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Room temperature operating InAsSb-based photovoltaic infrared sensors grown by metalorganic vapor phase epitaxy

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ABSTRACT

We have developed $InAs_xSb_{1-x}$-based photovoltaic infrared sensors (PVS) for room temperature operation by metalorganic vapor phase epitaxy (MOVPE). To obtain high performance, we improved the crystallinity of the $InAs_{0.12}Sb_{0.88}$ absorber layer and utilized a $Ga_{0.33}In_{0.67}Sb$ electron barrier layer. An investigation of $InAs_{0.12}Sb_{0.88}$ growth conditions using a high-quality InSb buffer layer showed that we were able to obtain the smallest full-width at half-maximum (FWHM) of the X-ray diffraction omega rocking curve, 560 arcsec, for a growth temperature of 520°C for a 1 μm thick layer. Moreover, we successfully grew a $Ga_{0.33}In_{0.67}Sb$ barrier layer coherently on an $InAs_{0.12}Sb_{0.88}$ absorber layer, which is the first report of $Ga_yIn_{1-y}Sb$ growth on Sb-rich $InAs_xSb_{1-x}$. An $InAs_xSb_{1-x}$ PVS with a responsivity at wavelengths of 8–12 μm was obtained, and estimated detectivity peak at room temperature was approximately 7×10^7 cm $Hz^{1/2}$ W^{-1}, which is 1.3 times higher than without a $Ga_{0.33}In_{0.67}Sb$ electron barrier. These results demonstrate that our $InAs_xSb_{1-x}$ PVS is a promising device for the 8–12 μm wavelength range at room temperature.

1. Introduction

Infrared sensors are promising devices for several applications such as human body detection and gas sensing. Pyroelectric detectors are generally used to detect human body at room temperature. However, these detectors require a metallic package to separate electromagnetic and thermal noise for high sensitivity, which makes it difficult for them to be miniaturized. Moreover, pyroelectric detectors cannot detect a stationary human body because they use the temperature change of pyroelectric material to generate an electrical output. Photon detectors are candidates to detect the stationary human body because they can detect the absolute quantity of infrared irradiation. High-performance miniaturized InSb photovoltaic infrared sensors (PVS) operating at room temperature have been reported [1].

However, to detect a stationary human body with high sensitivity, it is important that the spectral response of photon detectors be consistent with the infrared irradiation spectrum from the human body. The development of photon detectors having a spectral response in the range of 8–14 μm is thus required. $InAs_xSb_{1-x}$ hetero-junction photodiodes have been proposed for this [2,3], but insufficient sensitivity was obtained due to poor $InAs_xSb_{1-x}$ crystallinity and the Auger recombination process. The large lattice mismatch ($7.2\% < \Delta a/a < 14.6\%$) between $InAs_xSb_{1-x}$ and GaAs substrates makes it difficult to obtain a high crystallinity $InAs_xSb_{1-x}$ epilayer [4]. Poor crystallinity may decrease the lifetime of photo-excited carriers [5] and results in a low photocurrent (Ip). Moreover, high intrinsic carrier density in the $InAs_xSb_{1-x}$ absorber layer causes a high diffusion current and results in decreased resistance at zero bias (R_0). Because the signal-to-noise ratio (SNR) is proportional to $Ip\times R_0^{1/2}$ in photovoltaic mode, a decrease of Ip and R_0 results in low SNR.

In this work, we grew by metalorganic vapor phase epitaxy (MOVPE) an $InAs_xSb_{1-x}$ PVS for room temperature operation. To improve the sensitivity, it is important to improve the $InAs_xSb_{1-x}$ crystallinity, as the lifetime of a photo-excited carrier is likely to depend on crystallinity [5]. To reduce the lattice mismatch between $InAs_xSb_{1-x}$ and GaAs substrates, we used InSb as a buffer layer. The InSb buffer layer was grown using a two-step growth method that enables us to obtain high crystallinity and electrical transport properties [6]. Moreover, the potential barrier for electrons, formed by inserting a wide band gap layer such as AlInSb, is considered to suppress the diffusion of photo-excited electrons, resulting in an improvement of Ip and R_0 [7,8]. However, it is difficult to obtain high quality AlInSb by MOVPE due to C and O incorporation and pre-reactions between Al and Sb sources [9]. Therefore, we inserted a $Ga_{0.33}In_{0.67}Sb$ electron barrier layer as an alternative material in the $InSb/InAs_{0.12}Sb_{0.88}/InSb$ hetero-junction. We successfully grew $Ga_{0.33}In_{0.67}Sb$ coherently on an

