Auger recombination in heavily carbon-doped GaAs

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The recombination parameters in heavily carbon-doped GaAs are of considerable importance to current bipolar transistor technology. Here, we used time-resolved photoluminescence and quantum-efficiency techniques in parallel to measure the very short lifetimes expected at high doping. The samples were isotype double heterostructures, with the structure Al(0.4)Ga(0.6)As/GaAs/Al(0.4)Ga(0.6)As, grown by molecular-beam epitaxy. The doping level was varied from 5×10^{18} to 1×10^{20} cm^{-3} for the samples described here. For doping levels greater than 1×10^{19} cm^{-3}, the lifetime decreased as the inverse of the cube of the hole density, indicating that phonon and impurity-assisted Auger processes are dominant. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1357213]

The Auger recombination parameters in heavily carbon-doped GaAs are of considerable importance to heterojunction bipolar transistor technology.[1] The bases of AlGaAs/GaAs and GalnP/GaAs transistors are carbon doped above 1×10^{19} cm^{-3} for emitter/collector isolation. The base doping has been reported as high as 1×10^{21} cm^{-3} in some devices.[2] However, recombination loss in the base must be reduced such that the current transfer ratio, α, is not reduced. The Auger recombination rate generally increases as the square of the free-carrier density. The Auger lifetime in a p-type material is generally written as

$$\frac{1}{\tau_A}=C_p p^2(\mathrm{s}^{-1}), \tag{1}$$

where C_p is the Auger coefficient.

However, for GaAs, values of the C coefficient have not been estimated for doping ranges greater than 1×10^{19} cm^{-3}. Benz and Conradt[3] studied the photoluminescence of undoped GaAs diodes in heavy forward bias to produce injection levels in the range of 5×10^{17} cm^{-3}. From the intensity of the luminescence (at 1.86 eV and 4.2 K), Benz and Conradt estimated the GaAs Auger coefficient C_p as

$$C_p\approx10^{-31\pm1}(\mathrm{cm}^6\,\mathrm{s}^{-1}). \tag{2}$$

Using radiative quantum-efficiency measurements, Queisser and Panish[4] found that Auger processes are neglible in GaAs for $p<1\times10^{19}$ cm^{-3}. Benchimol and co-workers[5,6] used a time-resolved photoluminescence method to measure the lifetime of carbon-doped GaAs grown by three different epitaxial techniques. Their data showed that the lifetime in molecular-beam epitaxy (MBE) grown films is about two orders of magnitude lower than for films grown by chemical beam epitaxy (CBE) and metalorganic chemical vapor deposition (MOCVD). Benchimol *et al.* suggested that impurities in the carbon source may be source impurity incorporation in the film that degrades the MBE lifetime. Their CBE and MOCVD data[5,6] showed inflection points in the τ vs p curve at 1×10^{19} and at 1×10^{20} cm^{-3}, respectively.

Theoretical calculations of the Auger effect have been presented by Landsberg.[7–9] Takeshima[10] used the many-body approach to calculate the Auger coefficients for GaAs and GaSb, taking into account the pure collision, phonon-assisted, and impurity-assisted processes. In these calculations it was found that the latter two Auger coefficients increase with hole concentrations greater than $p>1\times10^{19}$ cm^{-3}. The impurity-assisted process was dominant in the range of 1×10^{19} cm^{-3}. In this case, one can write the total Auger coefficient as

$$C_p(p)=C_{\mathrm{coll}}+C_{\mathrm{ph}}(p)+C_{\mathrm{imp}}(p). \tag{3}$$

In this work, we prepared isotype double heterostructures with structure $Al_{0.4}Ga_{0.6}As/GaAs/Al_{0.4}Ga_{0.6}As$ grown on GaAs substrates by molecular-beam epitaxy. The carbon-doped layers used in the present study were grown in a Varian Modular Gen II MBE chamber. Carbon tetrabromide was used as a carbon precursor for p-type doping. The gas delivery system used here included a solid CBr_4 source maintained at 5 °C.

