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

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A technique to measure the diffusion coefficient of electrons under zero-field conditions in heavily doped GaAs is described. Carriers are photoexcited by a picosecond laser, diffuse across a p$^+$-GaAs layer and are collected by a p-n junction. From the measured electrical response, the minority carrier diffusion coefficient is extracted. For p$^+$-GaAs doped at $\simeq 10^{19}$ cm^{-3}, we find a minority carrier mobility which is only 40% of the electron mobility in comparably doped n$^+$-GaAs. The low mobility of electrons in p$^+$-GaAs has important implications for high-speed devices such as heterojunction bipolar transistors.

1. Introduction

Minority carrier diffusion across the base of III-V heterojunction bipolar transistors (HBT's) has a strong influence on the d.c. and a.c. performance of such devices. Measurements are needed to develop an understanding of minority carrier transport and to provide information essential for device design and optimization. Time-of-flight (TOF) measurements have been reported by Ahrenkiel [1], but at doping densities 10-50 times smaller than those now used for HBT's. Very recently, TOF measurements for doping densities exceeding 10^{19} cm^{-3} have been reported using a biased Hall-bar geometry [2]. Under such conditions, however, the minority electron mobility should be influenced by a strong, electron-hole drag effect [3]. In this paper we extend the Ahrenkiel's TOF technique so that it is applicable to p-type doping densities of 10^{19} cm^{-3} and greater. We also present experimental results which confirm earlier measurements for doping densities of $\simeq 2 \times 10^{18}$ cm^{-3} and new data for heavily doped, p$^+$-GaAs.

The measurement technique is illustrated in Fig. 1. Carriers are photoexcited near the surface by a high-speed laser, diffuse across a p$^+$-GaAs layer, and are collected by the p-n junction. The photocurrent charges the capacitance of the p-n junction, and the junction voltage versus time is monitored. We solve the minority carrier diffusion equation to obtain the $V_j(t)$ characteristic and adjust the diffusion coefficient to fit the measured response. In this paper we describe the experimental techniques and analysis procedures and present some recent results.

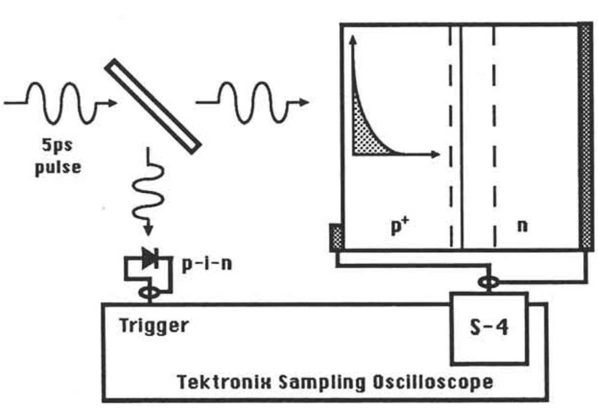

Fig. 1 Illustration of the time-of-flight technique used to study the diffusion of electrons across zero-field p$^+$- GaAs layers.

2. Experimental Procedures

Diodes for the experiments were fabricated on films grown in a Varian GEN II molecular beam epitaxy (MBE) system. Films were grown at 600°C using Si as the n-type dopant and Be as the p-type. The As_4:Ga pressure ratio was 25:1, and the growth rate was determined by counting RHEED oscillations. A typical film structure is illustrated in Fig. 2. For this film, we characterized electron transport across the 9×10^{18} cm^{-3}, 1.5 µm thick p^+-layer. The p-layer doping density was determined by Hall effect measurements (assuming a Hall factor of unity) and was verified by secondary ion mass spectroscopy (SIMS) and by electrochemical capacitance versus voltage profiling. The doping profiles were verified to be constant, so no built-in fields were present to influence the experiment. The measured Hall mobility of $\mu_H \simeq 98$ $cm^2/V{-}s$ is typical for heavily doped Be layers. The p^+ $Al_{0.21}Ga_{0.79}As$ layer was used to passivate the p^+-GaAs layer and is expected to produce a recombination velocity at the AlGaAs/GaAs interface of less than 10^4 cm/s.

Mesa-isolated diodes were fabricated from the MBE-grown films using conventional processing procedures. Typical junction dimensions were 540 µm × 520 µm. The top contact was a grid and bus bar which obscured a total of 37% of the junction.

For accurate TOF measurements, the diodes should be packaged to minimize parasitic circuit effects. Diodes were mounted on a test fixture incorporating a Wiltron K-connector sparkplug launcher. Test fixture dimensions were those prescribed by Wiltron and used by Biscoff *et al.* to mount high-speed photodetectors [4]. Electrical connection from the center contact of the launcher to the diode was made with a Wiltron microstrip stress relief contact to provide a very low inductance lead.

