Survey of defect-mediated recombination lifetimes in GaAs epilayers grown by different methods

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In GaAs double-heterostructure potential wells at moderate injection levels, surface, radiative, and Auger recombination can all be suppressed. This leaves only Shockley–Read–Hall recombination which is mediated by defects in the crystallographic structure. In a survey of organometallic chemical vapor deposition (OMCVD), liquid phase epitaxy, and molecular beam epitaxy, we find that all the growth methods produce better than expected material quality with recombination lifetimes at room temperature as high as $\sim 2\,\mu$s observed in the best OMCVD material. If this lifetime were to be maintained during device processing, then material quality would not be the limiting factor in the implementation of certain novel device concepts.

It is frequently assumed that the electron-hole recombination lifetime in the III-V semiconductors is limited to less than 100 ns. This arises from practical everyday experience where surface recombination, Auger recombination, or even radiative recombination can limit the lifetime. For example, at the high injection levels required in present day semiconductor lasers, Auger recombination or even spontaneous radiative emission can be very fast. In other cases, the surface defect recombination can prevent a long lifetime. As a result we have very little knowledge of the bulk material quality that is actually available from the different epitaxial growth methods and how they compare to each other and to the seed wafers on which they are grown. What experience we do have is often limited to the modeling of finished devices in which processing-induced defects often mask the quality of material that was present in the originally grown epilayers.

Therefore, it is highly desirable to develop the instrumentation required to survey the III-V semiconductor crystals for bulk defect-mediated recombination, both to compare the different epitaxial growth methods and to compare bulk material quality before and after device processing. The early pioneering work of Nelson and Sobers[1] eliminated the problem of surface recombination by working with isotype double-heterostructure samples, in which the carriers are restricted to a GaAs potential well bounded by wider bandgap AlGaAs layers. In our work we have controlled surface recombination by this approach as well as by the use of chemical surface modification strategies. The chemical approach for reducing surface recombination permitted us to study the properties of the commercially available seed wafers before they had been subjected to any high-temperature growth processes.

To accomplish these measurements, we adapted a contactless carrier lifetime probe which had previously been used to determine some remarkably long-lived[2–5] recombination properties of silicon and silicon surfaces. This inductively coupled radio frequency apparatus, which is illustrated in Fig. 1, monitors the absolute sheet conductivity of the semiconductor as a function of time. A brief flash of pulsed incoherent light, in this case from a Q-switched doubled Nd-YAG laser scattering off a white surface, injects electrons and holes into an epilayer or into the bulk substrate wafer itself. The recombination of electrons with holes is monitored by the decay of the conductivity associated with the optically injected carriers. In a numerical algorithm, conductivity is divided by the carrier-density-dependent mobility to convert it to a density decay curve. If the epilayer thickness L is sufficiently small, the decay of excess carrier density n is simply the sum of a bulk and a surface term[6]:

$$\frac{dn}{dt} = -\left(\tau_b^{-1} + \frac{2S}{L}\right)n, \tag{1}$$

where τ_b is the bulk recombination lifetime, S is the surface recombination velocity, and the factor 2 accounts for the front and back surfaces. The reciprocal of the quantity in brackets was called by Shockley[6] the "filament lifetime" τ, which, in general, may depend on n. Irrespective of the absorption depth of the light source, the injected carrier density n will become spatially uniform and Eq. (1) will be valid provided that $L \ll \sqrt{D\tau}$, where D is the ambipolar diffusion constant and $\sqrt{D\tau}$ is the diffusion length. If the front and back surfaces of the epilayer are inequivalent, then $(S_f + S_b)$ should be substituted for $2S$.

The bulk recombination lifetime may itself be expressed as an ascending power series in the excess carrier density n:

$$\frac{1}{\tau_b} = \frac{1}{\tau_{\mathrm{SRH}}} + Bn + Cn^2, \tag{2}$$

where τ_{SRH} is the defect-mediated Shockley-Read-Hall bulk lifetime, Bn is the radiative recombination rate ($n \simeq p$, i.e., the injected carrier density greatly exceeds the background doping), and C is the Auger recombination coefficient. For this particular study, the surfaces were generally covered with AlGaAs or chemically treated so that the surface recombination was negligible. Therefore, the logarithmic derivative $(1/n)(dn/dt)$ of the density decay curve is $1/\tau_b$, which can be fitted to a power series in n. The constant coef-

