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Spectral and Spatial Quantum Efficiency of AlGaAs/GaAs and InGaAs/InP PIN Photodiodes

Steven Alan Tabor
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This thesis reports a novel system capable of testing both the spectral responsivity and the spatial quantum efficiency uniformity of heterostructure photodiodes using optical fiber coupled radiation. Testing was performed to confirm device specifications.
This study undertakes to quantify the spectral bandwidth of an AlGaAs/GaAs double heterostructure photodiode and two InGaAs/InP double heterostructure PIN photodiodes at D.C., through the use of spatial scanning. The spatial scanning was done using lasers at 670 nm, 780 nm, 848 nm, 1300 nm, and 1550 nm, coupled through singlemode optical fiber. The AlGaAs/GaAs material system covers the 600-870 nm wavelength region of research interest in the visible spectrum. The InGaAs/InP material system covers the 800-1650 nm region which contains the fiberoptic communications spectrum.

The spatial measurement system incorporates a nearly diffraction limited spot of light that is scanned across the surface of nominally circular photodiodes using a piezoelectric driven stage. The devices tested range in size from 17 to 52 µ in diameter. The smallest device scanned has a diameter approximately four times the diffraction limit of the radiation used for spatial scanning. This is the smallest diode yet reported as being spatially mapped. This is the first simultaneously reported spectral and spatial scans of the same heterostructure PIN photodiodes in the InGaAs/InP and AlGaAs/GaAs systems. The testing arrangement allows both spectral and spatial scans to be taken on the same stage. The diodes tested were taken from intermediate runs during their process development. All testing was performed at room temperature.

This study describes the mechanical assembly, calibration and testing of a spatial quantum efficiency uniformity measurement system. The spectral quantum efficiency was measured with low power, incoherent broadband radiation coupled through multimode fiber from a tunable wavelength source to the device under test. The magnitude was corrected to the measured peak external quantum efficiency
(Q.E.), determined during spatial scanning at a mid-spectral bandwidth wavelength using continuous wave (CW) higher power lasers. A procedure to improve the accuracy of the correction is recommended.

This process has been automated through the use of National Instruments LabVIEW II software. The results from this procedure are plotted to show 2.5 D (pseudo 3D) and 2 D contour spatial quantum efficiency maps. These results give a quantified map of the relative homogeneity of the response. The non-homogeneity of the spatial scans on the smallest devices has not previously been reported.

The Q.E. measurements made agree well with previously published results for similar device structures. The AlGaAs/GaAs device achieved a peak external Q.E. of 58.7% at 849 nm with -10V bias. An InGaAs/InP device achieved 63.5% at 1300 nm with the same bias.

The Q.E. results obtained are compared to theoretical calculations. The calculations were performed using the best optical constant data available in the literature at this time. The measured peak Q.E. was found to agree with the theoretical calculations to within 16% at longer wavelengths for both devices tested.
SPECTRAL AND SPATIAL QUANTUM EFFICIENCY OF
AlGaAs/GaAs AND InGaAs/InP PIN PHOTODIODES

by

STEVEN ALAN TABOR

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
ELECTRICAL AND COMPUTER ENGINEERING

Portland State University
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TO THE OFFICE OF GRADUATE STUDIES:

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DEDICATION

This thesis work is dedicated to my loving wife Carrie, who has sacrificed so much for this goal to be achieved. Her solid dedication to the needs of our children and myself have at times required both extraordinary effort and endurance. She is a Saint.

This thesis is also dedicated to all those who have helped us in our hour of need, Dr. Raymond E. Benson, a Saint, foremost. He has supported my family with both financial resources and timely medical analysis and prescriptions. This work could never have been completed without his provision. My father, Mr. Eugene L. Tabor, has also contributed financially. I would also like to thank Dr. Bob Rathbone, another Saint, for the medical assistance he has offered, free of charge, to my wife and myself.

My premier gratitude goes to my Lord and Savior Jesus Christ who has enabled me to do all things through Him. May this labor glorify Him.
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CHAPTER I

INTRODUCTION

This paper describes the experimental equipment and software used to measure the spectral and spatial quantum efficiency of InGaAs/InP and AlGaAs/GaAs PIN photodiodes at room temperature. The spectral quantum efficiency has been normalized to the peak spatial quantum efficiency as determined from CW laser scans of the photodiode surfaces with near diffraction limited spots of light. The laser wavelength used to normalize the spectral Q.E. curves is approximately centered in the spectral responsivity bandwidth. Experimental results are shown for representative devices of both material classes. A comparison of the experimental results to the theoretically achievable maximum quantum efficiency is given. Device structure impact on spectral response bandwidth is discussed.

The need for high speed photodiodes in the market place and a comparison of the limits of competing technologies is given. A discussion of similar characterization work and how this differs, listing references based on literature searches is presented.

At this time fiberoptic telecommunications companies are applying new solutions to the world's data transmission rate problems with 200 Mb/s data rates and above. Research is being done in advanced wavelength division multiple access (WDMA) with expectations of 1 Gb/s by 1992 [1]. Electronic companies are interested in heterostructure photodetectors for use in optical to electrical conversion. They will be used in high speed, wide bandwidth optoelectronic testing and measurement equipment that would
serve the needs that will come about when building and maintaining these systems.

InP heterostructure PIN photodetectors are well matched to the task by being optically sensitive to the low loss wavelengths of silica based optical fiber (where erbium doped fiber amplifiers have peak gain) and being relatively low noise while having high responsivity. GaAs heterostructure PIN photodetectors suit the needs of visible L.E.D. and laser characterization for currently developed high speed local area networks and computer multi-processor communications.

High speed measurement equipment requires a bandwidth of three to five times the specified need to assure stable and repeatable measurements. These constraints force device geometries and tolerances to the micron and submicron level. The homogeneity of the device response becomes important as we consider the ability to align single mode optical fibers, with less than ten micron cores to these devices. This thesis reports a novel system capable of testing both the spectral responsivity and the spatial quantum efficiency uniformity in these devices using optical fiber coupled radiation.

The PIN photodiode is used extensively in microwave applications due to its small and nearly constant depletion layer capacitance. This capacitance is the typical frequency limiting device parameter. Low doping in the heterostructure intrinsic layer (I), enclosed between the p-type, (P), positive charge donating semiconductor and n-type, (N), negative charge donating semiconductor, leads to a significant electric field before electrical breakdown occurs. This assures that the intrinsic region can be fully depleted and that charges induced in it can be accelerated to their maximum attainable velocity.

Avalanche photodiodes compete with the PIN in the wide band, long wavelength marketplace. At low frequency operating conditions, the A.P.D. with its high internal gain has a sensitivity advantage. However, the high reverse bias requirements can make A.P.D.'s less desirable. A.P.D.'s maintain this advantage due to the inherently lower
noise equivalent power (NEP) [2]. This is less of a factor in relatively higher powered developmental telecommunications systems. At higher frequency, the PIN followed by a field effect transistor amplifier (PIN FET) is considered a better choice. The case has been made for the utility of PIN FET combinations over avalanche photodiodes in these systems [3].

The last decade has shown growing interest in heterostructure devices for microwave and optical applications including heterostructure L.E.D.'s and laser diodes as well as detectors. Several papers report on the characterization of silicon photodiodes for spatial uniformity of response [4],[5],[6]. One paper reports using a scanning HeNe laser ($\lambda = 632.8$ nm) to characterize the uniformity of the response in a GaAs avalanche photodiode [7].

This paper reports on devices that range in size from 17 to 52 µ. The smallest device scanned has a diameter approximately four times the diffraction limit of the radiation used for scanning. This is the smallest diode yet reported as being spatially mapped. This is the first simultaneously reported spectral and spatial scans of the same heterostructure PIN photodiodes in the InGaAs / InP and AlGaAs / GaAs systems.

This work shows the utility of using the same probe station to characterize both the spectral and the spatial responsivity (or quantum efficiency) using fiberoptic coupled radiation. A broadband tungsten halogen light source was coupled through a monochromator for wavelength differentiation, to a multimode optical fiber allowing spectral scanning. The addition of appropriate optics to minimize the output spot size and an optical chopper to allow lock-in amplification would allow full wavelength spectrum spatial scanning.

Five wavelengths of monochromatic, single mode radiation from 670 nm to 1550 nm are shown as examples for spatial scanning. Using the probe station developed here,
lasers of any wavelength can theoretically be coupled to a device to be tested through optical fiber. In fact, radiation of any wavelength that can be carried by optical fiber, could be used to expand the utility of the probe station developed here.

This thesis is divided into seven chapters. The second chapter discusses the necessary theory behind the work reported here. It begins with the theory of PIN device operation. As PIN photodiodes are optical to electrical converters, photonic theory is covered first. This is followed by the electrical characteristics of this diode type. An attempt is made to clearly tie theory to the experimental observations. Also in the second chapter we cover topics in the theory behind the testing that was accomplished. This includes what was done, the order of operations, and why this was important.

The third chapter deals with the experimental aspects of this work. As this is an experimental thesis, key elements of the experimental apparatus and procedures as well as measurements used in its characterization are discussed. This section is conveniently separated into the spectral, and spatial response and quantum efficiency sections. A discussion of the equipment limitations discovered during the course of this work is found here. Also in the third chapter is an overview of the software developed to allow convenient operator unassisted spatial scanning. An opportunity to receive this software is made available at the end of this chapter.

The fourth chapter discusses results obtained for PIN devices of two material classes the AlGaAs / GaAs and the InGaAs / InP. The differences between measured and theoretical values are examined and causes noted. Limitations to the methods used are discussed here. The errors are estimated for both measurement techniques. A Fourier analysis of the device geometries is presented to quantify the spot size and explain the appearance of the pseudo 3D plots.
The fifth chapter contains the conclusions that came out of the test results. A discussion of what was achieved relative to theoretical expectations and previously published information is made. A discussion of apparatus limitations and how they impact convenience, accuracy and repeatability is made. How these issues effect the conclusions reached is discussed.

The sixth chapter suggests improvements based on observations made in the previous chapter on conclusions. Methods of improving device testing speed and precision are discussed.

The seventh chapter discusses further work that could be done to expand the capabilities of the testing apparatus. Suggestions are made that would allow this apparatus to approach the limit of its capability including reduced device sizes and possible materials to be considered in device fabrication.
CHAPTER II

THEORY

DEVICE THEORY

Overview

Two PIN device types are studied here, InGaAs / InP and AlGaAs / GaAs. These heterostructure devices show different sensitivities to radiation of various wavelengths based on their absorption characteristics and the index of refraction differences between their layers. The optical interaction of these characteristics is discussed under Device Physics : Photonic. The electrical parameters that govern device operation are discussed under Device Physics : Electrical. The heterostructure material layers and doping levels of the two devices are schematically displayed in Figure 1.

Devices C5 and C6 are MOCVD (metallo organic chemical vapor deposition) grown InGaAs / InP PIN's which have the structure shown on the top of Figure 1. (MOCVD is a vapor phase epitaxial technique.) Device A3 is an MBE (molecular beam epitaxy) grown AlGaAs / GaAs PIN. Its structure is shown in the bottom of Figure 1.

A photon is an individual packet of light. Its quantization as an individual packet finds its roots in the photoelectric effect. The photoelectric effect states that electrons will be released from certain surfaces when light is incident on them, if the light is above a certain frequency.

\[ h \, \nu \geq \phi \]  

(2.1)
Figure 1. Device structures.
Here \( \phi \) is the work function (or ionization energy) of the material, \( h \) is Planck's constant, and \( v \) is the light frequency in hertz. Noting that \( (E = q \, V) \) shows that for a given potential \( V \), an elemental charge \( q \) (\( 1.6 \times 10^{-19} \) Coulombs) is emitted when hit with a discrete amount of light \( (h \, v) \). [8]

In metals the conduction and valence bands overlap allowing low resistance electron flow or conduction. In semiconductors, the conduction and valence bands are separated and thus offer a significant barrier to electron movement. This separation will be referred to as the band gap \( (E_g) \). This energy gap is of key importance in semiconductor theory.

The preceding discussion has highlighted the bundling or particle aspects of light by referring to discrete amounts coinciding with energy level differences. Light does however have wave character as well. This is most clearly seen by the color distribution emanating from an illuminated prism. It is also evident at the output of a tuned monochromator. A monochromator is a device used to separate and gauge the wavelength of radiation.

A PIN photodiode is made by sandwiching an intrinsic semiconductor between layers of p-type and n-type material. This diode construction greatly increases the depletion layer width which simultaneously decreases the device capacitance and increases absorption. The increased depletion layer width corresponds to an increased semiconductor volume in which electron hole pairs are generated. When reverse biased the speed of device response is increased since the carriers are accelerated in the depleted layer due to the applied electric field. Carrier velocity outside the depleted layer is slower and is referred to as diffusion velocity. An optimum reverse bias voltage exists that maximizes device responsivity and response speed.
Device Physics : Photonic

We note that photons, when impinging on a semiconductor surface, behave in one of three ways: a) they are reflected b) absorbed or c) transmitted. The functionality of photodiodes is dependant on their ability to absorb light. It is only those photons greater than a certain frequency that can be absorbed, since $h$ and $\phi$ are constant (see 2.1). Fundamental physics states that light frequency times wavelength is equal to $c$,

$$\nu = \frac{c}{\lambda} \quad (2.2)$$

where $c$ is the speed of light in vacuum. The wavelength $\lambda$ is fundamentally related to a minimum energy necessary to be absorbed and thus detected. Stated another way, the wavelength $\lambda = c / \nu = \frac{hc}{E_g}$ must be greater than some minimum value in order for the photons to have sufficient energy to excite a carrier from the valence to the conduction band (across the energy gap, $E_g$). The energy gap of GaAs, at room temperature, is 1.424 eV and of InGaAs, .75 eV.

The long wavelength cut-off $\lambda_c$ occurs due to the band gap of the intrinsic layer semiconductor, where

$$\lambda_c \ (in \ \mu) = \frac{hc}{E_g} = 1.2399 / E_g \ (in \ eV). \quad (2.3)$$

The short wavelength cut-off occurs because the light is absorbed too close to the surface. Due to a high concentration of absorbed carriers at the surface, recombination is the dominant mechanism thereby reducing the number of carriers and the average carrier drift velocity. Since carrier drift velocity is low, the collection of the remaining carriers is very low.

At the interface between dissimilar materials a certain amount of reflection of light usually takes place. This is due to a dissimilarity in the refractive index characteristic of the two materials.

$$\rho (\lambda) = \{(n_1 - n_2) / (n_1 + n_2) \} \quad (2.4)$$
The above equation is a generalized statement, in that \( n_1 \) is simply an overlying transparent medium of refractive index \( n_1 \) on an underlying transparent medium of refractive index \( n_2 \). The wavelength dependence of the amplitude or Fresnel reflection coefficient \( \rho \) is based on the changing refractive index with incident wavelength. The change in intensity that occurs at the interface is the field reflection coefficient squared, \( \{ \rho (\lambda) \}^2 \).

The index of refraction (\( N \)) is a unitless proportionality that relates the speed of light in vacuum (c) to the speed of light in a material (\( v \))

\[
c / v = N = ( n - i k ). \tag{2.5}
\]

The real part of the index of refraction, \( n \), is frequently mistakenly referred to as the "refractive index". The ratio of two real phenomena should always be a real number. However in an absorbing media, like anisotropic semiconductors, some electromagnetic attenuation of the wave is noted. This is accounted for by using the complex refractive index (\( n - i k \)). The imaginary part of the refractive index (\( k \)) is called the extinction coefficient. The equation below represents the attenuation of incident photons each vacuum wavelength (in cm), and \( \alpha \) is the absorption coefficient (in cm\(^{-1}\)).

\[
k = \alpha \lambda / 4 \pi \tag{2.6}
\]

The absorption coefficient is related to the skin depth, \( \delta = 2/\alpha \). This is the distance in which the amplitude of the incoming wave falls to 1/e of its initial value (.36 or 36%).

In order to couple the maximum amount of light into the photodiodes, a physics trick is used. This trick is to minimize the difference between the two materials by depositing an anti-reflection (AR) coating. The conditions that should be met are 1) that the thickness (\( t \)) of the AR material should be a quarter wave multiple of the incoming wavelength

\[
t = \lambda_0 m / 4 n_1 \tag{2.7}
\]
where $\lambda_0$ is the wavelength of the light in vacuum, $m$ is an odd integer and $n_1$ is the real refractive index of the AR coating. And 2)

$$n_1 = \sqrt{n_2}$$

(2.8)

where $n_2$ is the real refractive index of the underlying material (in our case a semiconductor). Reflection at a surface is due to a difference in the index of refraction between the two materials when the above conditions are not met. (See Figure 2 following for a diagram illustrating the above discussion.)

