Recombination lifetime of $In_{0.53}Ga_{0.47}As$ as a function of doping density

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We have fabricated devices with the structure $InP/In_{0.53}Ga_{0.47}As/InP$, with a InGaAs doping range varying from 2×10^{14} to 2×10^{19} cm^{-3}. These isotype double heterostructures were doped both *n* and *p* type and were used to measure the minority-carrier lifetime of InGaAs over this doping range. At the low doping end of the series, recombination is dominated by the Shockley–Read–Hall effect. At the intermediate doping levels, radiative recombination is dominant. At the highest doping levels, Auger recombination dominates as the lifetime varies with the inverse square of the doping concentration. From fitting these data, the radiative- and Auger-recombination coefficients are deduced. © *1998 American Institute of Physics.* [S0003-6951(98)01026-2]

Epitaxial InGaAs, that is lattice matched to InP, has proven to be a popular material for high-speed heterojunction bipolar (HBT) transistors. Because the lattice-matched composition $In_{0.53}Ga_{0.47}As$ has a band gap of 0.73 eV, the material is also finding application to infrared photosensors and thermophotovoltaic (TPV) energy converters.[1] All of these devices are minority-carrier-based devices, and therefore, the recombination or minority-carrier lifetimes are important parameters. For HBT applications, the transistor base doping is in the range 1×10^{19} cm^{-3} to 1×10^{20} cm^{-3}, and lifetimes at these doping levels are relevant to current gain. The doping levels in TPV converters typically span several orders of magnitude, and again, the lifetime at all doping levels is a critical parameter in predicting conversion efficiency. The doping range for the samples in this study ranged from undoped (2.5×10^{14} to 1.8×10^{15} cm^{-3}) to heavily doped (2×10^{19} cm^{-3}). The purpose of this work is to find the dominant recombination mechanisms over these five orders of magnitude of doping range and to compare any lifetime differences between *n*- and *p*-type material.

Measurements by Henry and co-workers[2] over the concentration range of $3\times10^{17}-1\times10^{19}$ cm^{-3} indicated that the lifetime decreased with doping level because of a combination of radiative and Auger recombination. This work also claimed that the lifetime is about a factor of 4 larger in *n*-type than in *p*-type InGaAs. Gallant and Zemel[3] measured the diffusion length in undoped *n*-type InGaAs ($\sim1\times10^{15}$ cm^{-3}) and, from that, deduced a hole lifetime of 18.5 μs. Early work by this group compared the lifetime of undoped and heavily doped (*n* type, 1×10^{18} cm^{-3}) InGaAs that was both lattice matched and mismatched with a grading layer to InP.[4] Recent work by this group described the lifetime in undoped InGaAs double heterostructures (DHs) that were grown on misoriented substrates producing Cu–Pt-type ordering of the In–Ga sublattice.[5]

Here, we grew isotype double heterostructures of both *n*- and *p*-type InGaAs on Fe-doped InP, [(100) 2° toward (110)] oriented substrates by metal–organic chemical vapor deposition. The basic DH structures used here were *n*-InP/*n*-$In_{0.53}Ga_{0.47}As$/*n*-InP and *p*-InP/*p*-$In_{0.53}Ga_{0.47}As$/p-InP. The growth took place in a purified hydrogen ambient at a temperature of 620 °C in a vertically oriented reactor. The reactants were phosphine, arsine, trimethyl indium, and triethyl gallium. The *n*- and *p*-type dopants were hydrogen sulfide and diethylzinc, respectively.

Recombination lifetime measurements were made by two complementary techniques. To measure the lower doping ranges, a radio-frequency photoconductive decay (RFPCD) technique was used.[6] This contactless technique was successful for lifetimes greater than about 20 ns. A variety of pulsed light sources were used here, ranging from small light-emitting diodes to a tunable optical parametric oscillator driven by a tripled YAG laser. A second RFPCD system provides variable sample temperature from about 80 to 300 K. Using temperature as a variable provides additional information for identifying the recombination mechanism, as well as providing data for low-temperature device applications.