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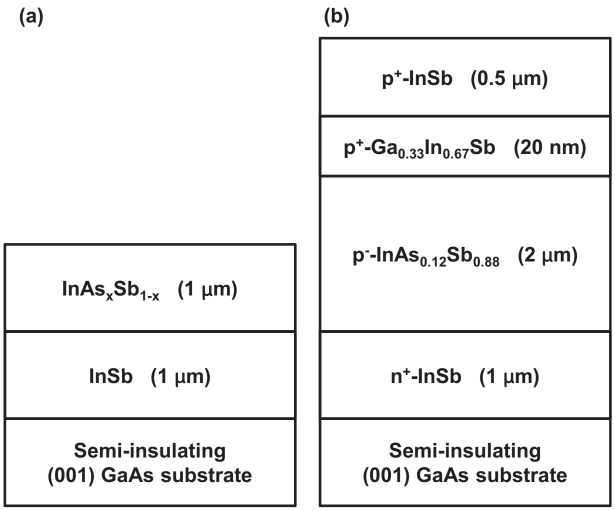

Fig. 1. Schematic diagrams of (a) $InAs_xSb_{1-x}$/InSb and (b) $InAs_{0.12}Sb_{0.88}$ PVS film structure.

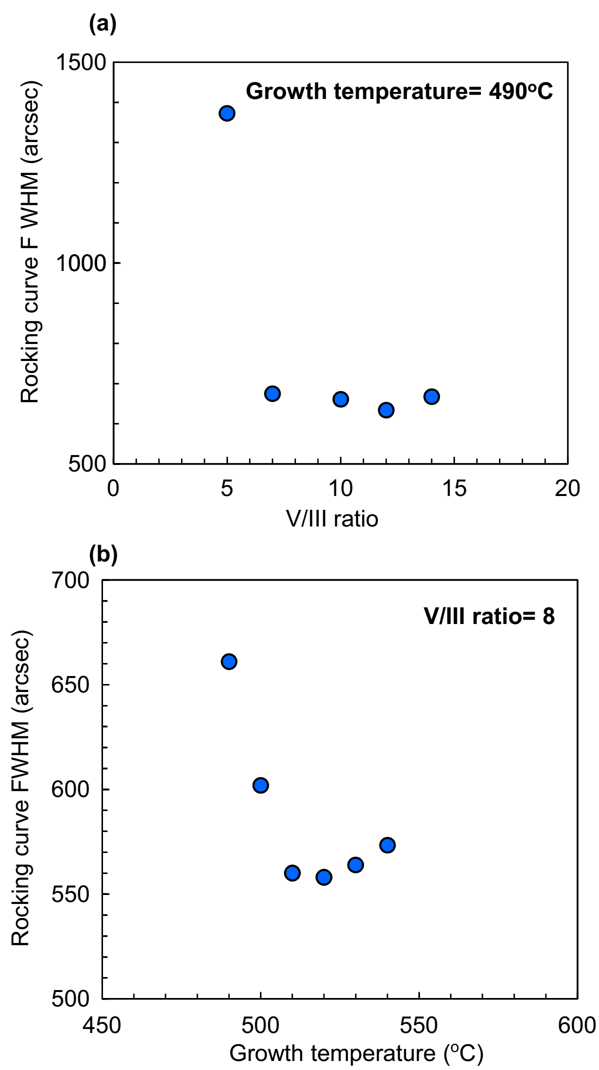

Fig. 2. Relations between the $InAs_{0.12}Sb_{0.88}$ (004) rocking curve FWHM and growth conditions: (a) V/III ratio, (b) growth temperature.