![Figure 2. Plane parallel index steps.](image)

The refractive indices of each material vary with the wavelength of incoming light. In that the indices do not vary in the same direction or at the same rate, the differences
between adjacent material indices also changes with wavelength. This, when viewed in
the context of the above equations means that the reflection at the interfaces between dif­
ferent materials changes with wavelength.

Since only one wavelength, \( \lambda \), and thickness, \( t \), can be chosen, wide wavelength
band detectors like those examined should show somewhat less than ideal matching to
the incoming wavelength away from the optimum for the design when only one AR coa­
ting layer is used. The single layer silicon nitride coating, used as an AR coating for the
InGaAs device only, is not shown in Figure 1.

Absorption takes place when the energy contained in the photons is transferred to
the semiconductor crystal lattice. Conversely, if it is not absorbed it is transmitted or
reflected. For index matched layers, where absorption goes to zero the material is trans­
parent, not allowing any carrier generation.

The absorption process takes place in each material as a function of wavelength. If
the radiation is absorbed in a non-semiconductor material it is immediately reemitted as
one of several types of energy, most commonly heat or lattice vibrations known as pho­
nons. The absorption curves of several semiconductor materials including those studied
here are found in Figure 3 following [2].

It should be noted that the light penetration depth (see right axis on Figure 3) of
GaAs decreases rapidly near the upper cut-off wavelength for the AlGaAs / GaAs
devices. Also the InP appears to be fully transparent at the lower cut-off wavelength for
InGaAs / InP devices. InGaAs has appreciable absorption until nearly 1700 nm. AlGaAs
(not shown) has some absorption until \( \approx 700 \) nm.

As can be seen in Figure 1, the top contacts of both devices, although thin, still can
absorb radiation. This can have a marked influence on the amount of radiation capable of
entering the depletion region of the device when it is in a highly absorbing region of the spectrum. This reduces the apparent efficiency of the devices if the carriers generated are not collected.

The small amount of absorption that can be seen in Figure 3 for $\lambda > \hbar c / E_g$ can be attributed to several factors including band tailing, free carrier absorption of the probing beam and absorption by defects [8].

Figure 3. Absorption vs. wavelength.
The absorption process takes place in a semiconductor crystal according to Beers Law

\[ I = I_0 \exp \left[ -\alpha z \right]. \]  

(2.9)

Here, \( I \) is the intensity at location \( z \) with \( z = 0 \) defined to be the surface of the material or the first interface, and \( I_0 \) is the initial intensity. (The introduction of this law clarifies the definition of the absorption coefficient \( \alpha \).) When this relationship is combined with what we already know of the reflectivity losses

\[ I = \left( 1 - (\rho(\lambda))^2 \right) I_0 \exp \left[ -\alpha z \right] \]  

(2.10)

where \((\rho(\lambda))^2\) is surface field reflectivity due to the refractive index mismatch.

Note in Figure 3 that \( \alpha \) typically increases with decreasing wavelength. This takes place since in the energy band diagram the density of electronic states available at shorter wavelengths increases (as \( \alpha \) gets smaller, \( E \) increases). Therefore, the number of possible energy states increases and the probability cross section increases with the number of states. Seen another way, the larger the number of states available to jump to, the more likely the transition will take place, and this makes absorption a more probable event.

The above information is expanded eloquently in the following passage taken from Introduction to Optical Electronics [9].

The cross section, \( \sigma \), is a measure of the probability that an exciting particle will strike an absorbing atom or molecule and be consumed by it. It is the cross sectional area of the absorbing species. This will cause the flow of exciting particles to be reduced by \( A dI \) where \( A \) is the cross sectional area of the beam and \( I \) is its intensity. The probability, \( P \), that an exciting particle will strike an absorbing particle is

\[ P = \frac{\sigma}{A} \quad \text{where} \quad \sigma = \pi b^2 \]

with \( b \) being the radius of the capture cross section. If we ignore the possibility that one absorbing specie "hides" behind another, the number of exciting particles being absorbed per unit time in a volume \( A \, dz \) is proportional to the number of absorbing particles, \( N \), in the volume element where
\[ N = n A \, dz \]

and \( n \) is the number of absorbing particles per unit volume.

Finally, the number of absorbing collisions per unit time is also proportional to the flux of particles in the exciting beam, \( A \, I \). Thus

\[
- A \, \frac{dI}{dt} = \left( \frac{\sigma}{A} \right) (n A \, dz) (A \, I) \]

The negative sign indicates an intensity decrease. [6]

The following calculations extend the results of Jones to explain the form of the equations used to calculate absorption in the diode structures.

Dividing through by area, \( A \), and cancelling terms, then multiplying through by \( 1/I \) results in the following equation.

\[
- \frac{(dI)}{I} = \sigma n \, dz \quad (2.11)
\]

Now we integrate both sides of the equation. The left side is integrated over the intensity change and the right side over the distance in which the intensity is simultaneously changing.

\[
\int_{I_o}^{I} \frac{dI}{I} = - \sigma n \int_{z=0}^{z} dz \quad (2.12)
\]

This integration yields the following result:

\[
\ln \left( \frac{I}{I_o} \right) = - \sigma n \, z \quad (2.13)
\]

or,

\[
\left( \frac{I}{I_o} \right) = \exp \left( -\sigma n \, z \right) \quad (2.14)
\]

and thus
\[ I = I_0 \exp(-\sigma n z). \] (2.15)

It can now be seen that the absorption coefficient, \( \alpha \), is equal to the probability cross section, \( \sigma \), times the number of absorbing particles per unit volume, \( n \) (See 2.9). This is an important physical relationship that ties theory to experimentally observed fact. Equally important is the relationship from solid state theory that requires that the incoming photon contain energy in discrete amounts of \( \pm kT \). (Here \( k \) is Boltzmann's constant and \( T \) is temperature in kelvin.) The probability that the energy will be absorbed goes up dramatically when the incoming energy equals the transition energy between band orbitals that surround each absorbing specie.

The optical constants for the materials used in the diodes tested is listed in the following five tables. This information was used in the theoretical calculations presented in this document. The data has in most cases been converted to wavelength format from energy format using (2.3). In all cases a linear interpolation between provided data points or an extrapolation assuming constant slope was used in the calculation.

The data for first table is for amorphous silicon nitride which is used as an antireflection coating on the InGaAs/InP photodiodes. This data is linearly interpolated from data taken from reference [8] until 1240 nm. Thereafter a constant slope \( \sigma = .001 / 40 \) nm was extrapolated to list \( \sigma \). This extrapolated slope is consistent with published graphs in the IR although these data points for the real part of the index are smaller by a constant \( \leq .1 \). The films used on these devices are sputter deposited and assumed to be stoichiometric.

The data in the second table is for crystalline AlGaAs optical constants, is taken from [10]. The data from 840 - 1000 nm is extrapolated graphically from the slope determined from the three previous data points on log-linear graph paper.
The data in the third table is for crystalline GaAs and was linearly interpolated between provided data points in [11].

The data in the fourth table, for crystalline InGaAs, was graciously provided in private communication with the author of [12], [13]. This data was converted from its provided form \( \varepsilon_1 \) and \( \varepsilon_2 \) where

\[
\varepsilon_1 = n^2 - k^2 \tag{2.16}
\]

\[
\varepsilon_2 = (2n \ k) \tag{2.17}
\]

The precision displayed appears to be within the precision of the measurement technique and sample preparation method utilized.

The data in the fifth table for the optical constants of crystalline InP was either taken directly from or linearly interpolated between provided data points in [14]. This data was found to be in excellent agreement with that published by the Optical Society of America [15]. The data discussed above is found in Tables I - V following.

All quantum efficiency (Q.E.) reported here is external quantum efficiency (\( \eta_e \)). External Q.E. takes into account reflections at interfaces and non-electrically productive absorption. Internal quantum efficiency (\( \eta_i \)) is defined as Q.E. based solely on the ability of the material to convert an absorbed amount of light at a given wavelength into detectable electrical energy. Responsivity is the amount of current generated (amps) divided by the known incident optical intensity (watts). The \( \eta_i \) is defined to be unity (or 100%) in the theoretical ideal.

The energy contained in each photon decreases with increasing wavelength (See 2.3). Therefore we should expect a reduction in responsivity with increasing wavelength in a constant intensity system. Thus \( \eta_i \) should decrease with increasing wavelength in a
constant intensity system. As will be seen, the effects of absorption and reduced reflections from the overlying material layers can combine to actually increase the responsivity with wavelength.

**TABLE I**

**SILICON NITRIDE OPTICAL CONSTANTS**

<table>
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<th>Wavelength λ (nm)</th>
<th>Real Refractive Index n</th>
<th>Extinction Coefficient k</th>
<th>Absorption Coefficient α (cm⁻¹)</th>
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TABLE I
SILICON NITRIDE OPTICAL CONSTANTS
(continued)

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<th>Wavelength $\lambda$ (nm)</th>
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### TABLE II

$\text{Al}_{0.315}\text{Ga}_{0.685}\text{As}$ OPTICAL CONSTANTS

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TABLE IV

In$_{43}$Ga$_{57}$As OPTICAL CONSTANTS

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### TABLE IV

$\text{In}_{43}\text{Ga}_{57}\text{As}$ OPTICAL CONSTANTS

(continued)

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**TABLE V**

InP OPTICAL CONSTANTS

<table>
<thead>
<tr>
<th>Wavelength $\lambda$ (nm)</th>
<th>Real Refractive Index $n$</th>
<th>Extinction Coefficient $k$</th>
<th>Absorption Coefficient $\alpha$ (cm$^{-1}$)</th>
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TABLE V
InP OPTICAL CONSTANTS
(continued)

<table>
<thead>
<tr>
<th>Wavelength $\lambda$ (nm)</th>
<th>Real Refractive Index $n$</th>
<th>Extinction Coefficient $k$</th>
<th>Absorption Coefficient $\alpha$ (cm$^{-1}$)</th>
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<td>1720</td>
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An evaluation of the device structures shown in Figure 1 was done with a thin film analysis program TFCalc. This program is produced by Software Spectrum. Its advantage is that it allows absorbing media as well as non-absorbing media as thin film layers. It can calculate the total transmission, reflection and absorption for any complex index film stack, entrance and exit media available in its materials and substrate data set. Additionally lasers are conveniently modelled as coherent single wavelength illuminants.
This program, used to perform the theoretical calculations, has the ability to superimpose inter-layer reflections. This appears as induced transmission (or reduced reflections at an interface) when materials of similar refractive index but relatively large extinction coefficient are adjacent films.

Since, within the program, the exit medium can be made any material, the transmission into any layer can be determined by retaining the overlying films in their appropriate order from top AR coat to the layer being analyzed. Additionally, the total absorption up to this layer is calculated and displayed. By sequentially making the exit medium the previous substrate and the new substrate the previously overlying layer, a complete analysis of the device structures was performed.

The data in the preceding tables was entered into TFCalc. Priority was given to the physical thickness of the device layers given in Figure 1. This was done to assure that the aforementioned intensity reflection coefficients, that are a function of real and imaginary refractive index and layer thickness, are calculated more exactly (See (2.7) and (2.8)). No layer optimization was done with the program in this investigation.

The procedure used here is to chose the substrate (InP or GaAs) as the thin films substrate. The substrate thickness is specified. The overlying layers of thin semiconductor films are the film stack that is analyzed.

These film stacks are separately assembled within a subsection of the program. They are input into a table starting with the substrate, progressing to the topmost layer. They are composed of the wavelength, refractive index and extinction coefficient.

The environment for the test is user chosen. This includes the wavelength range of interest and the choice of illuminant. For the first analysis, the exit medium (this would usually be air if a lens was being analyzed) is chosen to be the same as the substrate medium.
The result of this analysis is the intensity transmission, reflection and absorption in the assembly. The transmission is the optical transmission into the exit medium. The reflection is the reflection back into the incident media (always air). The absorption is the absorption of the substrate and films assembly. These results were recorded and are displayed in Table VI.

The wavelength region of interest and the wavelength of the user specified illuminant is now changed. The analysis is repeated until all wavelengths of interest have been examined.

At this point the previously last element in the film stack is reassigned as the substrate. The exit medium is now the previous substrate. The test is repeated as above.

Both device structures were analyzed using the above methods. The absorption is what remains when the reflection and transmission are subtracted from the incident intensity (normalized to one). This absorption is the theoretical maximum optical intensity that could be converted to electric current in the device. This results in current flow as a function of incident intensity referred to as responsivity (see 2.24). With a theoretical internal quantum efficiency of one, every photon absorbed produces an electron hole pair.

The percentage absorption calculated by the program at the above two defined conditions is taken as a range of values. To convert this data to external quantum efficiency the following process was followed. The energy per photon at each laser wavelength was calculated. The percentage absorption was taken as the normalized optical power coupled into the device structure at the specified wavelength. Both an internal conversion efficiency and an internal collection efficiency of 100% is assumed. Therefore an EHP is generated for each photon absorbed in the medium. The responsivity is defined as the amount of electric current (A) generated divided by the incident optical power (W). Once the responsivity is known the quantum efficiency can be calculated using equation
(2.25) following. With these assumptions the external quantum efficiency calculated is identical to the absorption percentage since $\eta_e$ is the number of collected carriers divided by the number of incident photons.

**TABLE VI**

**TFCALC : THEORETICAL QUANTUM EFFICIENCY**

<table>
<thead>
<tr>
<th>Device Structure</th>
<th>Laser Wavelength</th>
<th>Calculated Q.E. % Range</th>
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<tbody>
<tr>
<td>AlGaAs / GaAs</td>
<td>670 nm</td>
<td>66.6</td>
</tr>
<tr>
<td>AlGaAs / GaAs</td>
<td>780 nm</td>
<td>67.2 - 67.3</td>
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<td>AlGaAs / GaAs</td>
<td>848 nm</td>
<td>59.2 - 59.6</td>
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<tr>
<td>InGaAs / InP</td>
<td>848 nm</td>
<td>81.4</td>
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<td>InGaAs / InP</td>
<td>1300 nm</td>
<td>67.2 - 67.3</td>
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<tr>
<td>InGaAs / InP</td>
<td>1550 nm</td>
<td>44.6 - 44.8</td>
</tr>
</tbody>
</table>

Since there is no charge collection field in the highly doped substrate, absorbed carriers in the substrate do not contribute to the detectable signal. With no accelerating potential, EHP transfer efficiency depends totally on diffusion length and time of flight (TOF) before recombination.

**Device Physics : Electrical**

The photodiode is a semiconductor transducer which converts light into electricity. The device accomplishes this feat by inducing a layer of semiconductor to absorb the
light energy and (by methods discussed in the previous section) excite an electron from
the valence band to the conduction band. If the electron and hole do not recombine and
are separated by the applied field, this charge separation can be measured outside the cir­
cuit and is seen as an induced current ($I_p$). (See Figure 4, A following.) The thickness of
the intrinsic region, $t$, is typically depleted under reverse bias conditions.

When light is absorbed generating an electron / hole pair (EHP), a process referred
to as generation has been completed (See Figure 4, B). An EHP is viewed as a single
charged entity for the purposes of determining current flow in the device. Generally,
both electrons and holes are constantly being generated and recombining even without
the presence of absorbed light. The collection of these carriers along with surface
leakage currents, due to reverse biasing the device establishes the noise floor for low
intensity D.C. measurements.

We note and statistically average any increase in the number of collected EHP's
when a steady light impinges on the surface. When this steady state differs from the
equilibrium value, the amount of additional current is proportional to the amount of light
impinging on the semiconductor surface. (This proportionality is reduced by the extra
recombination that takes place because of an increase in the density of carriers near the
location of EHP generation.)

Once the electron hole pairs are generated they are separated and accelerated by the
reverse bias induced electric field. (See Figure 4C) The higher potential (on the left rela­
tive to the right) schematically implies that the electrons are moving to the lower poten­
tial energy position. This electric field accelerates the carriers, once separated, toward
the p and n contacts. The devices discussed in this work have been biased at -1 and -10
volt. This level of reverse bias was designed to partially and then fully deplete the intrin­
sic layer of free carriers.
Figure 4. Equivalent circuit and carrier separation.
It is now believed that both devices were fully depleted at the -1 V bias condition.

