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Electron Irradiation Induced Defects and Schottky Diode Characteristics for Metalorganic Vapor Phase Epitaxy and Molecular Beam Epitaxial n-GaAs

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A considerable body of information is available in the literature concerning the effects of high energy electron irradiation on the formation of deep trapping levels in GaAs. Most of these studies have dealt with bulk material or material grown by vapor phase epitaxy (VPE). However, whether these studies are representative of GaAs epilayers grown by metalorganic vapor phase epitaxy (MOVPE) or molecular beam epitaxy is not clear, particularly when the gallium and arsenic species used in the growth and hence optimal conditions for growth, differ widely between techniques. In fact, the results reported in this study show significant differences in the behavior of material produced by these techniques. Deep level transient spectroscopy (DLTS) is used in this work to characterize the deep electron traps formed during 7 MeV electron irradiation. In addition, the current voltage characteristics of the Schottky diodes used in the DLTS studies have been evaluated before and after irradiation to ascertain the effects of irradiation on device performance. It has been found that an additional trapping level is produced in MOVPE-grown material of high background doping and that the carrier removal in this material is not a simple function related to increased electron fluence as observed in previous studies on VPE material.

Key words: Deep level transient spectroscopy (DLTS), defects, electron irradiation, GaAs, metalorganic vapor phase epitaxy (MOVPE), molecular beam epitaxy (MBE)

INTRODUCTION

Over the past number of years, numerous studies have been reported which describe the formation of deep trapping levels in bulk and epitaxial layers of GaAs induced by high energy electron irradiation. Much of this work has been reviewed in the papers of Lang[1] and Pons et al.[2] In general, these past studies deal primarily with the characterization of the fundamental defects produced through irradiation of either bulk grown crystals or of epilayers grown by vapor phase epitaxy (VPE).[3] Far less work has been reported on GaAs grown by the more commonly used epitaxial growth techniques of metalorganic vapor phase epitaxy (MOVPE) or molecular beam epitaxy (MBE), although one might suspect that due to the different growth mechanisms, the formation of deep levels may be quite different, particularly if defect-impurity interactions are important.

In this paper, we report on the formation of deep electron trapping levels in MOVPE and MBE grown epilayers of GaAs resulting from 7 MeV electron irradiation. The trapping levels have been characterized using deep level transient spectroscopy (DLTS) on Au/n-GaAs Schottky diodes. Metalorganic vapor phase epitaxially grown GaAs with background carrier densities of ~$10^{15} \rightarrow 10^{17}$ cm^{-3} have shown significant differences in the introduction rates for the

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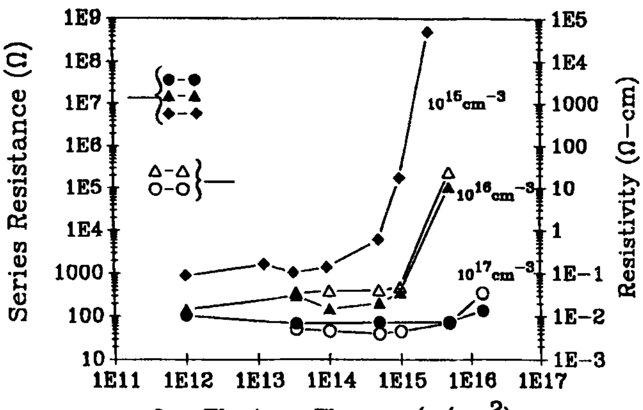

Fig. 1. Diode series resistance and material resistivity as a function of electron fluence for MOVPE grown material of various background carrier densities and measured at room temperature.

