Invited Paper

Arsenic-Implanted GaAs: An Alternative Material to Low-Temperature-Grown GaAs for Ultrafast Optoelectronic Applications

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Abstract

Arsenic-ion-implanted GaAs (or GaAs:As^+), with excess-arsenic-related deep level defects, has recently emerged as a potential alternative to low-temperature molecular-beam-epitaxy (LTMBE) grown GaAs for ultrafast optoelectronic applications. In this paper, we review results of our structural, ultrafast optical and optoelectronic investigations of as-implanted and thermally annealed GaAs:As^+. Picosecond photoconductive switching responses are reported for devices fabricated on thermally-annealed low-dose and high-dose implanted GaAs:As^+. Novel sign reversals in near-bandgap ultrafast optical responses were observed and explained.

Keywords: arsenic-ion-implanted GaAs, GaAs:As^+, ultrafast, photoconductive switch

I. Introduction

Photoconductors with ultrashort photo-excited carrier lifetime, good optical responsivity, high breakdown field and low dark current are essential for ultrafast optoelectronic switching applications. Various classes of semiconductors, e.g., intrinsic, impurity-dominated, radiation-damaged, polycrystalline, and amorphous, have been explored as ultrafast photoconductors. In particular, the ion implantation technique has been employed extensively. Carrier lifetimes as short as 0.5 ~0.6 ps have been reported as the saturation limit for GaAs samples irradiated by protons (H^+) and oxygen-ion-implanted silicon-on sapphire (SOS) materials. On the other hand, nonstoichiometric, arsenic-rich GaAs grown by molecular beam epitaxy (MBE) at low substrate temperature (LT-GaAs) have been the subject of intensive studies because of its nearly ideal electrical and optoelectronic properties. Appropriate annealing of the material is required, however. Recently an alternative arsenic-rich-material, arsenic-implanted-GaAs, or GaAs:As^+, has emerged as a potential candidate for ultrafast optoelectronic applications. The structural and electrical characteristics of LT-GaAs and GaAs:As^+ have been shown to be quite similar. Subpicosecond carrier lifetimes [1,2] and photoconductive responses [3] comparable to that of LT (low-temperature) MBE-grown GaAs were reported. In this work, we review structural, electrical and ultrafast optical properties of furnace-annealed GaAs:As^+. Ultrafast photoconductive switches fabricated on furnace-annealed GaAs:As^+ were demonstrated.

II. Sample Preparation and Experimental Methods

The samples were prepared by first implanting semi-insulating GaAs substrates with 200 keV arsenic ions at a dose of 10^{16} ions/cm^2 and then furnace-annealed ex-situ between T_a = 200 and 800 °C for 30 minutes. The effect of the furnace annealing process on the structural properties of As^+-implanted GaAs was examined by x-ray rocking curve and transmission electron microscopy (TEM) measurements. For electrical characterizations of the arsenic-ion-implanted GaAs subatrates, shottky diodes with thermally evaporated gold (0.5 mm thick) contacts were fabricated. Their current voltage (I-V) performance was measured by using a semiconductor parametric analyzer (HP4145B). Carrier lifetimes and transient indices of refraction of the annealed samples was measured by using a standard pump-probe system with a time resolution of about 130 fs. Photoconductive switches (PCS) with coplanar stripline structures were fabricated on samples annealed at 600°C. The choice of this annealing condition was based on good crystallinity, excellent dark resistivity and ultrafast carrier lifetimes as determined by structural, electrical, and optical characterization of the samples. These devices were then characterized by an external electro-optic sampling (EOS) system. The temporal and spatial resolutions of the EOS system are approximately about 1 ps and 5 mm, respectively.

III. Structural and Electrical Properties

The deviation of the lattice constant Δa and the related vertical strain parameter Δa/a of GaAs:As^+ furnace-annealed at various temperatures were determined from X-ray data, These are shown in Fig. 1. For the as-implanted sample, the maximum vertical strain, Δa/a ~ 0.35%, is located at about 0.09 mm below the surface. In comparison, the lattice expansion was evaluated to be 0.0053Å (Δa/a = 0.08~0.15%

and a = 5.659~5.660Å) for LT-GaAs (growth temperature ~ 200 ℃). As the annealing temperature is increased from T_a = 200 ℃, we observed that the X-ray side-peak gradually shifted toward and merged with the central peak for T_a>500 ℃. In comparison, the side-peak for LT-GaAs merged with the main peak at a lower annealing temperature of 450 ℃. That is, the rate of recovery for crystallinity of GaAs:As^+ is somewhat slower than that of LT-GaAs grown by MBE. The critical annealing temperatures for the complete recovery of crystallinity of As^+-implanted GaAs is estimated to be higher than T_a = 500 ℃.

