# Electrical and Structural Properties of Low-Temperature-grown $In_{0.53}Ga_{0.47}As$ on GaAs using an InGaAlAs Metamorphic Buffer

Seong June Jo, Soo-Ghang Ihn,Tae-Woo Kim, Ki-Ju Yee[†],
Moon-Seop Hwang[†], Dong-Han Lee[†], and Jong-In Song*

Dep. of Information and Communications, Gwangju Institute of Science and Technology (GIST),
1 Oryong-dong, Buk-gu, Gwangju, 500-712, Korea
[†]Dept. of Physics, Chungnam National University,
220 Gung-dong, Yuseong-gu, Daejeon, 305-764, Korea
Phone: +82-62-970-2277
Fax : +82-62-970-2204
*Email: jisong@gist.ac.kr

*Abstract* — **Electrical and structural properties of low-temperature-grown $In_{0.53}Ga_{0.47}As$ (LT-InGaAs) on GaAs using an InGaAlAs metamorphic buffer (M-buffer) were studied. Dependence of carrier lifetime of the LT-InGaAs on post thermal annealing was also investigated. Utilization of residual dislocation in the LT-InGaAs on the M-buffer was effective in reducing the carrier lifetime, producing the carrier lifetime of 2.14 ps that is comparable to that of the Be-doped LT-InGaAs.**

## I. INTRODUCTION

Photoconductors having a picosecond or subpico-second recovery time are used for applications including ultra-fast optical switching[1], terahertz signal detection[2], and subpicosecond phenomena measure-ments[3]. Since the dynamic response of a photo-conductor is primarily limited by the carrier lifetime, there have been efforts to produce a ultrashort carrier lifetime in various compound semiconductor materials. The most commonly used technique to achieve a ultrashort carrier lifetime is low temperature growth. Low-temperature-grown GaAs (LT-GaAs) shows a fast response (< 1 ps) and a good electric performance due to its high density of point defects such as As antisites, As interstitials, and Ga-related vacancies[4]. However, undoped low-temperature-grown InGaAs (LT-InGaAs) has a longer carrier lifetime (> 100 ps) since the density of point defects in the LT-InGaAs is much lower than that of the LT-GaAs[4]. The carrier lifetime of LT-InGaAs grown on InP substrate can be reduced by Be-doping that increases the effective density of defects[5]. The metamorphic buffer (M-buffer) growth technique, which offeres design flexibility of an $In_xGa_{1-x}As/In_yAl_{1-y}As$ heterostructures on GaAs substrate, can be potentially utilized for achieving ultra-short carrier lifetime of LT-InGaAs grown on the M-buffer, since the M-buffer can provide the LT-InGaAs with increased effective defect density due to residual dislocation.

In this paper, we investigate electrical and structural properities and carrier lifetime of LT-InGaAs in the wavelength region of 1550 nm grown on an M-buffer (on GaAs substrate).

## II. EXPERIMENTAL RESULTS

Samples, shown in Fig. 1, were grown by a VG-80H molecular beam epitaxy (MBE) on (001) GaAs substrates at 400 °C. They consist of, from bottom to top, a 1.1 μm $In_x(Ga_{0.18}Al_{0.82})_{1-x}As$ ($x = 0.05 \rightarrow 0.6$) linear graded metamorphic buffer, a 300 nm $In_{0.52}Al_{0.48}As$ buffer, a 300 nm $In_{0.53}Ga_{0.47}As$, and a 40 nm $In_{0.52}Al_{0.48}As$ cap layer. The M-buffer layer was grown at the growth rate of 0.56 μm/h under the V/III ratio of 9, maintaining a (2×1) reflection of high energy electron diffraction pattern. To avoid oxidation of Al rich layer and to increase the growth rate, gallium (18 %) was added from the initial stage of the M-buffer growth. The M-buffer was graded with an indium composition gradient of approximately 49 %/μm and terminated with an inverse step (IS) for effective relaxation of residual strains in the M-buffer layer[6]. After the growth, the samples were annealed at 550, 600, 650, 700, and 750 °C for 30 sec under $N_2$ environment in an RTA system.

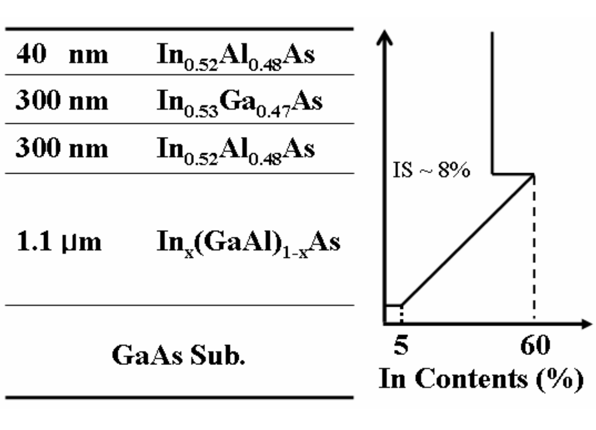


Fig. 1. Eptaxial layer structure of the LT-InGaAs and InGaAlAs M-buffer grown on GaAs.

