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Problems in low-temperature grown polycrystalline InAs layers on glass and their relief by inserting GaSbAs buffer layers

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ABSTRACT

We investigated the thickness dependence of structural and electrical properties of polycrystalline InAs layers grown on glass substrates at a substrate temperature of 230 °C by molecular-beam deposition. Degradation in electron mobility with decreasing thickness is shown and is attributed not only to the decrease in crystallite size but also to the existence of a defective layer adjacent to the substrate. In order to investigate the effectiveness of GaSbAs as buffer layers on these problems, polycrystalline InAs layers of 0.1 μm thickness were gown with GaSbAs buffer layers of various thicknesses and alloy compositions inserted between the InAs layers and the substrates. It is shown that, in spite of the low substrate temperature of 300 °C and the thin thickness of 0.1 μm, the polycrystalline InAs film can exhibit an electron mobility as high as 600 $cm^2/(V\,s)$ by inserting a 0.5-μm thick GaSbAs buffer layer of an Sb composition around 0.6.

1. Introduction

In recent years, numerous studies have been devoted for fabricating thin-film transistors (TFTs) not only on glass substrates but also on plastic substrates. In our previous study [1] on polycrystalline InAs (poly-InAs) films grown by molecular-beam deposition (MBD), it has been shown that poly-InAs is a promising n-type semiconductor for TFTs on plastic substrates, since it can be deposited even at substrate temperatures as low as below 250 °C, while deposited films of 1 μm thickness exhibit mobilities as high as above 600 $cm^2/(V\,s)$ in spite of the low substrate temperatures. However, it has been commonly observed for polycrystalline films of many semiconductors that mobility of carriers is apt to decrease with decreasing thickness, while the appropriate thickness of the active layer of TFTs is around 0.1 μm. It is therefore necessary to check whether the poly-InAs films exhibit sufficiently high mobilities even at such thin film thicknesses. In the present study, we first examine the thickness dependence of structural and electrical properties of poly-InAs single layers in Section 2. On the other hand, the insertion of an electrically-inactive buffer layer is commonly used to improve the quality of the active layer, not only in homoepitaxy but also in heteroepitaxy for field-effect transistors. In another study of ours [2], it has been found that single-phase poly-GaSbAs can be deposited even on plastic substrates at a substrate temperature as low as 300 °C, whereas the poly-GaSb film contains the metallic Sb phase when deposited at such a low temperature. It has also been found there that the non-doped poly-$GaSb_xAs_{1-x}$ films exhibit p-type conduction in the whole studied range of Sb composition, x, between 0.34 and 1. Furthermore, $GaSb_xAs_{1-x}$ can be lattice-matched to InAs by adjusting the Sb composition, x, to 0.92. If $x \approx 0.92$ the hetero-growth of InAs on poly-$GaSb_xAs_{1-x}$ is expected to occur without any misfit dislocations at the InAs/$GaSb_xAs_{1-x}$ hetero-interface in each crystallite. Thus, p-type poly-$GaSb_xAs_{1-x}$ with $x \approx 0.92$ is considered as an ideal buffer layer for n-type poly-InAs. We therefore investigate the feasibility of using the p-type poly-GaSbAs as a buffer layer for n-type poly-InAs active layer in Section 3.

2. Thickness dependence of poly-InAs single layers

Non-doped poly-InAs films of various thicknesses were grown on glass substrates at a substrate temperature of 230 °C by MBD. The As/In beam equivalent pressure (BEP) ratio during the deposition was 12, and the deposition rate was 1.2 μm/h. Fig. 1(a) and (b) respectively show the volume concentration and the mobility of free electrons at 300 K in the poly-InAs films as a function of the film thickness. As can be seen in Fig. 1(a) and (b), the free-electron concentration does not so depend on the thickness, while the electron mobility decreases with decreasing thickness. The poly-InAs films thicker than 0.6 μm do exhibit high

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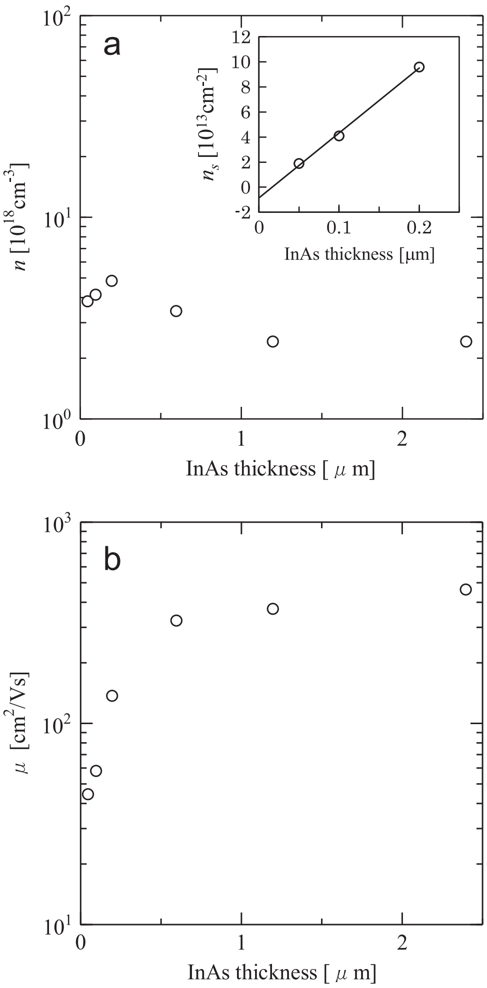

Fig. 1. (a) Volume concentration and (b) mobility of free electrons in the InAs single layer as a function of the thickness. The inset in (a) shows the sheet concentration of free electrons.

electron mobilities above 300 $cm^2/(V\,s)$, while thinner films than 0.1 μm exhibit only low electron mobilities below 60 $cm^2/(V\,s)$. The increase of mobility in polycrystalline semiconductor films with the film thickness has often been related to the increase in crystallite size with the film thickness [3]. Actually, the crystallite size estimated from the width of the (111) peak in the X-ray diffraction (XRD) pattern of our InAs samples was confirmed to increase from 13 to 26 nm when the film thickness was increased from 0.2 to 2.4 μm.

