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n^+pp^+ GaAs and n^+pP^+ GaAs/GaAs/$Al_{0.3}Ga_{0.7}As$ mesa diodes have been fabricated from films grown by molecular-beam epitaxy. The diodes made from films employing an AlGaAs buffer layer show marked improvements (a factor of 5 reduction) in recombination current densities. Deep level transient spectroscopy measurements moreover indicate that deep level concentrations are reduced by the AlGaAs buffer.

Suppression of recombination currents is an important factor in the design of high-performance AlGaAs/GaAs solar cells and bipolar transistors.[1,2] Nonradiative recombination is typically controlled by deep levels introduced by impurities and/or defects in the semiconductor bulk and surfaces. In this communication we demonstrate that relatively thick GaAs films grown by molecular-beam epitaxy (MBE) atop a 0.69-μm $Al_{0.3}Ga_{0.7}As$ buffer layer show a substantially lower deep level concentration than do films grown atop a GaAs buffer layer. *p-n* junctions fabricated in such films display a corresponding reduction in recombination current. Gale *et al.*[3] have previously employed AlGaAs buffer layers in the fabrication of GaAs solar cells by metalorganic chemical vapor deposition (MOCVD). These cells showed higher open-circuit voltages and conversion efficiencies than cells made with GaAs buffers. This improvement was attributed to the greater minority-carrier confinement achieved by the GaAs/AlGaAs potential barrier. Our work indicates that reduced recombination current, due to impurity reduction, may also have contributed to the improved solar-cell characteristics. Similar results have been obtained by Beneking *et al.*,[4,5] who observed reduced impurity concentrations for GaAs films grown by MOCVD and liquid-phase epitaxy on top of an indium-doped strained layer several micrometers thick. Our report of corresponding benefits for MBE-grown films using relatively thin AlGaAs layers suggests that the technique is suitable for the routine growth of high-quality MBE-grown AlGaAs/GaAs films for bipolar applications.

The MBE films used in this work were grown in a Perkin-Elmer 400 MBE system. The starting substrates were Zn-doped (1.5×10^{19} cm^{-3}) (100) horizontal Bridgeman material with an etch pit density of less than 500 cm^{-2}. The GaAs layers were grown at a substrate temperature of 605 °C and the AlGaAs layer at a substrate temperature 625 °C.

There were a total of five films grown for this work which we have labeled $F1$–$F5$. The first three samples, $F1$, $F2$, and $F3$, were grown on three consecutive days and the substrates were cleaved from the same wafer. There was a total of 28 μm of material grown in the MBE system prior to the growth of samples $F1$–$F3$. The first film, $F1$, had the Be-doped *p*-type base grown directly on the p^+ substrate. The second film, $F2$, had a 0.44-μm p^+ buffer layer below the *p*-type base while the third film, $F3$, had a 0.9μm p^+ buffer layer. (Film structures $F1$–$F3$ are shown in Fig. 1.) Ohmic contacts were made to the n^+ emitters by alloying Au-Ge, and mesa diodes were defined by photolithography and subsequent wet etching in H_2SO_4:H_2O_2:H_2O (1:8:40). The areas of the diodes ranged from 4×10^{-4} cm^2 to 1.6×10^{-3} cm^2. The MBE system was opened to repair a broken weld on its Ga oven before growing the second set of films $F4$ and $F5$. Films $F4$ and $F5$ were grown on two consecutive days with substrates cleaved from a second wafer. There was a total of 12 μm of material grown in the MBE system prior to the growth of samples $F4$ and $F5$. (Because of the shorter burn in time of the ovens, one would suspect samples $F4$ and $F5$ to be of inferior quality when compared to samples $F1$ through $F3$.) The first sample grown, $F4$, had a heterojunction pP^+ barrier while the second sample grown, $F5$, had an isotype pp^+ barrier as shown in Fig. 2.

The mesa diodes for all five films were characterized by dark current-voltage (*I-V*) measurements and by deep level transient spectroscopy (DLTS). The dark *I-V* characteristics were measured using a Hewlett Packard 4145A semiconductor parameter analyzer. The $n = 1$ and $n = 2$ saturation current densities were extracted from the measured *I-V* characteristics by curve fitting. The $n = 2$ current component is of particular interest because it is directly related to both recombination in the space-charge region and to surface recombination around the junction perimeter.[6,7] Thus, the $n = 2$ current can provide an indication of the MBE film quality. Table I shows the average $n = 2$ saturation current densities J_{02} for films $F1$–$F5$.

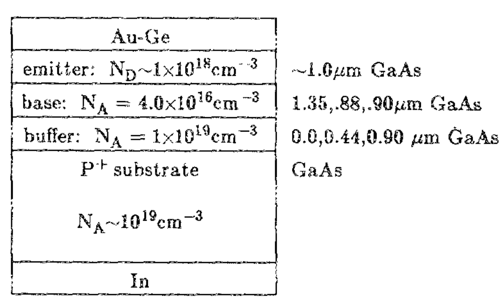

FIG. 1. Device structure for films $F1$, $F2$, and $F3$. The GaAs buffer layer thickness was 0.0, 0.44, and 0.90 μm; the thickness of the base was 1.35, 0.88, and 0.90 μm for films $F1$, $F2$, and $F3$, respectively.

