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Epitaxial Growth and Characterization of DyP/GaAs, DyAs/GaAs, and GaAs/DyP/GaAs Heterostructures

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There is a significant interest in the area of improving high temperature stable contacts to III-V semiconductors. Two attractive material systems that offer promise in this area are dysprosium phosphide/gallium arsenide (DyP/GaAs) and dysprosium arsenide/gallium arsenide (DyAs/GaAs). Details of epitaxial growth of DyP/GaAs and DyAs/GaAs by molecular beam epitaxy (MBE), and their characterization by x-ray diffraction, transmission electron microscopy, atomic force microscopy, Auger electron spectroscopy, Hall measurements, and high temperature current-voltage measurements is reported. DyP is lattice matched to GaAs, with a room temperature mismatch of less than 0.01% and is stable in air with no sign of oxidation, even after months of ambient exposure. Both DyP and DyAs have been grown by solid source MBE using custom designed group V thermal cracker cells and group III high temperature effusion cells. High quality DyP and DyAs epilayer were consistently obtained for growth temperatures ranging from 500 to 600°C with growth rates between 0.5 and 0.7 μm/h. DyP epilayers are n-type with electron concentrations of 3×10^{20} to 4×10^{20} cm^{-3}, room temperature mobilities of 250 to 300 cm^2/V·s, and a barrier height of 0.81 eV to GaAs. DyAs epilayers are also n-type with carrier concentrations of 1×10^{21} to 2×10^{21} cm^{-3}, and mobilities between 25 and 40 cm^2/V·s.

Key words: DyP, DyAs, MBE growth, rare earth group V compound, semi-metal

INTRODUCTION

There has been considerable interest in improving the high temperature performance of contacts to compound semiconductors such as GaAs. When these contacts are exposed to high temperature during fabrication or operation, interface reactions between the metal and semiconductor can take place that result in degradation in their structural and electrical properties. Reliability considerations require that the contacts be able to withstand inclement conditions, including elevated temperatures, for relatively long periods of time without any significant degradation. Rare earth group V (RE-V) compounds such as dysprosium phosphide (DyP) and dysprosium arsenide (DyAs) are possible candidates for high temperature contacts due to their high melting points.

Epitaxial metallization systems reported on GaAs include Al,[1] Ag,[2] Fe,[3] and body-centered-cubic Co.[4] These metal/semiconductor systems are not thermodynamically stable as the metal will react with As and/or Ga to form metal-As and metal-Ga compounds at relatively low temperatures. Rare earth metal arsenide compounds and other metals have also been studied by many groups. Excellent material and electrical properties have been obtained for CoGa[5] grown on GaAs and AlGaAs and ErAs grown on GaAs.[6] Epitactic Sc$_x$Er$_{1-x}$As,[7] ErP$_x$Sb$_{1-x}$,[8] and ErP$_{0.6}$As$_{0.4}$[9] grown on GaAs by molecular beam epitaxy (MBE) have also been reported.

Epitaxial growth of rare earth monophosphide (RE-P) and rare earth monoarsenide (RE-As) compounds can be performed at temperatures ranging from 400 to 600°C which are common in the growth of III-V semiconductors. In many cases, a precise adjustment of the III-V flux ratio is not needed as the group-V element atom excess does not adhere to the surface. However, unlike more common semiconductor heterostructures, the RE-V-semiconductor heterostructures involve two material systems which not only have different properties but also different crystal structures. Most of the rare earth monophosphide

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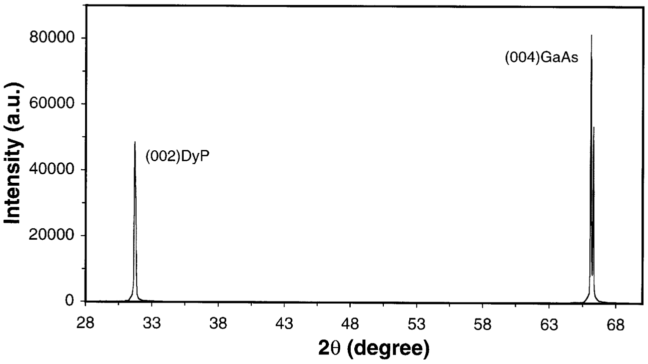

Fig. 1. X-ray diffraction pattern of (001) GaAs with DyP epilayer.