Epitaxial structures were grown on (100) GaAs substrates at 600 °C using gallium and As_2 solid sources. The heterostructures consisted of 1.5 μm carbon-doped GaAs layers grown between undoped AlGaAs barrier layers. The bottom confinement layer consisted of 0.3 μm thick AlGaAs. The latter prevented photoelectrons from escaping the carbon-doped GaAs in the substrate. A second AlGaAs top layer (50 nm thick) was used to reduce the surface recombination rate. The top $Al_{0.4}Ga_{0.6}As$ layer was then covered with a 60 Å GaAs cap layer. The carbon doping level in the active layer was varied from 5×10^{18} to 1×10^{20} cm^{-3}.

The free-hole density for all films was measured by the van der Pauw–Hall technique after removing the $Al_{0.4}Ga_{0.6}As$ top layer. The hole density was compared with the carbon density that was measured by secondary-ion mass

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spectroscopy (SIMS). In all cases, the doping activation was about unity even though the carbon acceptor lies about 26 meV above the valence band. The efficient activation is caused by the impurity band that merges with the valence band, producing a semiconductor–metal or Mott transition.[11] The Mott transition was found to occur at doping levels greater than about 5×10^{18} cm^{-3} in GaAs doped with Mn.[12]

For the lifetime measurements, we used time-resolved photoluminescence (TRPL), using upconversion, by mixing the photoluminescence (PL) photons with the pump-laser photons in a nonlinear crystal. The TRPL measurement system is described elsewhere.[13] A photoluminescence quantum-efficiency (QE) measurement was used in parallel to measure the same sample set. The radiative quantum efficiency, η, in low injection is defined by

$$\eta=\frac{\tau}{\tau_R}=B\tau p=\frac{I_{\mathrm{PL}}}{I_0}. \tag{4}$$

Here, τ is the total lifetime and τ_R is the radiative lifetime. Also, B is the coefficient of radiative recombination, p is the free-hole density, I_0 is the incident excitation intensity, and I_{PL} is the PL intensity. The optical system only collects a small fraction of the total PL radiation, so we write the measured PL signal as

$$S_{\mathrm{PL}}=\gamma I_{\mathrm{PL}}=\gamma I_0 B\tau p. \tag{5}$$

Because I_0, γ, and B are constants of the measurement, the measured signal is proportional to the product of the lifetime and the hole density. By using measured values of (τ,p) for a subset of the samples, we calibrated the QE system in terms of a lifetime/hole density product. With this calibration, we obtain lifetime values by means of the measured PL signal, S_{PL}.

We measured the Hall mobility for all samples at 77 and 300 K. The mobility varies approximately as $p^{-0.25}$ at 77 K and $p^{-0.12}$ at 300 K. The conductivity and mobility in heavily carbon-doped GaAs have been discussed by numerous authors. The carbon acceptor begins to form an impurity band at concentrations above about 2×10^{18} cm^{-3}, since the wave function overlap becomes significant.[14] As carbon doping increases, the impurity band broadens and merges with the valence band, producing the Mott or semiconductor–metal transition. The Hall effect measurements of Kim *et al.*[14] indicate that the conductivity displays metallic behavior at low temperatures rather than becoming insulating due to carrier freeze out. Our transport data are consistent with prior transport studies on similar epitaxial material.

Some lifetime data of these double heterostructures are shown in Fig. 1. The doping, measured by the Hall effect and by SIMS, is 4.9×10^{19} cm^{-3} for sample A and 1.05×10^{20} cm^{-3} for sample B. The measured lifetimes for these two samples are 5.48 and 0.4 ps, respectively. The recombination lifetime in this doping range is expected to vary as

$$\frac{1}{\tau}=Bp+Cp^2+\frac{1}{\tau_I}. \tag{6}$$

Here, B and C are the radiative and Auger coefficients, respectively. The impurity or Shockley–Read–Hall (SRH) recombination[15,16] is denoted by τ_I and is given by

