TIME RESOLVED LUMINESCENCE MEASUREMENTS OF GALLIUM ARSENIDE AND OF GALLIUM ARSENIDE PHOTODETECTORS

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This thesis describes the first detailed study of nonlinear luminescence in GaAs, and its application to the first time resolved luminescence measurements of carrier transport in an electric field. The first direct measurement of hole sweepout in a photoconductor, and of 1 ps carrier sweepout in a Schottky diode are described. Direct observation of the effects of 'intrinsic' circuits on carrier transport in the latter device may have important uses for high frequency circuit diagnostics.

Time resolved luminescence measurements are made possible by a nonlinear dependence of the band-band recombination luminescence on the input laser intensity. This nonlinearity has been investigated as a function of laser power, doping, and wavelength under ps photoexcitation, and a model based on the bimolecular nature of the recombination process is presented which explains many features of the data. A simple algorithm for data reduction is developed to account for the nonlinearity.

The technique was applied to measure hole sweepout in a 2 µm active length photoconductor. An average velocity deduced from the measurement was lower than expected, and initiated an investigation into field screening effects which might be important at the high photoexcitation densities needed here. Devices with nonohmic contacts(Schottky diodes) with a .3µm transit dimension were fabricated and pulsewidth limited decays obtained. A computer model of transport in these devices showed that transport perturbation due to screening is minimal because of fast transit times and high fields. However, the model clearly indicated that effects on transport for fields near the the peak velocity field will be substantial for densities above the doping density.

To show that the macroscopic circuit can affect microscopic transport within a device, experiments were done on Schottky diodes built into various monolithic circuits. High photoinjection levels result in large transient potential drops which can substantially perturb transport. Diodes incorporated into a large capacitor which clamped the voltage across the diode showed response consistent with transit times. Isolation from this large capacitance via an inductor integrated on-chip resulted in significantly slower observed sweepout times.

BIOGRAPHICAL SKETCH

The author was born in Erlanger, Kentucky where she attended grade school and high school. She graduated from Northern Kentucky University with a B.S. degree in Physics and Mathematics. During undergraduate school, she studied and taught ballet under Anneliese von Oettingen who was a close friend and inspiration. Following two years at the University of Michigan where she earned a M.S. in Physics, the author entered the Applied and Engineering Physics Department at Cornell and joined Professor Ballantyne's group. Her research has focused on picosecond optical studies of transport in GaAs. While at Cornell, she has also studied and performed with the Ithaca Ballet, and practiced Shorinji Kempo.

to

Mom and Dad

for their love and encouragement

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CHAPTER 1

Introduction

1.1 Motivation

The motivation for this work arose out of a general interest in transport phenomena, and as an extension of previous work on short transit time photoconductors [1]. In particular, there was a strong interest in using, or developing, an experimental technique to directly measure carrier sweepout times and other dynamic variables. An optical, rather than electrical, measurement technique was sought as a monitor of carrier transport to avoid circuit response time limits on the inherent time resolution of the technique. Optical techniques are inherently fast, being limited only by the laser pulsewidth. Currently, laser pulsewidths from 1 ps down to 200 fs are consistently achievable, making optical techniques extremely attractive for probing fast transport, carrier relaxation processes and other carrier dynamics in small structures. In this thesis, a new, all optical technique is described and analyzed[2]. The technique can be sensitive to both electron and hole transport depending on device design. In a first application, it is used to measure hole sweepout in a photoconductive detector on a 100 picosecond timescale[3,4].

The technique is also exploited to measure carrier sweepout in a submicron transit dimension Schottky diode on a 1 picosecond timescale[5,6]. It is clear that any technique that measures carrier sweepout from the active region of a device will also be sensitive to possible effects on transport due to parasitic or circuit impedances. In this thesis, the first direct observation of the effects of circuit parameters on device transport is reported.