The experimental apparatus, as displayed in Fig. 1, employs a laser system comprised of a synchronously pumped dye laser (Spectra Physics model 375 using Rhodmine 6G dye) pumped by an argon ion laser (Spectra Physics series 3090). Laser beam characteristics at 600 nm were carefully controlled at 5 ps FWHM with a 4 MHz pulse repetition rate. The intensity of the laser was kept low to maintain low-injection conditions in the p^+-layers. The transient voltage response of the diode, $V_j(t)$, was measured with a Tektronix 7854 sampling oscilloscope utilizing an S-4 sampling head. The device package was connected directly on the S-4 sampling head. Triggering was provided by a Hamamatsu photodiode excited by a portion of the same beam used to excite the TOF diode. The system was capable of a time resolution of 2 ps.

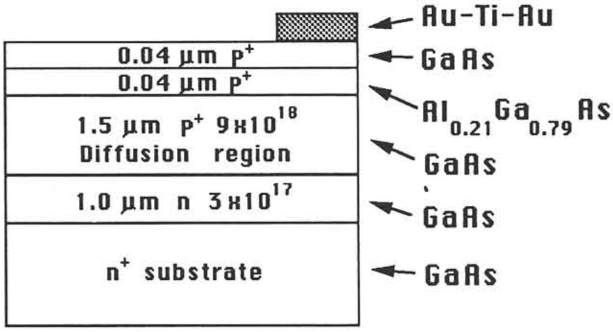

Fig. 2 The film structure for a time-of-flight diode used to study electron diffusion across p^+-GaAs layers doped at 9×10^{18} cm^{-3}. Similar structures were used for other doping densities.

Because the TOF diodes responded on a time scale on the order of one nanosecond, the ≃5 ps FWHM laser pulse could be treated as a δ-function in time, but it is important to determine t = 0 (when the laser pulse occurs) accurately. The solution we chose was to determine t = 0 with a GaAs p-i-n diode packaged in exactly the same manner as the TOF diodes. As shown in Fig. 3, the p-i-n diode responds much more quickly than does the TOF diode, so t = 0 is readily determined. About four minutes are required to acquire the TOF data. A p-i-n response is measured just before and just after acquiring the TOF data in order to assure time base stability to within ± 4 ps.

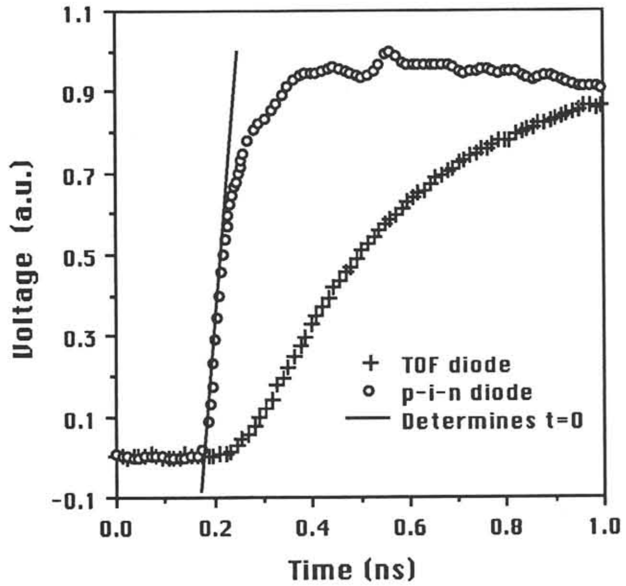

Fig. 3 Comparison of the measured response of a TOF diode (with p-type layer doped to $N_A \simeq 9\times10^{18}$ cm^{-3}) with that of a p-i-n diode mounted by the same techniques.

3. Analysis Procedures

Analysis of the experimental results began by numerically solving the minority carrier diffusion equation for an assumed front surface recombination velocity, S_F, minority carrier lifetime, τ_n, and minority carrier diffusion coefficient, D_n. To analyze the data, circuit effects must be carefully considered. We modeled circuit effects using a simple equivalent circuit and determined parameters from one-port microwave measurements.

Although circuit effects were considered in the analysis, the high-speed packaging techniques employed minimize their importance for the devices studied. During the initial part of the response, the region of interest for extracting D_n, the junction acts as a current integrator and the junction voltage is well-described by

$$V_j(t)=\int_0^t \frac{I_{ph}(t')\,dt'}{C_j}\,. \qquad (1)$$

The junction capacitance is nearly constant at its zero-bias value because the maximum change in junction voltage is limited to $\simeq 10$ mV. By differentiating the measured $V_j(t)$ characteristic, the photocurrent versus time, $I_{ph}(t)$, can be deduced. Typical measured results for a TOF diode with the p$^+$-layer doped to 9×10^{18} cm^{-3} are displayed in Fig. 4.

The analysis procedure began by assuming values for S_F, τ_n, and D_n and numerically evaluating $I_{ph}(t)$. The result was then inserted in the equivalent circuit, and the $V_j(t)$ characteristic and its derivative with respect to time were evaluated using the circuit simulation program, SPICE. The results were compared to those measured and the parameter values, S_F, τ_n and D_n were adjusted so that theory and experiment agreed. A typical fit between measured and simulated results is shown in Fig. 4. We generally found that the characteristics were insensitive to S_F as long as it was less than about 10^4 cm/s. We could fit the data for higher values of S_F, but such values are not expected for high-quality heterointerfaces. We could eliminate the possibility that the interface recombination velocity was high by examining the steady-state, internal quantum efficiency (QE) versus wavelength. We found that when an S_F significantly above 10^4 cm/s was assumed, it was not possible to simultaneously fit the measured transient TOF and steady-state QE results. For $S_F \lesssim 10^4$, the simulations were insensitive to S_F and the transient and steady-state results were well-fit by the same parameters.