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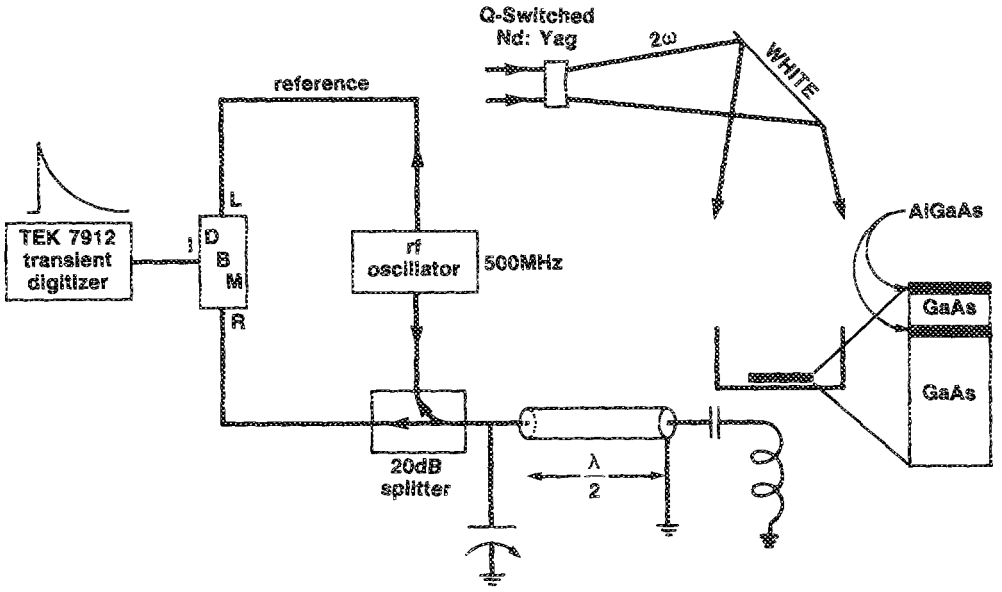

FIG. 1. Doubled Nd:YAG laser scatters off a white surface and injects carriers into a GaAs double-heterostructure epilayer. The transient conductivity is probed by rf induction at 500 MHz. The series resonant circuit, adapted from NMR technology, includes a $\lambda/2$ section of co-ax for convenient access to the tuning element. A 20-dB splitter separates the incoming from the reflected signal. The imbalance in the circuit caused by the carriers is phase detected by a wide dynamic range double-balanced mixer (DBM) and then digitized.

ficients of the power series are $1/\tau_{SRH}$, B, and C. At sufficiently low injection levels, the decay is a pure exponential whose lifetime τ_{SRH} is the main quantity of interest here. A typical example of such a decay curve in which $\tau_{SRH} \approx 1.5\,\mu s$ is shown in Fig. 2. That sample, grown by organometallic chemical vapor deposition (OMCVD), had a negligible background doping $\simeq 10^{14}\ cm^{-3}$ and will be discussed later.

In these samples, the conductivity responds to the plasma mobility, the sum of the electron and hole mobilities. The electron mobility is $\simeq 40$ times greater than the hole mobility and is the more important one. At low densities, the mobilities are equivalent to what they would be in any lightly doped sample of GaAs. As the optically injected density grows large, scattering from free holes becomes important and the mobility drops off with density. This is similar to the drop in mobility due to ionized impurity scattering in heavily doped samples. We need to know the density dependence of the plasma mobility in order to convert the measured conductivity to a carrier density. In addition to relying on published sources[7] of the plasma mobility, we also made our own measurements in the following way. We calibrated the intensity of our pulsed light source by monitoring the response of the rf bridge to silicon samples of known mobility. For equivalent optical injection, the ratio of peak response of a GaAs epilayer to that of a silicon wafer is the ratio of mobility of the two materials. In practice, we found that the plasma mobility was only slightly higher than the mobility due to ionized impurity scattering.[8] The mobility formula we used was $1/\mu = 1/8380 + 7.6\times 10^{-16}\times n^{0.65}$.

