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Effects of Si doping on the strain relaxation of metamorphic (Al)GaInP buffers grown on GaAs substrates

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ABSTRACT

We investigate the effects of Si doping on the strain relaxation of the compositionally step-graded (Al)GaInP buffers grown by metal-organic chemical vapor deposition on (0 0 1) GaAs substrates with different miscuts toward (1 1 1)A. It is found that in the 2° samples, high Si doping can reduce both the α and β dislocation densities by delaying and suppressing the formation of phase separation in the buffer. In contrast, in the 7° samples, Si dopants deteriorate the buffer quality through increasing the dislocation density accompanying with the tilt reduction along the [1 1 0] direction, and a striking feature, bunches of β dislocations away from the interfaces, is observed in the [1 1 0] cross-sectional transmission electron microscopy images. A cross-slip mechanism closely associated with the pinning effect of Si on α dislocation motion is proposed to explain the multiplication of β dislocations. These results indicate that selecting a moderate Si doping density and substrate miscut are critical for the design and fabrication of metamorphic optoelectronic devices.

1. Introduction

The lattice-mismatched growth technique has often been utilized to realize the pseudosubstrates with suitable surface lattice parameter, applied to the optoelectronic and electronic devices with the desired energy band-gap [1–4]. Such pseudosubstrates are obtained by growing compositionally graded but nearly strain relaxed metamorphic buffer layers on the commercially available substrates. In the metamorphic buffer, strain is mainly relieved by 60° dislocations, including α dislocations with line direction along $[1\bar{1}0]$ and β dislocations along [1 1 0] and accompanying with the generation of threading dislocations (TDs). Acting as the carrier nonradiative recombination and scattering centers [5,6], TDs are detrimental to the minority-carrier devices, such as solar cells, light emitting diodes (LEDs), and lasers. Therefore, it is critical to promote the glide of MDs while bring down the TD density as far as possible.

To obtain high quality metamorphic buffer, the growth conditions, i.e., growth temperature, growth rate, and V/III ratio, have been extensively investigated. Besides those, doping also has a great effect on the strain relaxation of the buffer. Tångring et al. have demonstrated 1.27 μm metamorphic InGaAs quantum well ridge waveguide lasers with a threshold current of 60 mA at 300 K for a $4 \times 1500\,\mu m^2$ cavity using a compositionally linear-graded Be-doped InGaAs buffer layer, while no lasing was achieved on a Si-doped buffer [7]. Compared with undoped graded buffers, the use of Be dopant significantly improves the structural, surface, and optical qualities, but the Si doping plays an opposite role [8,9]. Meanwhile, in GaN films, Si dopants limit the dislocation movement and the relief of the tensile stress developed during the growth, probably due to the formation of Si impurity atmospheres at the dislocations [10]. Although Be doping can give much freedom to design the metamorphic devices, it may lead to low electric conductivity due to the low hole mobility and more important, there is no Be source available in the metal-organic chemical vapor deposition (MOCVD) system. In comparison, Si as a conventional n-type dopant is beneficial to improve the electric conductivity and reduce the series resistance. In this paper, we investigate the effects of Si doping on the strain relaxation of the metamorphic $((Al)Ga)_{1-x}In_xP$ ($x = 0.48$–0.78) buffers grown on GaAs substrates with different miscuts toward (1 1 1)A. In the 2° sample, high Si doping greatly reduces the TD density in the buffer. In contrast, it exerts an adverse effect on the 7° samples, which means that heavy doping largely increases the TD density, especially the density of β dislocations. Then, the questions are how the Si dopants affect the dislocations and why the doping influences vary with different substrate miscuts in the metamorphic (Al)GaInP buffer, and they are considered in this paper.

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Table 1
Strain relaxation rate of the InGaAs cap layers in the [1 1 0] and [1 $\bar{1}$ 0] directions.

	UD2	UD7	HD2	HD7
[1 1 0]	95.1%	96.6%	95.8%	96.9%
[1 $\bar{1}$ 0]	96.0%	94.8%	96.1%	93.0%

2. Experimental

All the samples under investigation were grown by an Aixtron 200/4 horizontal low-pressure (100 mbar) MOCVD system on Si-doped (0 0 1) GaAs substrates with 2° or 7° miscuts toward (1 1 1)A which cause surface steps terminated with group III atoms. The carrier gas was Pd-diffused hydrogen (H_2) and the precursors included phosphine (PH_3), arsine (AsH_3), trimethylgallium (TMGa), trimethylaluminum (TMAl), and trimethylindium (TMIn) along with silane (SiH_4) as the n-type dopant source. The metamorphic (Al)GaInP buffer consisted of a lattice-matched 0.1 μm $Ga_{0.51}In_{0.49}P$, followed by nine $Ga_{1-x}In_xP$ layers step graded from x = 0.52–0.75 with each step layer 0.2 μm thick and nominally 0.22% lattice mismatched to the proceeding one and then a 0.6 μm thick $(Al_{0.3}Ga_{0.7})_{0.22}In_{0.78}P$ layer as the top buffer layer. The buffer layers were grown at 610 °C while a lattice-matched 1 μm thick undoped $In_{0.3}Ga_{0.7}As$ cap layer was grown at 675 °C on the top buffer. The samples can be classified into three types according to the doping levels of the buffer, i.e., the undoped (UD) samples, the lowly doped (LD) samples with a doping density of 5×10^{17} cm^{-3}, and the highly doped (HD) samples with a doping density of 1.5×10^{18} cm^{-3}. Meanwhile, the InGaAs cap layers were undoped and each type included samples grown in the same run on the 2° and 7° substrates. Compared to the UD samples, the influences of Si doping on the properties of the metamorphic buffer in the LD samples are unobvious. Thus, we mainly discuss about the UD and HD samples in this paper.