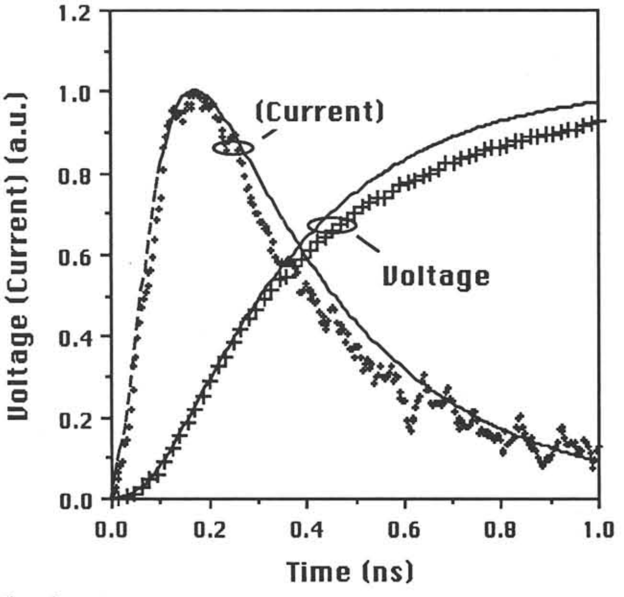

Fig. 4 Measured transient characteristics of the TOF diode with structural parameters displayed in Fig. 2. The lines are the fitted responses obtained by solving the minority carrier diffusion equation.

4. Results and Discussion

Samples with p-layer dopings from $\simeq 2\times10^{18}$ to $\simeq 2.4\times10^{19}$ cm^{-3} were measured and analyzed. For the lightest doped sample, $p_o \simeq 2\times10^{18}$ cm^{-3}, the results, $D_n \simeq 30$–40 cm^2/sec, are in good agreement with those previously reported [1]. For the sample doped at $p_o \simeq 9\times10^{18}$ cm^{-3}, we find $D_n \simeq 18$ cm^2/sec. For the sample doped at 2.4×10^{19} cm^{-3}, a diffusion coefficient about 60% greater than that at $N_A \simeq 10^{19}$ cm^{-3} was deduced. A small increase in mobility for heavily doped GaAs has been reported [2], but such a large increase was not expected. One possibility is that the front surface recombination velocity for this diode was high. If $S_F \simeq 10^6$ cm/s was assumed, the data could be fit with a diffusion coefficient of $\simeq 18$ cm^2/s. Devices were not available to test this possibility by measuring the steady-state internal quantum efficiency, but the fact that the laser power had to be doubled for this device suggests that a high surface recombination velocity is a possibility.

The results obtained for $N_A \simeq 2\times10^{18}$ cm^{-3} agree well with those previously reported [1,2]. For the sample doped at 9×10^{18} cm^{-3}, the mobility deduced from the Einstein relation is about 710 cm^2/V–s, which is about 40% of the electron mobility in comparably doped n^+ GaAs.

It is also interesting to compare our results to those recently reported by Furuta and Tomizawa [2] who employed a biased, Hall bar geometry. At $N_A \simeq 10^{19}$ cm^{-3} we find an electron mobility that is 10% lower than that reported by Furuta and Tomizawa. Our preliminary results for $N_A \simeq 2.4\times10^{19}$ cm^{-3} are about 30% greater than the minority electron mobility they report. These results are especially interesting because Furuta and Tomizawa employed a Hall-bar geometry which should have significantly lowered μ_n by the hole drag effect [3]. Agreement with their results was not expected and remains to be explained.

5. Summary

A time-of-flight technique previously used to measure the minority carrier diffusion coefficient in $\simeq 2\times10^{18}$ cm^{-3} p-type GaAs has been extended to p-GaAs doped at 10^{19} cm^{-3} and greater. The low minority electron mobility found for p-type GaAs doped at 10^{19} cm^{-3} needs to be understood because it has important implications for high-speed devices such as HBT's.

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References

[1] R.K. Ahrenkiel, *et al.*, *Appl. Phys. Lett.*, **51** (1987) 776.
[2] T. Furuta and M. Tomizawa, *Appl. Phys. Lett.*, **56** (1990) 824.
[3] D.D. Tang, *et al.*, *Appl. Phys. Lett.*, **49**, (1986) 1540.
[4] J.C. Bischoff, M. Zirngibl, M. Iiegems, P. Beaud, and W. Hodel, *Proc. of the Fifth International Workshop on the Physics of Semiconductor Devices*, Dec. 11-15, 1989, New Delhi, India (1989) 81.
[5] R.K. Ahrenkiel, D.J. Dunlavy, H.C. Hamaker, R.T. Green, and C.R. Lewis, *Appl. Phys. Lett.*, **49**, (1986) 725.