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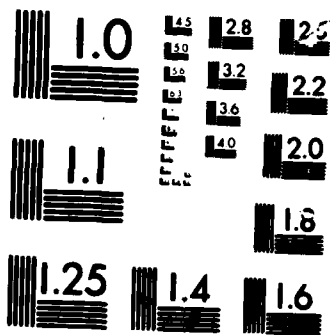
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William S. C. Chang, Albert L. Kellner,
Timothy Van Eck, L. M. Walpita and
H. H. Wieder

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La Jolla, Calif. 92093*

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Electroabsorption and electrorrefraction properties of heterostructures and multiple quantum-well structures in III-V semiconductors were investigated for spatial modulation and optical fibercommunication applications. Optical waveguides are fabricated and evaluated. A new device, the gate controlled photo diode (GCPD) has been conceived and demonstrated. It has potential applications in optical signal processing.

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INTERIM SCIENTIFIC REPORT

**Research on Materials and Components
for
Opto-Electronic Signal Processing**

AFOSR Grant No. 84-0389

October 1st, 1984 through November 30th, 1985

submitted by

William S. C. Chang (Principal Investigator)

Albert L. Kellner, Timothy Van Eck

L. M. Walpita and H. H. Wieder

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Department of Electrical Engineering and Computer Sciences

C-014

University of California, San Diego

La Jolla

California 92093

Tel: 619/452-2737



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1. INTRODUCTION AND OVERVIEW

It has been recognized for some time that optical signal processing holds considerable promise for high-speed signal processing in DoD applications due to its parallel processing capabilities. In addition, optical signals also need to be switched, processed, multiplexed, and demultiplexed in optical fiber communications. However, characteristics of the materials and components (including microfabrication processing technology) must be improved substantially before the full potential of combined opto-electronic signal processing can be realized. In III-V compound semiconductors, optical devices such as lasers and detectors have already been realized and used in many applications including optical fiber communications. Electronic devices such as GaAs MESFET, the InP MISFET and the HEMT have also been demonstrated. Thus, electronic and optical devices may potentially be integrated monolithically on the same chip. The advantages of integrated opto-electronic signal processing include high speed of operation (due to short interconnection delay time), parallel processing, versatility in combined optical-electronic signal processing schemes, simplification of interconnections and reliability and convenience of optical-electronic signal conversion. For these reasons we have proposed to investigate the opto-electronic properties of III-V semiconductors in this grant.

Currently there is an important deficiency of the electro-optical properties of III-V compound semiconductors. The conventional electro-optical coefficients in III-V semiconductors are an order of magnitude smaller than that of LiNbO_3 , which is already an order of magnitude or more smaller than that of liquid crystals or PLZT ceramics. In order to realize effectively the combined opto-electronic signal processing and the monolithic integration of optical and electronic devices, we need either (a) to find a new interaction

mechanism in III-V semiconductors that will produce a large electro-optical effect or strong optical interactions or (b) to conceive combinations of devices such as lasers, detectors and transistors that are interconnected in a pixel in such a manner that will perform electrically the signal processing function from the photo-excited carriers. Ultimately nonlinear optical interactions may be utilized to achieve modulation at frequencies beyond the microwave range.

In two-dimensional parallel processing, for example, in a two-dimensional spatial modulator, the optical radiation is incident normally onto the array, thus effective modulation must be achieved within a short interaction distance. Typically the interaction distance is only a few micrometers, limited by the effective depth of electric field produced from planar electrodes fabricated on the surface by microfabrication techniques. Thus materials, such as liquid crystal or PLZT are used currently in spatial modulators, despite their disadvantage of slow speed. We proposed to investigate the electroabsorption and electrorefraction effect of III-V semiconductors as they may give substantial modulation depth within short distance of interaction for spatial modulation applications. So far, recent data published in the literature and our results have been very encouraging. The multiple quantum-well structures such as GaAs/GaAlAs on GaAs, GaAs/GaInAs on GaAs and GaInAs/InAlAs on InP may yield very large electroabsorption and electro-refraction effect at very high speed.

An approach particularly attractive for opto-electronic interconnection in heterostructures and multiple quantum-well (MQW) structures of III-V semiconductors is the use of optical guided wave technique in conjunction with electronic circuits. The confinement of the optical energy in waveguide would allow us to channel the optical energy to specific locations in a chip and to

obtain effective modulation with long interaction distance (e.g., millimeters). Optical guided wave structures may be fabricated by the same planar microfabrication techniques as the electronic devices and circuits. Although the guided wave device array is suited primarily for $1 \times N$ parallel processing, the disadvantage in parallelism may be compensated by the gain in the speed of operations. Furthermore, anisotropy of the MQW structures with respect to TM and TE optical guided waves and the nonlinearity effect of MQW materials may potentially yield novel device properties of very high speed. Thus we have also initiated an experimental investigations of optical waveguide in hetero- and MQW-structures.