When examining a diode it is customary to examine its change in current with change in voltage (I-V curve). The standard diode curve has a small forward linear rise then an exponential rise in current with voltage. The reverse biased diode curve typically stays at near zero reverse current until a material breakdown occurs. This is referred to as reverse breakdown.

The reverse bias I-V curve is of higher importance due to the conditions of normal operation of devices used in this test. Reversed biased diodes in general have two types of current, diffusion current and electric field induced drift current. In a standard semiconductor diode diffusion current is the primary current when reverse biased in the absence of intense illumination.

Recombination is the process by which a generated EHP (either by device illumination or statistically occurring) comes back together or combines with its counterpart generated elsewhere. There are two types of recombination, Auger and radiative. Auger recombination is defined as direct recombination of EHP accompanying energy transfer to another hole. This process results when electrons are injected into the p+ region. Auger recombination in these devices should be considered band to band. Radiative recombination emits photons. The wavelength of these photons is a function of the energy of recombination.

Photon recycling is defined as an initial EHP recombining as a radiative recombination. The resulting photon is reabsorbed in a location in the crystal resulting in an EHP that can be sensed.

The reverse biasing causes the separation of EHP's that are constantly being generated even without the presence of light. This is called diffusion current.
illuminated reverse biased photodiode, electric field induced drift current is the dominant current. Diffusion is a slow process. PIN photodiodes operate at much higher speed due to the high carrier velocity of this induced drift current.

Photodiodes also have a diffusion current associated with being reverse biased when there is no light. This is called the reverse leakage or dark current since it must be measured in the absence of light. The primary source of dark current is the statistically generated EHP’s that are seperated and sensed due to the reverse bias. Other components of the dark current include surface leakage caused by a voltage across a resistive path at the mesa edge and tunneling of carriers (band to band) due to trap emptying (under sufficient reverse bias). The dark current measurements for the devices reported here follow in Figure 5.

Since PIN photodiodes are built to operate at higher speeds this corresponds to higher frequency in the frequency domain. High frequency roll-off in the frequency domain leads to pulse widening in the time domain. This pulse widening is the result of several processes with the diode. The first is the time it takes for carriers to diffuse out of undepleted regions. In these regions the electric field induced drift velocity is quite low due to the low field strength. The second is pulse widening caused by capacitively induced damped roll-off associated with R C low pass filter time constants.

\[ \tau = RC \]

Here R is a series resistor (ohms), C is a series capacitor (farads), and \( \tau \) is the decay time in seconds. Capacitors in general are defined in terms of charge and voltage \( (Q/V) \) or separation distance \( (t) \), area \( (A) \) and permittivity \( (\varepsilon) \) of the medium.

\[ C = \varepsilon \frac{A}{t} \]

The larger the capacitance the slower the response speed. The larger the area, and thinner the separation distance between p and n contacts, the greater the capacitance
becomes. Since its permittivity is a fundamental semiconductor material property and cannot be appreciably altered, the depletion layer thickness and the area of the contacts of the diode significantly influence response speed. Thus there exist optimum device dimensions to achieve the smallest capacitance (small area A) and the fastest carrier transit time (thin depleted intrinsic layer, t).

**Dark Current**

![Graph showing the relationship between bias voltage and reverse current for different devices](image)

**Figure 5.** Device dark current.

The third is the time it takes for carriers to drift across the depletion region. It was noted above that when the separation distance becomes large, the electron / hole transit
time becomes longer. This is so since the saturated carrier velocity has an upper limit which fixes drift time through the depleted region. The devices tested here appear to have this drift time as the primary speed limitation.

In practice, the shorter wavelengths are absorbed close to the p-contact. Since the holes (due to this absorption and EHP generation) are close to the their collection area, the electron velocity determines the speed of response at short wavelengths. This electron velocity is a function of applied electric field and reaches a maximum of $2 \times 10^7$ cm/s at $4$ kV/cm for both GaAs and InGaAs. This corresponds to a reverse bias of .72 volts for the GaAs intrinsic region (see Figure 1) and .36 volts for InGaAs. If the devices intrinsic region is fully depleted under these conditions, these reverse biases would correspond to the fastest response time.

The fourth speed limitation is due to charge trapping at heterojunctions. This limitation is due to both interface states induced during material growth and charge trapping due to recombination in the two dimensional electron gas. Lattice matching during material growth was done for both device types tested to reduce dangling bonds that would evidence themselves as interface states.

$\tau_r$ is the device rise time. $\tau_f$ is the device fall time.

$$\tau_r = .36 / B,$$  \hspace{1cm} (2.20)

where $B$ is the device bandwidth. This equation gives the 10% to 90% of full scale rise time. The 3 db optical bandwidth of the InGaAs / InP devices is greater than 35 GHz. Since $\tau_f > \tau_r$ typically, no definitive statement can be made regarding response time. Early results indicate that non-deconvolved responses less than 20 picoseconds are normal for these devices. The speed of device response is not a factor in the speed of testing reported here, giving us assurance that all detectable carriers are collected during testing.
The photos in Figure 6, both taken at a magnification of approximately 800 x, show the relative size of the two devices tested. The top photo shows the pattern used for device A3, the AlGaAs/GaAs PIN photodiode. The area tested is in the lower left. This diode is approximately 52 µ in diameter. The bottom photo shows the nominal 26 µ diameter pattern of device C6, the InGaAs/InP PIN photodiode. The 4 µ wide contact metal ring can be seen. The center opening is 12 µ in diameter. Device C5, also an InGaAs/InP PIN photodiode, is not pictured here. It has a nominal diameter of 17 µ. The contact metal width is 2 µ, the center opening is 7 µ.

In multi-layered heterostructure semiconductor photodiodes, like the ones studied here, the layers vary in refractive index and absorption coefficient with wavelength. Where the materials absorb all the radiation at the surface, without allowing it to the carrier depleted intrinsic region, the lower wavelength limit in sensitivity has been noted. This is so since the charges generated at the surface can not all be collected.

A recent publication [16] measures the time of flight of minority carriers in p-GaAs. The diffusion length for $10^{19}$ zinc doping is 2 - 5µ. This information implies that carriers generated in the thin undepleted p-contact region on the GaAs device could potentially diffuse to the depletion region. The diffusion distance is of the order of the diameter of diffraction limited spots of light at -1 V bias. This converts to a short carrier lifetime (less than 2 ns typical) at the velocities expected at these field strengths ($= 1 / 20^{th}$ of the velocity in the depletion region).

To this it should be noted that the two InGaAs devices, whose cross section is shown in Figure 1, do not show the overlayer of silicon nitride normally used as an anti-reflection coating and surface passivation. Without surface passivation, lower D.C. performance devices result due to an increase in surface recombination.
Figure 6. Device photographs.
Furthermore, surface contamination can decrease mobility by inducing image charges within the semiconductor [17]. Together, these material properties combine to limit both the sensitivity and measured external quantum efficiency (Q.E.).

The electrical characteristics that govern the operation of PIN photodiodes are: 1) carrier mobility (as transit time) and its change in the intrinsic region with bias voltage [18], [19]; 2) depletion width as a function of bias voltage for various thicknesses (t) of the intrinsic region; and 3) reverse current under dark conditions (dark current) [20]. Reverse voltage breakdown (V_b) in PIN photodiodes comes about when avalanche multiplication caused by impact ionization occurs.

Impact ionization is the dominant mechanism in PIN junction breakdown. Although impact ionization is used in some photodiodes to maximize signal, in the PIN devices studied here, it imposes an "upper limit" on the reverse bias.

It should be noted that at low electric field strengths, drift velocity is proportional to the electric field. This proportionality constant is the mobility, \( \mu \) in \( \text{cm}^2 / \text{Vs} \). Mobility is a fundamental device property and is usually further defined as electron \( \mu_e \) or hole \( \mu_h \) mobility. Only at high electric field strength does impact ionization begin.

Since \( \eta_e \) and \( \eta_h \) both depend on the ability to detect small amounts of current, particular care needs to be taken in establishing electrical connections. The electrical contacts to both devices are made with clean tungsten probes (See Appendix A). Device A3, with its topside p-contact, is probed directly. The backside contact is made to the clean device chuck. The InGaAs devices are mounted on hybrid carriers by die attach. A flexible microstrip coplanar transmission line (microstrap) is used to make electrical connection between the device and the hybrid carrier. (This is a Tektronix microwave bonding method.) The tungsten probes make contact to the gold lines on the hybrid.
Noise is an electrical term that refers to spontaneous fluctuations of voltage or current that occur while measuring devices. Microelectronic devices deal with relatively small amounts of current or voltage. Noise commonly determines the lower limit of the quantities to be measured. It is typically divided into three groups: thermal, flicker, and shot noise.

Thermal noise is that contribution to the collected EHP's that comes from thermally generated carriers in the depletion region. The mean-square thermal current is defined by

$$<i_T^2> = 4 K T \left( \frac{1}{R_{eq}} \right) B. \quad (2.21)$$

Here $K$ is Boltzmann's constant, $T$ is temperature in kelvin, $B$ is the electrical bandwidth in hertz, and $R_{eq}$ is the equivalent resistance in the testing circuit.

Based on the method of testing and the speed of device response, flicker noise (more commonly known as 1/f noise), does not impact the results presented. This noise is of importance only in low frequency ($f$) testing and therefore does not influence the testing reported here.

Shot noise is comprised of background radiation induced EHP's and the dark current contribution to measured current. The mean-square shot noise current is defined by

$$<i_S^2> = 2 q B I. \quad (2.22)$$

Here $q$ is the electronic charge (1.6 x 10^{-19} coulombs), $B$ is defined above and $I$ is potentially bipolar and therefore negative under reverse bias testing conditions.

TEST THEORY

Each of the tests requires that electrical contact be made to the device to be tested. A bias voltage is applied to sweep the optically generated carriers out of the depleted region to be collected at the contacts. A beam of light, whose wavelength band is chosen
to be in an area of high responsivity, is used to probe for the device to maximize response, thus confirming alignment. Typically a piezoelectric drive, which holds the final optics train (or optical fiber), is used to locate and maximize the response. The piezoelectric drive can be positioned a micron at a time which is not easily achievable with conventional mechanical means.

Once the incident light beam strikes the device a current is generated and displayed on the source measurement unit operated in manual mode. This source measurement unit simultaneously supplies a reverse bias to the diode and measures any current emitted by the device. With the response maximized at a low reverse bias voltage, the position is recorded and the testing proceeds. The position information is used to confirm that the fiber alignment has not changed during the spectral testing and to position the device in the available stage travel for spatial testing.

Spectral

The spectral quantum efficiency of devices is dependent on accurate knowledge of the optical power coupled to the device as a function of wavelength. Before testing begins care is taken to align the optical components to maximize optical power coupled from the source, through the monochromator, through the optical fiber to the device test stage. The monochromator is a device used to separate an optical spectrum into small wavelength regions or bands. The optical power through the fiber is measured every 20 nm from 400-1700 nm. The full spectrum is measured before testing begins. The device response both illuminated and dark is recorded. Then the optical power through the fiber is reconfirmed.

For the spectral tests, the response of the device is measured with a wavelength band of light coupled to the surface through a 50 µ core multimode fiber. The spectral bandwidth, passed through the monochromator, through the output optics to the fiber
input, is a function of the monochromator slit width. This apparent bandpass is believed to be greater than the experimental bandpass due to spatial filtering at the fiber optic input.

Optical fibers are used in both spectral and spatial measurement systems. Another important aspect of the differences in the real part of the refractive index of adjacent materials relates to the fiber numerical aperture, (NA). All optical fibers have similar structures, consisting of a concentric tube of lower refractive index cladding, \( n_2 \), overlying an inner guiding core of higher refractive index, \( n_1 \). The half angle of acceptance or emittance, \( \alpha \), is defined as that angle at which total internal reflection occurs at the core / cladding interface.

\[
NA = \sin (\alpha) = \sqrt{(n_1)^2 - (n_2)^2}
\]  
(2.23)

Singlemode fibers have smaller cores. These cores guide only the smallest fundamental modes of the radiation (TEM\(_{00}\)). Multimode fibers have larger cores, typically five to ten times the diameter of singlemode fibers.

As was noted in Tables I - V, the refractive indices of materials vary with wavelength. This means that the NA and angle of acceptance and emittance change with wavelength. The output beam from the multimode fiber used for spectral testing diffracts or expands as it exits the fiber. This over filled all the diodes tested since the largest diode is only 52 µ in diameter. The fiber does not touch the surface of the device to avoid surface damage.

Both an illuminated and dark measurement at two reverse bias voltages are taken at each wavelength setting. A dark measurement is a measure of the response of the device when all controllable sources have been eliminated. It also determines the noise floor for the minimum optical power that can be measured by the device at D.C. Once the data is taken, the monochromator is returned to zero wavelength (mirror) and several data points
are repeated. This gives a judgement of the accuracy of measurements. Additionally, at this time, the position of the optics column is recorded to determine if any movement of the column occurred during testing.

Once the dark measurement is subtracted the actual device response as a function of wavelength can be calculated. The responses \( A \) are divided by the previously determined incident light beam power \( W \) to determine responsivity in \( A \, / \, W \).

\[
R(\lambda) = \frac{I_p(\lambda)}{\Phi_i(\lambda)}
\] (2.24)

\( I_p(\lambda) \) is the photocurrent generated as a function of wavelength. \( \Phi_i(\lambda) \) is the previously measured optical power as a function of wavelength incident on the photodiode. The relative spatial position of peak power output (power density) from the multimode fiber changes with wavelength. This is due to the previously described change in numerical aperture with wavelength which occurs at the input and output of the multimode fiber. This is a primary error source in spectral measurements.

**Spatial**

As for spectral testing, the optical power coupled to the device must be accurately known at the device test stage for spatial scanning. The optical power was measured and determined to be continuous and stable. The size of the output beam spot size is measured to assure that the optics are properly aligned to produce a near diffraction limited spot. The device is carefully placed on the test stage within the available travel window of the piezoelectric stage. Electrical contacts are now made to the device. The device is located as previously with the S.M.U. in manual mode with a small reverse bias voltage.

For the spatial scan, the near diffraction limited beam is backed away from the device an appropriate amount to center the device in the piezoelectric positioning systems available scanning field. The available scanning field is small due to the inability of the
stage to return to its initiation point. The test is initiated by running a computer program. The program first sets the micrometer gauges to zero, on both sensing axes. Then it repeatedly takes a step, measures the device response at two bias voltages and records the x and y position. The process repeats by taking another step. At the end of the test the recorded information is automatically stored for subsequent examination and analysis.

The information is analyzed initially to properly reposition the device in the available scanning field. Then a change in the height of the output focussing lens position is made. The purpose of this change is to bring the focal point of the beam closer to the top surface of the device to be tested.

The relative change in z height (where z is the vertical axis) is small, typically .0002" or smaller in the region of significant responsivity. This distance was determined experimentally to give an appreciable change in the device response when near peak responsivity. The responsivity is recorded both for a focussing and defocussing beam.

It should be noted here that it cannot be confirmed that peak responsivity occurs at the minimum spot size in the plane of the device surface. It does however, appear that this is the case.

Initially responsivity is calculated using (2.24). The photocurrent measured (at the high optical power levels from lasers) was so much greater than the dark current that no correction was made to the data. The responsivity is then converted to external quantum efficiency using the following equation.

\[ Q.E. = 1.239 \frac{R(\lambda)}{\lambda (\text{in } \mu)} \]  

(2.25)

This Q.E. data is correlated to the positional data taken during the testing operation. The x, y, Q.E. data set at each bias condition is then plotted both 2.5 D (pseudo 3D) and 2D as contour plots.
External Q.E. is reported throughout this thesis as it is a more fundamental device parameter. Q.E. is the number of carriers detected divided by the number of incident photons.
CHAPTER III

EXPERIMENTAL

EQUIPMENT

Spectral Response and O.E.

Principle of Operation Overview. The spectral response of the devices is measured using the equipment in the layout following. Illumination is from the Newport model 780 source, a quartz lensed, quartz halogen tungsten filament bulb with output power self-monitored for intensity stability. The photofeedback stabilization is specified as maintaining ± .1% per hour. This lamp is a white pseudo-Lambertian source with a color temperature of 3200 kelvin.

The illumination from the source was coupled through the adjustable focussing lenses of the lamp housing to a spatial filter. This nearly collimated beam was spatially filtered to reduce stray light that would be transferred to the monochromator.

