Picosecond carrier lifetime in erbium-doped-GaAs

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The dependence of free-carrier lifetime on erbium concentration has been measured in molecular-beam epitaxial GaAs epilayers doped with erbium. A gradual reduction in the lifetime is observed with increased dopant incorporation. For a high doping concentration in the range of 10^{19} cm^{-3} or greater, a carrier lifetime of ~1 ps is obtained. Due to the high resistivity of these epilayers, they can also be used as a photoconductive switch, with good responsivity. This leads to new and novel applications for rare-earth doped III-V semiconductors.

In recent years, the successful incorporation of rare-earth elements in III-V compound semiconductors and the tailoring of their luminescence properties have lead to an interest in these material systems.[1,2] In particular, the observation of $\lambda = 1.54$ μm luminescence in erbium-doped-GaAs (GaAs:Er) and $Al_xGa_{1-x}As$, has stimulated research efforts because of their potential application to light sources in optical communications.[3,4] In this letter, we study a different aspect of the photoresponse behavior of this material. The dependence of the carrier lifetime on the doping concentration is investigated in GaAs:Er.[5] A reduction in the carrier lifetime down to ~1 ps is observed for the highest doping investigated. Together with the high resistivity observed for the higher doping values, this material serves as a novel photoconductor material for high-speed optoelectronics.[6]

The rare earths can be incorporated in III-V semiconductors by a number of methods: ion-implantation, during liquid-phase epitaxial (LPE) growth, and during molecular-beam epitaxial (MBE) growth. Due to the large ionic radius of Er^{3+} (0.88 Å) compared to Ga^{3+} (0.62 Å), the thermodynamic equilibrium solid-solubility limit is $\sim 10^{17}$ cm^{-3}. Hence the upper limit of Er incorporation in an equilibrium growth process like LPE is near the above value. Ion implantation at high doses leads to extensive damage to the crystal structure, and the post implanation anneal required to electrically activate the implanted Er, would lead to segregation of the Er due to its low solid solubility. On the other hand being primarily a reaction-kinetics controlled growth process, MBE allows a wide range of rare-earth doping in III-V semiconductors. For our study, four 1-μm thick GaAs:Er epilayers were grown on (001) oriented SI-GaAs substrates. The substrate temperature was 600 °C and the As/Ga flux ratio ~30. The Er-source temperature was varied from 750 to 950 °C to cover the range of doping from 7×10^{16} to 5×10^{19} cm^{-3}. This Er incorporation has been verified by secondary-ion-mass spectroscopy (SIMS). A uniform doping profile throughout the epilayer is obtained. The source cell temperature versus the measured Er concentration is plotted as shown in Fig. 1. It is to be remembered that SIMS gives a measure of the total amount of chemical species present in the epilayer, and not the electrically or optically activated fraction responsible for the respective properties. The surface morphology of the samples is good except for the one at the highest doping, where speckles are observed.

To study the dependence of the carrier lifetime on the doping concentration, the technique of time-resolved photoluminescence can be used. However it is observed that in the doping range studied, the GaAs band-edge luminescence disappears. Alternatively, one can measure the transient photoconductive current induced by a short pulse laser to determine the carrier lifetime. Metal electrodes in a coplanar-strip configuration having a 30 μm width and 15 μm separation is deposited on these epilayers using 500 Å/3000 Å Ti/Au metallization, defined by photolithographic techniques. The wave impedance of this distributed structure is 73 Ω. A 15 μm gap in one electrode serves as the photocoductor gap in the biased electrode, with the other electrode serving as the ground. This photoconductor gap is optically excited by ~100 fs wide optical pulses from a colliding-pulse-mode locked (CPM) dye laser operating at $\lambda = 620$ nm, and a repetition rate of 100 MHz. The average power in the excitation beam is ~5 mW. The photogenerated carriers in the gap are swept by the applied bias across the gap, and part of them recombine in the gap, and the rest are collected by the other electrode, resulting in a current pulse and hence a voltage pulse traveling down the broadband transmission line structure. The termination of the lines are sufficiently far away (~5 mm) to give a time window of ~5 ps which is free of any reflections. To detect this electrical pulse the technique of external-electro-optic sampling is used.[7] In this scheme the electric

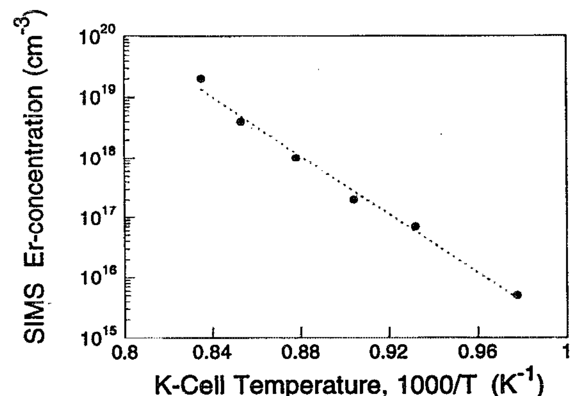

FIG. 1. Erbium concentration in GaAs epilayers, measured by SIMS, as a function of the MBE source cell temperature.