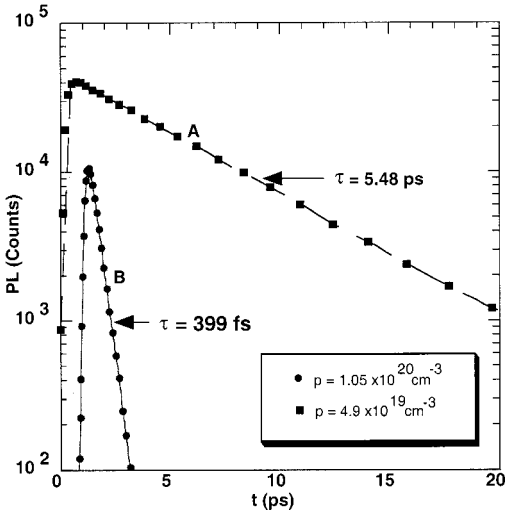

FIG. 1. Photoluminescence decay data for the samples doped to 4.9×10^{19} cm^{-3} (curve A) and 1.05×10^{20} cm^{-3} (curve B).

$$\frac{1}{\tau_I}=v_{\mathrm{th}}\sigma_n N_I=v_{\mathrm{th}}C_n \tag{7}$$

for midgap centers.

Here, v_{th}, σ_n, and N_I are the thermal velocity, electron capture cross section, and midgap impurity concentration, respectively. The contribution of radiative lifetime to total lifetime can be estimated from prior studies. Measurements in n-type GaAs double heterosturctures doped in the range of 1×10^{17}–2×10^{18} cm^{-3} indicated that B is 1.43×10^{-10} cm^3 s^{-1}.[17] Nelson and Sobers[18] arrived at a similar value of B in fitting their lifetime data on p-type GaAs. Therefore, at $p=1\times10^{18}$ cm^{-3}, the radiative lifetime, τ_R, is about 7 ns, and at $p=1\times10^{19}$ cm^{-3}, τ_R is about 700 ps. Our lifetime values are more compatible with the CBE and MOCVD data of Benchimol *et al.*[5,6] but two orders of magnitude larger than their MBE results. A recent analysis[19] of heterojunction bipolar transistor gain, with a base doping of 4.9×10^{19} cm^{-3}, indicated lifetimes ranging between 20 and 50 ps. Using these results and the current results, we have assumed that the effect of the radiative component on total lifetime is negligible above 1×10^{19} cm^{-3}.

Figure 2 shows the dependence of lifetime on the free-hole density as measured by both techniques. Data are shown that result from both TRPL (curve B) measurements and

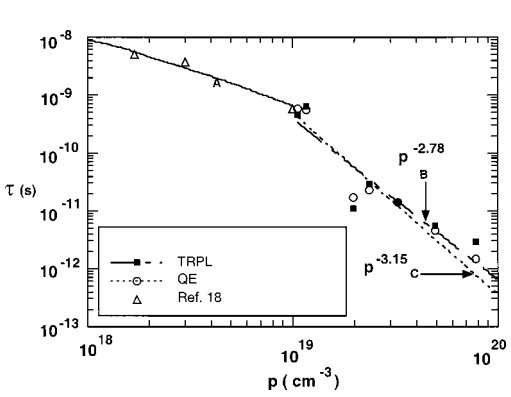

FIG. 2. Lifetime as measured by TRPL (curve C) and QE (curve B) for the sample set. The published data of Nelson and Sobers (Ref. 18) is shown in curve A.

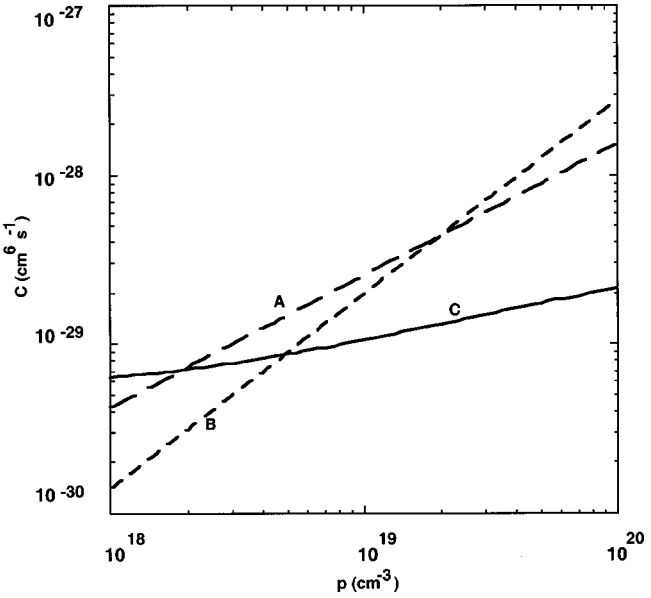

FIG. 3. Auger coefficient as a function of hole density derived from curve A: TRPL measurements and curve B: QE measurements. The values calculated by Takeshima (Ref. 10) are shown in curve C.