Samples in the higher doping ranges were measured by a photoluminescence photon-counting technique. As the intrinsic photoluminescence for InGaAs is in the infrared (~1.7 μm), a sum-frequency up-conversion technique is required for photon counting.[7] The samples were pumped by 90 fs pulses at 82 MHz from a Spectra-Physics femtosecond model-locked titanium-doped sapphire (Ti:S) laser running at 762 nm. The collected luminescence was mixed with the Ti:S laser pulse for sum-frequency generation (SFG) in a 1 mm lithium iodate ($LiIO_3$) crystal, and the SFG signal was dispersed by a SPEX 270 m spectrograph and detected by a Hamamatsu R464 photomultiplier tube. The system time resolution is approximately 110 fs, and the detection wavelength of 520 nm corresponds to an InGaAs luminescence peaking at 1.64 μm.

The undoped samples were measured using very weak light sources to find the low-injection lifetime. The lifetimes in the undoped active layers were primarily defect dominated and very dependent on the light intensity. Figure 1 shows the conductivity decay of an undoped DH with a residual *n*-type background density of 2×10^{14} cm^{-3}. The two components of the decay, 21.45 μs at the initial portion of the recombination process, followed by 15.45 μs for the last portion of

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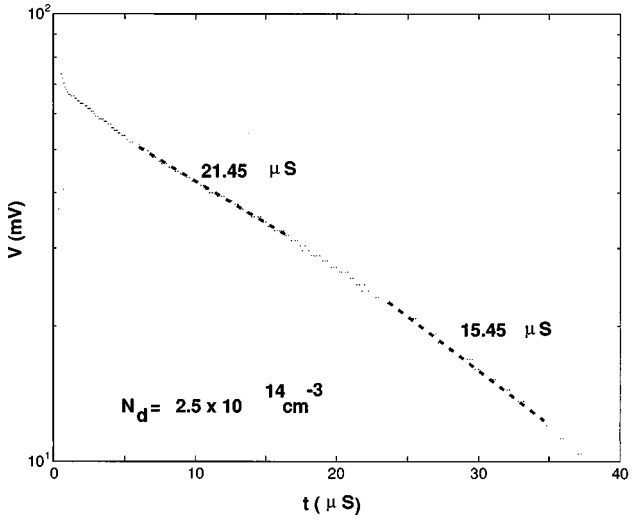

FIG. 1. The minority-carrier lifetime in undoped, *n*-type InGaAs as measured by the RFPCD technique. The background doping level here is 2×10^{14} cm^{-3}. The low-injection lifetime is 15.45 μs, and the high-injection lifetime is 21.45 μs.

the decay, is typical of the Shockley–Read–Hall (SRH)[8] process. These lifetimes may be the largest measured for $In_{0.53}Ga_{0.47}As$ and are larger than those typically found in undoped, epitaxially grown GaAs.[9] The recombination, at higher injection levels, decays with an effective lifetime of $\tau_n+\tau_p$, whereas the lower-injection process is the minority-carrier lifetime, or τ_p, in this case. Similar behavior was seen in several undoped DH samples for which the background doping varied from that above to about 2×10^{15} cm^{-3}. In the doping range from 10^{16} to 10^{18} cm^{-3}, the lifetime varied as $1/N$, where N is the doping density. This behavior is indicative of radiative recombination being the dominant mechanism. Here, the lifetime is given by

$$\tau_{n,p}=\frac{1}{BN}, \tag{1}$$

where the B coefficient is proportional to the sum of the dipole matrix elements connecting valence- and conduction-band wave functions. For example, the B coefficient has been calculated[10] and measured[11] for GaAs and is found to be about 2×10^{-10} cm^{-3} s^{-1}. Here, a fit to the data shows that B is about 1.43×10^{-10} cm^{-3} s^{-1} for $In_{0.53}Ga_{0.47}As$. This result is consistent with the common observation that InGaAs is a strong light emitter.

Figure 2 shows some lifetime measurements on two *p*-type samples with doping levels of (A) 1.2×10^{19} cm^{-3} and (B) 2.0×10^{19} cm^{-3}. These lifetimes were measured by the up-conversion technique, which was necessary for all lifetimes below about 10–20 ns. These data show lifetimes of 130 and 25 ps, respectively. Here, the lifetime is varying approximately as $1/N^2$, where N is the doping density. This behavior indicates the Auger recombination process.[12] In this case, one can describe the Auger lifetime by

$$\tau_A=\frac{1}{CN^2}. \tag{2}$$

Here, C is defined as the Auger recombination coefficient.