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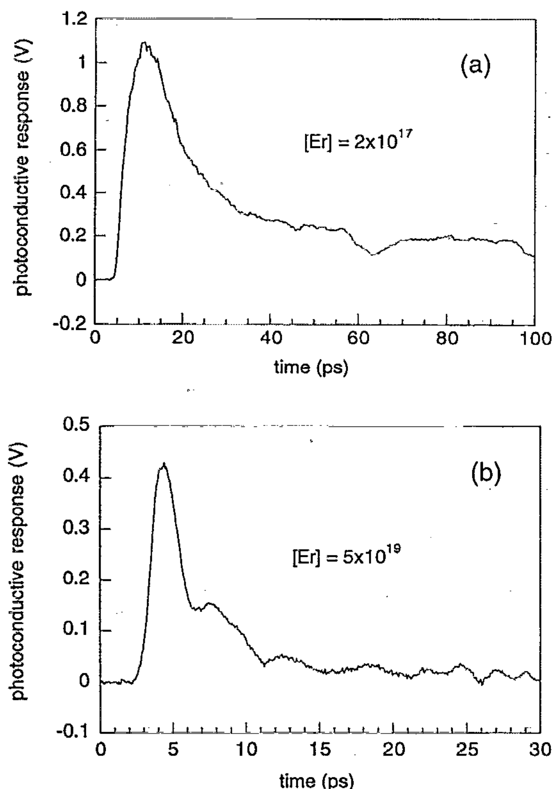

FIG. 2. Photoconductive switching transient as measured by electro-optic sampling for GaAs:Er epilayer with (a) $[Er]=2\times10^{17}$ cm^{-3}, and (b) $[Er]=5\times10^{19}$ cm^{-3}.

field of the voltage pulse changes the birefringence properties of a small nonlinear electro-optic crystal ($LiTaO_3$), which is detected by a delayed probe laser beam obtained from the above CPM laser. The rise time of the pulse is governed by the optical pulse duration and the circuit charging time constant of the carriers generated in the gap. The decay is primarily governed by the carrier recombination lifetime (τ_r) and the carrier transit time (τ_{dr}), which for a 15 μm gap is $\tau_{dr}\gg150$ ps assuming a saturated drift velocity of 107 cm/s. Hence for $\tau_r\ll150$ ps, the photoconductive current decay gives a measure of τ_r. The temporal resolution of this electro-optic sampling technique is about 0.5 ps.

The measured photoconductive transient for an applied modulated dc bias of 15 V across the 15-μm gap is shown in Fig. 2, for the samples with a doping of 2×10^{17} and 5×10^{19} cm^{-3}. Note the difference in the time scales. It is clearly observed that for the doping range investigated, the free-carrier lifetime is in the picosecond domain, with a decrease in the lifetime observed with increased doping. From the $1/e$ decay time of the transient, the carrier lifetime can be plotted as a function of the doping concentration. This is shown in Fig. 3 on a log–log plot. Note the linear curve obtained for the doping range investigated.

To explain the observed ultrafast recombination of photogenerated carriers, if one assumes the Shockley–Read–Hall theory of recombination at a single deep level, the minority carrier lifetime τ_r is given by

$$\tau_r=1/N_t v_{th}\sigma \qquad (1)$$

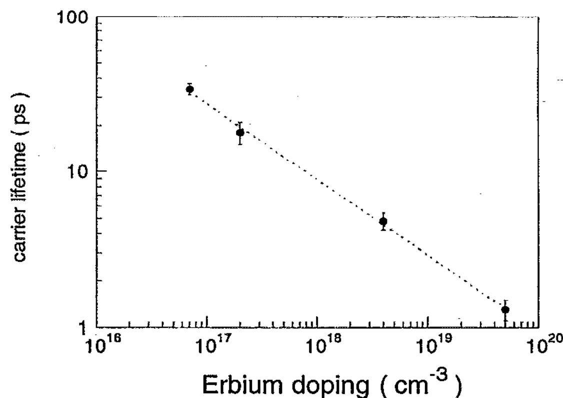

FIG. 3. Dependence of the carrier lifetime on the erbium-doping concentration, in the MBE grown GaAs:Er epilayers.

