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Heteroepitaxy of PbSe on GaAs(1 0 0) and GaAs(2 1 1)B by molecular beam epitaxy

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ABSTRACT

Heteroepitaxy of single-crystal PbSe on GaAs(1 0 0) and GaAs(2 1 1)B has been achieved using molecular beam epitaxy. Two-dimensional growth and smooth surface morphology are indicated by reflection high-energy electron diffraction (RHEED) patterns. X-ray diffraction spectra of the resulting single-crystal PbSe on GaAs(1 0 0) and GaAs(2 1 1)B demonstrated that the orientation of PbSe is (1 0 0) on GaAs(1 0 0), while on GaAs(2 1 1)B it is close to (5 1 1). Cross-sectional transmission electron microscopy revealed the presence of an abrupt interface between PbSe and GaAs and good crystallinity of the PbSe film for both orientations. Selective-area diffraction pattern confirmed the epitaxial relationship between PbSe and GaAs.

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1. Introduction

PbSe has attracted much attention for potential applications as infrared lasers and detectors due to its narrow and direct bandgap. Its high dielectric constant shields the influences of dislocations and consequently high dislocation densities are tolerable, and its growth is relatively straight forward [1]. Molecular beam epitaxy (MBE) has been established as a major technique to grow high-quality lead salt material with advanced detector architectures [2]. Compared to other epitaxial techniques, MBE growth occurs at relatively low temperatures and thus offers distinct advantages such as better interface stability, interface abruptness, and metallurgical and electrical junction profile control during growth. As a result, MBE is perhaps the most suitable technique to fabricate sophisticated structures for the next generation of infrared detectors. Unlike most II–VI and III–V semiconductors with zinc blende structure, PbSe has the rock-salt structure. That is the reason why it has been primarily grown on BaF_2 [3], BaF_2/CaF_2/Si(1 1 1) and CaF_2/Si(1 1 1) [4–7].

In this work, we report the direct growth of PbSe on GaAs(1 0 0) and GaAs(2 1 1)B. The GaAs(1 0 0) substrate is commonly used for heteroepitaxy in the semiconductor industry, since they are available in large sizes with high quality and at relatively low price compared with BaF_2. The properties of GaAs such as lattice constant, thermal expansion coefficient and bonding character are closer to PbSe than those of Si. Another advantage of GaAs compared to Si as a substrate for PbSe MBE growth is in that oxide desorption occurs near 580 °C for GaAs whereas for Si it takes place at much higher temperatures of 850–900 °C. This causes less outgassing of the substrate heater assembly and hence, reduces the risk of contamination of the substrate surface, which is critical during the initial growth of PbSe [8]. Growth and layer properties depend strongly on substrate orientation in other systems, for example, CdTe on GaAs(2 1 1)B grows as CdTe(2 1 1) or CdTe(1 3 3)

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with the suppression of twins, whereas, CdTe on GaAs(1 0 0) grows as CdTe(1 1 1) or CdTe(1 0 0) depending on the thermal cleaning conditions [9]. A (2 1 1)B surface with steps has the potential to improve the MBE growth, since the (2 1 1) surface provides energetically favorable sites arranged in a periodic array for atoms to nucleate and produce a more uniform and smoother layer [10]. Therefore, it is necessary to investigate the growth of PbSe on GaAs(2 1 1)B.

2. Experimental procedure

PbSe layers were grown in a RIBER 2300 MBE system. An effusion cell containing 99.999% purity stoichiometric PbSe was used for the growth of PbSe and another one, containing Te, was used to create a Te flux during oxide desorption from GaAs. RHEED was employed to monitor growth. The GaAs(1 0 0) and GaAs(2 1 1)B substrates with a diameter of 4 in were diced into 2 cm by 2 cm pieces in order to fit our spring plate and substrate holder. After being covered with photoresist to protect the surface then the 2 cm by 2 cm pieces were cleaned with acetone, methanol and de-ionized (DI) water and then etched in a 20:1:1 solution of H_2SO_4:H_2O_2:H_2O for 20 s. Subsequently, it was etched in a 1:4 solution of HCl:isopropanol for 2 min in order to remove any oxide on the surface. Finally, the substrate was rinsed in isopropanol, dried with 6 N pure nitrogen gas and then loaded into the UHV chamber [11,12]. The GaAs was thermally cleaned and oxide was desorbed at 580 °C for 10 min. This was done under Te flux in order to prevent the evaporation of As from the surface. Finally, the substrate was cooled down to the growth temperature of 400 °C. Growth was initiated when the PbSe flux was stable as monitored by an ion gauge.

Samples for TEM investigation were prepared with the cross-sectional geometry using routine mechanical polishing and dimpling, followed by argon-ion milling. Mechanical polishing reduced the thicknesses to 20–30 μm, and hole perforation was achieved by argon-ion milling at 4 kV and 4 mA using two guns with an angle of 15° with respect to the direction parallel to the sample surface. Low voltage (3 kV), low current (3 mA), and a small milling angle (8°) for 30 min was then used for final thinning in order to minimize any amorphous layers at the sample surface, note that the sample was kept at liquid nitrogen temperature throughout the ion-milling process to ensure that no additional structural defects were introduced [13]. The electron microscopy observations were carried out using a JEOL 3010 high-resolution transmission electron microscope (HRTEM), operated at 300 keV and equipped with a double tilt, top entry-type specimen holder. Selective-area electron diffraction (SAED) pattern was used to provide details of the interface between the PbSe epilayer and GaAs substrate. X-ray ω–2θ scan was carried out on high-resolution X-ray diffraction BetaD1 to investigate the orientation of the films.