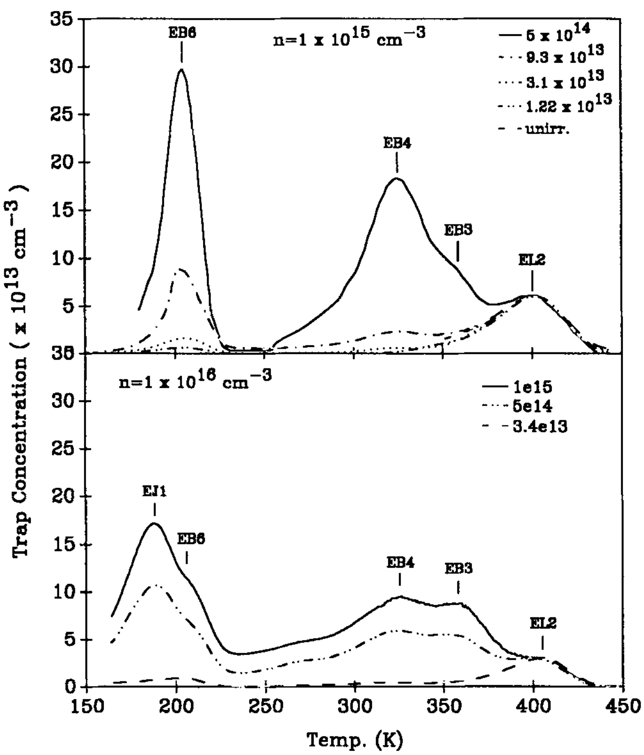

Fig. 2. Deep level transient spectra for MOVPE material with background carrier densities of n = 10^{15} and 10^{16} cm^{-3}.

various traps and in the number of trapping levels induced, while the MBE-GaAs studied here, shows significantly fewer radiation induced traps and lower trap introduction rates.

EXPERIMENTAL

The MOVPE/MBE-grown epilayer structures consisted of a 4 μm epilayer of undoped or n-type GaAs grown on either (001)n$^+$ - GaAs or (001) semi-insulating GaAs substrates. The background carrier densities of the three sets of samples were 2×10^{15}, 3.6×10^{16}, and 2×10^{17} cm^{-3}, respectively. These will be subsequently referred to as 10^{15}, 10^{16}, and 10^{17} cm^{-3} in the text. Ohmic contacts were formed by diffusing Sn balls through the epilayer surface to the substrate. The epilayers were then degreased in vapor condensed chloroform and then weakly etched in an ammonium hydroxide vapor. Au/GaAs Schottky diodes were then fabricated by sputter-depositing gold dots through a stainless steel mask. The depositions were performed using DC magnetron sputtering at an argon partial pressure of 30 mTorr. This pressure ensured a small mean free path for the sputtered gold atoms in our apparatus and a correspondingly low (thermal) arrival energy at the GaAs surface. This was found to give a very low interface defect density and hence nearly ideal Schottky diode behavior. In addition, the adhesion of the gold greatly exceeded that produced by thermal evaporation and this resulted in a far more durable diode that was less prone to damage during current voltage (I-V) probing. All diodes were irradiated at room temperature with 7 MeV electrons at MEVEX Corporation, Ottawa, Ontario, Canada. Deep level transient spectroscopy and I-V measurements were performed in the temperature range of $80K \le T_m \le 450K$ where it was found that all measured characteristics were reproducible with no observable annealing effects. The I-V characteristics were analyzed using the standard equations for emission/diffusion.[4]

The I-V characteristics (before and after irradiation) of all diodes were determined prior to the DLTS measurements to ensure that the diodes had not seriously degraded and that reliable DLTS measurements could still be performed. Hall effect measurements were performed in a Van der Pauw configuration on the same material used in diode fabrication and irradiated simultaneously with the diode structures.

Deep level transient spectroscopy spectra were measured over the temperature range of 450 to 80K with a Polaron 6400 DLTS system. The reverse bias of the diode was chosen to ensure that the bulk of the epilayer was probed and not the epilayer/substrate or Au/epilayer interface. Low fields were chosen to reduce the effect of field dependent emission from the traps. In addition to the trap concentration, the energy depth of the trap and its capture cross section were determined through the relation[5]

$$e_n(T) = \gamma_n T^2(\sigma_{n\infty} g_n \exp(\alpha/k)\exp[-(E_{i0} + E_b)/kT] \quad (1)$$

where $e_n(T)$ is the thermal emission rate, $\sigma_{n\infty}$, is the extrapolated value of σ_n for T = 0, E_{i0} is the extrapolated value of E_i for T = 0, g_n is the degeneracy factor, and γ_n is a constant equal to 2.28×10^{20} cm^{-2}s^{-1}K^{-2} for GaAs. A plot of e_n/T^2 vs 1/T will yield $\sigma_\infty g_n \exp(\alpha/k)$ (denoted by σ_{na}), and $E_{i0} + E_b$ (denoted by E_{na}). These two parameters σ_{na} and E_{na} give the unique "signature" for the trap.