where N_t is the trap density, v_{th} is the thermal velocity $\sim10^7$ cm/s at 300 K, and σ is the capture cross section. Hence a plot of τ_r vs N_t would be linear on a log–log plot, as shown in Fig. 3, assuming that all the Er incorporated contributes to the trapping/recombination, i.e., N_t=[Er]. It is not known what particular Er species is responsible for the observed recombination, e.g., Er^{3+}, etc. The linearity of the curve would support a simple picture as given by Eq. (1). However the measured slope of $-1/2$ is not expected from Eq. (1), which predicts a slope of -1. This discrepancy in the slope could be due to the deviation from such a simple approximation, or possibly due to the fact that the concentration of traps responsible for this behavior, N_t, is not a linear function of the Er concentration. Further work is in progress to determine the nature of levels responsible for the ultrafast carrier trapping/recombination properties in this material and its high-resistivity behavior. It should be noted that the observed ultrashort carrier lifetimes indicate the presence of strong nonradiative recombination processes (as the direct band-to-band recombination is in the nanosecond regime), and therefore the absence of band-edge photoluminescence in this material, as was noted earlier. In addition, this parallel nonradiative recombination channel inhibits efficient carrier transfer from the GaAs band to the impurity centers (Er), and thus the 1.54 μm luminescence related to the 4f-level transitions in Er are not observed for such high erbium-doped GaAs.

Although this deviation from the behavior as predicted by Eq. (1) is not understood at present, this material has important implications for use in ultrafast optoelectronics. From Fig. 2(b), for the 5×10^{19} cm^{-3} doped sample, nearly 0.5 V is switched from a 15 V bias across a 15-μm gap, using only a 50 pJ/pulse of optical energy. This is similar to the best material to date for photoconductive switching purposes, low-temperature MBE grown GaAs,[8] and better than the popular choice of O^+ ion-implanted silicon-on-saphhire (SOS).[9] It needs to be seen if further optimization of the MBE growth, and possible annealing conditions might improve the responsivity without sacrificing the high resistivity and short carrier lifetime properties. In addition, this material has practical advantages when used for high-speed photoconductive switching purposes. From Fig. 3 it is observed that the carrier lifetime is

a smooth function of the doping, and hence it is possible to tune the carrier lifetime for the desired application. This can lead to optimizing the response speed of optoelectronic devices, e.g., the bandwidth of semiconductor modulators. It should be noted that we have grown control samples of $In_{0.53}Ga_{0.47}As$ epilayers in the same MBE growth chamber, without erbium doping. A room-temperature mobility of 8500 cm^2/V s is obtained which shows that the presence of erbium cell source in the growth chamber does not seem to affect the quality of other materials grown in the same chamber. Similar behavior for the carrier lifetime is also expected in other erbium doped III-V compounds e.g., $In_{0.53}Ga_{0.47}As$, and therefore fast photoconductive detectors with low dark currents for the longer wavelength region may be feasible without using complicated barrier designs and processing techniques.

In conclusion, we have studied the dependence of the free-carrier lifetime on the erbium doping concentration in GaAs:Er. The lifetime decreases smoothly as the doping is increased. MBE growth allow very high doping of up to 5×10^{19} cm^{-3}, without deteriorating the crystallinity, and at these doping levels, carrier lifetimes of $\sim$1 ps are obtained. Therefore, this material when used as a photoconductive switch leads to efficient generation of picosecond transients.

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[1] C. Lhomer, B. Lambert, Y. Toudic, A. LeCorre, M. Gauneau, F. Clerot, and B. Sermage, Semicond. Sci. Technol. **6**, 916 (1991).
[2] P. Galtier, T. Benyattou, J. P. Pocholle, M. N. Charasse, G. Guillot, and J. P. Hirtz, *GaAs and Related Compounds* (IOP, Bristol, 1989), p. 327.
[3] T. Beyattou, D. Seghier, G. Guillot, R. Moncorge, P. Galtier, and M. N. Charasse, Appl. Phys. Lett. **60**, 350 (1992).
[4] G. S. Pomrenke, H. Ennen, and W. Haydl, J. Appl. Phys. **69**, 601 (1992).
[5] S. Sethi, S. Gupta, and P. K. Bhattacharya, Electronics Materials Conference, Boston, June 1992.
[6] D. H. Auston and P. R. Smith, Appl. Phys. Lett. **41**, 599 (1982).
[7] J. A. Valdmanis, Electron. Lett. **23**, 1308 (1987).
[8] S. Gupta, M. Y. Frankel, J. A. Valdmanis, J. F. Whitaker, G. A. Mourou, F. W. Smith, and A. R. Calawa, Appl. Phys. Lett. **59**, 3276 (1991).
[9] F. E. Doany, D. Grischkowsky, and C.-C. Chi, Appl. Phys. Lett. **50**, 460 (1987).