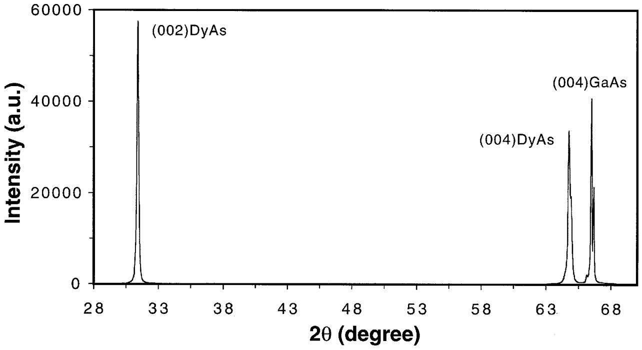

Fig. 2. X-ray diffraction pattern of (001) GaAs with DyAs epilayer.

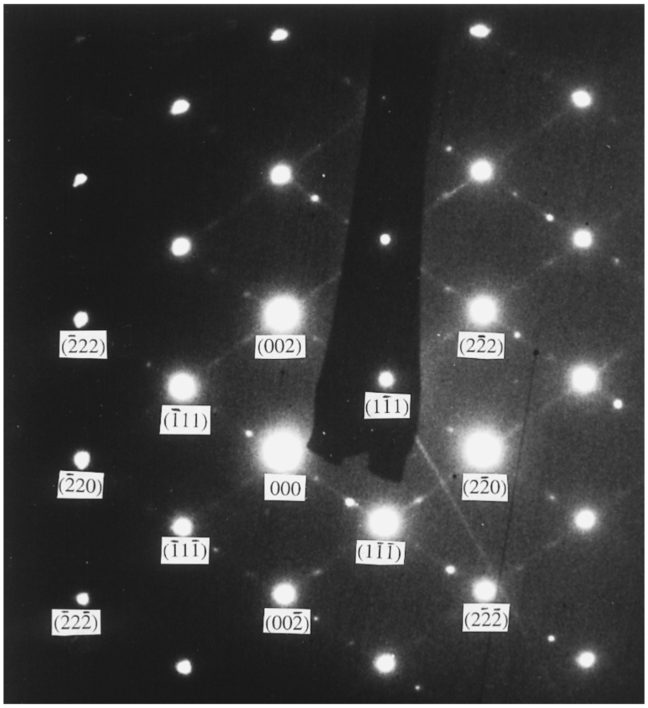

Fig. 3. Plane view selected area diffraction pattern from GaAs substrate with GaAs/DyP epilayers in the [110] beam direction.

and rare earth monoarsenide have the NaCl structure. The difference in crystal structures between RE-P and GaAs affects the growth of GaAs/RE-P/GaAs heterostructures.

This paper reports work on the structural and electrical characterization of DyP and DyAs on GaAs, and the growth of related heterostructures like GaAs/DyP/GaAs. Note that DyP and DyAs have only one stable phase with a sodium chloride structure and have lattice constants of 5.6534[10] and 5.7894Å,[11] respectively.

EXPERIMENTAL

The growth of DyP and DyAs were performed in an MBE system equipped with a 2200 liter/s diffusion pump and a liquid nitrogen cooled trap. Dy was evaporated from a high temperature effusion cell containing 99.99% pure Dy. The P and As fluxes were obtained from solid phosphorous and solid arsenic using custom designed thermal cracker cells. The substrates were either undoped, semi-insulating or Si-doped (001) GaAs. Substrate preparation consisted of standard degreasing, and etching using a 12:2:1 $H_2O:NH_4OH:H_2O_2$ solution. The native oxide was desorbed by pre-heating at about 610°C with an impinging As_2 flux prior to the growth. An undoped GaAs buffer layer about 2000Å thick was grown on the GaAs substrate. Substrate temperatures from 500 to 600°C were used for both DyP and DyAs growth, with growth rates between 0.5 to 0.7 µm/h, as determined from film thickness measurements. The GaAs buffer and capping layers were grown at substrate temperatures between 450 and 550°C. For this study, DyP and DyAs epilayers having thicknesses ranging between 0.05 to 0.5 µm were grown and used for different characterization techniques.