RESULTS

Deep level transient spectroscopy measurements were performed only on diodes having a low series resistance and an ideality factor n ≤ 1.1. The series resistance of all diodes as a function of electron fluence is given in Fig. 1. Also shown in the figure is the corresponding bulk resistivity of the epilayer as measured using a Van der Pauw technique on samples prepared from material identical to that used in the diode fabrication and radiation exposed under identical conditions. From Fig. 1, it is quite clear that the series resistance of the diodes can be accounted for on the basis of the changes in bulk resistivity rather than effects associated with contact resistance. It should be noted, however, that the resistivity does not increase linearly with electron fluence but rather decreases for low fluence, and then increases rapidly at higher fluences. The rapid increase in resistivity at high fluences has been reported earlier.[3,6] As expected, the onset of the rapid increase occurs at lower fluences for the more lightly doped material.

The calculated barrier height ϕ_B for the various diodes for different electron fluences decreases with increasing background carrier density but shows virtually no dependence on electron fluence, indicating that the electron trapping levels formed upon irradiation are "bulk-like" and are not concentrated near the Au/GaAs interface as would be expected if the surface were to act as a "sink" for the defects.[7] Similar results have been reported in Si Schottky diodes irradiated with neutrons and gamma rays.[8]

Deep level transient spectroscopy measurements have been attempted on all diodes both before and after irradiation. These diodes are the same diodes that were used in the I-V measurements. In most cases for the three series of MOVPE samples (A: ~ 10^{15}, B: ~10^{16}, C: ~10^{17} cm^{-3}) and the one set of MBE diodes (n = 10^{16} cm^{-3}), good DLTS transients could be obtained at least for samples exposed to low electron fluences. For high fluence, the series resistance of all samples increased and ultimately introduced severe instrumental errors into the DLTS capacitance transients. Trap distributions could not be obtained for these diodes. In addition, trap distributions for series "C" material could not be obtained at low fluences, since the trap density was too small relative to the background carrier density of ~ 10^{17} cm^{-3} to be reliably determined, (limit of detection is approx. 3 → 4 orders of magnitude below background carrier density). Deep level transient spectra for series A and B MOVPE material for various electron fluences are shown in Figs. 2a and 2b for a rate window of 400 s^{-1}. Trap identification was carried out following the convention given in Ref. 5.

The EL2 trap, which peaks at 400K in this figure, is a native defect observed for the MOVPE grown epilayers[9–12] and its density does not change on irradiation, although the absolute density of the EL2 trap is lower in the material with higher background doping. Presumably this arises from differences in the growth conditions for the two epilayers and/or the silicon dopant inhibits the formation of the EL2 antisite defect. The trapping levels labeled EB3, EB4, and EB6 are common in both series and appear to be related to the observed defect levels generated in VPE material[5] and thus are labeled accordingly. However, of particular note is the trap which we have labeled as EJ1. This level is similar to the EL7 level[4] reported for bulk MBE material. It is observed only in the more heavily doped material (n = 10^{16} cm^{-3}).

Figure 3 shows the DLTS spectrum for both MBE and MOVPE-grown material for an electron fluence of 5×10^{14} cm^{-2}. Note that the spectrum for the MBE material has been expanded by a factor of 10. In the

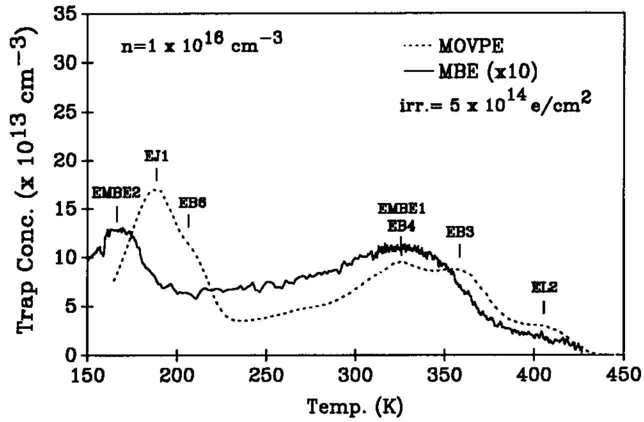

Fig. 3. Deep level transient spectra for MBE and MOVPE material with background carrier densities of n ≈10^{16} cm^{-3} for an electron fluence of 5×10^{14} cm^{-2}.