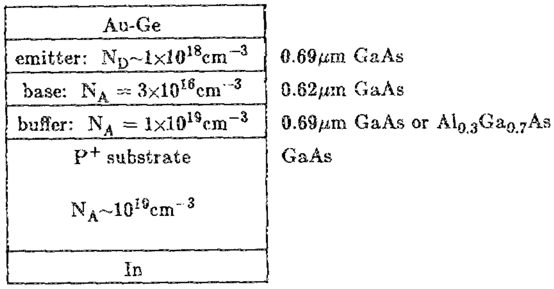

FIG. 2. Device structure for films $F4$ and $F5$. $F4$ had a 0.69-μm $Al_{0.3}Ga_{0.7}As$ buffer layer and $F5$ had a 0.69-μm GaAs buffer layer.

The first three isotype barrier films $F1$–$F3$ have J_{02} values that are five to six times lower than the J_{02} value for film $F5$. On the other hand, J_{02} for the heterojunction barrier film ($F4$) falls within the range of J_{02} values for films $F1$–$F3$. One would expect the impurity concentrations in film $F4$ to be greater than those in film $F5$ because film $F5$ was grown on the day following the growth of film $F4$. However, $F4$'s lower J_{02} value indicates that film $F4$ is actually of significantly higher quality than $F5$. It is our conclusion that the introduction of an AlGaAs buffer layer has caused the film quality of $F4$ to be comparable to that of $F1$–$F3$.

The MBE film quality was further investigated by means of DLTS. Our DLTS measurements have shown that deep level concentrations are greatly reduced when an AlGaAs buffer layer is used. We suspect that the AlGaAs layer traps impurities that are floating up from the substrate, and/or getters impurities from the subsequent GaAs layers during film growth. This is in agreement with McAfee *et al.*,[8] who observed a highly peaked spatial profile of deep levels located in a 140-Å-wide region at the GaAs/AlGaAs interface in MBE double heterostructure lasers. Photoluminescence[9,10] and capacitance-voltage[11] studies of GaAs quantum wells have also indicated the presence of impurities at the GaAs/AlGaAs interface.

Typical DLTS spectra for films $F1$–$F5$ are compared in Fig. 3. Figure 3(a), representative of films $F1$–$F3$, shows a prominent DLTS peak at about 320 K, a second peak at about 430 K, and lesser peaks at 360 K and between 100 and 200 K. Figure 3(b) is typical of film $F4$. Again there is a prominent peak at 320 K and lesser peaks to either side. Finally, Fig. 3(c) shows a representative DLTS scan for film $F5$. We reiterate that $F5$ was grown after $F4$ and is therefore expected to contain a lesser number of impurities. However, in addition to the ever present peak at 320 K, $F5$ has significant DLTS shoulders at 350, 260, 210, and 190 K. Clearly film $F5$ contains a greater number of deep levels than $F4$. With the exception of the deep level associated with the peak at 320 K, the AlGaAs buffer layer appears to have blocked and/or gettered impurities from the layers grown above it.

TABLE I. $n = 2$ saturation current densities for films $F1$–$F5$.

Film I.D.	Growth date	J_{02} (pA/cm^2)	Barrier
$F1$	8/11/86	263	p-GaAs/p^+-GaAs
$F2$	8/12/86	209	p-GaAs/p^+-GaAs
$F3$	8/13/86	252	p-GaAs/p^+-GaAs
MBE system was opened on 9/6/86			
$F4$	9/24/86	258	p-GaAs/P^+-$Al_{0.3}Ga_{0.7}As$
$F5$	9/25/86	1330	p-GaAs/p^+-GaAs

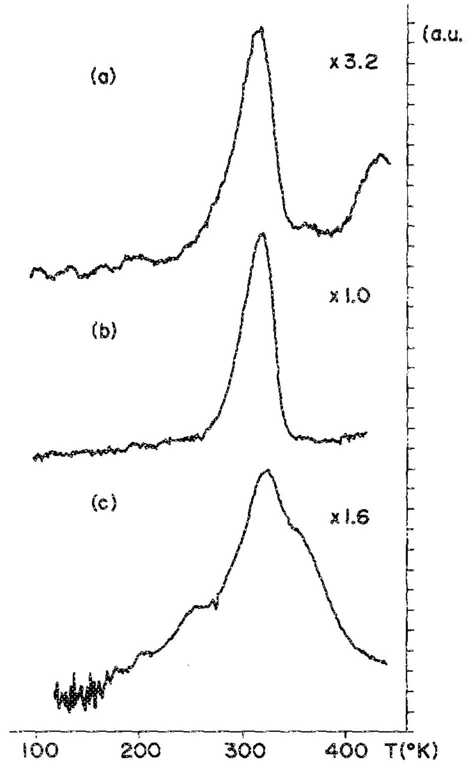

FIG. 3. Typical DLTS spectra for (a) films $F1$–$F3$, (b) film $F4$, and (c) film $F5$. The diodes were pulsed from 1.0 V reverse bias to 0.0 V with 1.0 ms fill pulses. The DLTS emission rate window was 200 s^{-1}.