The density of the neutral As_{Ga} antisite $[As_{Ga}^0]$ defects responsible for the trapping of photoinjected carriers has also been evaluated. From experimental values of $N[As_{Ga}^0]$ for the as-implanted As^+-implanted GaAs ($\approx 10^{20}$ cm^{-3}) and S.I. GaAs substrate ($\approx 10^{16}$ cm^{-3}) determined previously by our group.[6,7] We estimate that $N[As_{Ga}^0] \approx 5.56\times10^{22}(\Delta a/a)$ for GaAs:As^+. The proportional constant is slightly smaller than that for LT-GaAs (5.56×10^{22}). It may be explained by the relatively poor crystallinity of GaAs:As^+ prepared by as compared with that in LT-GaAs. Thus it requires higher annealing temperature to recover the crystallinity. As a supporting evidence, the $N[As_{Ga}^0]$ of the GaAs:As^+ sample annealed at temperature of 600 ℃ was in reasonably good agreement with previous results of ~3×10^{18} cm^{-3} obtained from the capacitance-voltage measurement.[8] A comparison of the structural and electrical properties of furnace-annealed GaAs:As^+ and related materials are summarized in Table 1.

IV. Ultrafast Optical properties

Previously, we have reported subpicosecond photoexcited carrier lifetimes (τ_c) ranged from 0.19 ps to 0.28 ps in GaAs implanted with 200 KeV arsenic ions at dosages from 10^{12} to 10^{16} ions/cm^2.[1] For RTA-annealed GaAs:As^+ at 600 ℃ to 800 ℃, τ_c's from 0.48 to 2.3 ps were observed.[2] From results of femtosecond time-resolved reflectivity measurements (see Fig. 2), we find that photo-excited carrier lifetimes of furnace-annealed GaAs:As^+ were in the range of ≈ 0.4 to 4.6 ps (200°C ≤ T_a ≤ 800°C) with an approximate $(T_a)^4$ dependence. This is also shown in

Fig. 3. For $T_a \leq 500$ °C, τ_c's evolved slowly with increasing T_a and were all in the subpicosecond range. The corresponding changes of the refractive index, Δn, were of the order of -2 to -3 x 10^{-3}. A novel sign reversal for Δn was observed for 600°C ≤ T_a ≤ 700°C. The peak magnitude of Δn was as large as 0.01 at T_a = 700°C. This can be explained if the bandgap of GaAs:As^+ shrinks due to bandgap renormalization toward shorter wavelength after annealing. This is in agreement with results of the cw photoreflectance experiment. The ultrafast carrier lifetimes are consistent with structural characterization of GaAs:As^+ that demonstrated ultrahigh densities of defect states present in the samples annealed at these temperatures. The density of neutral As_{Ga} antisite defects was determined to be $\approx 2 \times 10^{17}$ cm^{-3} at T_a=800°C. Effective captured cross-section of the photo-excited carriers for the GaAs:As^+ samples annealed at different temperatures were evaluated by using Schkoley-Read-Hall model and listed in Table 1. Arsenic precipitates, however, were not observed for $T_a \leq 600$ ℃. This suggests that arsenic clusters were not as important for the ultrafast carrier trapping process in GaAs:As^+ as for LT-GaAs. See also Table 1 for a comparative listing of ultrafast optical properties of GaAs:As^+.

V. Ultrafast Optoelectronic Applications

Fig. 4 shows the photoconductive response of a furnace-annealed GaAs:As^+ PCS. The duration of the electrical pulse generated by the photoconductive switch was ≈ 4 ps. The risetime (10% - 90%) and 1/e falltime were respectively ≈ 2 ps and 3 ps. These results were measurement-system limited. We estimated the actual response to be ≈ 2 ps, consistent with a photo-excited carrier lifetime of ≈ 1.8 ps. In comparison, Wang et al.[3] has reported a similar result that the response time of the similar device fabricated on same material RTA-annealed at 600 ℃ for 15 seconds was measured to be of 1.23 ps (FWHM). The dark current of an Auston-type GaAs:As^+ PCS with a gap size of 30 mm fabricated on the same substrate was measured to be as low as 5 nA at 40 volts. The applied electric field at this bias was estimated to be about 15 kV/cm. In comparison, the dark current of an S.I. GaAs based PCS is >10 nA at the same bias. With an injected optical average power of 100 mW (pulse mode) and 3 mW (CW mode) while biased at 20 volts, the responsivity of the PCS operated in CW and pulse mode were ~0.01 A/W and larger than 0.03 A/W, respectively. This is a few times larger than the responsivity of LTMBE-GaAs PCS's. This can be attributed to the contribution from bulk material of much larger mobility since the thickness of the implanted layer was too thin to absorb the injected photons entirely. The performance of GaAs:As^+ PCS's as compared with that of LT-GaAs PCS are listed in Table 2. We have also recently reported picosecond responses from low-dose-implanted GaAs:As^+.[10]