The LT-InGaAs on M-buffer had n-type conductivity and carrier concentrations of $4.68\times10^{17}/cm^3$ while the LT-InGaAs grown at 250 °C on InP had rather high carriers concentrations of $7.93\times10^{17}/cm^3$. In addition, the electron mobility of the LT-InGaAs on M-buffer was 2180 $cm^2/V\cdot s$, while that of the LT-InGaAs on InP was 914 $cm^2/V\cdot s$. Difference in the electrical properties of these materials were attribuited to the growth temperature. In general, higher growth temperature gives higher electron mobility and lower carrier concentrations.

Structural properties of the LT-InGaAs layer were studied by high resolution double crystal x-ray diffraction and 10 K photoluminescence (PL) measurements. In-plane ($a_p$) and out-of-plane ($a_v$) lattice constants of the samples were examined to determine the alloy composition, lattice mismatch, and fractional relaxation rate in the LT-InGaAs layer using (004) and (115) reflections. Fig. 2 shows dependence of the in-plane, out-of-plane, free standing ($a_o$) lattice constants, and indium composition of the LT-InGaAs layer on the annealing temperature. Unlike most of high-temperature-grown InGaAs (HT-InGaAs) layers grown on an M-buffer that have a high fractional relaxation rate (over ~ 80 %)[7], the fractional relaxation rate of the as-grown LT-InGaAs was 64 % and increased up to approximately 80 % as the annealing temperature was increased. The increased fractional relaxation rate in the annealed LT-InGaAs is attributed to the increased relaxation of compressive strain through annihilation and fusion of mobile threading dislocations as the annealing temperature was increased. From the reciprocal space maps (RSM), tilt of the graded buffer layer was observed in the as-grown LT-InGaAs in Fig. 3. There are two possible causes for the tilt in the graded metamorphic buffer layer. The first one is a miscut of substrate that introduces surface step. If the epitaxial layer is coherent in the growth direction, the lattice constant in the growth direction changes from that of the substrate at the riser of the step to $a^{\perp}_{epi}$ over the width of the step[7]. The epitaxial layer orientation is aligned to the off-cut direction. However, since the epitaxial layer was grown on (001) ± 0.1° substrate, the tilt from the miscut orientation of substrate can be ignored.

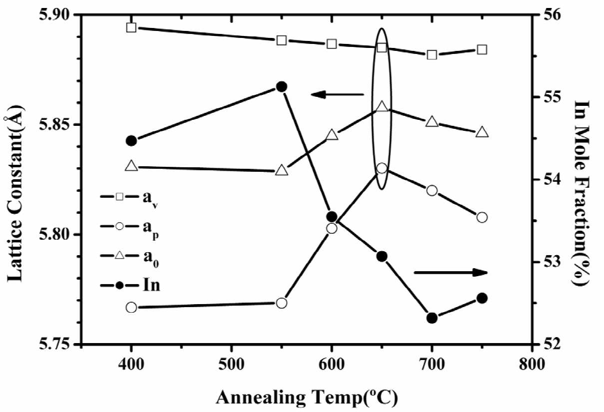


Fig. 2. Annealing temperature dependency of in-plane ($a_p$) and out-of-plane ($a_v$) lattice constant. The free standing ($a_o$) lattice constant and indium composition were calculated from $a_p$ and $a_v$.

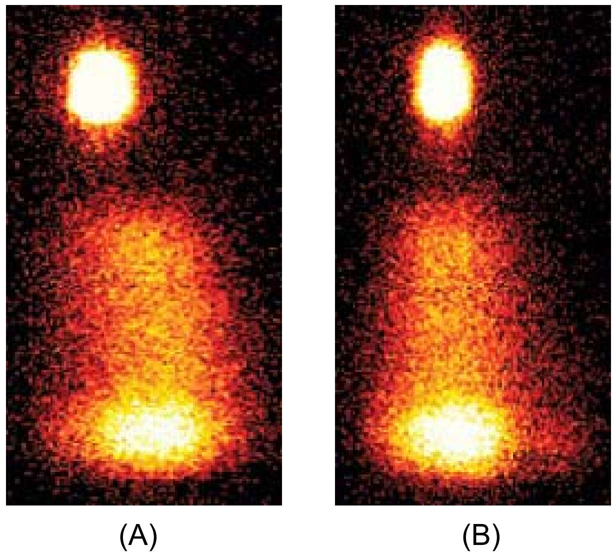


Fig. 3 The reciprocal space maps of LT-InGaAs. (A)As-grown, (B) Annealing at 650 °C for 30 sec.

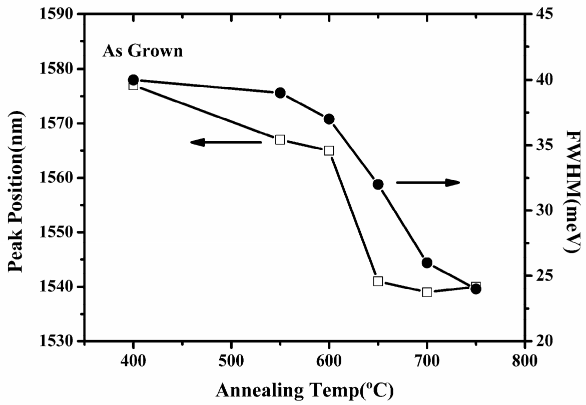


Fig. 4. Peak position and full-width-at-half-maximum (FWHM) of the LT-InGaAs samples obtained from 10K PL measurements as a function of the annealing temperature.