RESULTS AND DISCUSSION

Structural

The x-ray diffraction (XRD) patterns of GaAs with DyP and DyAs epilayers are shown in Fig. 1 and Fig. 2, respectively. According to these patterns, besides the (004) GaAs substrate peak, only the (002) peak of DyP and (002) and (004) peaks of DyAs have been observed. The XRD data has consistently indicated good quality DyP and DyAs epilayers on GaAs for substrate temperatures in the range of 500 to 600°C. The full width at half maximum (FWHM) of the GaAs (004) peak remained unchanged when DyP/GaAs layers were grown on top of it indicating that both the GaAs substrate and the DyP epilayer had a FWHM less than the resolution of the two theta x-ray system.

Figure 3 shows the plane view selected area diffraction pattern of GaAs and DyP epilayers on GaAs substrate in the [110] beam direction. The diffraction pattern indicates a strong epitaxy of the two layers with the substrate. Additional diffraction spots appear to be ordering in one of the [111] directions. The origin of this ordering is not clear at this point and is under further study. Figure 4 shows a cross-sectional high-resolution lattice image of the same sample looking at the buried DyP layer and the GaAs capping interface. No pinholes have been observed in the DyP layers. A thin white band is found at the interface, possibly due to the formation of either GaP, DyAs, or $DyAs_xP_{1-x}$, or DyGaP. In spite of the epitaxial growth

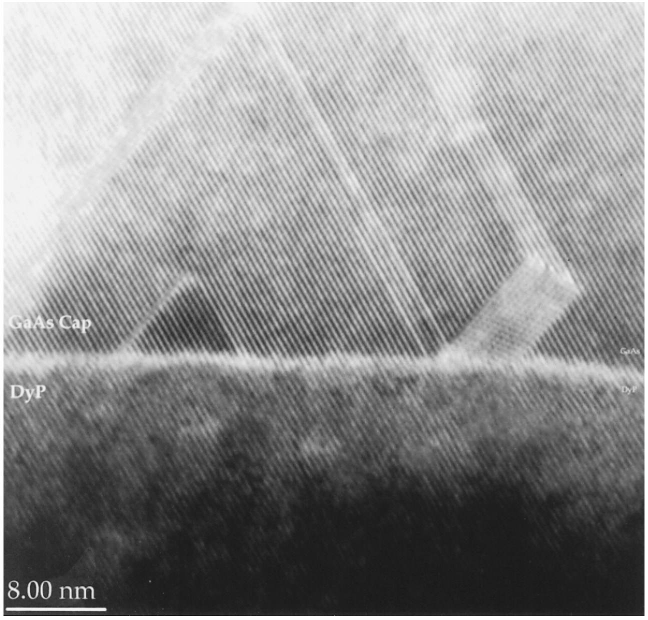

Fig. 4. Selected area cross-sectional HRTEM image of GaAs/DyP interface.

of DyP on GaAs, some of the GaAs grown on top of the DyP is twinned. This phenomenon has also been observed in the GaAs/ErAs/GaAs structure where the GaAs layer grown on top of the ErAs is usually heavily twinned with most of the twin boundaries lying parallel to {111} planes.[12] The difference in the crystal structures between DyP (rock-salt) and GaAs (zinc-blende) may affect the growth of GaAs/DyP/GaAs heterostructures.

The Auger electron spectroscopy (AES) profile of the GaAs/DyP/GaAs sample is shown in Fig. 5. The AES profile indicates abrupt interfaces with no significant impurities present in any of the layers. The atomic force microscopy (AFM) analysis of DyP (0.62 µm thick) revealed smooth surface with root mean square (rms) roughness of approximately 4Å. The surface roughness of DyAs (0.21 µm thick), on the other hand, was approximately 10Å, and may be due to the lattice mismatch between DyAs and GaAs.

Electrical

The electrical characterization data performed for DyP includes Hall measurements at temperatures between 77 and 300K and current-voltage (I-V) data between 300 and 600K. The resistivity values of DyP as determined by four-point probe and Hall measurements were found to be consistent and were in the range of 6.5×10^{-5} to 1.5×10^{-4} Ω·cm as seen in Fig. 6. The Hall measurements indicate that DyP films are n-type with electron concentrations on the order of 3×10^{20} to 4×10^{20} cm^{-3} and room temperature mobilities between 250 and 300 cm^2/V·s, as can be seen in Fig. 6. These Hall measurements are made with the assumption that only a single carrier type is present.