Lens 1 focuses the incoming beam into the monochromator, precisely matching the numerical aperture (NA = .143) of the monochromator. The monochromator is a dual grating, quarter meter Ebert monochromator from Jarrell - Ash. (This monochromator is sold as the Monospec 25 currently.) The monochromator has the ability to change gratings with the flip of a lever. It is equipped with a 590 grooves / mm grating with a 1.2 µ blaze angle and an 1180 grooves / mm grating blazed for .6 µ. It also has adjustable input and output slit widths.
The monochromator was calibrated using a Hg pencil lamp covered with a Pyrex test tube to reduce the number of secondaries between 400 and 1700 nm. Secondaries are due to a portion of the light at each wavelength being reflected from the surface of the grating at integer multiples of the fundamental wavelength. That is, a small portion of the radiation emitted from the source at 400 nm is transferred through the monochromator at 800 nm. An even smaller portion of the 400 nm radiation is transferred through the monochromator at 1200 nm (this is a tertiary). Covering the Hg lamp with Pyrex, the optical bandpass of which increases rapidly after 360 nm to reach 90% at 400 nm, reduces the effects of the strong 254 and 360 nm ultra-violet Hg lines.

The wavelength drives were calibrated to ±1 nm over the wavelength range of interest. This required the alignment of both gratings for maximum transfer efficiency (see Appendix B).

The monochromator was fitted with 2 mm slits at input and output to couple the maximum amount of radiation from the source to the device under test for spectral testing. The bandpass of the monochromator (caused by linear dispersion from the grating) at 2 mm slit setting is 13.2 nm for the 590 grating and 6.6 nm for the 1180 grating. (Due to spatial dispersion in the beam from the monochromator, the actual spectral bandpass coupled into the multimode fiber is judged to be less than what is reported above.)

The output lens (lens 2) captured the monochromators output and collimated the radiation. The NA of the lens is matched to the monochromator. The final element, lens 3, in the spectral measurement equipment is a focussing lens chosen to match the NA of the 50 µ core multimode fiber used (nominal NA = .2) to transfer the radiation of the test station.

The multimode fiber connectorized with a ST connection, is attached to an adapter plate which is attached to a 3 axis micrometer adjustable stage on a magnetic base. (This
adapter plate was custom designed and built in the Tek Labs model shop.) The stage is used to maximize the radiation coupled from the monochromator output through the optical fiber to the device under test.

The HP 8152A optical average power meter is used to measure optical power at the fiber output as a function of wavelength. The power meter has the ability to accept two heads simultaneously. The heads have been factory calibrated on channel A to be within ± 4% typical. The power meter is capable of comparing the user set wavelength setting to an internal curve for more accurate optical power measurements. The optical power meters heads were allowed to stabilize (with screw on dark covers in place) for a minimum of 30 minutes. Each scan head is electronically zeroed in this condition prior to beginning measurements.

During the calibration sequence the wavelength setting was set to the monochromator wavelength setting. Only heads attached to channel A were used to measure optical power. Channel B is used to maintain power and thus cooling to the inactive detector to maintain stability and measurement accuracy.

The power is measured at the fiber-chuck output on the device testing stage using an HP 81520A cooled silicon PIN photodiode for the wavelength region from 400 - 1020 nm. The HP 81521B cooled germanium PIN photodiode is used from 900 - 1700 nm. The fiber end was stripped and cleaved close to normal. Both sensor photodiodes have a 5 mm diameter which allows easy fiber to detector alignment. (Detector uniformity is assumed.) A graph of the power coupled to the device under test (D.U.T.) is shown following.

The relative position of the fiber is adjusted using the Microflex 65P x, y piezoelectric stage and integral mechanical lead screws. This stage is coarsely adjusted with these mechanical leadscrews that allow 3 mm of travel in each axis. The z-axis micrometer
built into the fiber holder is used to lower the fiber to the device. An angled zoom micro-
scope, model ZMM-45B from Titan Tool, is used to monitor fiber position for initial
rough alignment. This microscope is equipped with a 45 degree angle eye tube and 20 X
objective and allows a 1 to 4 zoom ratio while maintaining a 2.276" working distance.

Fine alignment is accomplished with the piezo controlled stage. The position is
monitored using the attached Ono Sokki digital micrometers. These micrometers are
used to assure that the relative position of the fiber has not moved during the course of
the test.

The Keithley 236 Source Measurement Unit is used to reverse bias and measure the
current generated by the device when illuminated and unilluminated. An opaque card is
alternately removed and returned to its position at the monochromator exit for the illumi-
nated and dark measurements.

The system was designed and built in three modules. Module 1 includes the Model
780 source with its integral lens assembly, the spatial filter, the focusing lens for the
monochromator and the monochromator. Module 2 includes the collimating and focusing
lens and the 3-axis mechanical positioner for the fiber input. Module 3 includes the
optical fiber and associated positioning hardware at the device test stage.

The optical alignment of the entire system was done using a 633 nm HeNe laser.
Figure 7 following shows the described optical elements and the path of the optical beam
through the monochromator.

**Optical Elements.** The optical elements used in the spectral scans are devoted
solely to maximizing the power at the output. They simultaneously work to maintain a
narrow spectral bandwidth.

The output beam of the source needs to be collimated as much as possible to image
the filament on the entrance slit of the monochromator. This is accomplished by adju-
Figure 7. Spectral testing schematic.
sting the focal length of a gathering collimating lens assembly (depicted as a single lens, 
(lens 1), see Figure 7) of the Newport model 780 source. The same tungsten halogen 
bulb was used for all tests whose results are presented here.

The first lens assembly is followed by a spatial filter to minimize spurious radiation 
at the output of the monochromator. This 22.8 mm spatial filter allows the second lens to 
focus a sharp image of the filament at the 2 mm entrance slit to the monochromator. The 
choice of focal length of lens 2 and the spatial filter is made to match the numerical ap­
erture of the monochromator.

The monochromator is equipped with the capability to change gratings to maximize 
the spectral band pass efficiency. It also has replaceable slits. The 2000 µ or 2 mm slits 
available from the manufacturer were used to maximize optical power throughput. The 
monochromator calibration sequence is found in Appendix C.

The output of the monochromator is gathered by lens 3. This lens is identical to the 
input lens so as to maximize optical power acceptance by matching the numerical ap­
erture of the monochromator output. The lens is simultaneously positioned to maximize 
collimation of the output beam to lens 4.

The final lens, (lens 4), is used to focus as much optical power as possible within 
the acceptance angle of the 50 µ core optical fiber (NA = .2). This is done by the proper 
choice of focal length and lens 4 diameter.

The optical fiber input was connectorized by the author and held rigid by a custom 
fixture attached to a 3-axis micrometer stage with a magnetic base. The output of the 
fiber is a cleaved end held rigidly in a fiber chuck. The fiber chuck is a miniature collet 
with polymer grips to avoid fiber stress and damage. The relative maximum intensity 
position of the fiber input is assured at a mid spectral point by adjusting the 3-axis stage. 
All optical elements listed in Table VII, are then fixed for the duration of the scans.
The optical fiber output has a cleaved end. Both ends of the fiber were examined. Both had smooth, defect free cores with no polishing scratches through the core on the ST connectorized end.

**TABLE VII**

**OPTICAL ELEMENTS : SPECTRAL SCANNING**

<table>
<thead>
<tr>
<th>Optical Element</th>
<th>Type ID</th>
<th>Focal Length f</th>
<th>AR coated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Filter</td>
<td>Tek made</td>
<td>not applicable</td>
<td>not applicable</td>
</tr>
<tr>
<td>Lens 2</td>
<td>achromat LAO-114 Melles Griot</td>
<td>80 mm</td>
<td>no</td>
</tr>
<tr>
<td>Lens 3</td>
<td>achromat LAO-114 Melles Griot</td>
<td>80 mm</td>
<td>no</td>
</tr>
<tr>
<td>Lens 4</td>
<td>achromat PAC-040 Newport</td>
<td>50.8 mm</td>
<td>yes</td>
</tr>
<tr>
<td>Multimode optical fiber</td>
<td>50/125 CPC3 Corning</td>
<td>50 μ core diameter</td>
<td>not applicable</td>
</tr>
</tbody>
</table>

The lenses above were scanned with the Shimadzu UV-3100 Scanning UV-VIS-IR spectrophotometer by the author. On the non-coated lenses, peak transmission was found at 550 nm. Transmission exceeded 95% until 850 nm, and exceeded 90% through 1700 nm. On the coated, lens maximum transmission was at 550 nm with a reduction in transmission to 90% by 850 nm and was less than 80% at 1700 nm.
Source Calibration. The calibration of the optical power available from the source is necessary to determine the responsivity as a function of wavelength. The calibration is done to maximize optical power to the fiber output while maintaining spectral purity. The 2 mm slits on the monochromator correspond to a bandpass of 6.6 nm on the 1180 grating and 13.2 nm on the 590 grating used for longer wavelengths. The actual bandpass is expected to be less than half this amount due to spectral spatial separation in the monochromator translated to the 50 µ core fiber which is acting as a spatial filter at the input. This core diameter is necessary to maximize the intensity transfer from the lamp to the device stage.

Two detectors are used to cover the wavelength regions of interest. The HP 81520A is a cooled silicon PIN photodiode with .1 picowatt (pW) resolution. It has a listed 1% linearity and ± 4% absolute accuracy. Its wavelength range of sensitivity is 400-1020 nm. This detector was used to confirm optical power in the visible and near infrared spectral region. The HP 81521B is a cooled Germanium PIN photodiode with 10 pW resolution. Its linearity is also listed as 1% with a ± 3.5% absolute accuracy. The wavelength range is 900-1700 nm.

During the course of testing it was noted that secondaries from the grating caused a more than 5% increase in the optical power sensed at the output. To minimize spectral error in the response the 830 nm highpass filter was added at the output to the monochromator. This position maximized power transferred while minimizing aberrations in the optical path.

The optical power is measured immediately prior to measuring the spectral responsivity of the photodiodes. The data acquisition includes dark and illuminated responsivity measurements. These measurements are taken in a completely darkened room. For device C6 the measurement time from 600 nm - 1760 nm in 20 nm steps was 50 minutes.
Once the diode response to dark and light has been recorded a detector was repositioned at the output to reconfirm the spectral output power. The confirmation of data points took an additional 10 minutes. The power reproduced the calibration curve to ± .1 nW for the test results displayed. This reproduction of the calibration curve is done at 10-15 data points.

The procedure used sets the monochromator wavelength drive and optical power meter to the same wavelength. The detector then is moved toward the stationary optical fiber output and it is halted when a mid spectral data point is reproduced. This procedure may induce error due to variation in calibrated detector position, angle and relative position of the fiber output to the detector. This procedure is considered justified however by the stated stability of the 780 source and the observation that at 1080 nm the output power remained steady ± .1 nW for greater than an hour.

The spectral output power curve used for the spectral responsivity measurement of device C6 is shown in Figure 8. This curve is measured at the device test stage. The grating and the detectors used as well as the spectral position of the highpass filter addition are noted.

Probe Station Assemblies. The probe station has been designed to accommodate an optics column or a fiber chucked fiber. For spectral testing a fiber chuck is employed to hold the optical fiber. A fiber chuck is a miniature collet specifically designed to hold firmly and evenly without damaging the fiber.

The fiber itself is cleaved with a G.T.E. precision fiber cleaving tool with diamond cutter. The cleave is examined microscopically using a Panasonic 100 x, illuminated fiber examination tool to assure that it is normal or nearly normal at the fiber core and that no cleave damage of the fiber core occurred.
The fiber is positioned in the chuck to exit as close to normal to the fiber chuck as possible. The fiber is then fitted into a specially designed fixture that is attached to the piezoelectric stage which holds the fiber chuck normal relative to the stage base. The stage base and device test stage were compared with a bubble level to assure they were parallel planes.

The core diameter of the multimode fiber used is 50 microns nominal with an NA of .2. This corresponds to an exit defocussing angle of approximately eleven degrees.

Since the fiber cleaved end can be near but not contact the device top surface, even the largest 52 \( \mu \) diameter diode was over filled. This overfilling was the basis for an

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**Figure 8.** Spectral power to device.
attempt to judge the off contact distance for purposes of correcting the optical power coupled to the device. These calculations required many assumptions and, when completed, lacked credibility and were discarded.

**Electrical Measurements.** Electrical measurements to determine spectral response were taken using the Keithley 236 source measurement unit (SMU) run under the control of a LabVIEW VI (virtual instrument, a computer program simulating the control panel of the instrument) "Keithley 236-2". This program allows a preset initial and end bias voltage (always zero volts) with two independent bias voltages during which measurements are made.

The Keithley 236 SMU performs two functions acting as a precision voltage source and current sense in this application. This voltage source reverse biases the photodiode, which has been shown previously to be a two terminal device. The control of the instrument is through the IEEE-488 interface bus. The SMU has sub-nanoamp sensitivity.

Two bias voltages were chosen to compare what was expected to be a partial depletion condition at the low applied bias (-1 V) and a fully depleted intrinsic region at the high applied reverse bias (-10 V).

Immediately after photo response measurements were taken, the light path was blocked and a dark current measurement was taken. This dark measurement, when subtracted from the photo response measurement, assures that spurious light in the room was taken into account when calculating the spectral response.

The electrical probes' mechanical bases were built in the Tektronix Laboratory model shop. The electrical contact probes were made from tungsten and assembled to the bases by the author. The probes need to make consistent low resistance contact without damaging the devices or their packaging. Additionally, the angle of entrance to the device needed to be kept shallow to avoid interfering with the scanning head movement.
Furthermore, the angle of approach was chosen to assure no direct restriction of light to the device and far enough away to eliminate the possibility of reflection from the probe to the device. The probe sharpening and forming procedure is detailed in Appendix A.

**Spatial Response and O.E.**

**Principle of Operation Overview.** The spatial response and quantum efficiency is measured by scanning a diffraction limited, monochromatic spot of light across the surface of very small PIN photodiodes. In order to determine the spatial response, the spatial position must be known, the electrical source and sense measurement taken must be precise, the optical power incident on the device must be of known intensity and wavelength and the intensity must be stable. Additionally the noise sources, both photonic and electrical, should be kept low to avoid measurement error.

The size of the diodes required that diffraction limited spots of light be used as the optical probe. To accomplish this feat monochromatic single mode radiation needed to be used. Single mode radiation allows the use of simple lens systems to be used to maximize collimation and thus focussing.

The radiation was transferred from the diode laser to the device under test using singlemode optical fiber. The singlemode optical fiber acts as a spatial filter at the input and adds the necessary degrees of freedom in the mechanical movement. The output end of the fiber was positioned precisely in the final optics column.

This column contained two achromatic lenses one for collimating the beam, the other for focussing the output radiation. As previously explained, the lenses were chosen to maximize optical power coupling between the fiber and the lens. The final lens was chosen to minimize the spot size while allowing an adequate working distance to make electrical contact.
The relative position of the optical fiber output in the final optics column determines the degree of collimation gained by the first collimating lens. Good collimation allows a nearly diffraction limited spot to be produced. Particular care was taken to position the fiber relative to the lens so as to minimize the spot size. Some minor loss of available power resulted from this minimization. This spot size was measured at each laser wavelength used for scanning with the same fiber and lens used for the actual scan. The actual values obtained can be found tabularized in the following section.

This near diffraction limited spot is then used to scan the diode. The position is noted, and measurements are taken. The output beam is moved again, the position is noted and measurements are taken. The information for each step is recorded along with a header indicating test initiation and conclusion time, device identification, laser wavelength, and intensity and the test date on a magnetic disk.

The complete test sequence is given in Appendix D. The fundamental testing procedure is outlined here.

Initially the laser is turned on and allowed to stabilize. The optical power is measured with the HP 8152 A optical power meter and an appropriate photodetector. The power output is adjusted for stable operation at a convenient power level (say 100 µW). The laser is temporarily turned off. The diode is placed on the test stage under the final optics column and electrical contacts are made. The IV curve of the device is taken to assure a "live" device is to be tested. The laser is turned back on and the optics train is moved into position closer to the diode using the Z axis. The room lights are turned off. The Keithley 236 SMU is placed in manual mode and a reverse bias is applied to the diode. The mechanical controls on the piezoelectric stage are adjusted to maximize response indicated on the SMU.
When a response is noted the z-axis is adjusted downward to approach a minimum spot size. Initially an increase in responsivity is noted since this increases the optical power density at the photodiode surface. Thus more optical power is coupled into the diode. This occurs until the spot size diameter is smaller than the diode diameter. At this point positioning becomes critical as the apparent response of the photodiode is reduced if the focusing beam is not centered on the device. This is due to reducing the beam radius and thereby, if not precisely aligned, reducing the intensity directly on the diode.