Another device that may be useful for two-dimensional signal processing is a semiconductor device that will yield an output current or voltage which is proportional to (or nonlinearly dependent on) the product of two optical intensities (or the product of an optical intensity with an electrical voltage). An array of such a device may be used as (1) a matrix multiplier, (2) a vector rotator, (3) an adjustable detector array to guarantee the uniformity of the responsivity for all the pixels, or (4) an intelligent detector array with spatial filtering, automatic gain control or adaptive control capabilities. In a previous contract (AFOSR 80-0037) we have studied a coupled photodiode and photoconductive detector. During this contract period, we have conceived a new idea, the gate controlled photodiode. As an initial step, such a device has been fabricated in silicon. In this preliminary device multiplication properties have been demonstrated at a speed of 150 nanoseconds. Experimental and theoretical investigations are currently underway to improve its performance and to analyze its characteristics. Experimentation of the device using III-V semiconductors will be undertaken in the future when the device characteristics in silicon is clearly understood.

2. SUMMARY OF RESEARCH PROGRESS

2.1 Electro-optical Properties III-V Semiconductors

The work concerning the measurement of Franz-Keldysh electrorefraction and electroabsorption in bulk InP and GaAs (reported under contract AFOSR 80-0037) has been completed. A refinement of the theory based on the effective mass approximation has been carried out to include the effect of the experimental absorption tail. The corrected theory fits the experimental data of InP very well. A paper based on this work has been submitted to Applied Physics Letters for publication.

Two other papers have also been published. (a) "Cross Modulation of Light in Semiconductor Materials in the Presence of Electric Fields" by L. M. Walpita, W. S. C. Chang, H. H. Wieder and T. E. Van Eck has been published in Applied Optics, Vol. 24, pp. 2481-2483, 1985. (b) "Modulation of an Optical Beam by a Second Optical Beam in Biased Semi-insulating GaAs" by L. M. Walpita, W. S. C. Chang, H. H. Wieder and T. E. Van Eck has also been published in Picosecond Electronics and Optoelectronics, edited by G. A. Morrow, D. M. Bloom and C. H. Lee, Springer Verlag, N.Y. pp. 176-179 (1981).

The most important progress is probably that heterostructures of AlInAs lattice-matched to InP substrate, as well as quantum wells and heterostructure of $\text{Ga}_{1-x}\text{In}_x\text{As}/\text{GaAs}$ on GaAs substrate with $x < 20\%$ have been grown successfully in our MBE reactor. The MBE reactor was purchased under partial funding from AFOSR. The growth was carried out in a collaboration research program at UCSD funded by ONR.

A multiple quantum-well structure is made up of thin alternating layers of two semiconductors with different bandgaps. The electrons and holes in such a structure are confined to the material with the smaller bandgap; this material is called the well. The material with the larger bandgap is called the barrier. If the well width is sufficiently thin then the electrons and holes behave as confined particles rather than free ones. One result of this carrier confinement is a change of the optical absorption spectrum, including a shift of the absorption edge to higher energy. Another result of carrier confinement is a much sharper and stronger excitonic absorption feature which can be shifted by an applied electric field[1]; this result is the basis of the recently introduced SEED device[2], which is a very versatile device with applications in optical signal processing. The goal of our research is to be able to predict the electrorefraction and electroabsorption in multiple quantum-well structures as a function of optical wavelength, applied voltage, and various structure parameters, such as well width, bandgap discontinuity, and lattice mismatch. The strong electroabsorption and electrorefraction of the exciton line are applicable to two-dimensional spatial modulation.

For spatial light modulation applications there are two quantum-well structures that are of special interest to us. The first consists of GaAs quantum wells with AlGaAs barriers, grown on a GaAs substrate. This is a lattice-matched system, i.e., the lattice constants of AlGaAs and GaAs are nearly equal, so AlGaAs can be grown epitaxially on a GaAs substrate. These are well known quantum-well structures that have already been reported in a number of papers in the literature. However, at the wavelength of interest for electroabsorption in the multiple quantum-well layer the radiation is absorbed completely by the GaAs substrate. We have been developing a selective chemical etching process that will remove the substrate in the area

