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Zero-Field Time-of-Flight Measurements of Electron Diffusion in P^+-GaAs

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Minority electron diffusivities in p^+-GaAs-doped $N_A \simeq 1.4 \times 10^{18}$ and $\sim 10^{19}$ cm^{-3} have been measured in zero-field conditions with an extension of the zero-field time-of-flight technique. Extension of the technique to make it applicable to heavily doped p^+-GaAs is described and zero-field data are discussed. Unexpectedly, majority carrier drag effects are not evident in a comparison of this data with recently reported high-field data. Low zero-field mobility of electrons in p^+-GaAs has important implications for high-speed devices such as heterojunction bipolar transistors.

KEYWORDS: p^+-GaAs, zero field, minority carrier diffusion, radiative lifetime, surface recombination velocity, transient voltage response, steady-state quantum efficiency

Minority carrier diffusion across heavily doped bases of III-V heterojunction bipolar transistors (HBT's) has a strong influence on the d.c. and a.c. performance of such devices. Consequently, measurements of minority carrier transport properties in p^+-GaAs are needed to develop an understanding of these properties and to provide essential information for device design and optimization. Very recently, field-dependent mobilities of minority electrons in p^+-GaAs doped at $\sim 10^{19}$ cm^{-3} or higher have been reported.[1] However, due to majority carrier hole drag, minority carrier mobilities measured with applied fields are expected to be lower than the zero-field mobility,[2] and therefore should not be expected to characterize the mobility in the base of HBT's. Zero-field time-of-flight (ZFTOF) measurements have been reported by Ahrenkiel *et al.*,[3] but at doping densities 10–50 times smaller than those now used for HBT's. The procedure was not, however, applicable to measurements of p^+-GaAs.

In this letter, we describe the new experimental and analytical procedures required to extend the ZFTOF technique to heavily doped GaAs. Also reported are first measurements of minority carrier electron diffusivities in p-type GaAs doped to $\sim 10^{19}$ cm^{-3} under zero-field conditions. Surprisingly, the mobility for field-free conditions was found to be comparable to that recently reported for an applied field of 2.5 kV/cm.[1] The extended technique has also yielded a more precise diffusivity of moderately doped GaAs.

The ZFTOF measurement technique is illustrated in Fig. 1. A high-speed laser photoexcites electrons near the surface, and the electron-hole pairs (ehp) diffuse across a p^+-GaAs layer to the pn-junction where the local electrostatic potential at the junction separates the ehp's. Phenomenologically, this transient photocurrent ($i_g(t)$) charges the p-n junction capacitor, thereby perturbing the junction voltage ($v_j(t)$) which is monitored as a function of time. To extract the diffusion coefficient, $i_g(t)$ and $v_j(t)$ characteristics are numerically simulated with the diffusion coefficient as a parameter adjusted to achieve a good agreement with the experimental data.

To apply the ZFTOF technique to heavily doped p^+-GaAs, the p-type active layer must be thin. Radiative lifetimes for p^+-GaAs are of the order of tenths of nanoseconds. Such short lifetimes require thin samples to generate adequate signal strength while maintaining low level perturbations, but a more stringent restriction on thickness occurs because photon recycling effects must be minimized.[4] Qualitatively, one would expect photon recycling to be more important for thicker samples because the generally longer optical pathlengths result in higher probabilities that photons emitted in recombination events would be reabsorbed before escaping from the sample. Reabsorption, or photon recycling, is known to reduce the net recombination rate in AlGaAs–GaAs double heterostructures from that predicted by the radiative lifetime.[5] In the context of ZFTOF experiments, photon recycling represents another transport mechanism which must be minimized by using thin active layers for p^+-GaAs.[4]