The position of maximum response is noted along with the relative height for future reference. Since the piezoelectric stage does not drive linearly in both the forward and reverse directions careful notations of the mechanical position must be made when an area of greater than fifty percent of the anticipated responsivity is achieved. This responsivity has been previously determined by spectral scanning.

When the beam diameter approaches the device dimensions, the piezoelectric drivers must be used to move small distances to maximize response. The x and y positions of highest responsivity are noted by reading the micrometer gauges. The piezoelectric control voltages are now returned to their lowest setting. Then the mechanical controls on the stage are utilized to position the beam away from the device to be tested approximately 50 µ along each axis. This is necessary due to the inability of the piezoelectric stage to return to its initial starting point under program control. Now the automated test program can begin.

Once the test has been completed, the data is examined using DeltaGraph, a 3D plotting package. The stage response is noted. Since the stage does not return to its previous zero point the expected 100 µ x 100 µ scan area is reduced to 50 - 70 µ x 120 µ. The relative z-height of the final optics column is changed by ≤ .0002 " and the stage repositioned mechanically to assure that the full diode will be tested. At this point the
laser monitor current or voltage is recorded to assure stability and the test is reinitiated. This sequence is repeated until peak responsivity has been achieved and responsivity begins to drop.

It should be noted that using mechanical probes to make device contact requires the careful control of room vibration. For this reason testing was done during the late evening and early morning hours.

Additionally the mechanical probes must have a low profile and an angle of entrance into the scanned field that minimizes the obstruction of the scan field. This limits or eliminates reflection from the probe to the device surface.

The Keithley 236 is programmed to average 32 measurements at each data point location. The device response has been stated to be so rapid that it is not a test consideration. A schematic of the testing apparatus can be found in Figure 9 following.

The stability of response on device A3 was repeatedly confirmed by moving the optics to device center (peak response) and monitoring the output with the SMU in manual mode. Maximum variation noted was typically less than ± .5% of the peak response. This test was performed using the same sense range (usually µA) and 32 measurements averaging used during test data acquisition.

**Optical Elements.** The optical elements used in spatial scanning are the fibers, the lasers and the lenses in module 3. The single mode fibers used act as spatial filters as well as single mode retainers. This assures that relatively simple lenses can be used to produce the diffraction limited spots used to scan the devices.

The laser sources listed below in Table VIII are powered by two separate means. The ST connectorized diode lasers were powered by the ILX Lightwave Ultra Low Noise Current Source, model LDX 3620. The Tektronix packaged lasers were powered by the Tek model LDC-600, power and thermoelectric cooler supply.
Figure 9. Spatial testing schematic.
### TABLE VIII
**OPTICAL SOURCES: SPATIAL SCANNING**

<table>
<thead>
<tr>
<th>Device</th>
<th>Laser Wavelength</th>
<th>Power Source</th>
<th>Optical Power Thru Module 3</th>
<th>Minimum Spot Size Measured</th>
<th>B - A Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laser Mode</td>
<td></td>
<td></td>
<td>SMF</td>
<td>Connector Type</td>
</tr>
<tr>
<td>A3</td>
<td>670 nm SM</td>
<td>ILX 3620</td>
<td>109 µW</td>
<td>4.8 - 5.8 µ</td>
<td>1.178 ST</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SMF 630</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>780 nm MM</td>
<td>ILX 3620</td>
<td>100.5 µW</td>
<td>5.4 - 5.9 µ</td>
<td>1.175' ST</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>850 SMF</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>849 nm MM</td>
<td>ILX 3620</td>
<td>45.0 µW</td>
<td>5.4 - 5.6 µ</td>
<td>.787 ST</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>850 SMF</td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>848 nm SM</td>
<td>ILX 3620</td>
<td>212 µW</td>
<td>4.8 - 5.2 µ</td>
<td>.956 ST</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>850 SMF</td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>1300 nm SM</td>
<td>Tek LDC-600</td>
<td>101 µW</td>
<td>8.6 - 9.4 µ</td>
<td>.7568 Fiberchuck</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SMF-28</td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>1550 nm SM</td>
<td>Tek LDC-600</td>
<td>1100 µW</td>
<td>6.6 - 7.4 µ</td>
<td>.684 FC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SMF-28</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>1300 nm SM</td>
<td>Tek LDC-600</td>
<td>103 µW</td>
<td>8.6 - 9.4 µ</td>
<td>.7568 Fiberchuck</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SMF-28</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>1550 nm SM</td>
<td>Tek LDC-600</td>
<td>1095 µW</td>
<td>7.4 - 7.8</td>
<td>.678 FC</td>
</tr>
</tbody>
</table>
The optical power coupled through module 3 is the optical power used for the calculation of the spatial quantum efficiency. The power levels are based on curves generated for each laser with the optical fiber and lenses used in the actual testing of the device before testing begins. The monitor voltage which is a measurement of the current to the laser, is measured over a wide range. Additionally when all testing is completed on a device at a particular wavelength the optical power coupled to the device stage and the monitor reading for that optical power are recorded. The monitor reading for each test is recorded as testing begins and is retained in the data header.

The minimum spot size measurement listed has been measured at the given B - A distance, and using the connectorized fiber listed adjacent (see Figure 10). This brass to aluminum (B - A) distance is a measure of the relative position of the single mode fiber used for spatial testing, at which the minimum spot size was achieved. Variation in the B - A distance, determined during spot size minimization, is due to differing thicknesses of the custom Delrin inserts which hold each connector type.

The spot size measurements for the 670, 780, and 848 nm lasers were measured using a DataScan scanning slit spot size measurement unit. The modal filtering of the singlemode fibers, when wrapped around a 3 inch diameter cylinder, eliminated all spurious modes and coma at the spot size measurement stage for the multimode lasers listed in Table VIII.

The spot sizes for the 1300 and 1550 nm lasers were measured with the Photon Inc. BeamScan II. This spot size measurement tool uses a rotating drum 1µ slit and germanium detector. The spot sizes show a greater than 82% gaussian fit in all cases. As mentioned previously, the BeamScan gave an 848 nm minimum spot of 9.0 ± .5 µ, (at the same B - A distance) which is nearly twice the result of the DataScan. Both instruments were operated in automatic mode.
The optics used in the module 3 are listed in Table IX. Lens 1 is the collimating lens in the final optics column of module 3. It is used to match the apparent numerical
aperture of the output of the optical fiber. Lens 2 is the final focusing element. This lens was chosen to minimize the spot size (a demagnification of approximately 2 times) while maintaining a long working distance. A long working distance is needed to make electrical contact without interfering with the scanning lens assembly. The AlGaAs devices were tested in wafer form.

Source Calibration. Optical power to the device surface was measured using the HP 8152A optical power meter corrected for wavelength. Each source was activated and monitored for 16 to 24 hours to ensure that the monitor voltage and optical power coupled through the final lenses was stable. The monitor voltage is a measure of the current
through the laser diode across a series resistor. Examples of the monitor voltage versus light output curves can be found following. The stability of lasers of both classes can be found in Appendix B.

The data used to generate the curves in Figure 11 are from the two Tektronix lasers used during spatial scanning. The lasers are turned on and stabilized at constant current. Data is then taken with a 2 minute settling period between the changes in current and the optical power reading being recorded. The slight curve evident in Figure 11 is due to stabilizing at the 100 µW optical power levels displayed and stepping up in values for the first data points recorded. After reaching 130 µW, the subsequent readings were taken going in the downward direction from the 100 µW level.

The optical power versus monitor voltage curves was taken on all lasers used for spatial scanning. This data was used to more accurately predict laser energy coupled to the device under test. This information was used during testing to calculate the peak quantum efficiency measured without removing the device from the stage. This was done to assure that results obtained were credible without delaying testing. Lifting the probes and withdrawing the stage is necessary to accurately position the HP 8152A optical heads used to measure the optical power.

The optical power used to calculate the Q.E. results was reconfirmed at the specified monitor voltage after all testing at a given wavelength was completed. The monitor voltage at the initiation of testing is recorded with each scans data set.

The key issues in source calibration are optical power and stability as well as minimum spot size. The minimum spot size is a function of the position of the fiber optic input to the collimating lens in module 3 and the relative position of the spot measurement tool to the final lens. Minimum spot sizes measured for each laser used in spatial scanning are listed in Table VIII.
Optical Power Coupled to Device
TEK LDM 1301 s/n 64, 1300 nm

Optical Power Coupled to Device
TEK LDM 1551 s/n 1104, 1550 nm

Figure 11. Optical power coupled to device stage.
Spot Size Measurement. Spot size measurement was done to confirm optics alignment and that the design did produce nearly diffraction limited spots. The position of the optical fiber output into the first lens of the final optics telescope needed to be set and confirmed to accomplish this task.

The optical fiber output is a cleaved fiber or the polished exit surface of an connectorized single mode fiber. This connectorization was done by the author. First, a brass, male threaded, hollow bolt with 64 threads per inch is fitted over the fiber. This piece exactly mates to the optics column threads. The diameter of the optical column was chosen to conveniently install the collimating achromatic telescope (lens 1) from the top. The focussing achromat is installed from below. Brass is used against the aluminum column threads to avoid aluminum to aluminum cold welding. Sixty-four threads per inch corresponds to $1.1 \mu$ per degree of rotation. It was chosen to allow easier threading of the pieces to one another. Additionally, it is more durable than finer threads (i.e. less prone to dirt or dust induced galling.)

Second, a Teflon washer is put over the circular barrel of the connector. The washer has sufficient clearance to assure free rotation. This washer was found necessary to avoid twisting the securely held fiber during the threading of the hollow bolt into the optics column.

Thirdly, the thin tubular section of the fiberchuck, FC, or ST connector is inserted in a Delrin guide fixture. Individual Delrin guides were machined for each connector type. These fixtures clamp and hold the connector centered in the aluminum optics column. The center hole (which holds the connector) is slightly oversized (.002") and off center toward the set screw inlet. This assures that the thin tubular section of the FC and ST connectors are held rigidly, normal, and on center within the optics column.
Fourth, a spring is inserted into the column. This spring sits on an aluminum ridge above and surrounding the first lens. The spring's purpose is to force the Delrin connector holder up away from the lens. Its fully compressed length is such that the fiber cannot come into physical contact with the first collimating lens.

Now the hollow brass bolt can be threaded into the optics column. A knurled ring at the top of the brass bolt gives precise mechanical control of the threading. The smooth under surface of the curled ring gives a convenient surface to measure and record the depth of the fiber in the optics column. This distance from underneath the brass ring to the top of the aluminum optics column for each fiber is listed as B to A distance in Table VIII.

In the visible region of the spectrum, a scanning slit instrument based on a silicon photodiode is used. This instrument, made by DataScan, displays a two dimensional representation of the scanned beam with a gaussian overlay and a percentage of fit. Minimum spots recorded at 670, 780 and 848 nm where 5.5 µ, 5.4 µ, 5.65 µ respectively with greater than 90% fit.

In the infrared region of the spectrum a barrel type, rotating slit head backed by a germanium detector was used. This instrument the Photon Inc. BeamScan II was supplied for evaluation purposes. The minimum spots achieved at 1300 and 1500 µ were 8.6 - 9.0 µ and 7.4 - 7.8 µ with greater than 85% fit.

These fit percentages are relative to a Gaussian overlay. This overlay has its roots in the mode field diameter. For Gaussian power distributions, the mode field diameter is defined as the 1 / e² value (or 13.5 %) of the peak intensity of light at the near field. The fit percentage appears to be a measure of the difference between the Gaussian overlay and the measured intensity as a function of position. The spot size provided by the instrument is the actual 1 / e² beam width.
The minimum spot measured by the Photon Instruments BeamScan at 848 nm was 9.0±.5 µ under the same conditions that the DataScan measured 5.4 - 5.6 µ. Since spatial testing in the visible had already been accomplished indicating the spot size at peak responsivity was as small or smaller than that indicated by the DataScan, the Photon Instruments spot sizes were considered to be in error.

The spatial testing defined the spot size based on the responsivity versus area map for a known physical dimensioned diode. If the responsivity of the diode has a sharp cutoff at the device edge, (as expected), the responsivity map should show nearly zero response at the width of twice the spot size plus the device diameter. The devices metallization were measured using a microscope, an optical filar, and a stage micrometer. The mesa diameters were determined from scanning electron photomicrographs of adjacent die mesas on the same tile. Device C6 has a diameter of 26 µ and C5 has a diameter of 17 µ. Device A3 has a diameter of 52 µ. This information coupled with the spatial maps implies that the 1300 nm and 1550 nm spot sizes are ≤ 5 µ or that the devices have little responsivity at the mesa edge. Note that this estimate is very near the diffraction limit for the radiation wavelengths used to test these devices.

Electrical Instrumentation. The heart of the measurement system is the Keithley 236 Source Measurement Unit (SMU). The SMU is a fully programmable instrument capable of sourcing and measuring voltage or current simultaneously. The SMU used in this work will source a bipolar voltage from 100 µ V to 110 V and current from 10 femptoamps (fA) to 100 mA. It also has a current sensitivity of 10 fA. It has programmable delay and user selectable filtering which takes a number of measurements, then calculates and averages and outputs the average. This work used the instrument in auto range with filtering to enhance measurement accuracy. Specifications for the SMU claim a response to IEEE-488 command (a minimum source, delay, measurement cycle) of 25 ms. Actual
times for the source and measure sequence used in this test were greater than 1 second.

The National Instruments company manufactures computer cards that fit in slots of the Macintosh series of personal computers. The NB-MIO-16 is a multi-function analog, digital and timing input/output computer card that is the backbone of the piezoelectric positioning system. This card contains two analog channels that are configured unipolar for zero to 10 volt output. The voltages are requested digitally and converted by 12 bit digital to analog converters with 2.44 mV resolution.

Connections from the NB-MIO-16 card were made to an external box where coaxial female connectors were mounted. Coaxial cable is used to supply step voltages to the Photon Controls MDA 500-3 piezoelectric control box.

This box converts analog steps of zero to plus five volts into appropriate supply voltage levels (0 - ±150 V) to allow a 100 µ travel in both axes. The MDA 500-3 is specially designed to drive the capacitive loads of its piezoelectric device stages. These supply voltages are output from the converter box smb connectors to the smb connectors on the Microflex 65p integral x, y piezo stage. This stage, as previously described, is designed to have 100 microns movement by piezo in the x and y directions (with z being vertical). Additionally, the stage has 3 mm of x and y travel with manually adjustable lead screws. This stage is reported to have 40 nm resolution when used with the MDA drivers.

The Ono Sokki gauges are read by an RS-232 communication box, the BH-100. This box is capable of sending and receiving from the computer, commands used to set-up the gauges and to ship data. This includes requesting specific data format, polling the gauges in a specific order and setting the gauges to zero.

An effort was made to locate the source of transients that frequently destroyed devices while on the testing stage. Testing was performed using a Tek 2440 (500 MHz)
digital storage oscilloscope. Signals were sensed at the probe station probes which were connected to the Keithley 236 SMU (serial # 491588). Output low on the back of the SMU was attached to the scope ground. Output high on the SMU was attached to the 2440 source. The scope was plugged into a separate power source to reduce the effect of ground loops. The scope was placed in single event transient capture mode and measurements were taken.

The following observations were made. When the SMU was turned from off to on a 100 ns, 2.8 V (-1.4 V to + 1.4 V) multiple pulse transient was recorded. When the SMU is on and in standby and its power fails, a single 1.7 V 100 ns pulse is captured. These were considered to be predictable results in amplitude but not in speed. Additional testing was done using the same sense attachments described above. The SMU is on, in local and standby and connected to the Macintosh II by the GPIB cable. The SMU and Macintosh were powered from different plugs on the same circuit. When the Mac II is powered up a 1.7 V 250 ns pulse was recorded. This test was repeated to assure its accuracy.

An additional result was noted when the relative humidity had dropped to below 30%. The TEK 2440 was attached to the two probes at the probe station. The probes by coax to the coax to triax conversion box and the conversion box by triax to the Keithley SMU. Static charge apparently builds up on the ungrounded metal furniture in the room. When these different potential items came into contact significant transients were recorded. The premier transient, a 37 V, 21 ns pulse (-14 to +23 V) was recorded when two adjacent metal chairs touched.

The significance of this result is that all of the above recorded transients are sufficient to destroy the smaller (and thus less robust) InGaAs / InP PIN photodiodes.
Several unsuccessful attempts were made to correct this problem by adding LC circuits to the measurement circuit. Tests were conducted simulating device electrical characteristics using a 1 pf capacitor between the probe tip and the device stage. The resulting analysis indicated that the primary source of the transients was within the Keithley 236 SMU and not due to the coax from the probes to the conversion box nor from the conversion box by triax to the SMU rear connections.