3. Results and discussion

RHEED patterns from the PbSe/GaAs (1 0 0) [0 1 1] azimuth direction after 10 min. growth and 120 min growth are shown in Fig. 1(a) and (b), respectively. RHEED patterns from the PbSe/GaAs (1 0 0) [0 $\bar{1}$ 1] azimuth direction after 10 min growth and 120 min growth are shown in Fig. 1(c) and (d), respectively. Fig. 1(e) and (f) show RHEED patterns from the PbSe/GaAs (2 1 1)B [1 $\bar{1}$ $\bar{1}$] and [0 $\bar{1}$ 1] azimuth direction after 120 min growth, respectively. The streaky and bright RHEED patterns are indicative of smooth surface morphology and good crystalline quality. In case of PbSe on GaAs (1 0 0), based on the distance between diffraction streaks,

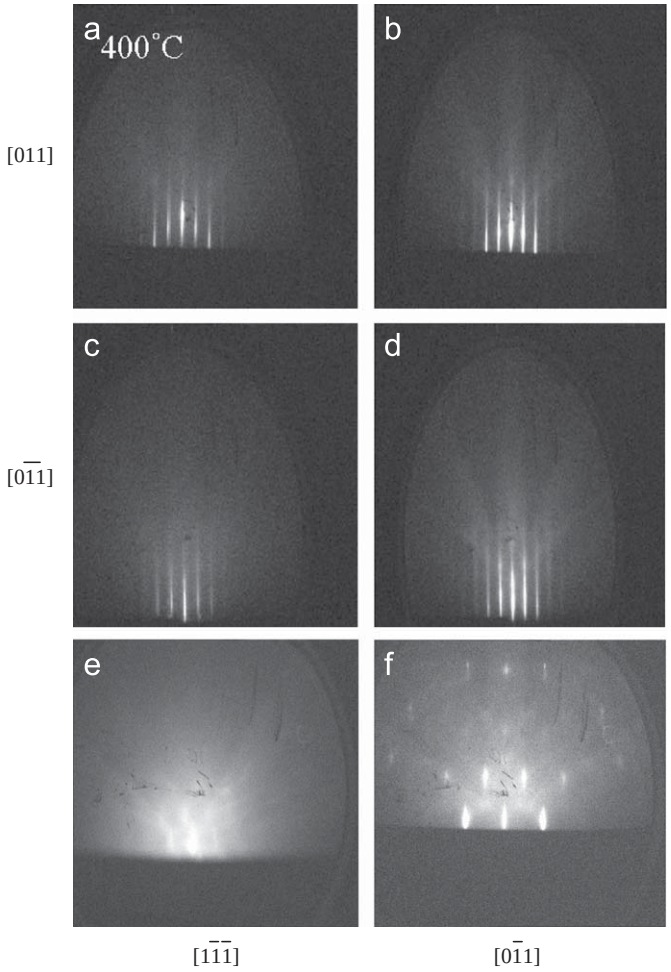

Fig. 1. (a) and (b) RHEED images from the [0 1 1] azimuth of PbSe/GaAs(1 0 0) after 10 and 120 min growth, respectively; (c) and (d) RHEED images from the [0 $\bar{1}$ 1] azimuth after 10 and 120 min growth, respectively; (e) RHEED image from the [1 $\bar{1}$ $\bar{1}$] azimuth of PbSe/GaAs(2 1 1)B after 120 min growth;(f) RHEED image from the [0 $\bar{1}$ 1] azimuth after 120 min growth, respectively.

the PbSe lattice can be shown to be almost completely relaxed. On GaAs (2 1 1)B surface, RHEED shows that PbSe grows with an orientation close to (2 1 1) and with better crystallinity in the [0 $\bar{1}$ 1] azimuth direction than [1 $\bar{1}$ $\bar{1}$]. Fig. 2(a) and (b) shows ω–2θ scans from X-ray diffraction measurements on PbSe/GaAs (1 0 0) and PbSe/GaAs(2 1 1)B, respectively, with about 2 μm thick PbSe epilayers. A superposition of a symmetric scan showing the GaAs(4 2 2) peak and an asymmetric scan on the sample tilted 3° with respect to the substrate normal direction showing the PbSe(5 1 1) peak, indicates a 3° tilt between PbSe(5 1 1) and GaAs(2 1 1)B. The XRD results suggest that PbSe has the (1 0 0) orientation on GaAs(1 0 0) whereas it has a orientation close to (5 1 1) on GaAs (2 1 1)B instead of the (2 1 1) orientation. In case of PbSe on GaAs(1 0 0), epilayer is nearly relaxed since the lattice constant of PbSe, which is 6.122 Å according to an analysis of Fig. 2(a), within experimental error matches the unstrained lattice constant of PbSe (6.124 Å). Some residual strain in PbSe on GaAs(2 1 1)B is present according to the lattice constant for PbSe of 6.097 Å calculated from the PbSe peak position. The full-width at half-maximum of the rocking curve of PbSe on GaAs(2 1 1)B is rather large (1700 arcsec) while that of PbSe on GaAs(1 0 0) is 266 arcsec. PbSe(1 1 1) would have (3 3 3) X-ray diffraction peak at the exact same position as the (5 1 1) peak, but since (1 1 1) and (2 2 2) peaks (at 25.16° and 51.65°) are not seen, the presence of PbSe(1 1 1) can be ruled out.

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