Besides the small crystallite size, another cause can be speculated for the low mobilities in our thin InAs films. In each of the XRD patterns of these InAs films, additional weak diffraction can be noticed at a diffraction angle of $2\theta = 24.0^\circ$ other than the usual diffraction peaks due to cubic InAs crystal. This weak diffraction is indexable as the $(10\bar{1}0)$ diffraction of the hexagonal wurtzite phase of InAs. Vlasov and Semiletov [4] observed the $(10\bar{1}0)$ diffraction of the hexagonal phase in the electron diffraction patterns of the InAs films deposited at substrate temperatures below 400 °C, and attributed it to the formation of staking faults in the cubic crystals. Farukhi and Charlson [5] pointed out that the amount of the hexagonal region will be sufficient to be noticeable in XRD patterns if periodic occurrence of stacking faults is introduced in some manner. Actually, the shift and the asymmetry of several XRD peaks suggested large densities of stacking faults in our InAs samples. The net stacking-fault probability in (hkl)-oriented crystallites $\alpha^{SF}_{(hkl)} = \alpha^{ISF}_{(hkl)} - \alpha^{ESF}_{(hkl)}$ ($\alpha^{ISF}_{(hkl)}$ and $\alpha^{ESF}_{(hkl)}$ being intrinsic and extrinsic stacking-fault probabilities, respectively) can be estimated through a peak-shift analysis of XRD [6]. For the (111)-oriented crystallites of our InAs sample deposited at 230 °C, the net stacking-fault probability $\alpha^{SF}_{(1\,1\,1)}$, was estimated to be as high as 0.02. Such a high density of stacking faults may be an additional cause of the low electron mobilities in the very thin films of poly-InAs deposited at the low substrate temperatures.

Furthermore, as shown in the inset of Fig. 1(a), when the sheet concentration of free electrons in the InAs films is plotted against the film thickness, the plotted data for our InAs samples with thicknesses of 0.05, 0.1, and 0.2 μm almost lie on a straight line, and the intersection of the extrapolated straight line with the abscissa indicates the existence of a depletion layer of about 0.016 μm in thickness adjacent to the substrate. This can explain the decrease in the apparent volume concentration of free electrons with decreasing thickness observed for the plotted data of the thinnest three samples in Fig. 1(a). A high density of defects generated in the early stage of the deposition, such as stacking faults, may be the cause of the interfacial depletion layer. In order to improve the electron mobility in low-temperature grown poly-InAs thin films of thickness of the order of 0.1 μm, it is necessary not only to increase the crystallite size but also to eliminate the interfacial defective layer. For this purpose, we inserted the poly-GaSbAs layer as the buffer layer between the poly-InAs layer and the substrate, as described in the next section.

3. Effects of poly-GaSbAs buffer layers

InAs layers of 0.1-μm thickness were deposited on glass substrates by MBD with $GaSb_xAs_{1-x}$ ($0 \le x \le 1$) as the buffer layers between the InAs layers and the substrates. The BEPs of In, Ga, and As were fixed at about 9×10^{-8}, 5×10^{-7}, and 2×10^{-6} Torr, respectively. These BEPs of In and Ga resulted in the growth rates of 0.2 and 1 μm/h for InAs and GaSbAs, respectively. The As/In BEP ratio of 22 used here is rather high for the InAs deposition to achieve high electron mobility [1], but was adopted so as to ensure the group-V stabilized surfaces during the deposition of the $GaSb_xAs_{1-x}$ buffer layers even with $x=0$. In the first series of deposition (Series A), the cell temperature of Sb was fixed so that the Sb composition, x, of the $GaSb_xAs_{1-x}$ buffer layers was fixed at about 0.9, while the thickness of the buffer layers was changed from 0 to 1 μm by changing the deposition time. On the contrary, the deposition time was fixed at 0.5 h so that the thickness of the buffer layers was fixed at 0.5 μm, while the Sb composition, x, of the $GaSb_xAs_{1-x}$ buffer layers was changed from 0 to nearly 1 by changing the BEP of Sb in the second series of deposition (Series B). The substrate temperature was kept at 300 °C through the deposition of the $GaSb_xAs_{1-x}$ ($0 \le x < 1$) buffer layers and the InAs top layers. On the other hand, for the deposition of the sample with a GaSb buffer layer of 0.5 μm, the substrate temperature was set to 450 °C for the deposition of the GaSb buffer layer, since the GaSb layer would contain the metallic Sb phase when deposited below 400 °C [2]. After completing the deposition of the GaSb layer, the substrate temperature was lowered to 300 °C for the deposition of 0.1-μm thick InAs.

XRD measurements were performed for estimating the alloy composition of the GaSbAs buffer layers through the Nelson–Riley plots [2]. Fig. 2 shows the semi-log plots of the XRD patters of the samples in Series A with the buffer layers of different thicknesses. Arrows in the figure indicate diffraction angles for the reflections from various diffraction planes of cubic InAs with the lattice constant of the bulk value. In the XRD pattern of the sample with the 0.25-μm thick buffer layer, the diffraction peaks of the GaSbAs buffer layer cannot be resolved from those of the InAs layer,