VII. Conclusions

In conclusion, we have performed extensive material and device characterization of a new optoelectronic material, furnace-annealed GaAs:As^+. The effect of thermal annealing on the key parameters of this material are listed in Table 1. Current-voltage analysis of the shottky diodes on samples annealed at different temperatures reveals that the optimal annealing temperature for obtaining highly resistive substrate should be at between 500~600 ℃. The photo-excited carrier lifetimes were found to increase from 0.26 to 4.6 ps as T_a was increased up to 800 ℃. Sign reversal in Δn was observed and explained. Auston-type PCS fabricated on the optimal-conditioned substrate was measured to be 3~4 ps by using an external electro-optic sampling system. The performance of GaAs:As^+ as compared with that of S.I. GaAs and LT-GaAs are listed in Table 2. We showed that arsenic-ion-implanted GaAs could be a potential useful and alternative material to LT-GaAs for ultrafast optoelectronic applications. This work was supported in part by the National Science Council of the Republic of China.

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Table 1.

The structural and electrical characteristics of GaAs:As^+ samples annealed at different temperatures.

	as-implant.	200 ℃	400 ℃	600 ℃	800 ℃
Δa/a	1.8e-3	1.06e-3	4e-4	~3.79e-5	<3.8e-6
$N[As_{Ga}](cm^{-3})$	≅1e20	5.9e19	2.2e19	2~3e18	~2e17
D_{As}(nm)	-	-	-	2~3	20
$I_{dark}(nA/mm^2)$	12	~0.6	0.12	5.2e-5	~3.3
τ(ps)	0.26~0.3	0.4~0.42	0.58~0.6	1.6~1.9	4.2~4.6
$\Delta n(x10^{-2})$	-0.11~-0.13	-0.26~-0.33	-0.12~-0.18	-0.27~-0.32	0.85~0.97
$\sigma(x10^{-14}\ cm^2)$	~0.19	~0.21	~0.39	~1.5	≥6

Table 2.

The performance of $GaAs:As^+$ PCS samples and related devices.

Performance	**LT-GaAs**	**$GaAs:As^+$**	**$GaAs:As^+$**
Sample condition	200 ℃ grown 20 mm gap	10^{-13}, RTA 30 μm gap	10^{-16}, furnace 30 μm gap
Dark current	<1 μA (10 volts)	30mA (40 volts)	5 nA (40 volts)
Switching Response	1.6 ps	2.7 ps	4 ps
Optical responsiivity	0.001 A/W	0.007 A/W	0.004 A/W

Table 3.

The characteristics of S.I. GaAs, LT-GaAs, and $GaAs:As^+$ materials.

	S.I. GaAs	**LT-GaAs**	**$GaAs:As^+$**
Condition	LEC	Furnace-annealed 600℃, 30 min	Furnace-annealed 600℃, 30 min
TEM, As-cluster	No	6-60 nm	2-3, 20-30 nm
TEM, σ_{trap}	—	$< 2.83\times10^{-13}$ cm^2	0.7-2×10^{-14} cm^2
TDC, Ea	0.75 eV	0.64 eV	0.6 eV
N_{trap}	$< 2\times16$ cm^{-3}	$> 1\times19$ cm^{-3}	2×18 cm^{-3}
Break-down field	< 50 kV/cm	> 150 kV/cm	>150 kV/cm

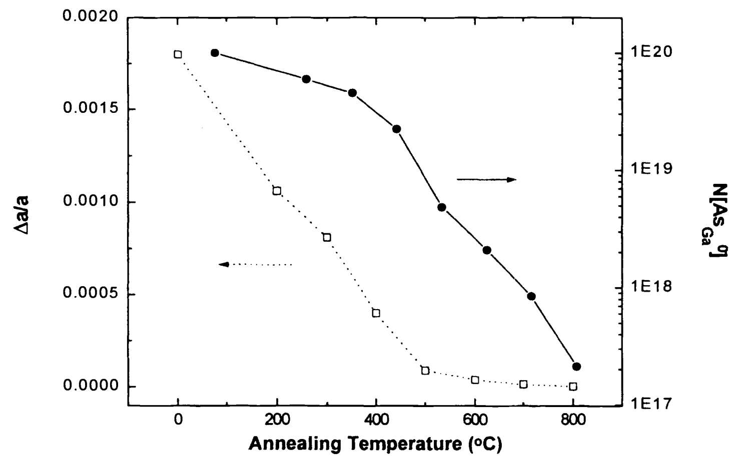

Fig.1 The vertical strain and associated arsenic antisite defect density as a function of annealing temperature.

