Experimental observation of a minority electron mobility enhancement in degenerately doped p-type GaAs

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The variation of minority electron mobility with doping density in p^+-GaAs has been measured with the zero-field time-of-flight technique. The results from a series of nine GaAs films doped between 1×10^{18} and 8×10^{19} cm^{-3} show the mobility decreasing from 1950 $cm^2 V^{-1} s^{-1}$ at 1×10^{18} cm^{-3} to 1370 $cm^2 V^{-1} s^{-1}$ at 9×10^{18} cm^{-3}. For the doping range 9×10^{18}–8×10^{19} cm^{-3}, the decreasing trend in mobility is reversed. The measured mobility of 3710 $cm^2 V^{-1} s^{-1}$ at 8×10^{19} cm^{-3} is about three times higher than the measured value at 9×10^{18} cm^{-3}. These results confirm and extend recent transistor-based measurements and are in accord with recent theoretical predictions that attribute the increase in minority electron mobility in p^+-GaAs to reductions in plasmon and carrier-carrier scattering at high hole densities.

For devices such as heterojunction bipolar transistors, which are controlled by minority carrier flow in heavily doped regions, it is important to know the mobility of minority carriers with respect to doping in order to optimize device designs. In this letter we report measurements that show a factor of ~3 increase in minority carrier mobility when the hole concentration is increased from 9×10^{18} to 8×10^{19} cm^{-3}. By utilizing the zero-field time-of-flight (ZFTOF) technique[1] on a series of nine GaAs diode film structures, the minority electron mobility has been mapped out for p-GaAs doped between 1×10^{18} and 8×10^{19} cm^{-3}. Both carbon and beryllium doping were included in this study, and no difference in the measured results due to dopant species was observed. These results generally support and extend those of Kim *et al.*[2] and are in good accord with the theory of Lowney and Bennett.[3]

The ZFTOF technique utilizes an ultrafast laser pulse to generate an impulse function in time and space of electron hole pairs at the top of the p^+ region in a vertical p^+n diode (see Fig. 1). The electrons then diffuse toward the junction and cause a current to flow as they are collected by the junction. This current flow charges the junction capacitance, which is then measured externally as a fast voltage transient with a high speed sampling oscilloscope. The minority carrier diffusivity is obtained by fitting the measured transient response to the one-dimensional minority carrier diffusion equation, with the fitting parameters being the surface recombination velocity S_f, the minority electron lifetime τ_n, and the diffusion coefficient D_n. The effect of S_f on the measured D_n is negligible for $S_f<10^4$ cm/s, and the sensitivity to lifetime is reduced for high collection efficiency structures. The minority carrier mobilities are then calculated from the measured diffusivities with the Einstein relation.

The GaAs p^+n junctions were grown in two Varian Gen II molecular beam epitaxy (MBE) systems with beryllium (solid source) and carbon (CCl_4 source) used as p-type dopants. The device structures are shown in Fig. 1 and Table I. The AlGaAs window is included in order to passivate the top surface of the emitter region and ensure that $S_f<1\times10^4$ cm/s. The ZFTOF diode mesas were fabricated with wet chemical etching, and the p^{++} GaAs cap was contacted with nonalloyed Au:Ti:Au contacts shadowing less than 3% (37% for the sample doped 1.4×10^{18} cm^{-3}) of the diode mesa while the back sides of the n^+ GaAs wafers were contacted with alloyed AuGeNi:Ti:Au or In. The devices were packaged in high speed Wiltron K Connector® packages in order for the high speed transient responses to be measured accurately.[1,4]

The measurement system consists of a Coherent Mira 900f titanium sapphire laser pumped with 14 W from a Coherent Innova 415 Argon Ion laser. The Mira produces pulses with less than 100 fs [full width at half-maximum (FWHM)] at a wavelength of 890 nm. A Conoptics Pockels cell pulse selection system reduces the pulse repetition rate to ~5 kHz in order to allow sufficient time for the transient response to decay before the next pump pulse arrives. A 2 mm BBO crystal is used to double the tita-

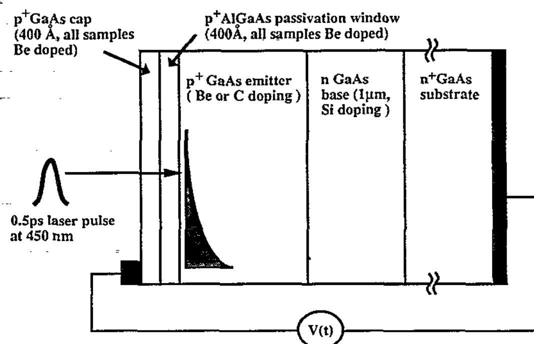

FIG. 1. Structure of GaAs films used in the ZFTOF experiment. The AlGaAs window passivates the p^+ GaAs emitter and the cap layer provides ohmic contact to the emitter. The cap layer is not removed in order to ensure that the passivation layer remains intact.

