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Growth of very-high-mobility AlGaSb/InAs high-electron-mobility transistor structure on si substrate for high speed electronic applications

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The growth of the AlGaSb/InAs high-electron-mobility transistor (HEMT) epitaxial structure on the Si substrate is investigated. Buffer layers consisted of UHV/chemical vapor deposited grown Ge/GeSi and molecular beam epitaxy-grown AlGaSb/AlSb/GaAs were used to accommodate the strain induced by the large lattice mismatch between the AlGaSb/InAs HEMT structure and the Si substrate. The crystalline quality of the structure grown was examined by x-ray diffraction, transmission electron microscopy, and atomic force microscopy. Finally, very high room-temperature electron mobility of 27 300 cm^2/V s was achieved. It is demonstrated that a very-high-mobility AlGaSb/InAs HEMT structure on the Si substrate can be achieved with the properly designed buffer layers. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2431567]

Integration of III-V semiconductors on Si substrates has been investigated for microwave and millimeter-wave devices and monolithic integrated circuits in the past.[1–5] Recently, the growth of compound semiconductor heterostructures on Si substrates has attracted continuous attention because of the possible integration of III-V device on Si substrates for logic applications. The use of GaAs-on-Si to replace GaAs substrate has the following advantages: high thermal conductivity, potential wafer-size expansion, mechanical hardness of substrates, and lower cost for Si substrates.[5–7] For high speed electronic applications, antimony (Sb)-based high-electron-mobility transistors (HEMTs) with InAs channel layer have been studied in recent years.[8–12] The InAs layer was chosen as the channel material for the HEMT due to its high electron mobility and high quantum confinement in the channel region. In this letter, the growth of the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT on Si substrate for high speed electronic application is studied.

There are two problems to be overcome for the growth of high-quality $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT epitaxial layers on Si substrate. One is the strain induced by the large lattice mismatch of 11% between the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure and the Si substrate, the other is the residual stress due to the large difference in the thermal expansion coefficients of these two material systems.[13] To obtain high quality the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT on Si, two buffer layers of $Ge/Ge_{0.95}Si_{0.05}/Ge_{0.9}Si_{0.1}$, and $Al_{0.5}Ga_{0.5}Sb/AlSb/GaAs$ were used. First, the $Ge/Ge_{0.95}Si_{0.05}/Ge_{0.9}Si_{0.1}$ layer was used as the buffer layer for the growth of GaAs on Si substrate, because Ge and GaAs have similar lattice constants and thermal expansion coefficients.[13] Then, the $Al_{0.5}Ga_{0.5}Sb/AlSb$ layers were grown to accommodate the strain induced by the large lattice mismatch between the $Al_{0.5}Ga_{0.5}Sb/InAs$ system and the GaAs layer.[10] The crystalline quality of the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure grown on Si was analyzed by X-ray diffraction analysis, transmission electron microscopy (TEM), and atomic force microscopy (AFM). The thickness of the epitaxial layers, the dislocation distribution, and the threading dislocation density were evaluated using the above analytical tools. A very high room-temperature electron mobility of 27 300 cm^2/V s and a sheet density of $3.04\times10^{12}/cm^2$ for the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure grown on the Si substrate were obtained.

The $Al_{0.5}Ga_{0.5}Sb/InAs$ structure grown on Si is shown in Fig. 1. A Si (100) substrate wafer with 6° off-cut toward the [110] direction and three epitaxial growth systems were used for the growth of the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure on Si in this study. First, an ultrahigh vacuum chemical vapor deposition (CVD) system was used to grow the $Ge/Ge_{0.95}Si_{0.05}/Ge_{0.9}Si_{0.1}$ layers. Then, a thin GaAs film was grown by a commercial metal organic chemical vapor deposition (MOCVD).[13] Finally, the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure was grown by a molecular beam epitaxy (MBE) system.

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GaSb	3 nm
$Al_{0.5}Ga_{0.5}Sb$	13 nm
InAs	15 nm
$Al_{0.5}Ga_{0.5}Sb$	50 nm
GaSb/AlSb	(2.5 nm/2.5 nm) x 10
$Al_{0.5}Ga_{0.5}Sb$	1 μ m
GaSb/AlSb	(2.5 nm/2.5 nm) x 10
AlSb	100 nm
GaAs	1 μ m (by MBE)
GaAs	1.5 μ m (by MOCVD)
Ge	1 μ m
$Si_{0.05}Ge_{0.95}$	0.8 μ m
$Si_{0.1}Ge_{0.9}$	0.8 μ m
Si substrate	

FIG. 1. Structure of the AlGaSb/InAs HEMT grown on the Si substrate.