This problem was resolved and avoided by wrapping the exposed metal surfaces of lab furniture with clear plastic tape and implementing static guarding procedures in the vicinity of the probe station. This included verifying an earth ground in the lab. Upon entering the lab (and frequently during testing) otherwise floating potential metal items in the Optics Lab were grounded. The isolation and identification of this problem was the single most time consuming problem solved to allow the successful testing on InGaAs / InP PIN devices once the apparatus was built and tested.

The RS-232 connection is made by custom cable from the Mac II modem port, (an 8 pin output) to the BH-100 (a 25 pin input). The Mac serial port uses RS-422 format, which is reported to be better for longer distance data transmission. To convert to RS-232 the transfer data plus (TXD+) and the receive data plus (RXD+) were grounded. The transfer data minus (TXD−) was used to send data (zero instructions) to the gauges. The receive data minus (RXD−) was used to receive position data from the gauges.

**Piezoelectric / Mechanical Positioning.** The piezoelectric / mechanical positioning system is a Photon Controls Microflex 65p x, y stage. This stage has mechanical lead screws that give it a full 3x3 mm travel in the x, y plane. It also has a piezoelectric device amplified by a flexure leaf spring assembly. The piezoelectric positioner is actuated with a Photon controls MDA controller. This controller translates 0 - 5.5 V drive voltage from the computer to appropriate drive voltages for the piezoelectric stage.
The piezo stage was tested unloaded using a LabVIEW VI and National Instruments boards. The system was carefully studied to assure that the appropriate signal voltages were being transmitted to the device controller.

The stage which claims to have a load capacity of 1 kg, was outfitted with two machinists micrometer gauges to minimize stage loading. A LabVIEW program was designed to step the stage from 0 - 100 µ (or max travel) in the x direction in 10 µ steps while holding the y axis at 0 µ. The stage, after reaching its maximum travel, was asked to return to zero. The y axis was now asked to take a single 10 µ step. This sequence repeats until the y axis reaches its maximum travel (100 µ). This is stepping scheme 1. The results were disappointing. No detectable movement in either axis was noted until the third step in the x direction. The x axis claimed a new minimum (zero) position at ≈ 30% of maximum travel upon return to zero. This eventually yielded 70 by 120 µ of available stage travel. It was noted that the travel in both axes was not orthogonal to the adjacent axis.

It was also noted during the initial evaluation that the full travel position of the lead screws in the stage caused a rotation in the top surface to which the optics column was attached. A similar occurrence resulted from withdrawing the lead screw to minimum travel. Together these operations resulted in slightly less than three millimeters of practical stage travel without rotation.

This information was forwarded to the manufacturer and a new stage was provided, at no cost, as a replacement. Upon testing it had the same axial non-orthogonality and non-return to zero phenomena. Due to constraints on cost and time, the work continued without resolving this issue.

Several stepping programs were developed to increase the speed of test and to reduce the effect of the non-return to zero phenomena. It was found that the available
field of travel was stepped most uniformly with this stepping procedure. All test data presented in this thesis were taken with stepping scheme 1. (The actual step size requested was reduced from 10 µ to < 5µ for all results tested here.)

The position of the optics column relative to the device under test changes from test to test due to the grease plate on which the devices are tested. This grease plate does allow quick adjustment of position, but changes its relative height slightly with insertion and withdrawal. No movement during testing was noted.

Positional measurements needed to be established to quantify the spatial position of the device under test. The resolution requirement of 1 µ with an ability to transmit the position by RS-232 was combined in spindle type micrometer gauges from Ono Sokki. The model EG-925, (acquired from the Tektronix model shop) has dual readout capability at .001 mm and .0001 inch. A model DG-225 with metric readout was purchased for this work.

The two gauges were evaluated to determine the force necessary to depress the spindle on each gauge. The pressure required to initiate spindle movement was notably greater on the DG-225. This subjective test was quantified using a controlled pressure versus distance test in the Dynamics Laboratory in the Test and Measurement Group at Tektronix. The information provided by them was forwarded to the manufacturer and a new DG-225 gauge was shipped as a replacement. This new gauge was tested and the information used to establish the equal forces on both axes of the stage. This reduced off axis force inequities in an attempt to maximize linearity and distance moved on the stage.

The two Ono Sokki micrometer gauges were positioned to oppose one another on a micrometer positioned aluminum plate. The micrometer was positioned mid-travel. Both gauges were zeroed. It was found that the two gauges tracked one another to within 1 µ for ± 500 µ of traverse backward and forward. (It was difficult to align the
gauges completely normal to one another. Differences outside this ±500 µ window were considered to be due to relative positioning errors.) It was within this equal force linear tracking window that the micrometers were attempted to be positioned for each scan.

SOFTWARE

In order to integrate the multiple gauges and instruments to act as a single system, several choices needed to be made. The development platform was mandated to be an Apple Macintosh II. This platform was equipped with software and hardware from National Instruments Corp. This software, LabVIEW, promised the ability to integrate analog, digital, RS-232 and IEEE-488 busses into a single functional block for real time data acquisition using the National Instruments Real Time System Integration (RTSI) bus.

Additionally, a spreadsheet graphics utility from Delta Point Software, DeltaGraph was used. This software allowed rapid visualization (in graphical form on the computer screen) of data immediately after the device scans were completed. This information was used for confirmation and documentation of stage travel restrictions and to properly judge the starting position of the next scan.

The software developed for use in taking the measurements for the spectral and spatial responsivity was written in the icon based programming language LabVIEW. LabVIEW is an acronym for Laboratory Virtual Instrument Engineering Workbench. This software allowed the interfacing of divergent command and control sequences of operation on 3 different data busses to be integrated, controlled, and monitored by one Virtual Instrument (VI) on the computer. The software is based on the data flow diagramming technique.
A data flow diagram is a graphic representation of a system in which processes performed on data (sourcing, manipulation or storing) are shown as nodes. The logical flow of data is along pipes connecting nodes. Data then flows from node to node, regardless of the location of one node relative to another. Loops which are not an inherent attribute of data flow programming are available as separate expandable icons during programming. Additionally temporal sequences are available by using additional "movie frames" which overlay one another on the computer screen. All controls that need to be changed for each initiation of the program are set on the control panel.

The attached hierarchical view is of the VI "Faster Spatial Data". This view displays the computer programs developed during the course of this thesis to perform spatial scanning. Several of the sub-VI’s contained in this view are explained below.

"Digital Gauge Reading" is a virtual instrument (a sub-VI of "Faster Spatial Data") that zero’s the digital gauges when first initiated over the RS-232 C data bus. Thereafter it reads the Ono Sokki micrometer gauges when polled. This data is supplied to the data matrix along with electrical measurements taken by the VI "Keithley 236 2 DC".

"D.U.T. Stepper back fast" is a controller of the Photon Controls piezoelectric stage. Its key attribute is the order in which it addresses each axis so as to follow a comb like pattern. It initially leaves the y axis at 0 and steps in the x direction from 0 to the maximum of travel. It then returns the x axis position to its nominal zero and steps the y axis one step. This is continued until the y axis has taken all programmed steps. (This has previously been described as stepping scheme 1.)

"Keithley 236 2 DC" is again a virtual instrument controlling the Keithley 236 SMU over the IEEE-488 interface bus. It sets up the instrument, establishing the measurement range and compliance, two sourcing voltages, and a steady state between measurements (zero volts). It alternately supplies the first bias voltage, takes 32 readings
and averages them. The instrument then returns to steady state. This process is repeated for the second bias voltage. It then returns to steady state and sends the average values over the IEEE-488 bus to the host computer (FIFO).

The "Global set up Boolean" VI is depicted as a switch. It is used to determine if "Keithley 236 DC 2" needs to be set up (programmed for bias voltages and filtering). This saves time and internal switching wear. It has a Boolean output response with true representing that the instrument does not need to be re-setup.

"Global End Boolean" determines if all requested steps have been taken. If so, it informs "DUT Stepper Back Fast", this allows a rapid return to nominal zero. "Global Pause Boolean" is an internal timing tool to avoid bus errors caused by simultaneous talking by instruments and the computer.

The icon with dollar signs and arrows is the "Simple String Mathematics" VI. Its purpose is to accept two strings as input. The indicated mathematical function is performed on the parsed strings. It returns the result in string form.

"Piezo Stage Driver", "Piezo Drive Single" and "Piezo Drive Single Test" are sub-VI's used to control the piezoelectric stage. Together they elicit the correct response from "D.U.T. Stepper Backfast".

"Step Me True" calculates bias voltage steps to be taken by the piezoelectric stage. These stage steps are initiated within the program on command by applying an analog voltage between 0 and 5V.

"Analog Out" is a VI that initiates the changes in voltage mandated by "Step Me True". These analog voltage level shifts are established using the National Instruments NB-MIO-16L Input / Output card.
Figure 12 following, shows the interrelationship of the aforementioned VI's through the use of connecting lines. The vertical height relative to "Faster Spatial Data", (at the top of the Figure), indicates the level of the VI at which it is called, rather than complexity.

Because of space limitations in the bound thesis, the software developed is not published here. Interested parties can make arrangements to receive a copy of the software until June 2002 by contacting the Portland State University, Electrical Engineering Department at the address below. The software as stored will require a copy of LabVIEW 2.0 (or presumably higher assuming downward compatibility) and an 800 K, 3.5 inch diskette drive to be retrieved. It will require 3 diskettes to receive all of the software developed in the course of this work.

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CHAPTER IV

RESULTS

SPECTRAL RESULTS AND DISCUSSION

The following graphs show the as-measured and normalized spectral quantum efficiency of an AlGaAs/GaAs PIN (A3) and InGaAs/InP PIN (C6). The responsivity of the devices was measured using the procedure outlined under Experimental: Spectral Response and Quantum Efficiency.

The normalized responsivity was attempted due to inaccuracies noted (due to the transferred radiation overfilling the diodes) during spectral testing. This overfilling caused an obvious reduction in responsivity which is converted to a reduction in quantum efficiency through calculation. Initial attempts to normalize the curves demonstrated that a mid-spectral data point needed to be taken. This was due to minor variations at shorter wavelengths being magnified by the slope of the responsivity curve.

The wavelengths chosen for normalization are 780 nm and 1300 nm for devices A3 and C6 respectively. The normalization is accomplished using the peak Q.E. (measured spatially) at the designated wavelength observed on both devices. This peak, at 780 nm, on device A3 is near the average for the full device surface. (No significant variation across the device surface was noted.) The peak on device C6 is taken from the center of the device where the top surface contact ring causes the least reduction in beam energy transfer for radiation at 1300 nm. These wavelengths are in regions of the spectrum where reduced change in device responsivity (reduced responsivity slope) is noted on the as measured responsivity spectrum.
The as measured quantum efficiency of device A3 at two bias voltages is shown in Figure 13. The general increase in responsivity that causes the Q.E. curve to stay steady or increase slightly with wavelength is due to the increasing penetration depth and high absorption at longer wavelengths for GaAs.

The A3 normalized quantum efficiency (Figure 14) is found to be somewhat lower than other published results of this device type [8]. In some respects this should be expected as the devices tested are intermediate in the process development. Also device A3 has no AR coat. Without surface passivation afforded by the AR coat, surface states, which reduce the EHP collection efficiency, are likely to exist.

The as measured quantum efficiency of device C6 follows in Figure 15. The 50 µ core optical fiber used for spectral scanning produced a beam diameter which overfilled this diode. This over filling changes with wavelength. The normalized curves were produced to counteract this inaccuracy.

The C6 normalized quantum efficiency (Figure 16) is close to the maximum expected for this device type. This may be due to the AR coating being precisely matched for this wavelength. This may alternatively suggest that the normalization factor may in fact be too large. This is possibly due to 1) the slope of the spectral curve at 1300 nm and 2) increased Q.E. due to increased device response using photon recycling. Photon recycling refers here to photon trapping in the intrinsic region due to total internal reflection or EHP generation and radiative emission outside the depletion region. This radiation diffuses to the depletion region where it is absorbed and generates additional free carriers which are immediately separated and detected. This reflection increases acceptance but should broaden the response tails as well. This broadening is not desirable, if it occurs, in high speed PIN devices. Devices from this class were examined and the response characteristics do not support a strong photon recycling effect.
Figure 13. A3 spectral Q.E. as measured.
Figure 14. A3 spectral Q.E. normalized to 780 nm.
InGaAs PIN C6, -10V bias, (as measured)

![Graph showing quantum efficiency vs. wavelength for InGaAs PIN C6 with -10V bias.]

InGaAs PIN C6, -1V bias, (as measured)

![Graph showing quantum efficiency vs. wavelength for InGaAs PIN C6 with -1V bias.]

Figure 15. C6 spectral Q.E. as measured.
Figure 16. C6 spectral Q.E. normalized to 1300 nm.
It may be reasonable to recommend that two points be used to correct the spectral Q.E. curve. This method, if used on the InGaAs devices, would reduce the Q.E. at 1550 and increase the short wavelength Q.E. possibly reducing any error at 850 nm. This procedure has not been attempted on this data.

SPATIAL RESULTS AND DISCUSSION

The spatial results for three devices follows. The spatial scans presented represent the maximum external quantum efficiency measured spatially at each wavelength. All scans in the following figures show a pseudo 3D and matching 2D contour plot of the device. The contour curves shown are for 10% increments in quantum efficiency. The profiles have been turned to enhance shading which improves the ability to observe subtle differences in Q.E.

The plots that follow are generated from a graphics software package SURFER Version 4.1 from Golden Software. Duplicated data points have been averaged. The gridding method used is designated minimum curvature. This method is reported to cause the least error of available gridding methods [21]. An inaccuracy caused by data points being closer than the spot size diameter exists. This should be seen as a spatial averaging or smoothing. The existence of points positioned closer than the diameter of the near diffraction limited spot is due to the non-linearity of the stage travel.

The AlGaAs / GaAs device has no anti-reflection coating. This coating is used normally to both increased transmission into the surface and as a passivation layer to reduce surface states that contribute to recombination. The collection efficiency of these devices is dependant on material quality and defects at heterostructure interfaces. This device was grown by molecular beam epitaxy (MBE) and is from an early run during device development. All of these phenomena are presumed to reduce the external Q.E.
The spatial results for the AlGaAs/GaAs device A3 at 670 nm, 780 nm, and 848 nm follow in Figures 17-20. The scans display the expected reduction in Q.E. as the beam scans the reflecting top metal contact. (See Figure 6. Device photographs.) Also note that the height of the mesas changes as we increase in wavelength from 640 to 780. This increase in Q.E. can be seen in the contour plots of the spatial scans of this device.

The peak external quantum efficiency determined for AlGaAs PIN A3 can be found in Table X. The device responsivity was calculated, using the measured photocurrent determined during spatial scanning and the optical power coupled to the device stage, with (2.24). The external Q.E. was calculated using the responsivity and (2.25).

The applied bias voltages represent a fully depleted intrinsic layer operating condition. The increase in Q.E. with increased bias is attributed to increased absorption volume and improved collection efficiency.

<table>
<thead>
<tr>
<th>Laser Wavelength</th>
<th>Q.E. % -1 V bias</th>
<th>Q.E. % -10 V bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>670 nm</td>
<td>29.4</td>
<td>34.4</td>
</tr>
<tr>
<td>780 nm</td>
<td>48.1</td>
<td>51.1</td>
</tr>
<tr>
<td>849 nm</td>
<td>51.5</td>
<td>58.7</td>
</tr>
</tbody>
</table>

At 780 nm (see Figures 19 and 20) a reduction in quantum efficiency occurs near the mesa center. This reduction could potentially be due to a piece of dust, or other debris temporarily obscuring the device surface. Again, at this wavelength the top
Figure 17. Spatial scan, Device A3 Q.E. at 670 nm, -1V bias.
Figure 18. Spatial scan, Device A3 Q.E. at 670 nm, -10V bias.
Figure 19. Spatial scan, Device A3 Q.E. at 780 nm, -1V bias.
Figure 20. Spatial scan, Device A3 Q.E. at 780 nm, -10V bias.
contact of the device (visible at the bottom of the plots) blocks the beam reducing quantum efficiency to near zero. The contour maps show that the device was at a slight angle relative to the scanning beam.

The spatial scans of device A3 at 850 nm are shown in Figures 21 and 22. The uniformity of the device Q.E. can be seen in the large open area of the lower contour plots. The minor deviations from the expected circular shape are due to irregular stepping of the probing beam.