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TABLE I. Results of ZFTOF and IQE measurements on nine GaAs p^+n diodes at room temperature (297 K). The hole density (p_0) and hole mobility (μ_p) were measured by Hall effect. The minority electron mobility (μ_n) was calculated from ZFTOF measurements of minority electron diffusivities (D_n). Also shown are the minority electron diffusion lengths (L_n), and Al mole fraction of the AlGaAs window.

p_0 ($\times 10^{19}$ cm^{-3})	Dopant species	Al mole fraction	μ_p (cm^2 V^{-1} s^{-1})	Emitter thickness (μm)	D_n (cm^2 s^{-1})	μ_n (cm^2 V^{-1} s^{-2})	ZFTOF t_n (ns)	ZFTOF $L_n = \sqrt{D_n\tau_n}$ (μm)	IQE L_n (μm)
0.14	Be	0.70	180	3.0	50	1950	> 1.00	> 2.24	3.30
0.75	Be	0.27	105	1.0&1.7	38	1480	1.50	2.39	2.40
0.89	C	0.20	105	1.0	35	1370	1.75	2.47	2.45
1.2	Be	0.27	96	1.0	40	1560	0.50	1.41	1.20
2.6	C	0.20	87	1.0	50	1950	0.40	1.41	1.12
3.0	Be	0.27	80	1.0	70	2740	0.15	1.02	0.87
4.7	Be	0.27	77	1.0	80	3130	0.13	1.00	0.85
7.9	C	0.20	70	1.0	95	3710	0.04	0.62	0.73

nium: sapphire output frequency to 445 nm in order for the majority of the electrons to be generated near the AlGaAs/GaAs interface. Dispersion in the Pockels cell and the BBO crystal broadens the pulse, however, the final pulse width is estimated to be less than 0.5 ps. The resulting voltage transient is measured with a 34 GHz Hewlett Packard 54124T sampling oscilloscope.

Diffusion coefficients and lifetimes were extracted from the measured responses using the technique discussed by Lovejoy.[1] Figure 2 shows a typical measured and simulated response. The results from a series of nine diodes with varying p-layer dopings are listed in Table I. Independent data about the fitting parameters are obtained by measuring the steady-state internal quantum efficiency (IQE) of solar cell structures fabricated adjacent to the ZFTOF diodes. The IQE experiment consists of measuring the steady-state photocurrent response of the solar cells to monochromatic light. The IQE versus wavelength is then fit with an analytical solution of the minority carrier diffusion equation, which allows the determination of a minimum diffusion length.[5] This minimum diffusion length will be the actual diffusion length (L_n) when $S_f < 1\times10^4$ cm/s, which allows us to decouple the lifetime from the diffusion coefficient in the ZFTOF experiment under the assumption of low S_f.

There are three major sources of experimental error in the measured diffusivities. The first error is due to the uncertainty in $t=0$ as determined using an identically mounted GaAs p-i-n photodiode structure with a measured risetime (10%–90%) of 14 ps. The error in the time zero, including the time drift (< 1.0 ps), slight package variations, and distortion of the p-i-n response due to the finite risetime of the oscilloscope is estimated to be ± 2 ps. This results in an experimental error of about 12% for the diode with $D_n = 95$ cm^2/s and about 6% for the diodes with $D_n < 40$ cm^2/s. The next major source of error is due to inaccuracies in the emitter thickness calculated from the growth rate as determined by reflection high energy electron diffraction (RHEED) oscillations at the beginning of each growth. We estimate the emitter thickness error to be less than 3%, which results in about a 6% error in D_n for all dopings. The final source of error is due to lifetime estimation. For the samples doped less than 1×10^{19} cm^{-3}, the diffusion length measured with IQE is greater than the emitter thickness, which implies that there is little error in the measured D_n due to lifetime.[1] For the samples doped greater than 1×10^{19} cm^{-3}, the diffusion length is on the order of the emitter thickness, which indicates significant recombination within the emitter region. The error due to lifetime was investigated using a minimum lifetime as determined by the IQE measurement and a maximum lifetime estimated with the radiative limit of $\tau_n = 1/(B\times p_0)$, where $B = 1\times10^{-10}$ cm^3/s and p_0 is the equilibrium hole concentration.[6] From this investigation, it was determined that the error due to lifetime estimation is less than 10%.

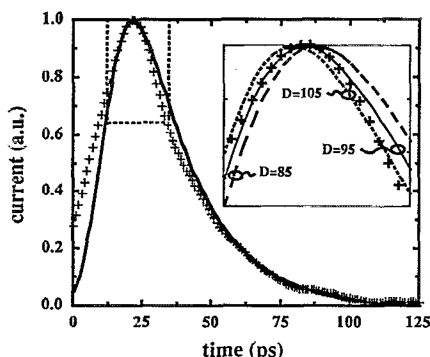

FIG. 2. Current response of ZFTOF diode film doped 7.8×10^{19} cm^{-3}, including the simulation response for $D_n = 95$ cm^2/s and $\tau_n = 0.04$ ns. The inset shows a blow up of the peak with $D_n = 95\pm10$ cm^2/s simulations.