The DLTS peak at 320 K requires additional discussion, since it appears in all of the samples and seems unaffected by the AlGaAs layer. The average deep level concentration N_T associated with the 320 K peak for films $F1$–$F3$ was $N_T = 4.4\times10^{13}$ cm^{-3}. For film $F4$ the average trap concentration was $N_T = 1.0\times10^{14}$ cm^{-3}; for film $F5$ it was $N_T = 7.8\times10^{13}$ cm^{-3}. The results suggest that the concentration of this particular deep level is correlated with the amount of MBE material grown prior to each film growth. This observation in turn would imply that the deep level is related to impurities introduced by the system during film growth. Failure of these impurities to be gettered by the AlGaAs layer may indicate that they occupy substitutional lattice sites, or form vacancy complexes that do not readily diffuse to the AlGaAs layer during film growth. They appear to be continually incorporated into the film during the growth process along with the Ga, As, and dopant atoms.

The thermal activation energy for the 320 K peak was measured by DLTS to be $E_T - E_V = 0.55$ eV. The capture cross section for the majority-carrier holes was found to be $\sigma_p = 6.8\times10^{-16}$ cm^2. The impurity could therefore be iron,[12,13] or possibly a Ga vacancy[14] or vacancy complex. We suspect that this particular deep level does not control the J_{02} current. This is suggested by a comparison of the carrier lifetimes as determined from DLTS and dark I-V data. For the deep level concentrations encountered here, the measured σ_p would imply hole lifetimes,

$$\tau_p \equiv 1/\sigma_p \langle V_{TH} \rangle N_T,$$

on the order of 0.1–1.0 μs. However, the average recombination lifetime $\sqrt{\tau_n \tau_p}$, as determined from the measured $n = 2$ saturation current density (J_{02}) was on the order of 1.0 ns. Consequently, τ_n would have to be ~ 1.0 ps and σ_n on the order of 6.8×10^{-10} cm^2. A capture cross section on the order of 10^{-9}–10^{-10} cm^2 is unusually large.

The concentration of the 0.55-eV level does not correlate with the recombination current density. This further confirms our suspicions that the 0.55-eV level does not dominate the recombination current. However, the controlling recombination rate, whatever the mechanism, does appear to have been reduced by the presence of the AlGaAs layer. It is possible that a deep level, as yet undetected by our DLTS measurements, is controlling the $n = 2$ current. Another factor to consider is surface recombination around the device perimeter, which may make a significant contribution to J_{02}; gross defects (e.g., oval defects) are another possible contributor. Further work is needed to establish the controlling recombination mechanism.

In summary, we have shown that p-n junctions, fabricated from MBE GaAs films, show marked reductions in recombination current when an AlGaAs buffer layer is employed. Deep level concentrations are also reduced by the presence of an AlGaAs buffer layer. One deep level, possibly iron or a Ga vacancy/vacancy complex, remains unaffected by the AlGaAs buffer layer. This impurity/defect is either rigidly incorporated into the lattice during MBE film growth, or is highly soluble in AlGaAs. Fortunately, the cited deep level does not appear to significantly affect the $n = 2$ current density. The use of AlGaAs buffers should be independent of growth technology and could provide significant improvements in AlGaAs/GaAs films grown for bipolar applications.

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Improved shallow p^+ diffusion into InGaAsP by a new spin-on diffusion source

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Shallow p^+ diffusion into InGaAsP ($\lambda = 1.3$ μm) has been improved by employing a new spin-on source based on Zn-doped alumina. Thereby the thermal expansion coefficients of diffusion source and semiconductor are better matched together than in case of the more common Zn-doped silica films. Consequently, besides an excellent mechanical stability of the spin-on films over a wide temperature range, the influence of mechanical stress on the diffusion process is effectively reduced. Applying diffusion temperatures around 600 °C surface hole concentrations above 6×10^{19} cm^{-3} and extremely low specific p-contact resistances of 2–3$\times 10^{-6}$ Ω cm^2 have been achieved.

Presently, optoelectronic devices in the InGaAsP-InP material system are widely used in optical communication system in the wavelength ranges around 1.3 and 1.55 μm, where dispersion and attenuation of optical fibers exhibit their minimum values. For these devices, in particular for light emitting diodes and laser diodes, low resistive contacts are required in order to minimize heat generation and to enable high-speed operation. In case of laser diodes, the maximum temperature for cw operation is decisively influenced by the contact resistance on account of the superlin-