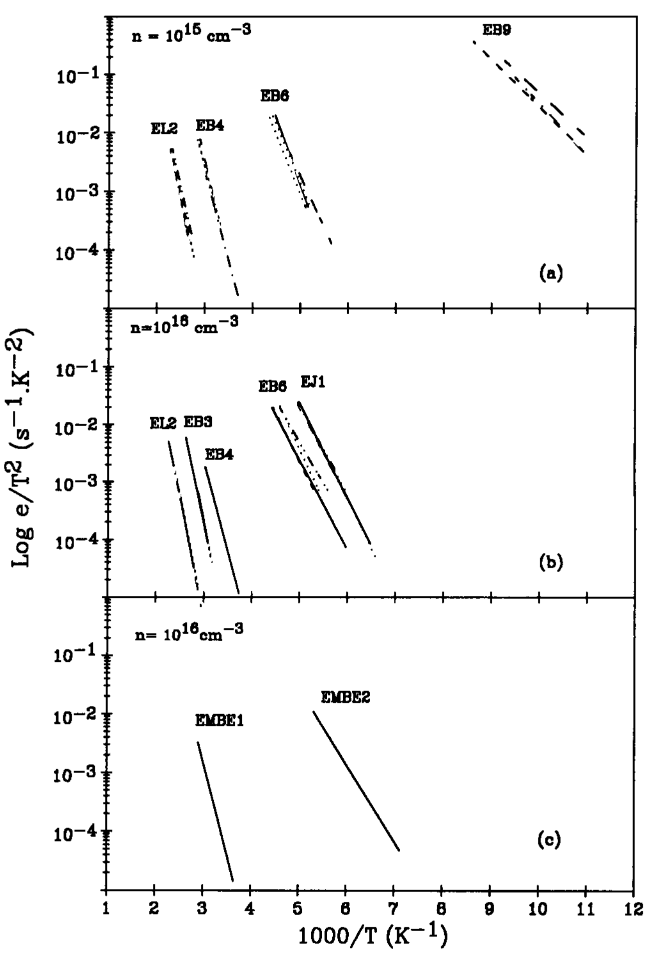

Fig. 4. Emission rate vs reciprocal temperature for (a) MOVPE material with n ≈10^{15} cm^{-3}, (b) MOVPE material with n ≈ 10^{16} cm^{-3}, and (c) MBE material with n ≈ 10^{16} cm^{-3}. The data for all diodes studied for all irradiation levels are shown in the figures.

Table I. Capture Cross Sections and Energy Depths Below the Conduction Band for the Electron Traps Observed in This Study

Material	Trap Level	σ_{na} (cm^2)	Energy (meV)	Comments
MOVPE (10^{15} cm^{-3})	EL2	2.1×10^{-14}	750	unirr/irr
	EB4	1.1×10^{-14}	657	irr
	EB6	1.8×10^{-14}	387	irr
	EB9	6.5×10^{-14}	165	irr
MOVPE (10^{16} cm^{-3})	EL2	6.9×10^{-14}	802	unirr/irr
	EB3	1.6×10^{-12}	822	irr
	EB4	1.7×10^{-14}	608	irr
	EB6	1.6×10^{-15}	334	irr
	EJ1	1.0×10^{-14}	323	irr
MBE (10^{16} cm^{-3})	EMBE1/EB4	2.2×10^{-14}	632	irr
	EMBE2	3.5×10^{-16}	258	irr

Table II. The Introduction Rates for the Observed Electron Traps for MOVPE/MBE GaAs for Various Electron Fluences