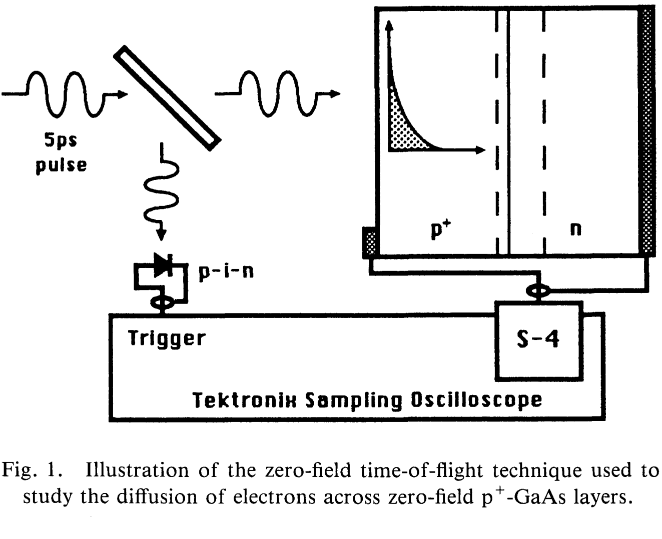

Fig. 1. Illustration of the zero-field time-of-flight technique used to study the diffusion of electrons across zero-field p^+-GaAs layers.

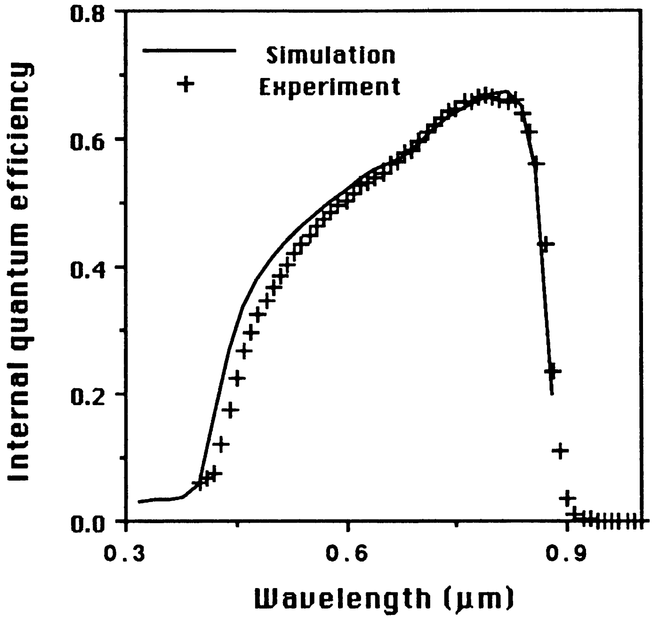

Fig. 2. Measured transient characteristics of a ZFTOF diode with p$^+$-GaAs doped at $N_A \simeq 9.2 \times 10^{18}$ cm^{-3}. The solid lines show the simulated responses with $S_f \leq 10^4$ cm/s, $\tau_n = 0.9$ ns and $D_n = 18$ cm^2/s.

Minimizing the influence of photon recycling with thin active layers produces very fast transient responses. Typical ZFTOF transient responses for p$^+$-GaAs experiments have rise times of less than 1 ns. The fast response was not an issue in the application of the ZFTOF technique to moderately doped GaAs but had to be addressed in the study of p$^+$-GaAs.

Extension of the technique to allow measurements of heavily doped GaAs is as follows. Experimental advancements include the use of picosecond lasers ($\lambda = 600$ nm, ~ 5 ps FWHM) for photoexcitation, employing high-speed packaging techniques to minimize circuit effects, and fabrication/packaging of p-i-n diodes to accurately correlate the arrival of the laser pulse to the measured transient response. To maintain fixed electrical lengths, p-i-n diodes are packaged in identical ZFTOF packages. Extrapolation of the much faster p-i-n response allows accurate definition of $t = 0$ (see*). The final new experimental procedure is to characterize the high-speed packages with microwave characterization techniques; the resulting equivalent circuit parameters for ZFTOF photo-diodes are included in the data analysis.