The total error was determined by considering the worst case combination of time zero, emitter thickness, and lifetime error. The ZFTOF responses were then analyzed with this combination in order to determine the resultant error in diffusivity. Consequently, we estimate the total error to be less than 22% for the sample doped 7.9×10^{19} cm^{-3}, with the error then decreasing to about 12% for the samples doped less than 1×10^{19} cm^{-3} (see Fig. 3). Additional experimental error is present in the measurement of the sample doped 1.4×10^{18} cm^{-3} due to the deconvolution of signal distortion caused by excess contact shadowing.[1]

There are two additional effects that could cause additional systematic errors to be present in the measured diffusivities. One important consideration would be hot carrier effects due to the 445 nm excitation, which would

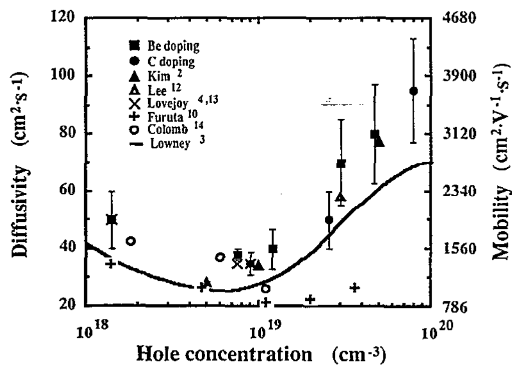

FIG. 3. Comparison of recent experimental measurements and theoretical predictions of minority electron diffusivity (mobility) in p^+-GaAs at room temperature (297 K). The theoretical curve of Lowney and Bennett assumes a plasmon cutoff factor of 1.00. The error bars for the 1.4×10^{18} cm^{-3} sample include uncertainties due to the deembedding of shadowing effects.

cause the electrons to have $\sim$1.3 eV initial excess energy. Experimental evidence indicates that photoexcited minority electrons rapidly thermalize in less than 0.5 ps and then cool to the temperature of the lattice in 1–2 ps,[7,8] which would not be sufficient time for hot carriers to significantly alter the results presented here. A second effect that could cause additional systematic error in the measured diffusion coefficient is photon recycling,[9] which produces additional electron hole pairs throughout the device due to the absorption of photons emitted when radiative recombination occurs. The structures used here are designed to minimize recombination, however, in the heaviest doped samples there is significant recombination due to short lifetimes. Even in these samples, the peak of the current response occurs before a significant number of the electrons have recombined, which should minimize the effects of recycling on our fitting algorithm. In addition, numerical simulations[1] of the effects of photon recycling on the heaviest doped sample yield no effective change in the measured diffusion coefficient, and only a small effective enhancement in the lifetime.

The measured results are compared with recent measurements[2,10,12–14] and theoretical predictions[3] of minority carrier mobility for heavily doped p GaAs in Fig. 3. Note that results presented here show a considerably higher mobility than those of Furuta,[10] who measured the minority mobility using a conventional time-of-flight technique with a high electric field applied to the sample. The majority carrier drag caused by holes flowing in the opposite direction to electrons[11] may explain the lower observed mobility observed by Furuta. Our ZFTOF results agree well with the measurements of Kim[2] performed by measuring the frequency response of HBT structures and calculating the base transit time from these measurements. Finally, our results are in good agreement with the theoretical predictions of Lowney and Bennett,[3] who find that the increase in mobility is due to a reduction in plasmon and carrier–carrier scattering as the doping density is increased above 1×10^{19} cm^{-3}. The mobility results presented here are slightly higher than the theoretical results of Lowney and Bennett, which may be because of theoretical uncertainties due to the various approximations discussed in Ref. 3.

In conclusion, we present results of the zero-field time-of-flight experiment on nine p^+ emitter GaAs diode structures doped between 1×10^{18} and 8×10^{19} cm^{-3}. These results show a sharp valley in the measured mobility around 1×10^{19} cm^{-3}, with a factor of 2.7 increase in mobility when the doping is increased from 1×10^{19} to 8×10^{19} cm^{-3}. The results support recent theoretical predictions[3] and extend recent experimental[2] work. The implications of such a large increase in mobility are extremely important for bipolar device design.

Note added in proof: Measurements of carbon-doped GaAs using a similar zero-field time-of-flight technique have recently been published in the Journal of Applied Physics.[15] In contrast to our results, they observe a continual decrease in minority electron mobility with increasing p-type doping, with more than an order of magnitude lower observed mobilities for the heaviest dopings.

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