Material (cm^{-3})	Fluence (e/cm^2)	EB3 (cm^{-1})	EB4 (cm^{-1})	EB6 (cm^{-1})	EB9 (cm^{-1})	EJ 1 (cm^{-1})
MOVPE 10^{15}	1.2×10^{13}			0.49		
	3.1×10^{13}		0.19	0.55		
	9.3×10^{13}		0.25	1.0	0.024	
	5.0×10^{14}		0.36	0.58	0.036	
MOVPE 10^{16}	3.4×10^{13}	0.15	0.14	0.27		0.20
	5.0×10^{14}	0.11	0.12	0.14		0.21
	1.0×10^{15}	0.09	0.10	0.11		0.17
MBE 10^{16}	5.0×10^{14}		EMBE1/EB4 0.022	EMBE2 0.019		

MBE material, no trapping levels were detected before irradiation while two defect levels labeled here as EMBE1/EB4 and EMBE2 were detected in the irradiated material. This absence of the EL2 level (observed in MOVPE-grown GaAs), results from the much lower V/III ratio used in MBE growth and hence a significant reduction in the formation of arsenic antisite defects.

The energy depths for all traps was obtained by plotting the thermal emission rate as a function of reciprocal temperature as shown in Figs. 4a–4c [see Eq. (1)]. Trap EB9, shown in Fig. 4, was observed at lower temperatures only in the case of the lightly doped Series A material. The various lines represent the reproducibility of the measurements from sample-to-sample and run-to-run.

The capture cross sections and energy depths for the various electron traps are given in Table I. Although EB3 is shown in Fig. 2a, it could not be followed at low fluences and thus no data has been included in the table. For all other levels, the agreement between the measured values of capture cross sections and energies with those given in Ref. 5 appear to be in accordance with the variation between various laboratories.

The trap densities show a near linear dependence as a function of electron fluence for all levels, except for the EL2 trap which does not change with electron irradiation. The introduction rate for the traps are shown in Table II. In the case of the MOVPE epilayers, the introduction rate for a specific trap appears to be smaller for the more heavily doped material while the number of traps and their introduction rates for the MBE material is about an order of magnitude lower than in the MOVPE layer of similar background carrier density.

Finally, Fig. 5 and Fig. 6 show the free carrier density and mobility as a function of electron fluence for MOVPE material with pre-irradiation carrier densities of 10^{16} and 10^{17} cm^{-3}.

DISCUSSION

High energy electron irradiation of MOVPE and MBE grown epilayers of GaAs clearly introduces deep trapping states that directly affect the material's electrical properties. The trapping states that are formed do not, in all cases, follow the same pattern that has been observed in VPE or bulk-grown GaAs.[2,5] In particular is the trap level labeled as EJ1 which appears only in the more heavily doped MOVPE-grown epilayer (~10^{16} cm^{-3}). The appearance of this trap would indicate a possible interaction of the initial defect with impurity atoms—giving rise to a more complex defect site—since the density of this trap follows the same dependence on electron fluence as levels EB3, EB4, and EB6. Also of note is the relative concentrations of levels EB3, EB4, and EB6 for material of low and high background carrier density. EB4 appears suppressed relative to EB6 and EB3 in the highly doped material, while EJ1 has grown, perhaps at the expense of EB4. This needs to be investigated further.

As reported in a number of other studies, the introduction of these electron traps has a direct effect on the free carrier density. These studies have shown that for VPE grown GaAs, carrier removal increases linearly with increasing electron fluence and is independent of the dopant species.[13] The effect of these levels on the electron mobility was not reported. Clearly from the present results (Fig. 5 and Fig. 6), these traps not only reduce the free carrier densities ($n = 10^{15}$ cm^{-3}, $n = 10^{16}$ cm^{-3}) but also the electron mobility due to scattering. However, in contrast to these earlier studies, for material with $n = 10^{17}$ cm^{-3}, the carrier density initially *increases* at low fluence giving a negative value for carrier removal. Assuming that the same trapping levels are generated in this material as in the material with $n = 10^{15}$ cm^{-3} and 10^{16} cm^{-3} then this would indicate that not only are electron traps formed, but also donor levels! The combined effect of mobility reduction and the increase/decrease in carrier density, results in an increase in resistivity at high fluences. This gives a corresponding increase in the series resistance of the Schottky diode. Clearly, the response of the diode, due to a decrease in carrier mobility and increase in series resistance will be degraded. On the other hand, the barrier height remains largely unaffected.