To extract the diffusion coefficient from the fast transient response of thin active layer devices demanded the accurate modeling of effects which were of less importance for thicker devices with slower responses. Such effects include the finite absorption coefficient, finite surface recombination velocity of the active layer and circuit effects. To include these effects, a numerical simulation program was developed. As mentioned earlier, ZFTOF responses of p$^+$-GaAs occur on the scale of 1 ns, so the 5 ps laser pulse used in this study can accurately be modeled by a δ-function in time; the initial condition for the minority carrier concentration is considered to be an exponential distribution characterized by the absorption coefficient. Boundary conditions for the numerical simulation allowed for nonzero surface recombination velocity at the AlGaAs–GaAs interface and maintained the concentration at the depletion region at zero. A program option treats photon recycling in a formalism similar to that used by Kuriyama *et al.*[6] SPICE, a circuit simulation program, was used to simulate the measured response of the deduced equivalent circuit excited by the numerically computed photocurrent.

Transport parameters are extracted by fitting the experimental data with the simulated responses. The front surface recombination velocity (S_f), minority carrier lifetime (τ_n) and minority carrier diffusion coefficient (D_n) are adjusted in the simulations to achieve a good agreement with the measured voltage response. Experimental photo-current is calculated from the voltage response assuming the equivalent circuit deduced from microwave characterization; parameters extracted from the voltage response fit were required to fit the photocurrent response as well. ZFTOF fits of the data for $N_A \simeq 9.2 \times 10^{18}$ cm^{-3} reported in this letter are shown in Fig. 2.

In addition to requiring S_f, τ_n and D_n to fit experimental voltage and photocurrent responses, the parameters are also required to accurately describe the steady-state internal quantum efficiency (QE) vs wavelength characteristic. This additional consistency requirement is necessary for thin active layer ZFTOF experiments with p$^+$-GaAs because S_f can dominate in thin layers when it is sufficiently large. The QE fit of the data for $N_A \simeq 9.2 \times 10^{18}$ cm^{-3} reported in this letter is shown in Fig. 3.

ZFTOF diodes required for this study were fabricated on MBE films with grid pattern gold contacts on the active layers, and the p$^+$-GaAs surfaces were passivated with 0.04 µm $Al_{0.2}Ga_{0.8}As$ layers. For the device structures reported below, numerical simulations including photon recycling indicated a negligible contribution to transport by recycling. All diodes were mounted on test fixtures incorporating Wiltron K-connector sparkplug launchers. Details of the laser system, material growth, fabrication techniques and packaging have been reported previously (see*). Samples with 3 doping levels were investigated, and concentrations were determined from the Hall Effect, assuming a Hall factor of 1, (SIMS) measurements as follows: 1.4×10^{18} (2.0×10^{18}), 9.2×10^{18} (1.0×10^{19}) and 2.2×10^{19} (2.4×10^{19}) cm^{-3}.

Measurements on samples doped at 1.4×10^{18} cm^{-3} yielded $D_n = 30$ cm^2/s and $\tau_n = 2.5$ ns. This result is about 20% less than that previously reported.[3] We believe that it is more accurate, primarily because circuit parasitics and photon recycling have been minimized. The lifetime found for this doping agrees well with published radiative lifetimes,[5] confirming that recycling effects are negligible in this experiment.

A study of p$^+$-GaAs doped at $N_A \simeq 9.2 \times 10^{18}$ cm^{-3}

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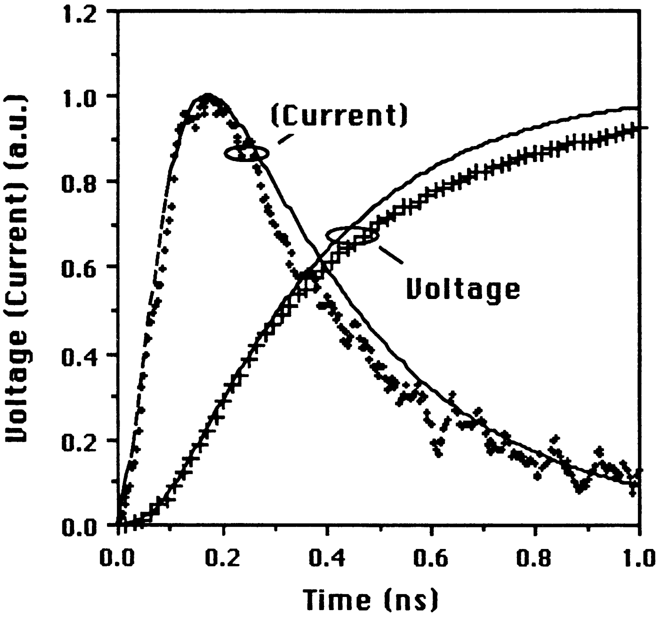