The second cause of the tilt can be a preferential nucleation of misfit dislocations having a finite value of the Burgers vector component normal to the surface[8]. As the annealing temperaurte increased, the layer tilt of the M-buffer was decreased since the annealing effectively reduces the misfit dislocation density.

The indium composition determined from the PL peaks of the LT-InGaAs, shown in Fig. 4, was almost identical to that estimated from the x-ray measurements. The FWHM of the LT-InGaAs layer decreased monotonically as the annealing temperature was increased, indicating that the quality of the LT-InGaAs improved due to the reduction in dislocation density.

Measurements of carrier lifetime were performed by using a time resolved pump-probe technique based on a mode-locked Ti:Sappire laser source (λ = 800 nm) having a pulse width of 30 fs, an average pumping power of 50 mW, and a repetition rate of 90 MHz. Change of refractive index (Δn) is induced by photoexcited carriers through nonlinear effects including bandfilling, bandgap shrinkage, and free-carrier absorption[9]. Fig. 5 shows dependence of the carrier lifetime of the LT-InGaAs on

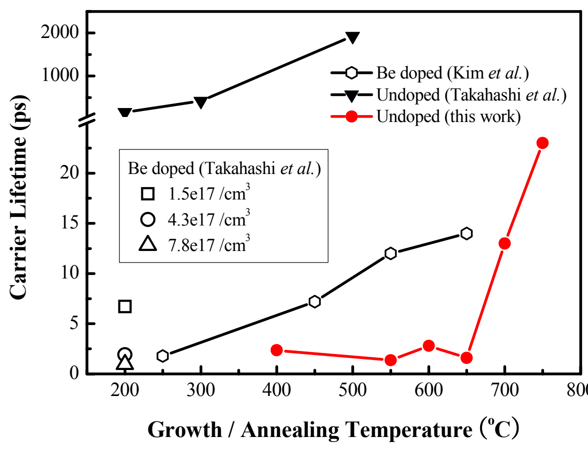


Fig. 5. Carrier lifetime of the LT-InGaAs on the M-buffer and the undoped (Takahashi *et al.*) and Be-doped (Kim *et al.*) InGaAs on InP as a function of the annealing/growth temperature.

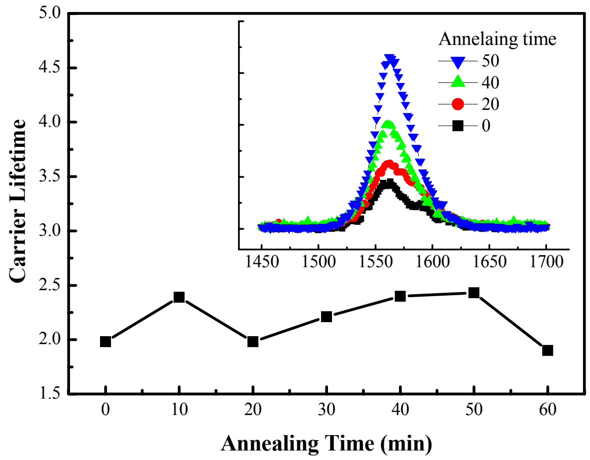


Fig. 6. Carrier lifetime of the LT-InGaAs on the M-buffer as a function of the annealing time at 500 °C. The inset shows the response of photoexcited carriers.

the annealing temperature. The carrier lifetime of the LT-InGaAs layers (as-grown and annealed up to 650 °C) on the M-buffer was shorter than those of the undoped LT-InGaAs on InP grown at 200 °C[10] and comparable to that of the Be-doped LT-InGaAs on InP grown at 250 °C[11]. For annealing temperatures above 700 °C, the carrier lifetime increased dramatically.

Fig. 6 shows the dependence of the carrier lifetime of the LT-InGaAs on the annealing time when the annealing temperature is identical to that used for conventional InGaAs growth (~ 500 °C ). As can be seen in the Fig. 6, the the carrier lifetime of the LT-InGaAs remained almost unchanged for the annealing time upto 60 min, which indicates that LT-InGaAs layer can be integrated with subsequent device layers without carrier lifetime degradation. In addition, the PL peak intensity increased with increasing annealing time up to 50 minutes.

## III. Conclusion

We reported characteristics of the LT-InGaAs grown on a linearly graded InGaAlAs M-buffer having a short carrier lifetime comparable to that of the Be-doped LT-InGaAs on InP. Utilization of residual dislocation in the LT-InGaAs on the M-buffer was effective in reducing the carrier lifetime. The results indicate the potential of the LT-InGaAs on an M-buffer for use in fabrication of ultrafast optical devices on GaAs in 1550 nm wavelength region.

## Acknowledgement


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