from QE measurements (curve C). The QE measurements were calibrated by averaging the S_{PL} of each sample in the set to the $p\tau$ product of the same sample. The average value of $\gamma I_0 B$ was then used to derive the lifetime values shown in Fig. 2. Curve A is the published data of Nelson and Sobers[18] for $p>1\times10^{18}$ cm^{-3}. Our data agree with the latter at $p=1\times10^{19}$ cm^{-3}. We see from Fig. 2 that the lifetime decreases much more steeply than $1/p^2$ for $p>1\times10^{19}$ cm^{-3}. We fit the TRPL and QE data with the following functions:

$$\tau_{\mathrm{TRPL}}=2.6\times10^{43}p^{-2.78}(\mathrm{s}),$$
$$\tau_{\mathrm{QE}}=3.4\times10^{50}p^{-3.15}(\mathrm{s}), \tag{8}$$

where p is the free-hole concentration in cm^{-3}. These data are consistent with the calculations of Takeshima[10] that show C_p increasing with the free-carrier concentration.

Figure 3 shows the calculated Auger coefficient of carbon-doped GaAs using the fits from both the TRPL (curve A) and QE (curve B) lifetime measurements of Fig. 2. Looking at curve A, we see that the Auger coefficient increases from about 6×10^{-30} cm^6 s^{-1} at $p=1\times10^{19}$ cm^{-3} to about 1.5×10^{-28} cm^6 s^{-1} at $p=1\times10^{20}$ cm^{-3}. The data from the QE varies as $1/p^{3.15}$ with hole density and therefore C increases with p. Curve C shows the calculations of Takeshima[10] for GaAs, and the slope is considerably smaller than that presented by the data. The calculated values vary from 6.5×10^{-30} at 1×10^{18} cm^{-3} to 2×10^{-29} at 1×10^{20} cm^{-3}. However, the theory produces values that are about an order of magnitude smaller than the data at 1×10^{20} cm^{-3}. Also, the theoretical variation of $C(p)$ with hole doping is considerably weaker. Considering the complexity of the many-body calculations, the disagreement of the absolute values is not surprising. The disagreement of the dC/dp between the experiment and theory is possibly more disturbing.

In the analysis, we have implicity assumed that the radiative and the impurity recombination terms do not vary with hole density, p. If one considers the possibility that the SRH contribution increases with carbon doping, then the latter could contribute to lifetime in the 1×10^{19} to 1×10^{20} cm^{-3} doping range. Using the Takeshima value of C at 1×10^{20} cm^{-3}, we calculate an Auger lifetime of 5 ps where the data shows a lifetime of about 0.5 ps. If we assume, for example, that the lifetime is controlled by SRH recombination, then we calculate a capture coefficient of about 2×10^5 cm^{-1}. Thus from Eq. (7), this lifetime would require 1×10^{20} cm^{-3} midgap recombination centers with a capture cross section of 2×10^{-15} cm^2. Cross sections of this size are observed for deep donors, but donors would strongly compensate for and reduce the free-hole concentration. No such effects were seen here as the SIMS carbon concentration and the free-hole concentration track very closely. Therefore, the assumption of impurity recombination in this doping range is inconsistent with the standard SRH model and with other data. We will tentatively conclude that the lifetimes in the 1×10^{19}–1×10^{20} cm^{-3} hole density range are controlled by the Auger effect, or at least by the impurity induced Auger effect.

In summary, we have shown that the Auger coefficient of heavily carbon-doped GaAs increases with hole density for values greater than 1×10^{19} cm^{-3}. These data should be of value in designing GaAs-based heterojunction bipolar transistors.

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