Fig. 3. Measured steady-state internal quantum efficiency versus wavelength for the ZFTOF diode structure. The solid line is the fitted response obtained using the same parameters used to fit the transient response.

yielded unexpected mobility results. The determined lifetime of $\tau_n = 0.9$ ns does indeed agree with the radiative lifetime.[5] $D_n = 18\ \mathrm{cm^2/s}$ was found; utilizing Einstein's relation, this corresponds to a room temperature mobility of $\sim 710\ \mathrm{cm^2/V \cdot s}$. This is ~40% of the electron mobility in comparably doped n^+-GaAs[7] and is much lower than that predicted for minority carrier electrons in uncompensated material.[8] Such a low minority mobility may be an indication that electron-hole plasmon scattering is strong for thermal electrons; this effect has been shown to be important for hot electrons in GaAs.[9] Unexpectedly, zero-field mobility was found to be comparable to high-field (≥ 2.5 kV/cm) mobility[1] which was expected to be significantly lower due to hole drag. The larger ratio of effective masses (hole/electron) found in GaAs as compared to Si, in which hole drag was observed,[2] implies that the effect should be stronger in GaAs.

Because steady-state QE data for samples doped at $N_A \simeq 2.2 \times 10^{19}\ \mathrm{cm^{-3}}$ were not available to determine independently S_f, we could only determine bounds for D_n. Assuming a low S_f, analysis of the ZFTOF transient yielded $D_n = 30\ \mathrm{cm^2/s}$ and $\tau_n = 0.3$ ns. Assuming a high S_f yielded $D_n = 18\ \mathrm{cm^2/s}$ and $\tau_n = 0.3$ ns. The considerably higher laser power required for this sample suggests that the surface recombination velocity was high, which implies that D_n is low. The carrier lifetime deduced for this doping level is independent of S_f and agrees well with published radiative lifetimes.[5]

In summary, the ZFTOF technique has been extended to allow measurement of zero-field diffusivity in p^+-GaAs doped at $\sim 10^{19}\ \mathrm{cm^{-3}}$ or higher. The extension includes new experimental techniques to address photon recycling and package parasitics, and demanded a new analysis technique to include circuit effects, a finite absorption coefficient, nonzero surface recombination velocities and photon recycling. An improved measurement at a moderate doping, $D_n = 30\ \mathrm{cm^2/s}$ at $N_A \simeq 1.4 \times 10^{18}\ \mathrm{cm^{-3}}$, was realized with the new procedure. Utilizing Einstein's relationship to compute mobility yields, $\mu_n = 710\ \mathrm{cm^2/V \cdot s}$ at $N_A \simeq 9.2 \times 10^{18}\ \mathrm{cm^{-3}}$, which is ~40% of the electron mobility in comparably doped n^+-GaAs. This value is comparable to minority mobilities measured in an applied field of 2.5 kV/cm,[1] implying hole drag may not be strong in $\sim 10^{19}\ \mathrm{cm^{-3}}$ p^+-GaAs. For $N_A \simeq 2.2 \times 10^{19}\ \mathrm{cm^{-3}}$, upper and lower bounds for D_n are reported ($18 \leq D_n \leq 30$); indirect indications suggest that the diffusivity is close to the lower bound. The low electron zero-field mobility found in this study has important implications for transit time delays in HBT's.

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