For the $Ge/Ge_{0.95}Si_{0.05}/Ge_{0.9}Si_{0.1}$ layer growth, the Si substrate was first cleaned by 10% HF dipping and then went through high-temperature baking at 800 °C in the growth chamber for 5 min. Then, a 0.8 μm $Si_{0.1}Ge_{0.9}$ layer, a 0.8 μm $Si_{0.05}Ge_{0.95}$ layer, and a 1.0 μm Ge layer were grown at 400 °C in sequence on the Si wafer as the buffer layer.[13] After that, a 1.5 μm GaAs layer was grown on Ge at a temperature of 600 °C by MOCVD. The growth conditions of GaAs are as follows: growth pressure is 40 torr, V/III ratio is 100, and growth rate is 1.7 μm/h.[13] Finally, the $Al_{0.5}Ga_{0.5}Sb$/InAs HEMT was grown on top of the Ge layer by MBE system and the wafer was baked at 630 °C for 1 min before the growth. The growth of the $Al_{0.5}Ga_{0.5}Sb$/InAs HEMT structure can be divided into two major parts: buffer layer growth and InAs channel layer growth. The growth of the buffer layers includes a GaAs layer, an AlSb layer, two GaSb/AlSb supperlattice, and two $Al_{0.5}Ga_{0.5}Sb$ layers; the buffer layers were grown before the channel region to accommodate the 7% lattice mismatch between the $Al_{0.5}Ga_{0.5}Sb$/InAs HEMT structure and the Ge layer. The growth temperature of the buffer layers was set at 560 °C. A 1 μm GaAs layer was grown on Ge first. After that, a 100 nm AlSb layer, a superlattice of 50 nm with ten pairs of GaSb/AlSb, and a 1 μm $Al_{0.5}Ga_{0.5}Sb$ were grown layer by layer. Then, 50 nm GaSb/AlSb superlattice (ten pairs), a 50 nm $Al_{0.5}Ga_{0.5}Sb$ layer, a 15 nm InAs layer, a 13 nm $Al_{0.5}Ga_{0.5}Sb$ layer, and a 3 nm GaSb layer were grown. To obtain good quality InAs channel layer, the growth temperature was set at 520 °C after the growth of the $Al_{0.5}Ga_{0.5}Sb$ layer. The growth rate of InAs channel layer was 1.5 Å/s, and the 13 nm $Al_{0.5}Ga_{0.5}Sb$ layer and the 3 nm GaSb layer are the Schottky layer and the cap layer, respectively. The $Al_{0.5}Ga_{0.5}Sb$/InAs HEMT on Si structure grown is shown in Fig. 1.

We have reported the use of SiGe buffer layer for the growth of Ge on top of Si substrate before.[13] Because the $Ge/Ge_{0.95}Si_{0.05}/Ge_{0.9}Si_{0.1}$ interface can be used to accommodate the strain induced by the large lattice mismatch, the upwardly propagated dislocations were bent sideward and terminated very effectively at the $Si_{0.05}Ge_{0.95}/Si_{0.1}Ge_{0.9}$ and $Ge/Si_{0.05}Ge_{0.95}$ interfaces. Almost no threading dislocation can propagate into the top Ge layer.[13] Figure 2 shows the cross-sectional TEM images of the $Al_{0.5}Ga_{0.5}Sb$/InAs HEMT on Ge with SiGe buffer layer, the interfaces of buffers were quite smooth as shown in this figure. Figure 3 presents the TEM micrograph of the InAs layer. As can be seen in this figure, the defect density in the InAs layer was very low.