$InAs_{0.12}Sb_{0.88}$ absorber layer, which is the first report of $Ga_yIn_{1-y}Sb$ growth on Sb rich $InAs_xSb_{1-x}$. $InAs_{0.12}Sb_{0.88}$ PVS with sensitivity at wavelengths of 8–12 µm was obtained, and estimated detectivity peak at room temperature was approximately 7×10^7 cm $Hz^{1/2}$ W^{-1}.

2. Experimental procedures

2.1. Growth conditions study of $InAs_xSb_{1-x}$

$InAs_xSb_{1-x}$ was grown on semi-insulating GaAs (001) substrates by using a close-coupled showerhead reactor system. The 1-µm-thick InSb was utilized as a buffer layer, as shown in Fig. 1(a). Trimethylindium (TMIn), trisdimethylaminoantimony (TDMASb), and tertiarybutylarsine (TBAs) were used as In, Sb, and As sources, respectively. The growth pressure was maintained at 100 mbar with purified H_2 as a carrier gas. The growth temperature on the substrate surface was measured with a two-wavelength pyrometer. The InSb buffer layer was grown by a previously reported two-step growth method [6]. The 1-µm-thick $InAs_xSb_{1-x}$ was grown at various growth temperatures and V/III ratios with 2 µm/h growth rate while the growth condition of the InSb buffer layer was constant. The As content varies with V/III and growth temperature [10]. Therefore we changed the As/Sb ratio in order to obtain the same As content at each growth conditions.

The film thickness was estimated by X-ray fluorescence analysis. There is a proportional relationship between thickness of $InAs_xSb_{1-x}$ and intensity of secondary X-ray from In element. Therefore the intensity of secondary X-ray from In element was measured for these samples and reference sample, and the layer thickness was calculated from them. The crystallinity and As content of $InAs_xSb_{1-x}$ film were evaluated by X-ray diffraction measurements and the surface morphology was observed by atomic force microscopy (AFM).

2.2. Device fabrication and characterization

The $InAs_{0.12}Sb_{0.88}$ PVS film structure is shown in Fig. 1(b). It consists of a 1-µm-thick n^+-InSb layer followed by a 2-µm-thick p^--$InAs_{0.12}Sb_{0.88}$ absorber layer, a 20-nm-thick p^+-$Ga_{0.33}In_{0.67}Sb$ barrier layer, and a 0.5-µm-thick p^+-InSb top-contact layer. The growth pressure was maintained at 100 mbar with purified H_2 as a carrier gas. Triethylgallium (TEGa), diethylzinc (DEZn), and diethyltellurium (DETe) were used as Ga source, p-type, and n-type dopant, respectively. Other sources were the same materials as used in the growth conditions study of $InAs_{0.12}Sb_{0.88}$. The n^+-InSb layer was grown by a two-step growth method [6]. The p^--$InAs_{0.12}Sb_{0.88}$ absorber layer and the p^+-$Ga_{0.33}In_{0.67}Sb$ barrier layer were grown at the growth temperature of 520°C and V/III ratios of 8 and 5, respectively. Then, the top p^+-InSb contact layer was grown at the growth temperature of 500 °C and V/III ratio of 5. The growth rate of the InSb and $InAs_{0.12}Sb_{0.88}$ layers was 2 µm/h. The Zn concentrations of the p^- layer and p^+ layer were 1×10^{17} cm^{-3} and 3×10^{18} cm^{-3}, respectively. After MOVPE growth, the mesa structure was formed by photolithography and metals were deposited for the n-type and p-type contacts.

To confirm the lattice relaxation state of the $Ga_{0.33}In_{0.67}Sb$ barrier layer, XRD reciprocal space mapping measurement was carried out. The output voltage of $InA_{s0.12}Sb_{0.88}$ PVS was measured by using a 700 K blackbody with light chopping at room temperature. Infrared light was irradiated onto the backside (GaAs substrate side) of the sample. The chopping frequency was 10 Hz. The $InAs_{0.12}Sb_{0.88}$ PVS was operated in photovoltaic mode. R_0 is the averaged value of the resistance, obtained by applying a voltage of ±0.01 V to $InAs_{0.12}Sb_{0.88}$ PVS. Finally, the detectivity of the $InAs_{0.12}Sb_{0.88}$ PVS at room temperature was calculated by using output voltage and R_0 values [2,3].