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Evidence of interface-induced persistent photoconductivity in InP/$In_{0.53}Ga_{0.47}As$/InP double heterostructures grown by molecular-beam epitaxy

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The impact of interface switching sequences on interface quality and minority carrier recombination in $In_{0.53}Ga_{0.47}As$/InP double heterostructure (DH) grown by solid-source molecular-beam epitaxy (MBE) was studied. As_2 exposure at the lower $In_{0.53}Ga_{0.47}As$/InP interface prior to $In_{0.53}Ga_{0.47}As$ growth was found to cause enhanced As diffusion into the underlying InP that correlates with steadily increased photoconductive decay (PCD) lifetimes beyond the theoretical radiative and Auger limit. Low-temperature PCD measurements reveal that a persistent photoconductivity (PPC) process is responsible for the high "apparent" lifetimes. The PPC effect increases monotonically with As_2 exposure on the InP surface, implying the involvement of interfacial defects in the carrier recombination dynamics of $In_{0.53}Ga_{0.47}As$/InP DHs grown by MBE. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1994948]

The interfacial quality of $In_xGa_{1-x}As$/InP heterostructures is of great importance for achieving high-performance electronic and optoelectronic devices. Key properties such as energy band offsets,[1] two-dimensional carrier confinement and superlattice band gaps[2] are extremely sensitive to the quality of the III-As/III-P interfaces in these heterostructures.[3] However, atomically abrupt interfaces are difficult to achieve due to an As–P exchange mechanism that has been attributed to P to As (or As to P) substitution[1–5] related to the highly reactive nature of P with Ga.[6] This effect has been reported for many III-As/III-P interfaces including InGaAs/InP,[1–4] InGaP/GaAs[7] and InAlP/GaAs.[8] It is reasonable to expect that carrier recombination will be sensitive to such interface degradation, which is an important issue for optoelectronic applications. This letter demonstrates how systematic variation of P-As switching conditions influences minority carrier recombination lifetimes of InP/$In_{0.53}Ga_{0.47}As$/InP double heterostructures (DHs) grown by molecular-beam epitaxy (MBE).

InP/$In_{0.53}Ga_{0.47}As$/InP DHs were grown on (100) InP substrates at 485 °C by solid-source MBE. Substrate surface temperatures were measured with *in-situ* pyrometry. Substrate oxide desorption was done at 510 °C under a phosphorus overpressure of $\sim 1 \times 10^{-5}$ Torr, which was confirmed by a strong, streaky (2×4) reflection high-energy electron diffraction (RHEED) pattern on the (100) InP surface. All DHs consisted of a 200 nm unintentionally doped (uid) n-type ($n \sim 1 \times 10^{15}\ \mathrm{cm}^{-3}$) InP buffer, a 500 nm uid n-$In_{0.53}Ga_{0.47}As$ layer and an uid 50 nm n-InP barrier layer. The lower ($In_{0.53}Ga_{0.47}As$ on InP) and upper (InP on $In_{0.53}Ga_{0.47}As$) interfaces are referred to as interface I and interface II, respectively. For the experiment described here, the growth transition conditions of interface I ($In_{0.53}Ga_{0.47}As$ on InP) were investigated by varying As_2 exposure times between 20 and 150 s on the InP surface during a growth stop prior to $In_{0.53}Ga_{0.47}As$ growth with a constant P_2 exposure time of 20 s. Conversely, the growth conditions at the upper interface (InP on $In_{0.53}Ga_{0.47}As$) were kept identical for all the films, where the $In_{0.53}Ga_{0.47}As$ layer was exposed to P_2 flux for 20 s prior to upper InP layer growth. Figure 1 shows the shutter/valve sequences used here. The InGaAs layer composition and overall structural quality were characterized using a Bede D1 high-resolution x-ray diffraction (XRD) system using four-bounce diffractometer conditions, a Si channel cut crystal and 0.5 mm slits on both source and detector. The As and P concentration profiles were measured using secondary ion mass spectroscopy (SIMS), and the hole minority carrier lifetimes were estimated by using the ultrahigh frequency photoconductive decay (UHFPCD) technique.[9]