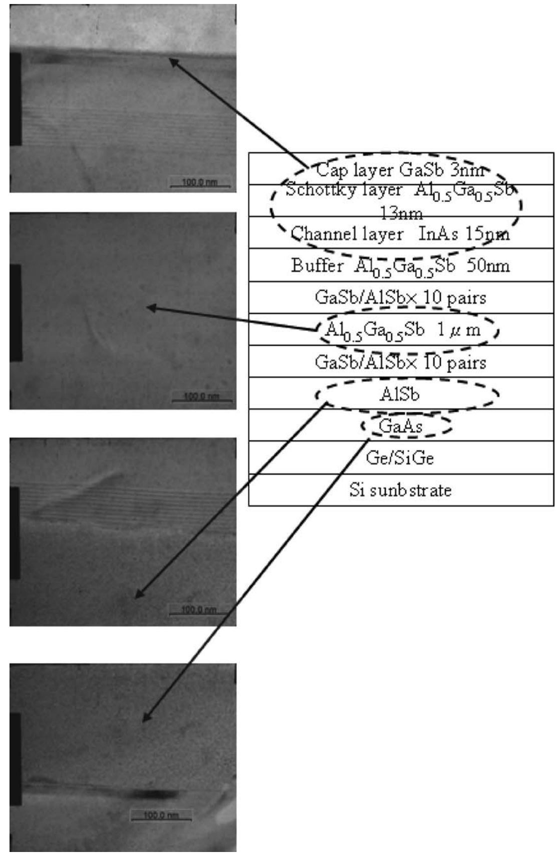

FIG. 2. Cross section of the TEM images of the AlGaSb/InAs HEMT on Si substrate.

The surface roughness of the $Al_{0.5}Ga_{0.5}Sb$/InAs HEMT grown on Si wafer was compared to the $Al_{0.5}Ga_{0.5}Sb$/InAs HEMT structure grown on the GaAs substrate. Figure 4 presents the AFM images of the two different substrate wafers. No cross-hatching patterns were observed on the wafer surface. The root mean square (rms) of the $Al_{0.5}Ga_{0.5}Sb$/InAs HEMT on Si wafer surface was 19.1 Å, in comparison with

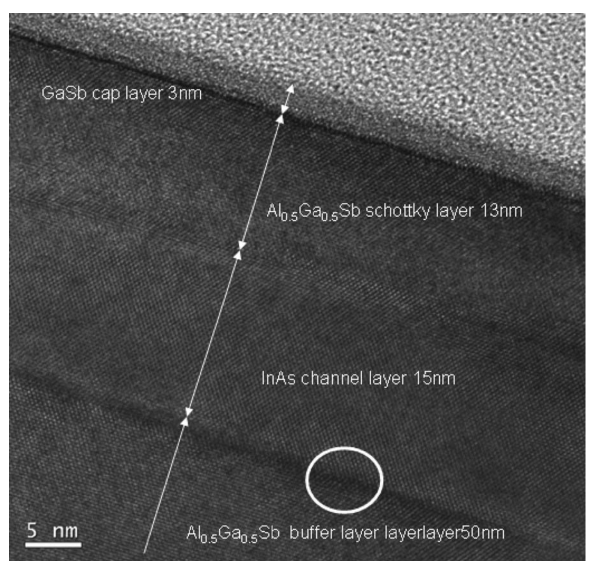

FIG. 3. Cross section of the TEM images of the InAs layer in the AlGaSb/InAs HEMT grown on Si substrate.