1.2 Time Resolved Optical Measurements of Carrier Transport

Optical techniques are generally classed as absorption/transmission, reflectivity, or luminescence experiments. Early time resolved measurements in the picosecond regime include a reflectivity experiment by Shank et. al.[7] at 77K in which the first measurement of the subpicosecond relaxation of carriers from states with energies high in the band to states near the band edge in GaAs was made. Another reflectivity experiment by Frigo[8], using a novel two-wavelength laser, monitored picosecond exciton dynamics in CdSe at low temperatures and resulted in an interesting carrier density-dependent diffusion model to explain the rapid recovery of the excitonic feature at high densities. Other experiments included 'light gate' or luminescence upconversion experiments at low temperatures (also in CdSe) by Daly and Mahr[9]. In the past year, transmission experiments by Erskine et. al.[10] in the femtosecond regime have illuminated the various contributions to hot carrier relaxation dynamics in GaAs, AlGaAs and quantum well structures. At the time this thesis was initiated, only one optical measurement of transport phenomena had been reported. This was the work of Shank et. al. [11] describing the observation of velocity overshoot in a GaAs PIN photodiode at 77K. In that experiment, the change in absorption near the band edge was monitored via the Franz-Keldysh effect.

To avoid restrictions on device design inherent in a transmission experiment, and to avoid low temperature operation necessary to achieve good signal levels in a luminescence upconversion experiment, we initially investigated the use of the reflectivity to monitor carrier transport. This technique monitors the change in reflectivity which results when an electron-hole plasma is created in a material. Using a simple Drude model, the change in reflectivity can be calculated, with the result that the magnitude of the plasma-induced change in the bulk reflectivity is roughly 10^{-3} for a carrier density of $10^{18}/cm^3$, 10^{-4} for $10^{17}/cm^3$ etc. For input power densities>10^5 W/cm^2 (corresponding to carrier densities$>10^{19}$ cm^{-3}), changes in the reflectivity on the order of 50-100% were observed. This spurious signal was found to be due to thermal(heating) effects: at high powers, damage to the sample at the position of the laser spot could clearly be observed. This heating effect put an upper limit on the carrier density and hence on the magnitude of the plasma reflectivity signal. For densities$<10^{18}$ cm^{-3}, in order to observe an entire experimental decay, extremely good signal to noise ratio is required (roughly 10^4). Using the equipment available and simple experimental techniques we were not able to achieve consistently good enough signal to noise ratios to warrant further investigation. Recently, successful transport measurements in graded AlGaAs layers [12] using this technique have been published: the extremely high sensitivity in these experiments was achieved through the use of a radio frequency chopping and phase sensitive detection technique.

In the course of searching for the origin of the unexpectedly large signal described above, we examined the luminescence to determine the size of the signal due to it at the detector. Surprisingly, we discovered the nonlinear dependence of the luminescence signal on the input laser power, and realized its immediate application to time resolved experiments. Subsequently, we found that shortly before, von der Linde et. al.[13] had published their observation of the effect and applied it in a picosecond measurement of hot carrier relaxation at low temperatures. The effect fundamentally arises from the bimolecular nature of the band-to-band recombination in GaAs and other direct gap semiconductors. That the effect was not realized earlier is somewhat surprising, in view of the necessity of accounting for the bimolecular term in explaining, for example, the current dependence of the spontaneous carrier lifetime in GaAs-AlGaAs double heterostructure lasers[14].

The time resolved luminescence technique facilitated by the nonlinearity is simple and versatile, and is described in detail in Chapter 2. In Chapter 3, the behavior of the nonlinearity is investigated in detail, the physical origin of the nonlinearity is discussed and the results of a rate equation model, showing reasonable qualitative agreement with the data, are presented.

1.3 Synopsis of Further Chapters: Transport measurements

Chapter 4 introduces the application of the time resolved luminescence measurements to GaAs under high electric field conditions. The first experiments were done on a GaAs photoconductor, and resulted in the first optical measurement of hole sweepout in GaAs. An average hole velocity was inferred from the data. Chapter 5 describes the results of measurements made on a planar Schottky diode with a 0.3 micron transit dimension. In order to realize transit time limited response, even in an optical measurement, the device circuit must be carefully considered. That is, the transport in the active region of the device can be inhibited by the circuit. The devices were fabricated in both 'fast' and 'slow' monolithic circuits, and the effects of the circuit on carrier transport, reflected in the luminescence decay, were measured directly for the first time. Simple circuit models used to predict the voltage transients across the device due to photoinjected carriers correspond reasonably well with the data. A one dimensional numerical simulation of transport in the device was done to estimate the possibly large perturbation of the equilibrium potential and field distribution due to the high photoexcited carrier density, and to calculate the luminescence signal.

In Chapter 6 all results are summarized and suggestions for future experiments are discussed. Appendix 1 briefly describes the fabrication of the Schottky diode structures. Appendix 2 details the numerical simulation of transport in the devices.

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