Finally, the behavior of the MBE grown layers appears significantly different than those deposited by MOVPE. In contrast to the results of Blood and Harris[14] and DeJule et al.,[15] no trapping levels are observed before irradiation indicating a trap density $N_T < 10^{12}$ cm^{-3}. The introduction rates for the two observed traps given in Table II are significantly lower than in the MOVPE-grown material. It is also noted that only trap EB4 is observed in both MBE and MOVPE material which would suggest that traps EB6 and EB3 (observed in the MOVPE samples) are associated with the EL2 antisite defect. This needs to be investigated further.

CONCLUSIONS

Deep electron trapping levels in MOVPE and MBE-grown epilayers of GaAs have been measured by DLTS and their effect on Schottky diode properties studied. In contrast to previous reports, the number of trapping levels and free carrier removal was found to depend on the pre-irradiation carrier density. In all cases, the observed barrier heights of the Schottky diodes showed virtually no dependence on electron fluence, indicating that the Au/GaAs interface or material surface does not act as a sink for the traps formed during irradiation. No interface traps were detected through DLTS in these samples before or after irradiation. Finally, it is clear that material deposited by different growth techniques, or possibly under different growth conditions, can show significantly different behavior under high energy electron irradiation. Clearly not all material is created equal and that variations in growth parameters—which can give rise to initial concentrations of antisite defects—may play a significant role in radiation tolerance. These results show a lower defect density, fewer types of defects and an improved radiation hardness for the MBE grown GaAs observed in this study, as compared to the MOVPE material.

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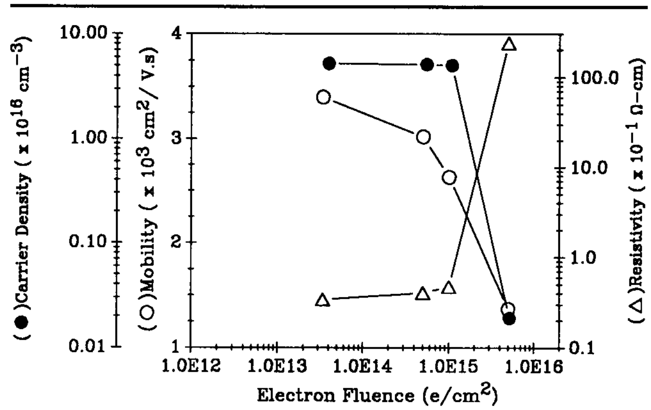

Fig. 5. Room temperature carrier density, mobility, and resistivity of n ≈ 10^{16} cm^{-3} MOVPE material as a function of electron fluence.

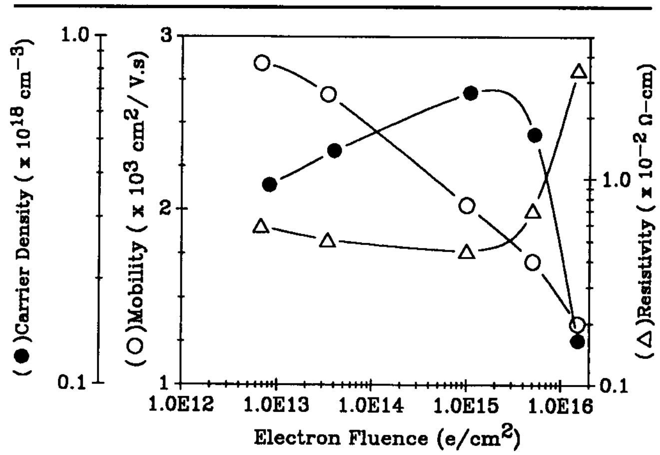

Fig. 6. Room temperature carrier density, mobility, and resistivity of n ≈ 10^{17} cm^{-3} MOVPE material as a function of electron fluence.

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