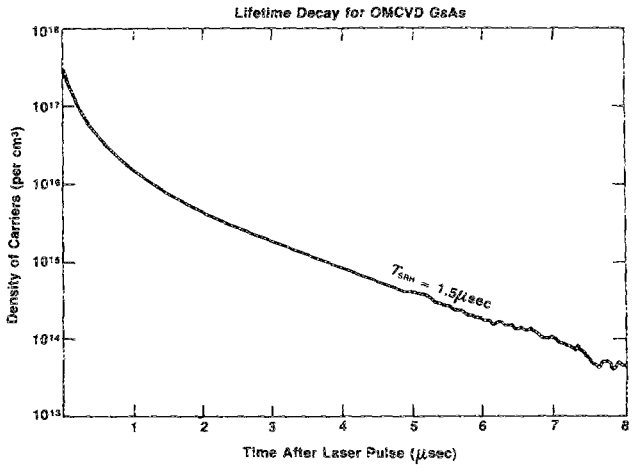

FIG. 2. Decay of carrier density in an OMCVD GaAs double heterostructure excited by delta function optical injection at $t = 0$. At long times and low densities bulk Shockley–Read–Hall recombination dominates all surface, radiative or Auger recombination and leads to an exponential decay lifetime $\sim 1.5\,\mu s$.

All three major types of material growth, liquid phase epitaxy (LPE), organometallic chemical vapor deposition, and molecular beam epitaxy (MBE), were surveyed in this experiment. No intentional doping was introduced into any of the samples which had active layer (GaAs) thicknesses from 2 to $10\,\mu m$. At these thicknesses, interfacial recombination (at the AlGaAs interface) is negligible, and radiative lifetime is significantly extended by photon recycling effects. The upper and lower AlGaAs layer composition in these samples varied from 65% Al for LPE and 50% Al for OMCVD to 40% Al for MBE. In all three cases, the height of the potential step was sufficient to confine the carriers in the GaAs layer. Growth was conducted at 850–800 °C for LPE, 700 °C for OMCVD, and 580 °C for MBE. The experimental results for τ_{SRH} are summarized in Table I. In a survey of this type, we do not aim to determine a fundamental material constant. The lifetimes given in Table I should be regarded neither as upper nor lower limits but rather as an indication of what is available in present-day technology. What is remarkable is that the lifetimes for all three growth methods are as long as they are.

In addition to the epilayers we also tested bulk wafer material, both Cr compensated and nonintentionally doped material. This necessitated the use of chemical treatments[9] instead of AlGaAs epilayers to suppress surface recombination. None of the substrate wafers had lifetimes exceeding 30 ns, in keeping with the more commonly quoted recombination rates in GaAs.

The bulk Shockley–Read–Hall lifetime is often ex-

TABLE I. Lifetimes should be regarded neither as upper nor lower limits but rather as an indication of what is available in present-day technology.

Growth Method	OMCVD	LPE	MBE
τ_{SRH} the bulk Shockley–Read–Hall lifetime	1 μs–2 μs	0.5 μs–1 μs	0.25 μs–0.5 μs

pressed as $1/\tau_{SRH} = N_t v_{th} \sigma$. Typical values of the carrier thermal velocity are $v_{th} \approx 10^7$ cm/s and for the capture cross section $\sigma \sim 10^{-15}$ cm^2. Then the deep recombination carrier density N_t would be approximately 10^{14} defects/cm^3, which is a reasonable deep trap concentration for our high-quality material. A possible objection to this interpretation of our rather long measured lifetimes is that they may have been increased by the ratio of time spent in traps to the time spent as free electrons. In many dirty photoconductors,[10] the shallow trap density is higher than the injection level and the carriers become stored in shallow traps where they neither recombine nor contribute to the conductivity. Then the lifetime is increased by the ratio of the number of trapped electrons to the number of free electrons. There are two reasons why this is not happening here. (1) If a significant fraction, say 10%, of the injected electrons were in traps, they could not contribute to the photoconductivity and would present a 10% error in the absolute signal level, which would easily have been detected. (2) The excellent bulk quality ensured that all traps would be saturated at injection levels above 10^{15}/cm^3. It may be worth noting that Nelson's photoluminescence decay lifetime experiment,[1] which does lend itself to absolute calibration, could not rule out the possibility of a shallow trap dominated lifetime.

There might be a possible suggestion that the τ_{SRH} we have measured should have been even longer but was limited in our experiment by radiative recombination due to residual background doping. Capacitance-voltage (C-V) measurements on our material showed that the background doping was in the range 10^{14}–10^{15} electrons/cm^3. This combined with the known values of B and the photon recycling effects implies that the radiative contribution to the constant term in Eq. (2) was negligible.

The long lifetimes measured here show that GaAs material quality need not be a limitation to the performance of electronic devices. In practice, however, considerable deterioration arises during device processing and it would be valuable to repeat this type of measurement at each processing step to identify the dangerous step. If this could be done, then material quality would not be the limiting factor in such bipolar devices as ultralow threshold[11] semiconductor lasers.

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