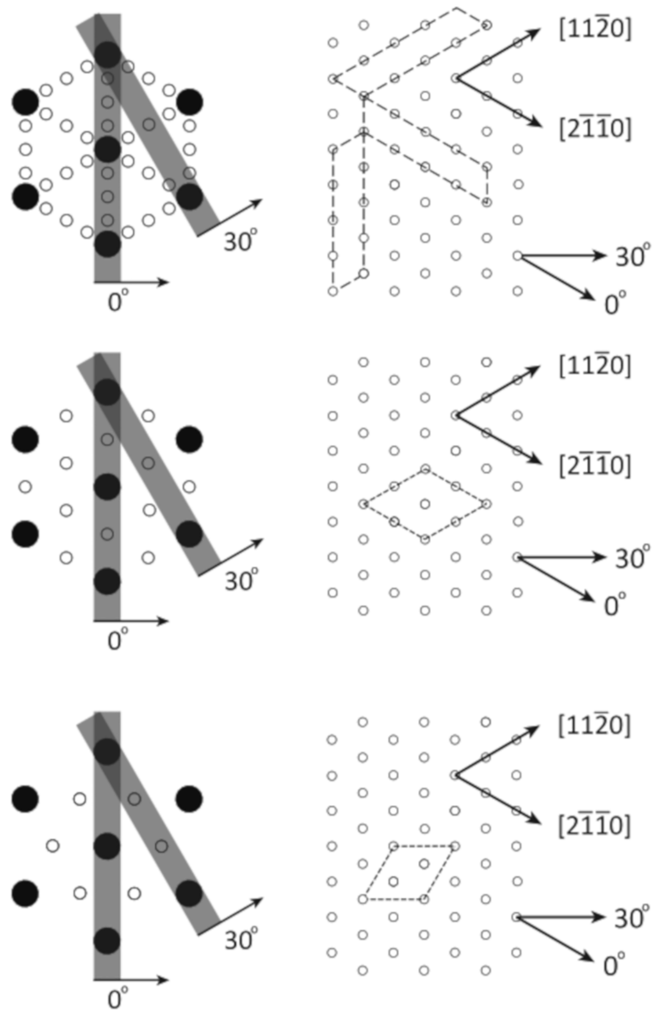

Fig. 2. Interpretation of RHEED periodicities for CrSb(0001), with reciprocal space on the left and real space meshes on the right. Shaded regions represent the regions of reciprocal space accessed by RHEED. From top to bottom are shown td(1 × 4), (2 × 2), and (√3 × √3)R30°.

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