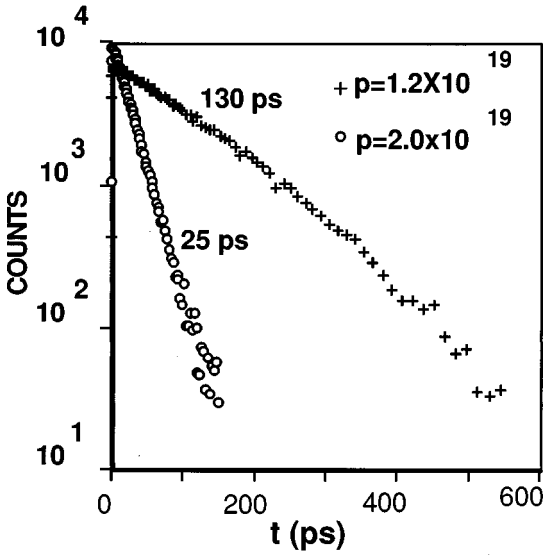

FIG. 2. The minority-carrier lifetime in heavily doped *p*-type InGaAs. The sample represented by curve A is doped to 1.2×10^{19} cm^{-3}, and the sample represented by curve B is doped to 2.0×10^{19} cm^{-3}.

By the law of addition of reciprocal lifetimes, the total DH lifetime is given by

$$\frac{1}{\tau}=\frac{1}{\tau_{\mathrm{SRH}}}+\frac{1}{\tau_R}+\frac{1}{\tau_A}. \tag{3}$$

In terms of the doping concentrations N, one can rewrite Eq. (3) as

$$\tau=[\tau_{\mathrm{SRH}}^{-1}+BN+CN^2]^{-1}. \tag{4}$$

Figure 3 shows a composite of the lifetime data over five orders of magnitude. Here, we plotted τ versus the *n*- and the *p*-type doping density of a number of samples. The data over this range are fit by a least-squares routine to Eq. (5), and the parameters produced are

$$\tau=[2.11\times10^{4}+1.43\times10^{-10}N+8.1\times10^{-29}N^2]^{-1}\ \text{(s)}, \tag{5}$$

where N is the doping density in cm^{-3}. Here, the SRH limit, $(N=0)$, for the fit is 47.36 μs, and the B coefficient is

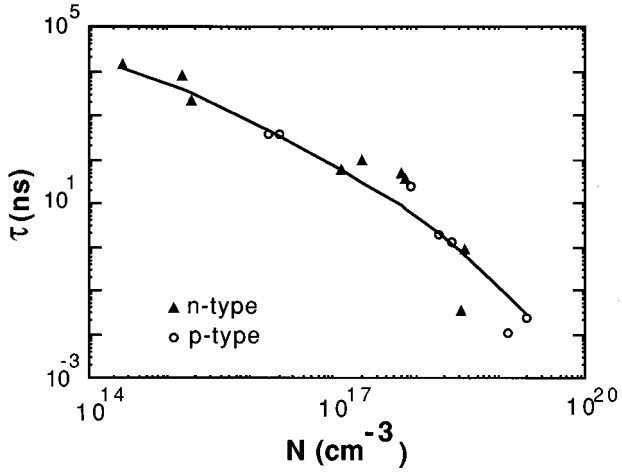

FIG. 3. A composite of the lifetime measurements for both *n*- and *p*-type InGaAs. The solid line is a least-squares fit of Eq. (5) to the data.

1.43×10^{-10} $cm^{-3}\,s^{-1}$, as noted before. The data indicate a common Auger coefficient for both *n*- and *p*-type InGaAs with the value being

$$C_{n,p}=8.1\times10^{-29}\ cm^{-6}\,s^{-1}. \tag{6}$$

These results disagree with the results of Henry and co-workers,[2] who found somewhat larger lifetimes at all doping levels. They also found that the lifetimes for *n*-type material are about four times larger than in *p*-type material for equivalent doping levels. The origin of this disagreement is not known at this time.

In summary, these results give minority-carrier-lifetime data over doping ranges from 10^{14} to 2×10^{19} cm^{-3} for $In_{0.53}Ga_{0.47}As$ that is lattice matched to InP. The corresponding lifetimes ranged from about 20 μs to 25 ps, covering six orders of magnitude. These data can be used to model current device technologies that are sensitive to recombination lifetimes.

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