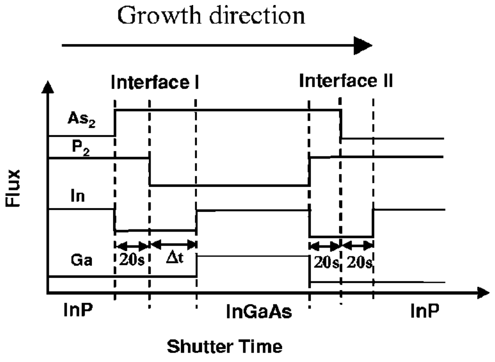

FIG. 1. Growth switching sequences of shutters and valves for source materials used for growth of InP/$In_{0.53}Ga_{0.47}As$/InP double heterostructures. Δt is the As_2 exposure time (20, 60, 90, 120, and 150 s) on InP surface during a growth stop prior to $In_{0.53}Ga_{0.47}As$ growth at the lower interface ($In_{0.53}Ga_{0.47}As$ on InP).

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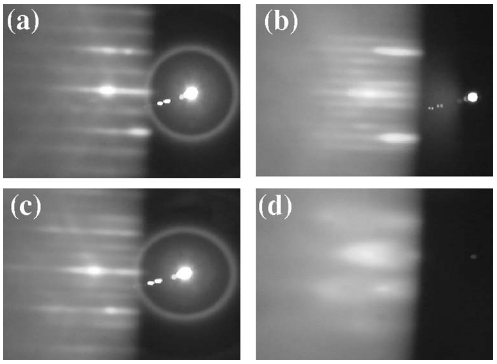

FIG. 2. RHEED patterns of the (100) InP surface along (a) [110] and (b) $[1\bar{1}0]$ azimuthal directions after a 20 s exposure to As_2, and of the (100) $In_{0.53}Ga_{0.47}As$ surface along (c) [110] and (d) $[1\bar{1}0]$ azimuthal directions after a 20 s exposure to P_2 flux, respectively.

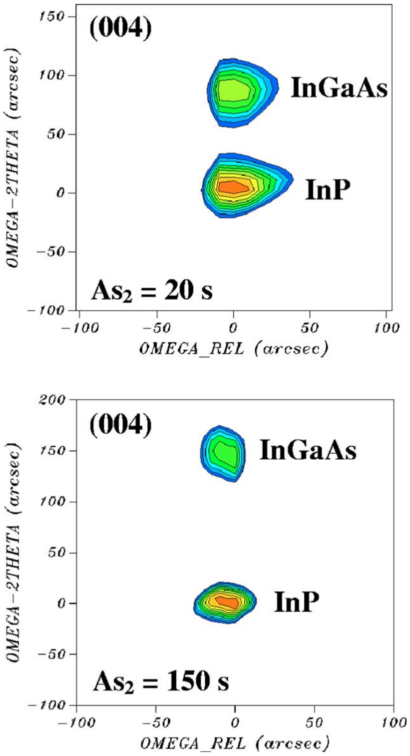

FIG. 3. (Color online). Symmetric (004) reciprocal space maps of $InP/In_{0.53}Ga_{0.47}As/InP$ DHs with As_2 exposure times of 20 and 150 s at InP surface during growth stop prior to $In_{0.53}Ga_{0.47}As$ growth obtained using a incident beam along the [110] direction.

RHEED measurements were first used to observe possible changes in the surface structure due to As_2 exposure on InP during the growth interruption at interface I. Figures 2(a) and 2(b) show RHEED patterns of the (100) InP surface along the [110] and $[1\bar{1}0]$ azimuthal directions, respectively, after a 20 s exposure to As_2. The well-defined (2×4) reconstruction, which is identical to the initial, clean (100) InP surface, remains stable even after As_2 exposure for 150 s. While no changes in surface reconstruction at interface I (As_2 exposed InP) were apparent, P_2 exposure on the (100) $In_{0.53}Ga_{0.47}As$ surface (interface II) caused an immediate change in surface structure. The initial (2×4)-fold pattern of the (100) $In_{0.53}Ga_{0.47}As$ surface changes to a pattern that is clearly threefold symmetric along the [110] direction and somewhat blurry along the $[1\bar{1}0]$ direction, within 10 s of P_2 flux exposure. Figures 2(c) and 2(d) show the RHEED patterns of this P_2-exposed (100) $In_{0.53}Ga_{0.47}As$ surface along [110] and $[1\bar{1}0]$ azimuthal directions, respectively, after a 20 s P_2 exposure. While this surface structure persisted up to the longest P_2 exposure duration we studied (120 s), we observed the RHEED pattern immediately reverts to a clear (2×4)-fold reconstruction once the In shutter is opened for InP growth. Therefore, the two interfaces of $InP/In_{0.53}Ga_{0.47}As/InP$ DHs are not equivalent. While little can be said about interface I at this point due to the invariant RHEED pattern, it should be noted that InAsP alloys also exhibit a streaky (2×4) RHEED pattern and the possible formation of such a layer will become important later.