The spatial results for the InGaAs/InP device C6 are found in the following figures. This device was grown by using a metal organic chemical vapor deposition (MOCVD) epitaxial process. It has had a silicon nitride anti-reflection coating deposited during processing. As previously, improvements in Q.E. are noted at the higher applied bias condition. This minor increase in efficiency is possibly due to 1) an improved hole collection efficiency due to higher velocity in the drift region and 2) an increase in the effective depletion width which corresponds to an increased absorption volume. The applied bias voltages represent a nearly complete and fully depleted intrinsic layer operating condition.

Examining Figures 23 and 24 we note (at 848 nm) this nominally circular diode with a ring contact (see Figure 6) shows a non-circular response. This result is at least partly due to an inadequate data density used for plot preparation. (Scans at this wavelength were the first ones completed.)

In this case the author believes that the bottom edge of the contour plot which corresponds to the right edge of the pseudo 3D plot is a "cut" through the metal line that extends from the ring p-contact. The less than 10% response noted is similar to the contact scanning response of A3. That is that the p-contact metal blocks a portion of the mesa area. A possibility exists that the p-contact metal also reflected a small amount of
Figure 21. Spatial scan, Device A3 Q.E. at 850 nm, -1V bias.
Figure 22. Spatial scan, Device A3 Q.E. at 850 nm, -10V bias.
Figure 23. Spatial scan, Device C6 Q.E. at 850 nm, -1V bias.
Figure 24. Spatial scan, Device C6 Q.E. at 850 nm, -10V bias.
radiation. This thought seems particularly applicable in the -10V bias condition due to
the peaks adjacent to the area of p-contact entrance to the mesa surface. Another possible
explanation includes improved surface generated carrier collection. (That is collection
due to the proximity of the spot to the metal.) When carriers are generated within one
diffusion length (~1 - 4 µ) of the metal, electrons may diffuse to the depleted region and
where collection is more efficient.

The 1300 nm results for device C6 are shown in Figures 25 and 26. The effect of
the circular contact is very clear in this plot. The entrance of the metal line to the circular
contact has changed from the previous scan. The author believes this line now
approaches from the lower left on the contour plot and directly from the front on the
pseudo 3D plots. Additionally the light coupling in the center of the device top contact
appears to be significantly improved over both the 850 and 1550 nm device scans. This
result is most probably due to the minimum reflection accorded by the specific AR coat­
ing thickness on this device. This points out the need for multi-layer AR coating on these
devices to maximize the useful spectral bandwidth.

The 1550 nm results are shown in Figures 27 and 28. The incoming metal line is in
the same orientation as described above for the 1300 nm scans for this device. The non-
circular response seen on the contour plots is again due to an insufficient number of data
points. This result shows a lower Q.E. than would otherwise be anticipated based on the
normalized spectral Q.E. curve.

It should be noted that the peak Q.E occurs again in the device center. The peak
Q.E for device C6 can be found in Table XI below. It is a slightly lower peak Q.E. than
is expected based on the theoretical calculations in Table VI. These results are more fully
discussed in the following section.
Figure 25. Spatial scan, Device C6 Q.E. at 1300 nm, -1V bias.
Figure 26. Spatial scan, Device C6 Q.E. at 1300 nm, -10V bias.
Figure 27. Spatial scan, Device C6 Q.E. at 1550 nm, -1V bias.
Figure 28. Spatial scan, Device C6 Q.E. at 1550 nm, -10V bias.
TABLE XI

PEAK QUANTUM EFFICIENCY : InGaAs PIN C6

<table>
<thead>
<tr>
<th>Laser Wavelength</th>
<th>Q.E. % -1 V bias</th>
<th>Q.E. % -10 V bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>848 nm</td>
<td>35.2</td>
<td>36.2</td>
</tr>
<tr>
<td>1300 nm</td>
<td>61.4</td>
<td>63.5</td>
</tr>
<tr>
<td>1550 nm</td>
<td>40.0</td>
<td>42.0</td>
</tr>
</tbody>
</table>

The results for the InGaAs PIN C5 can be found in Figures 29 - 32. This device has a nominal 17 µ circular mesa diameter. As for device C6, the quantum efficiency of these devices appears non-uniform. Most notable is the very small area of peak Q.E. in Figures 29 and 31 both of which are taken at only -1V bias. The peak quantum efficiency determined by spatial scanning at both bias voltages can be found in Table XII.

Great care was taken in assuring that this smaller device was thoroughly scanned. Data points were taken every 1 - 3 µ along both axes. Data taken only three microns away along either axis showed a reduction in Q.E to less than half the peak value at both wavelengths. This significant non-uniformity in device response was unexpected.

The cause of this non-uniformity is partially due to the spatial averaging of the probing beam. If the actual beam diameter can be read from the pseudo 3D plots (twice the maximum spot size plus the mesa diameter = response width) it is ≤ 5 µ. The device geometry, which has an approximately 7 µ diameter clear aperture within the center of the top p-contact ring, when scanned with a = 5 µ beam spot, contributes to this apparent non-uniformity.
Figure 29. Spatial scan, Device C5 Q.E. at 1300 nm, -1V bias.
Figure 30. Spatial scan, Device C5 Q.E. at 1300 nm, -10V bias.
Figure 31. Spatial scan, Device C5 Q.E. at 1550 nm, -1V bias.
Figure 32. Spatial scan, Device C5 Q.E. at 1550 nm, -10V bias.
Since device C5 is of the same structure as device C6, the same peak Q.E. should be achieved. Neither of these conditions has been met. The peak Q.E. of device C5, achieved during the displayed spatial scans, is compiled in Table XII following.

To more fully understand the interaction of the gaussian beam with the device geometry, a fourier analysis was performed. This analysis has been determined to be a more accurate method for the determination of spot size than the method described above. The fourier analysis convolves the device metallization (measured optically) with a mathematically ideal gaussian beam. (It is convolved with the metallization pattern, in cross section, since the metal pattern blocks all radiation that would produce detectable carriers. This is justified optically since the diffraction which occurs at a line edge is normally collected by the device. This is so since the metal line is in direct contact with the semiconductor surface.) This was accomplished for the measured dimensions of device C5 using Igor Version 1.2, a graphing and data analysis program from WaveMetrics.

<table>
<thead>
<tr>
<th>Laser Wavelength</th>
<th>Q.E. % -1 V bias</th>
<th>Q.E. % -10 V bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300 nm</td>
<td>45.8</td>
<td>47.8</td>
</tr>
<tr>
<td>1550 nm</td>
<td>37.3</td>
<td>39.2</td>
</tr>
</tbody>
</table>

The results of this analysis were not finalized at the submission date of this thesis. The results calculated to date show that the general bell shape spatial results of C5 taken in cross section imply that the beam waist was between 8 - 11 μ. The same technique when applied to the device geometries of C6 showed a similar beam waist range.
As was noted for device C6, the quantum efficiency achieved for device C5 is greater at the higher applied bias conditions. As was stated previously, this is most likely due to increased absorption volume at higher applied bias as well as more efficient collection due to carriers reaching saturation velocity at > 40 kV/cm in both devices. The differences between the Q.E. measured for these two devices is attributed to differences in the AR coating thickness and the coupling efficiency due to partial beam blockage within the center contact ring.

RESULTS COMPARISON AND ERROR ANALYSIS

A summary of the results obtained during this work is shown in Table XIII. The device structures referenced in the table are defined in Figure 1. The monochromatic singlemode radiation used to obtain the spatial results are listed in the table. The theoretically determined Q.E. range is calculated using TFCalc a software program from Software Spectrum. This program and the method of analysis are described in Chapter II. The measured spatial peak Q.E. is the actual peak achieved during spatial scanning.

The methods and techniques used to acquire this data are detailed in Appendix D following. The normalized spectral Q.E. data is taken from measured curves that have been normalized to the peak measured spatial Q.E. using a single point normalization method. This single data point normalization method is described above under Spectral Results and Discussion.

A comparison of the measured spatial Q.E. to the theoretical Q.E. shows that they are in close agreement (≤ 3%) at longer wavelengths. The measured spatial Q.E. is used as the standard of comparison due to the relatively small error bars on this data (± 4% through 1000 nm and ± 3.5 % from 1000 - 1700 nm). The assumption of 100 % collection efficiency and > 95 % conversion to EHP’s (> 95 % η) appears to be justified at longer wavelengths. The short wavelength theoretical Q.E. differs significantly from the
measured spatial Q.E. value. This difference is attributed to significant absorption at short wavelengths for the GaAs p-contact layer in the AlGaAs /GaAs device and to the InGaAs p-contact layer in the InGaAs /InP devices (see Figure 1). The inability of the absorbed photons to produce detectable EHP's can be attributed to surface recombination processes.

TABLE XIII
RESULTS SUMMARY

<table>
<thead>
<tr>
<th>Device Structure</th>
<th>SM Laser Wavelength</th>
<th>Theoretical Q.E. % Range</th>
<th>Measured Spatial Peak Q.E.%</th>
<th>Normalized Spectral Q.E.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlGaAs / GaAs</td>
<td>670 nm</td>
<td>66.6 - 67.3</td>
<td>34.4</td>
<td>29.8</td>
</tr>
<tr>
<td>AlGaAs / GaAs</td>
<td>780 nm</td>
<td>59.2 - 59.6</td>
<td>51.1</td>
<td>51.1</td>
</tr>
<tr>
<td>AlGaAs / GaAs</td>
<td>849 nm</td>
<td>59.2 - 59.6</td>
<td>58.7</td>
<td>45.3</td>
</tr>
<tr>
<td>InGaAs / InP</td>
<td>848 nm</td>
<td>81.4</td>
<td>36.2</td>
<td>21.9</td>
</tr>
<tr>
<td>InGaAs / InP</td>
<td>1300 nm</td>
<td>67.2 - 67.3</td>
<td>63.5</td>
<td>63.5</td>
</tr>
<tr>
<td>InGaAs / InP</td>
<td>1500 nm</td>
<td>44.6 - 44.8</td>
<td>42.0</td>
<td>51.5</td>
</tr>
</tbody>
</table>

Since the normalization method for the normalized spectral data utilizes the spatial peak data at the mid-spectral data point, they should and do agree. The difference observed at 849 nm on the AlGaAs /GaAs is attributed to the width of the spectral band used for probing. The change in normalized Q.E. is 14 % between 840 and 860 nm. The difference noted at the 670 nm is within the error bars of the measured spatial data (± 4 %).
The difference noted between the normalized and measured Q.E. at 848 nm for the InGaAs/InP devices is greater than anticipated. This is possibly due to reduced collection efficiency of surface generated carriers and increased surface recombination.

The difference between the normalized and measured peak Q.E. on the InGaAs/InP devices at 1550 nm is most likely due to an error in the spectral measurement method. The normalized spectra being greater at 1550 nm implies that longer wavelength radiation has a reduced diffraction angle as they exit the 50 µ core optical fiber used for spatial scanning. This would increase the optical power density at the device surface at longer wavelengths. This improved power density would translate to higher responsivity and thus higher Q.E. at longer wavelengths. A two data point correction method (1300 and 1550 nm) would increase the Q.E at 850 nm and decrease the Q.E. at 1550 nm.

Photon related noise sources as error in the spectral measurements are very small. The Newport model 780 source has an optical power stability specification of .05% in 10 minutes and .1% in any hour. The optical power transferred to the device is confirmed by measuring the optical power before and after the spectral scans. Differences between the initial scan were on the order of ± .2 nW (≈ .3% of total coupled intensity). These differences were deemed due to positional variation in the photodetector used for optical power measurement.

All electrical measurements for the spectral scans were taken in a darkened room. This eliminates the effect of stray light in the room during testing. Both illuminated and dark measurements are taken during the spectral scans. The data is corrected by subtracting the dark measurements from the illuminated measurement data.

The relative spatial uniformity of the optical power output of the 50 µ core fiber used for spectral testing changes with wavelength. The position of the image of the bulb
filament transferred (thru the monochromator, highpass filter, collimating and focusing lenses) to the input end of the optical fiber, changes with wavelength. The critical angle within the fiber changes with the wavelength band chosen to pass through the fiber. This causes an unmeasured change in the output angle (or NA). It is not possible to quantify these variations in optical power uniformity at the surface of the devices tested. An estimate of the maximum combined error for spectral Q.E. over the spectral band is 25% of the measurement.

The photodetectors used for optical power measurement are annually due for recalibration. The calibration was due when the measurements for this thesis were made. A discussion with the instrument calibration engineer at Hewlett Packard, disclosed that it is rare that the optical heads, when returned for annual recalibration require more than a 1% change in the internal calibration curve. With this information, testing proceeded.

The error in the spatial measurements are due to two sources 1) the inaccuracy in the measurement of optical power coupled to the devices and 2) the variation in spot size and thus power density coupled to the device surface during testing. The relative size of the open area on the device surface compared to the probing beam, has been shown indirectly, through the use of fourier analysis, to impact the measured responsivity.

The first is due to the claimed accuracy in the HP 8152A Optical Power Meter used to determine the optical power coupled to the device stage. This absolute accuracy is ± 4% on the short wavelength silicon detector and ± 3.5% on the long wavelength germanium detector. It is not known whether the spatial uniformity of the detector area (5 mm diameter) is contained in the stated power measurement specification. The optical power is inversely related to the quantum efficiency through the responsivity (see (2.24) and (2.25)).
The second is due to 1) vibration induced variation in the spot size during testing and 2) the top surface metal geometry on the InGaAs devices. The variation in spot size listed in Table VIII is from the spot size measurement tools. This variation is measured when the stage is at rest. If variation occurred while testing was underway, it can not now be detected. Testing of the InGaAs devices was done after hours to reduce the effect of building vibrations on the stability of the position and spot size.

Any inaccuracies in the magnitude of the electrical measurements are considered small relative to other inaccuracies and do not contribute. The observed inaccuracy of the positional measurements is ± 1µ and contributed to the non-circular quantum efficiency contour maps.

These errors then are dominated by the stated accuracies of the detectors used for optical power measurements and unquantifiable variation in optical power density at the device surface during testing. The author believes that the measured spatial Q.E. results are accurate to ± 10%.
CHAPTER V

CONCLUSIONS

In this work a new, computer controlled data acquisition system has been designed, assembled and characterized. This system has been used for optical spatial scanning of heterostructure PIN photodiodes to determine peak quantum efficiency. This system uses optical fiber to transfer radiation to the devices to be tested. The same testing arrangement can be used for spectral responsivity measurement. The peak quantum efficiency achieved during spatial scanning at a mid spectral bandwidth wavelength has been used to calibrate the spectral quantum efficiency curves.

This work reports on three devices that range in size from 17 to 52 µ. The smallest device scanned has a diameter approximately four times the diffraction limit of the radiation used for spatial scanning. This is the smallest diode yet reported as being spatially mapped. This is the first simultaneously reported spectral and spatial scans of the same heterostructure PIN photodiodes in the InGaAs/InP and AlGaAs/GaAs systems. The diodes tested were taken from intermediate runs during their process development. All testing was performed at room temperature.

The spatial scanning apparatus uses a nearly diffraction limited spot of light. The quantum efficiency attained compares favorably to the maximum external quantum efficiency data published elsewhere [2], [8]. Theoretical calculations using the optical constants data published in this document have accurately predicted the measured results at longer wavelengths. The short wavelength predictions may be improved with further examination of the calculation method used for TFCalc. The single point method of
determining an appropriate correction factor for spectral quantum efficiency curves has been shown to be inaccurate. Correction of the spectral quantum efficiency curves based on a two point method has been suggested.

It is presumed that the maximum quantum efficiency for any specific photodiode occurs when the TEM$_{00}$ singlemode radiation has reached its minimum spot size. This should place the theoretically flattest wave front and highest power density within the device. This assumes that the intensity of the incoming beam is within the linear region of responsivity of the PIN device (=6 orders of magnitude). The maximum responsivity to infrared radiation for the InGaAs devices requires a diffraction limited beam. The testing done in this thesis was to achieve maximum responsivity that was converted to quantum efficiency.