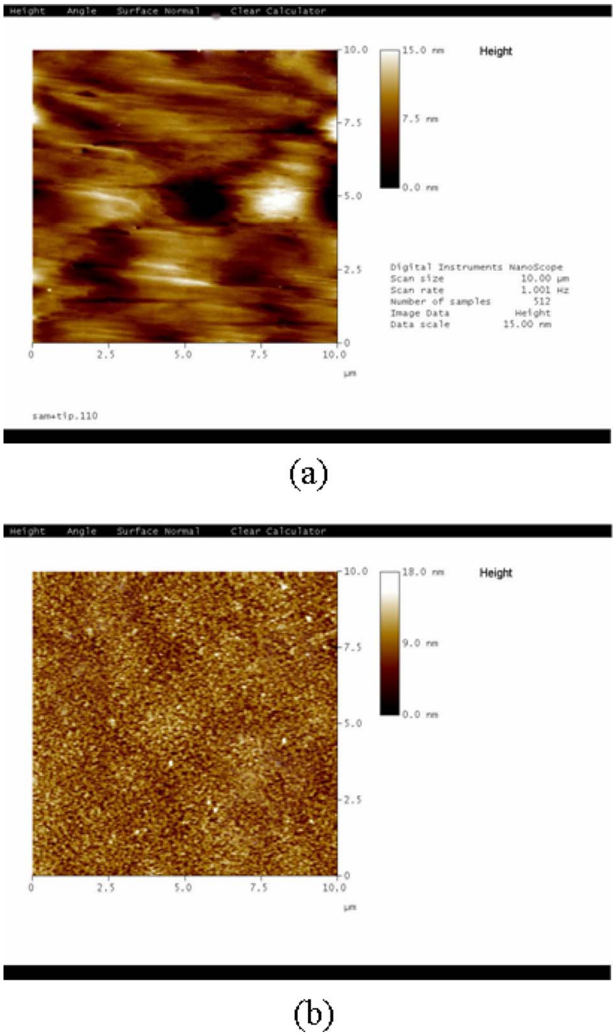

FIG. 4. Surface morphology of (a) the AlGaSb/InAs HEMT structure grown on Si substrate and (b) the AlGaSb/InAs HEMT structure grown on GaAs substrate.

rms of 15.5 Å for the surface of $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT on GaAs substrate wafer. Figure 5 is the x-ray diffraction curve of the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure on Si substrate wafer. The diffraction pattern has seven major peaks and was identified as GaAs, Ge, Si, AlGaSb, InAs, AlSb, and GaSb peaks, respectively. It indicates that the crystalline quality of the HEMT epitaxial layers is very good. Very high room-temperature electron mobility of 27 300 $cm^2/V\ s$ and a sheet density of $3.04\times10^{12}/cm^2$ were measured for the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure grown on the Si substrate due to the high-quality epitaxial layers grown. It is demonstrated that a very-high-mobility $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure can be grown on Si substrate with properly designed $Al_{0.5}Ga_{0.5}Sb/AlSb/GaAs$ and SiGe buffer layers.

The growth of the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure on Si substrate is reported in this letter. We have designed an $Al_{0.5}Ga_{0.5}Sb/AlSb/GaAs$ and SiGe buffer structures for the growth of the high-quality $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure on the Si substrates. The cross-sectional TEM images of the AlGaSb/InAs HEMT on Ge show very smooth interfaces of the structure grown and low defect density InAs channel layer. The AFM images of the wafer show no cross-hatching pattern and bending on the wafer surface. The root mean square (rms) of the surface roughness of the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT on Si wafer surface was 19.1 Å.

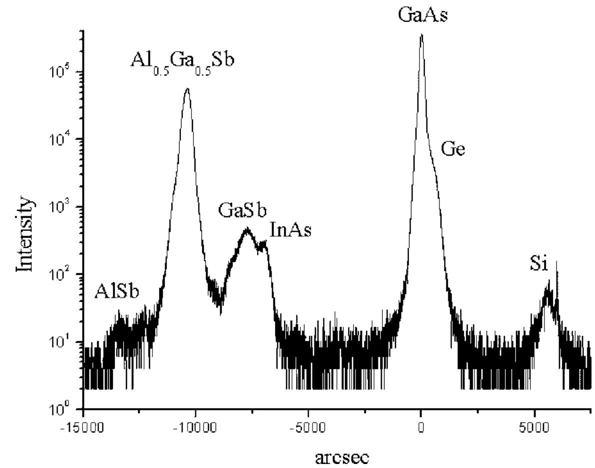

FIG. 5. Double crystal x-ray diffraction patterns of the AlGaSb/InAs HEMT on Si substrate.

The x-ray diffraction patterns of the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure on Si substrate wafer exhibited clearly seven major peaks and the diffracted peaks indicated that the crystalline quality of the HEMT structure was very good. The room-temperature electron mobility of 27 300 $cm^2/V\ s$ and a sheet density of $3.04\times10^{12}/cm^2$ were achieved for the $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT grown on Si substrate using $Ge/Ge_{0.95}Si_{0.05}/Ge_{0.9}Si_{0.1}$ as the buffer layer. This is the highest mobility for a HEMT structure grown on Si substrate reported so far and we have demonstrated that a very-high-mobility $Al_{0.5}Ga_{0.5}Sb/InAs$ HEMT structure can be grown on Si substrate if the buffer layers are properly designed.

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