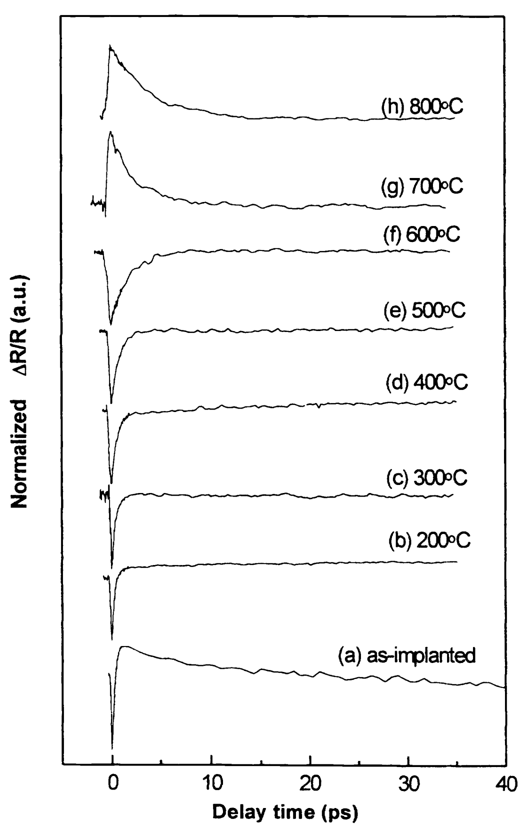

Fig.2 The transient reflectivity of GaAs:As^{+} samples annealed at different temperatures.

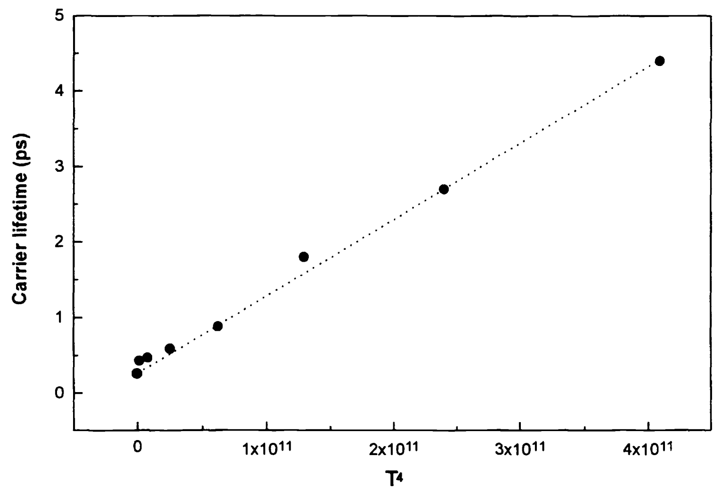

Fig.3 The carrier lifetime of GaAs:As$^+$ samples annealed at different temperatures as a function of T^4.

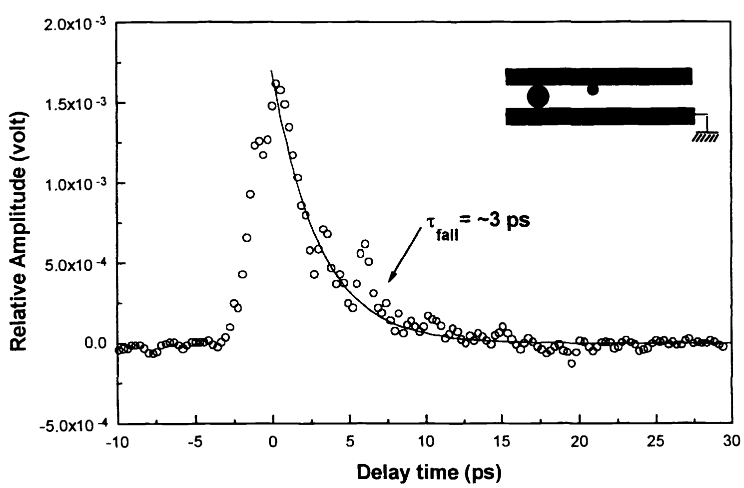

Fig.4 The switching response of 600 ℃-annealed GaAs:As$^+$ PCS measured by using external electro-optic sampling.