To assess the impact of growth transition conditions on InGaAs layer quality and In composition after growth, x-ray rocking curves and reciprocal space maps (RSMs) from both symmetric (004) and asymmetric (115) glancing incidence reflections with the incident beam along the two orthogonal [110] and $[1\bar{1}0]$ directions were obtained from these DH structures as a function of As_2 exposure times during the growth interruption at interface I. Figure 3 shows only the (004) symmetric RSMs of two DHs with As_2 exposure times of 20 and 150 s with the incident beam along the [110] direction. From (004) and (115) RSMs, the In compositions were determined to be 52.7% ±0.3%, very close to the target composition, with no evidence of mosaicity for all interface formation conditions, suggesting no compositional or structural degradation of the bulk InGaAs layers. However, in spite of the apparent crystal quality invariance from the XRD analysis, high-resolution SIMS depth profiles (Fig. 4) reveal a monotonic increase in As diffusion into the lower InP layer with no such effect at the upper interface. This enhanced As diffusion inside the InP film for longer As_2 exposure time with no apparent P diffusion (see Ref. 10, which describes details of the As diffusion into InP during As exposure) into the $In_{0.53}Ga_{0.47}As$ layer suggests that As diffusion is occurring prior to InGaAs growth, under As stabilized InP surface conditions. Potentially, this could cause the formation of a very thin $InAs_yP_{1-y}$ interfacial layer prior to InGaAs growth,

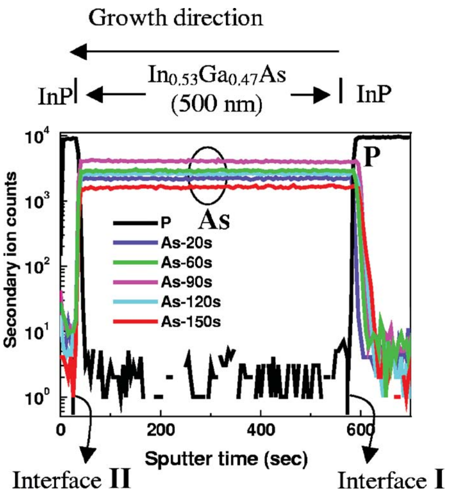

FIG. 4. (Color) SIMS depth profiles of As and P for $InP/In_{0.53}Ga_{0.47}As/InP$ DHs with As_2 exposure times at InP surface during growth stop prior to $In_{0.53}Ga_{0.47}As$ growth. Note that only one P depth profile was included in this figure to preserve clarity. Negligible P diffusion into the $In_{0.53}Ga_{0.47}As$ layer was detected for all cases, and details of this process where As_2 exposure of InP surfaces tends to convert the surface to a mixed InAsP region can be found in Ref. 10.

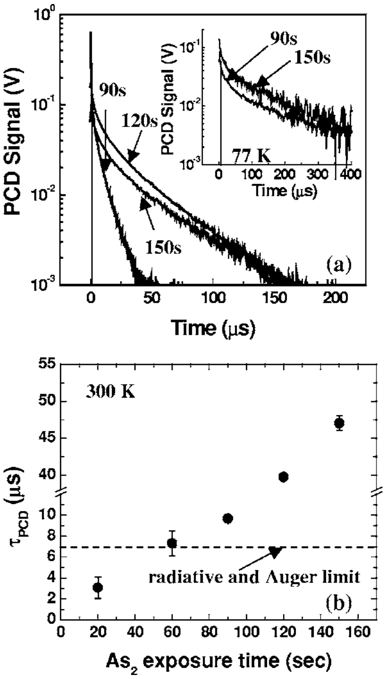

FIG. 5. (a) Measured PCD data and (b) extracted low-level injection PCD lifetimes [Eq. (1)] as a function of As_2 exposure time at interface I measured using 1670 nm excitation wavelength (λ_{gap} of $In_{0.53}Ga_{0.47}As$ is 1675 nm). A photon flux of approximately 10^{13} photons/cm^2 was maintained to ensure low-level injection conditions at 300 K (inset: 77 K with 1600 nm excitation wavelength). As_2 exposures of 20 and 60 s are not included in (a) to maintain clarity. The dashed line in (b) indicates the theoretical radiative and Auger recombination lifetime limits for $In_{0.53}Ga_{0.47}As$ with $n \sim 1 \times 10^{15}$ cm^{-3} using Eq. (2) (see Ref. 12).