Current-voltage measurements were performed on DyP/n-type GaAs and indicated a Schottky behavior. The corresponding barrier height was found to be 0.81 eV. High temperature I-V measurements for diodes, using DyP as Schottky contacts and patterned Au-Ge-Ni as ohmic contacts on n-type GaAs, indicated that the DyP contacts performed efficiently up to temperatures of 325°C.

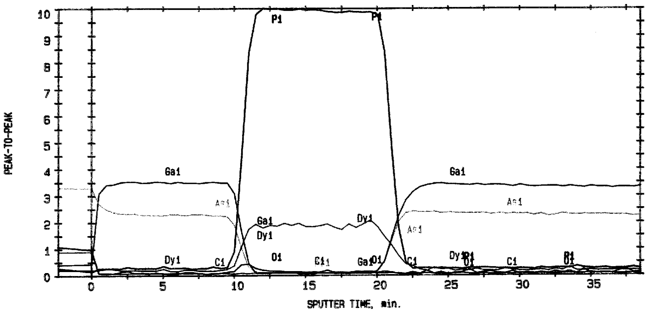

Fig. 5. AES profile of GaAs/DyP/GaAs sample.

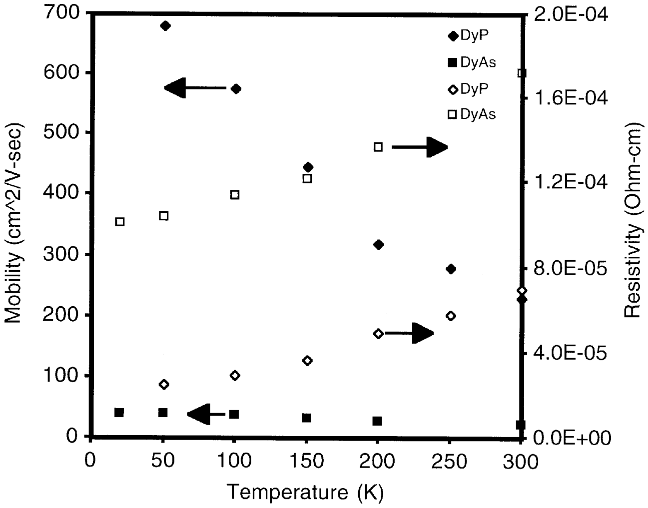

Fig. 6. Resistivity and mobility dependence of DyP and DyAs obtained from Hall measurements.

The optical characterization using photothermal deflection spectroscopy (PDS) and Fourier transform infrared spectroscopy (FTIR) showed the absence of a definitive absorption edge. This indicates the absence of a bandgap and is consistent with the semi-metallic properties of DyP where electron and hole concentrations are approximately equal. However, magneto-transport studies are needed to verify this semi-metallic property.

The Hall measurements for DyAs were performed between 20 and 300K and the resistivity was found to be in the region of 1.0×10^{-4} to 1.5×10^{-4} Ω·cm as seen in Fig. 6. The DyAs was found to be n-type with carrier concentration on the order of 1×10^{21} to 2×10^{21} cm^{-3}. As a result of the high carrier concentration, the mobilities were between 25 and 40 cm^2/V·s and showed an increase with a decrease in temperature as shown in Fig. 6.

Further electrical and optical characterization of DyAs epilayers is presently in progress.

CONCLUSIONS

High quality epitaxial layers of DyP and DyAs on

GaAs were grown by solid source MBE and were characterized by TEM, AES, XRD, variable temperature Hall measurements, and I-V measurements. Both DyP and DyAs samples were found to be n-type with carrier concentrations of 3×10^{20} to 4×10^{20} cm^{-3} and 1×10^{21} to 2×10^{21} cm^{-3} with corresponding room-temperature mobilities of 250 to 300 cm^2/V·s and 25 to 40 cm^2/V·s, respectively. DyP was found to be stable in untreated air and I-V measurements show that DyP forms a Schottky contact to n-type GaAs. The absence of a bandgap between 0.2 to 2 eV, as found by PDS and FTIR measurements, seem to indicate the possibility of DyP being a semi-metal. Further electrical and optical characterization is in progress for DyAs epilayers.

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