It appears that this maximum was achieved at the minimum spot size for all device types. No calculations were done or independent measurements attempted, that accurately model a slightly focussing or defocussing beam. An improved apparatus that uses an improved method (optical interferometer) to judge diode to final focussing lens distance could be built to extend this work. This information with improved beam spot size measurement equipment could determine, with precision, which case actually allows the peak quantum efficiency to be achieved. (The accuracy of spot size measurement tools used to quantify the spot size used here is in doubt. This is due to differences between the measured spot size with different commercial instruments and the apparent spot size determined during spatial scanning analyzed by fourier transform.) The method of spot size measurement (a single slit) is considered quite accurate for the conditions under which it was used. The only limitation should be minor diffraction effects. Thus the differences noted between spot size test systems were considered to be due to the specific piece of equipment used for the testing.
Fundamental limitations of the scanner include speed of testing, travel limitations on the stage leading to limits to the size of the device to be tested and the optical stability of commonly available connectorized lasers.

The speed of testing is slow due to three factors. First the software timing of the controller to gather and collate the data in real time appears to require significant computer timing overhead. Second the time necessary to move the stage, stop the stage, and test the device is too long. This is due in part to stage limitations (a pause time to allow stage movement settling) and part to instruction execution and bus transfer speed in the Keithley 236 SMU. Additionally the SMU has internally set default settling times between changes of the applied bias potential. Third the relative height between the device and final lens is not accurately known and therefore cannot be accurately reset to a specific testing condition. This therefore requires repeated tests to assure that the peak responsivity has been achieved. (Note that the change in separation distance must be small between sequential tests. Also the peak is noted by approaching, then reaching the peak and then making a small step beyond and re-testing. This requires three tests minimum, at greater than an hour per test.)

The limits to the size of the devices to be tested can be overcome with newer models of piezo actuated stages. It has been reported by Photon Controls, the stage vendor, that relaxation times and linearity of device response (reduced hysteresis and repeatable positioning as well as return to zero positional response at low slew rates) has been improved.

The optical stability of the connectorized lasers used in the testing was inferior to the Tektronix packaged lasers. The stability of connectorized lasers is a restriction in the absolute accuracy of the tests conducted with them. The optical power from the lasers used in this test is measured with calibrated photodetectors. These photodetectors have a
claimed precision of \( \pm 4\% \) for the measurements made in this test. These are the primary source of error used in this work. A precise optical standard \((\pm < 1\%)\) would improve the accuracy of the optical power data used in calculation of quantum efficiency and improve the precision of the testing performed with them.

Together these limitations reduce the efficacy of the spatial testing apparatus. They do not reduce the convenience of the apparatus for spectral scanning. Spectral scanning should be automated, and focusing lenses added to improve coupling efficiency.
CHAPTER VI

SUGGESTED IMPROVEMENTS

Several methods can be used to improve the device testing speed. The most notable improvements will be found by changing the mechanism used for movement of the collimating / focussing assembly. Several companies produce stages with 1 micron positional precision.

Photon Controls also produces piezoelectric stages with improved linearity and positional feedback. These two functions integrated into one system subcomponent solves two problems. First, the nonlinearity of the x and y axis in up travel and return to zero. This includes settling time of the piezo device. (This is related to the spring pressure asserted against the stage by the micrometer gauges.) Second, the potential of improved positional accuracy. Current accuracy is $\pm 1 \mu$ ($\pm .5 \mu$ is desired). Third, stacking of piezo stacks should increase the available scanning field.

Burleigh makes precision stepper motor driven stages. These stages have very large available scanning fields. This stepping method may have considerable space requirements and undesirable vibrational side effects however. Additionally the positional tolerances and reproducibility would need to be confirmed, before choosing this method.

The timing and sequencing has been documented in the LabVIEW programs. LabVIEW may have an inherent speed limitation due to its program overhead. The software could be rewritten-in C which could increase speed of execution.

Spectral scanning could be automated with the addition of an electrically actuated iris for automated dark and light measurements. Increased optical intensity coupled
through the monochromator from a broadband source, would be desirable. This would require a smaller filament and/or a higher color temperature. An increase in the ease and precision of spectral scanning through the addition of achromatic focusing elements at the device testing stage is recommended. The Jarrell-Ash monochromator was equipped with a standard 25 pin "D" connector by the author through which the operations of the monochromator could be automated.
CHAPTER VII

FURTHER WORK

Several areas of technology could be pursued to expand and compliment this work. The first would be the microwave responsivity as a function of wavelength and diffraction limited beam position. This should be done to confirm the applicability of D.C. results to the microwave frequency regime. The existing design of the testing apparatus would be sufficient to pursue this work without modification.

The second would be the expanded temperature range testing of the spatial responsivity. This would be of importance in confirming and expanding the spectral Q.E. in the cryogenic temperature ranges where new high temperature superconductors could be used to enhance device performance. The capability of using a refrigerant in the device stage was built into the existing testing stage. Special cautions to insure maximum thermal conductivity and low thermal mass were made in the stage fabrication to allow rapid thermal changes. Other work may include verification of higher temperature operation of photodiodes for confirmation of instrument specifications (performance derating with temperature). Additionally it may be used to study heterostructure device physics, for example, the thermal emptying of traps.

The third aspect of future work would be in the area of materials development. In addition to the above mentioned superconductor work, an effort in transparent top contacts (for example, doped ITO) to minimize blocked area in the smaller diodes should be pursued. Other aspects of this work would include developing low resistance p-contacts
to GaAs and InP directly. This eliminates the need of potentially optically absorbing semiconductor layers currently used to improve contact resistance. (This may increase the available Q.E. of the devices if it allowed more photons to enter the depletion region.)

The fourth area of future work should be in wide band AR coatings on devices of both classes. This in itself should offer immediate device performance benefits. The confirmation of these coatings could be rapidly done using TFCalc using the data in Tables I through V. Additional coating materials, particularly in the near infrared, if chosen, may require experimental data to be taken. Little near infrared optical constant data was found for materials in otherwise common use for this purpose.

The fifth region of improved work could be in the testing of diffraction limited devices. (A 6 µ circular mesa diameter is envisioned. The top contacts would invade only 1 µ at the perimeter of the top semiconductor. The optically sensitive surface would be the majority of the photodiode surface. The surface generated carriers have a higher probability of drifting in the low field region to a contact.) High Q.E. in such devices would depend on 1) diffraction limited input signal beams and 2) efficient collection of surface generated carriers by keeping the p-contact layer very thin. This device size is expected to have the lowest capacitance and thus the fastest (i.e. cleanest microwave signal) pulse response.

The sixth area of additional work is in the area of test automation. The capability exists for the spectral responsivity measurements to be done unattended. The monochromator has a wavelength drive motor. The Macintosh computer has several digital outputs that could be used for start/stop, and directional control on the monochromator and open and closed instructions on an optical shutter. Initial tests have been conducted to reduce the spot size from multimode fiber coupled to the devices through the use of additional lenses. Inadequate optical power at the device stage experienced could be improved.
through the use of lock-in amplification. The system has already been shown to have the
ability to accept measurement information on the IEEE-488 interface bus. The improved
operating speed of a compiled run time program with a linear, positional feedback stage
with true orthogonal axes, to do spatial testing also falls into this category.

The seventh area of further improvement would be in the technology area of optical
alignment between optical fiber output and small devices (~ 6 µ). This is clearly beyond
a mere extension of this work due to the stability and precision alignment needs such a
system would require.
REFERENCES


APPENDIX A

PROBE FABRICATION AND SHARPENING
Sharpening of Tungsten Probe Tips Using the TEK 576 Curve Tracer

Note: This same procedure can be used to clean probe tips.

Tungsten wire can be conveniently formed by gripping the wire on opposite sides of the section to be bent and touching it to the tip of a hot soldering iron. Bend while hot, remove from the iron until cool. Cut the section free with wirecutters.

1. Find the bottle of 50% by weight KOH in H2O (potassium hydroxide in water). Note this solution generates heat when mixed. Mix only in a Pyrex container and cool before pouring into the plastic storage bottle.

2. Set up the curve tracer: Connect Collector (C) to the probe, and Emitter (E) to the stainless steel plate in the solution. Put the curve tracer in polarity NPN, Normal mode, with Emitter grounded and Base in step gen. Set the SERIES RESISTORS to 6.5 ohm, and the MAX PEAK VOLTS to 75V. Use 50 mA vertical and 5 V horizontal scales for coarse etching.

3. Etching off the old tip or removing a crushed end section: Immerse the probe tip only. Switch appropriate E, B, C connections on using the toggle in the lower right, next to the E, B, C connections. Crank up the drive to ~ 30V (using the knob on the left of the EBC Connections) and observe the solution steaming and bubbling as the old tip is burned off. (Note: If you have a long, skinny tip, cut it off with wirecutters first.)

4. Forming the new tip: Use 20mA vertical and 5V horizontal scales for sharpening. Back off the drive to 10 - 15 V and hold the tip in solution for several seconds. Slowly lift the tip out of solution. (Higher drive voltages produce rougher finish tips.) Dip the tip in and out of the solution to draw a gentle tapered sharp tip.
5. Rinse the tip with the squirt bottle of DI. Blow dry with N₂. Replace probes in your probe holders.

6. Place the beaker in a secure location with a larger beaker placed on top of it upside down to minimize evaporation.

Note: This procedure uses W = tungsten wire of 20 - 50 mils in diameter.
APPENDIX B

MONOCHROMATOR CALIBRATION
Optics Train Alignment Procedure

A HeNe laser (633 nm) was leveled relative to the optical table. A turning mirror was attached to the main optical rail and used to direct the beam into a 340 µm pin hole attached to the rail at the input to the optical path. The height of the beam from the table was measured at the exit from the pin hole and was adjusted to that same height, 8 feet away, at the opposite end of the optical table. Adjustments were made using the turning mirror. The 340 µm pin hole was removed.

A 250 µm pin hole was positioned at the rail end (a distance of about 2 feet) and the laser beam centered on the hole. The DataScan beam profiler was positioned behind the pin hole. The relative gaussian fit was maximized and beam alignment symmetry assured. The 340 µm pin hole was replaced in its previous position.

A platform with adjustable height and tilt capability was built for the monochromator. The monochromator was positioned so as to allow the beam to enter the center of a 150 µm slit, traverse the monochromators interior, reflect off the grating set to "white", and exit through a 150 µm slit on center. The monochromator position was maintained by setting all six feet on double sticky tape. When all manual recommended adjustments to the grating frame positioner were completed, the beam was centered in the input and output slits. The beam was clearly centered and detectable at the exit side of the 250 µm pin hole at the last position on the optical rail.
Monochromator Calibration Procedure

The laser was turned off and a Pyrex covered Mercury Arc lamp was positioned at the input to the monochromator. The Pyrex test tube has a spectral bandpass starting at approximately 400 nm. This reduces the confusion of secondaries and tertiaries in the spectrum of interest from 400 nm to 1750 nm.

The grating movement mechanically initiates a gear chain that changes the wavelength readout. (The gears in this chain were changed, along with one of the two gratings, prior to the calibration sequence being started.) The wavelength was noted when specific colors were noted at the output. The colors were compared to standard charts which list the wavelength at which they occur. The position was confirmed as reproducible by moving the grating, and thus the wavelength drive, in one direction from low to high wavelength. This eliminates error due to backlash.

The minor corrections recommended in the monochromator manual calibration procedures were implemented to achieve the calibration shown in the following curves. These procedures adjusted the wavelength drive gears and the relative position of the grating.
Figure 33. Monochromator calibration variation.
APPENDIX C

OPTICAL STABILITY OF LASERS
The laser diode is fundamentally a current regulated device, thus its stable operating mode should be in the constant current regime. The constant current mode was chosen for all the devices used in these tests.

Thermal variation effects on the output power of the non-temperature stabilized 848 nm laser were mitigated by avoiding contact between the diode and thermally conductive surfaces during the testing procedure. The laser with integral monitor diode and ST connector assembly is securely housed. The relatively large thermal mass, in comparison to the device size, reduced the short term temperature effects on the laser.

The laser was connected to the custom built 848 nm single mode fiber connectorized by the author with ST connectors. The throughput of the fiber was checked by comparing power coupled when different ends were attached to the laser. Significant differences were noted and attributed to the relative core alignment to the laser diode output.

The stability of the drive current from the ILX Lightwave model LDX 3620 used for the 848 nm laser is specified at ≤ 10 ppm over any 30 minute period. Additionally its temperature coefficient is ≤ 10 ppm per degree C. This was confirmed in short term stability verifications where the 848 nm singlemode laser diode was monitored every five minutes for an hour. The initial power setting was 135 µW. The maximum variation observed was .9 µW in the first half hour, .1 µW in the second half hour and .3 µW in any subsequent 24 hour period. The 848 nm laser was run on the 200 mA range under A.C. line operation.
The monitor voltage displayed on the LDX 3620 is the negative of the average monitor photodiode current in mA. (See Figure following) The average variation observed in the time region where final measurements are made was less than 10 µA corresponding to ≤ 2 µW.

The Tektronix LDC-600 is an ECL laser driver with integral thermo-electric cooler power supply. The 1300 nm and 1550 nm lasers used both had integral temperature stabilization. The voltage variation displayed is a direct measure of the current driving the laser. The voltage corresponds at 40 µA / mV to a maximum current variation of ≤ 20 µA at the time of final measurement. This variation corresponds to an insignificant variation of 30 nanowatts at 1550 nm and 2 nanowatts at 1300 nm. The increased stability is attributed to the integral thermo-electric coolers and the high coefficient of fiber stability ($f_p$) in these laser packages.
Laser Stability
Constant Current Sources

![Graph showing laser stability over active time with different wavelengths and sources.]

Figure 34. Laser stability.
APPENDIX D

SEQUENCE OF TESTING
Outline of Testing Sequence : Spatial Scanning

Attach optical fiber to Module 3 , final lens assembly, using appropriate fixturing (FC, ST or fiber chuck)

1 ) Turn on and stabilize light source at max power
   a) center the piezoelectric stage over its base

2 ) Confirm laser stability and output power (HP 8152A corrected for λ) of the laser attached to module 3
   a) minimize the spot size (confirm the fiber output is the correct distance from the first module 3 lens) by measuring the B to A distance.
   b) determine approximate module 3 to device distance at minimum spot and note it (photograph the minimum spot if using the DataScan or other beam profiler)

3 ) Locate beam with a photoluminescent sheet
   Use the Quantex model Q-32-R for visible.
   Use the ElectroPhysics model IRL-32-R for near IR.
   Use the Quantex model Q-31-R for IR.
   a) position the contact probes (2 for InGaAs, 1 for AlGaAs) directly over spot (normally the monocular zoom scope is best suited to this task and device alignment)

4 ) Raise the probe or probes (z axis only) and remove the IR sensor
   a) Withdraw the stage
      1) clean if necessary- (scotch brite followed by IPA on a Kimwipe)
   b) Touch the grounded optical table
      1) put on the grounded wrist strap
   c) Verify that the stage ground is connected to the optical table
   d) Connect probes to the coax to triax connection box at Keithley 236
e) Touch both probes to the grounded stage

5) Load the device to be tested (D.U.T.) onto the clean stage

6) Position the device under the probes by moving the stage on the grease plate.
   a) Lower the ground plane probe first (on InGaAs PIN)
   b) Position the top force probe to the p-contact
   c) Verify device contact using the Keithley 236 SMU (run Keithley 236-1 VI 0 to .2V and 0 to -10V)

7) Lower z axis of module 3 to the distance expected for the minimum spot.

8) Confirm device position

   (Assuming input power level is 1 microwatt or higher)
   Turn on Keithley 236 SMU
   Function = DC
   Source/measure = V I
   Filter = 32 readings.
   Compliance = 100 uA
   Auto range
   Then press operate

9) Using the mechanical controls on the piezoelectric stage, seek the maximum response from the device (anticipate the responsivity based on previous peak efficiencies achieved)
   a) Note the position on the digital gauges when significant responsivity is achieved.
      (In this way a preliminary map can be drawn.)
   b) Minimize the spot, by changing the module 3 Z axis height, and noting an increase in responsivity. This insures that the scan will produce a near peak responsivity.
10) Turn on the piezoelectric drive controller and BH-100 conversion box. Confirm that the Ono Sokki DG-925 and EG-225 micrometer gauges are on.
   a) zero the gauges
   b) confirm that both axes of the piezoelectric stage are set at 0.0 volts

11) Using mechanical controls on piezoelectric stage position the stage back away and left of the peak or edge of the device.
   a) the amount of back travel is dependent on previously noted non return to zero distance.

   (Tip for set-up on re-scanning: move both axis back a similar amount ~ 300 microns, move one axis almost into position say back 20 microns from the desired position, then position the other axis to back 10 microns. Now return to the first axis and move it only if necessary.)

   Judgement call area: the operator must discern pressure or vibration induced changes in gauge output from actual movement by mechanical screw.

12) Initiate LabVIEW stepper/data acquisition program: Faster Spatial Data