consistent with the earlier (2×4) RHEED observations. Although slight, such interface mixing can be expected to impact optoelectronic properties of these DHs,[1,11] and to investigate this possibility, UHFPCD measurements were performed. Figure 5(a) shows the photoconductivity decay (PCD) obtained from the InGaAs layers of the DHs for several interface I switching times. By fitting the PCD data (V_{PCD}) to

$$V_{PCD} = k_1 \exp\left(-t/\tau_{PCD}\right) \tag{1}$$

within the low-level injection regime between 10^{-3} and 10^{-2} V, PCD lifetimes (τ_{PCD}) were extracted and are shown in Fig. 5(b). The τ_{PCD} values monotonically increase with As_2 exposure times, reaching ~ 48 μs for a 150 s As_2 exposure at interface I. However, this PCD lifetime is well in excess of the theoretical radiative and Auger lifetime limit in n-type $In_{0.53}Ga_{0.47}As$ at $n \sim 1 \times 10^{15}$ cm^{-3}, which is ~ 7 μs as calculated from[12]

$$\tau = [1.43 \times 10^{-10}\, n + 8.1 \times 10^{-29}\, n^2]^{-1} (s). \tag{2}$$

The very long PCD lifetime with respect to the Auger and radiative limits suggests the presence of a process such as persistent photoconductivity (PPC) where carrier trapping and de-trapping via deep levels prior to recombination can extend photoconductivity and thus yield a high "apparent" lifetime. PPC effects are well known in III-V heterostructures and have been reported in $InP/In_{0.53}Ga_{0.47}As$ DHs previously.[13,14] Such a possibility is supported by the SIMS results, since the As diffusion into the underlying InP prior to InGaAs growth would likely form a very thin $InAs_yP_{1-y}$ layer on which InGaAs growth would presumably be lowered in quality (Unfortunately, x-ray simulations to determine the thickness and composition of such an interfacial layer was not possible due to the presence of the thick $In_{0.53}Ga_{0.47}As$ overlayer). However, the RSM results of Fig. 3 do not show evidence of misfit dislocation formation so defects within the InGaAs in the vicinity of the interface are either point defects, or are constituted by a very low misfit dislocation density. While a specific defect or defects present at interface I cannot be directly verified, low-temperature PCD measurements were performed on selected samples since this method can provide evidence for the presence of deep level mediated PPC. Figure 5(b) shows 77 K PCD measurements for two of the samples, A (90 s As_2 exposure time and 10 μs PCD lifetime at 300 K) and C (150 s As_2 exposure time and 48 μs PCD lifetime at 300 K). For PPC to be a dominant factor, the apparent lifetime should increase significantly at lower temperature due to reduced thermally stimulated deep level emission rates.[15] Indeed, the PCD lifetimes for both samples increase to a convergent value of ~ 170 μs at 77 K. This is compelling evidence that the increased lifetime observed in the samples with longer As_2 exposures is attributed to PPC resulting from deep states related to either a low density of misfit dislocations, or point defects within the InGaAs interface region, or both, that trap carriers prior to recombination.

In conclusion, the impact of interface transition sequences on the properties of MBE-grown $In_{0.53}Ga_{0.47}As/InP$ DHs was studied. Long As_2 exposure times at the lower $In_{0.53}Ga_{0.47}As/InP$ interface prior to $In_{0.53}Ga_{0.47}As$ growth causes enhanced As diffusion into the underlying InP layer that correlates with monotonically increasing PCD lifetimes beyond the radiative and Auger limit. Low-temperature PCD measurements were used to confirm that a deep level mediated PPC process appears responsible for the extended carrier lifetimes. This also suggests that simple extraction of the minority carrier recombination lifetimes in such structures without knowledge of PPC effects may be ambiguous.

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