The strain relaxation rate and the threading dislocation densities of the InGaAs cap layers were evaluated through the (2 2 4) and (0 0 4) rocking curves with the incident X-ray beam along the [1 1 0] and [1 $\bar{1}$ 0] directions using a high resolution Bruker D8 Discover X-ray diffractometer. The tilt between the epilayers and the substrate was obtained from the symmetric (0 0 4) reciprocal space mappings (RSMs) with the incident X-ray beam along the [1 1 0] direction. The sample microstructures were characterized by cross-sectional transmission electron microscopy (TEM) using a Tecnai G2 F20 S-Twin microscope operated at 200 kV. For TEM characterization, the samples were cleaved along ⟨1 1 0⟩ directions and polished to about 10 μm, then thinned by ion milling. The composition analysis was performed using scanning transmission electron microscopy (STEM) with a HAADF detector.

3. Results

Fig. 1(a) and (b) shows the (0 0 4) rocking curves of the InGaAs cap layers on 2° and 7° substrates, respectively, with the incident X-ray beam along the [1 1 0] and [1 $\bar{1}$ 0] directions and the full width at half maximum (FWHM) was summarized in Fig. 1(c). Each FWHM was the average value of four times measurements at different positions of the samples. As displayed in Fig. 1(c), the FWHM of the HD samples on 2° substrates (HD2) in both [1 1 0] and [1 $\bar{1}$ 0] directions decrease greatly in comparison with those of the UD samples on 2° substrates (UD2). Whereas an opposite tendency was observed in the samples on 7° substrates. Table 1 shows that the strain relaxation of the InGaAs cap layers in all the samples was above 92% in the range of ± 3% error in ⟨1 1 0⟩ directions, indicating that the broadening of the (0 0 4) rocking curves was mainly attributed to the dislocations rather than strain field. The square of the FWHM of the (004) rocking curves with the incident beam along the [110]

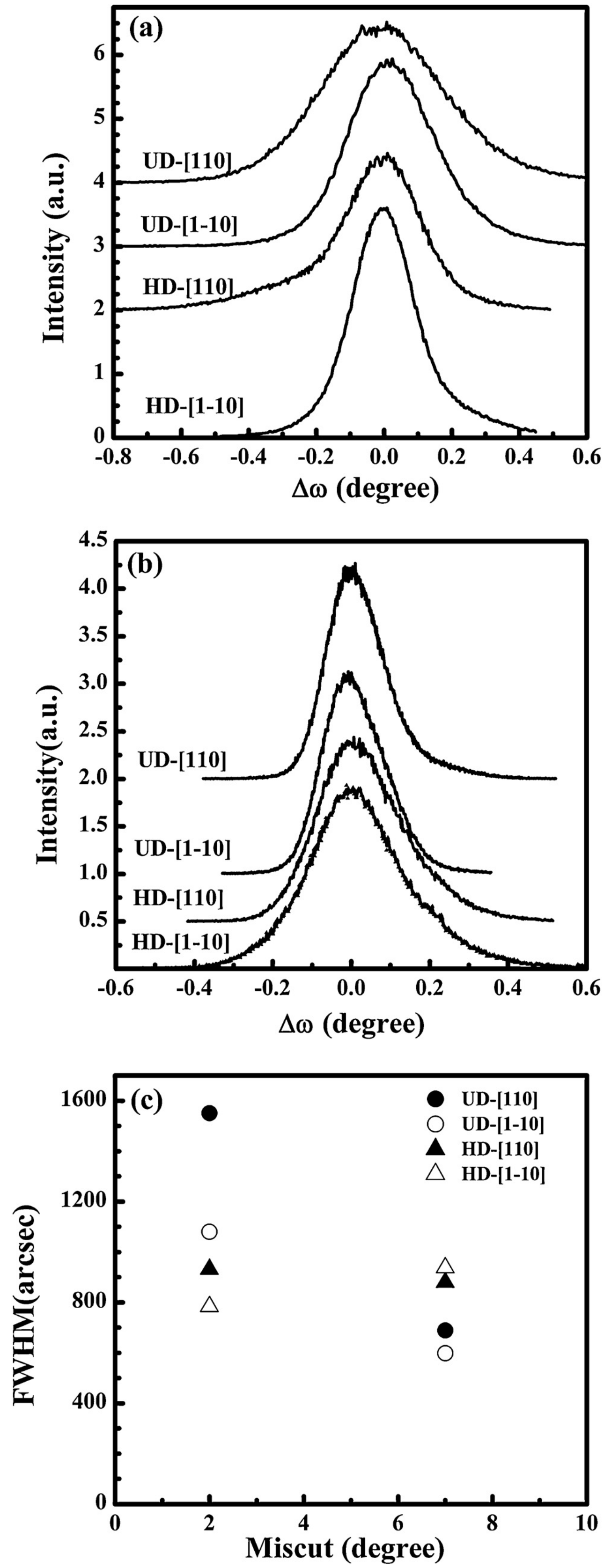

Fig. 1. The (0 0 4) rocking curves of the InGaAs cap layers of the samples on 2° substrates (a) and 7° substrates (b) with the incident X-ray beam projection along the [1 1 0] and [1 $\bar{1}$ 0] directions. The FWHM of the (0 0 4) rocking curves were summarized in (c).