where light must pass, without etching the quantum-well layers. We plan to measure the electroabsorption and the electrorefractive properties after the selective etching. The second system consists of $\text{In}_x\text{Ga}_{1-x}\text{As}$ ($x < 0.2$) quantum wells with GaAs barriers on a GaAs substrate. With this system the GaAs substrate does not absorb the radiation at the wavelength of interest, as the substrate can be left in place. However, this is not a lattice-matched system and very little is known about the effect of the strain on the properties of the quantum wells. Thus we shall be first investigating the photoluminescence properties of the exciton lines. We shall grow a number of samples with different thickness, composition or doping to understand its properties, followed by measurement of electroabsorption and electrorefraction. The objective for investigating both of these quantum-well structures is to seek strong electroabsorption and electrorefraction of the exciton lines for spatial modulation applications at the near infrared wavelength. Spatial modulation at the near infrared wavelength has the advantage of availability of good detectors such as Si or GaAs detectors and more effective absorption or phase shift than the quantum wells at the longer infrared wavelengths.

We have constructed an apparatus to measure the photoluminescence spectrum of the various semiconductor samples we have prepared either by molecular-beam epitaxy or liquid-phase epitaxy.

Photoluminescence is a technique where carriers are injected in a semiconductor by an optical pump beam. Some of these carriers recombine radiatively. Sharp peaks are observed in the luminescence spectrum at the characteristic energies of the excitons associated with these radiative transitions. This information about the optical transitions can be used to determine the bandgap of the semiconductor, with appropriate calibration the composition of the semiconductor can be inferred. The sharpness of the

exciton luminescence is also an indication of the electroabsorption that may be expected.

The experimental apparatus is shown in Fig. 1. The 488 nm 600 mW output from an argon ion laser is modulated by a mechanical chopper and passed through an adjustable aperture. The aperture spatially filters out the spontaneous emission of the pump laser; this prevents the IR spontaneous emission of the laser from interfering with the luminescence spectrum.

The sample is mounted on a copper cold finger and placed in an evacuated liquid nitrogen dewer. The pump beam passes through an AR-coated quartz window and strikes the sample at grazing incidence. The luminescence from the sample passes through a sapphire window and is collected by an 0.5 meter, F/6.9 scanning spectrometer. The spectrometer has a 600 groove/mm diffraction grating blazed for 1.25 μm , giving a useful operation region from 0.65 μm to 2.5 μm . The output of the spectrometer is filtered by a KRS-5 (thallium bromiodide) window which attenuates any of the pump wavelength which is scattered through the spectrometer.

The output is detected by either a GaAs photocathode photomultiplier, a Si photodiode, or a PbS photodiode. The output from the detector is amplified and heterodyne detected with a lock-in amplifier. The output from the lock-in is plotted on a strip chart recorder.

Figure 2 shows the photoluminescence spectra of samples MBE-108 and MBE-109, both at room temperature (300°K) and at liquid nitrogen temperature (77°K). MBE-108 is a multiple quantum-well structure consisting of ten 100 Å-thick

$\text{In}_{0.13}\text{Ga}_{0.87}\text{As}$ wells sandwiched between ten 200 Å-thick GaAs barriers, on a 4000 Å-thick GaAs buffer layer. MBE-109 is a single layer of $\text{In}_{0.13}\text{Ga}_{0.87}\text{As}$, 9000 Å thick. Both samples are Si-doped n-type ($\sim 10^{17} \text{ cm}^{-3}$) on an n-type ($3 \times 10^{18} \text{ cm}^{-3}$) GaAs substrate. The peak of MBE -108

is at 1.350 eV ($\lambda = 0.9185 \mu\text{m}$) at 77°K and 1.270 ($\lambda = 0.9764 \mu\text{m}$) at 300°K. The peak of MBE-109 is at 1.337 eV ($\lambda = 0.9274 \mu\text{m}$) at 77°K and 1.259 eV ($\lambda = 0.9850 \mu\text{m}$) at 300°K. In comparison, the photoluminescence peak of GaAs is at 1.51 eV ($0.8200 \mu\text{m}$) at 77°K and at 1.42 eV ($0.8700 \mu\text{m}$) at 300°K. Notice the change of multiplication factors in Fig. 2. For example, the photoluminescence of the MQW structure (MBE-108) is 10 lines stronger and sharper than the single layer of $\text{In}_{0.13}\text{Ga}_{0.87}\text{As}$ (MBE-109). Our next step will be to measure their transmission properties.

For the GaAs/AlGaAs MQW material system it is necessary to remove the GaAs substrate from the MQW layer so that light at the wavelength of interest can propagate through the MQW layer. This can be achieved with the selective etchant $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$, which etches GaAs much more rapidly than AlGaAs[4]. The etching characteristics (i.e., GaAs etch rate, selectivity, etched surface quality) of $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$ vary when the composition of the etchant varies. For example, when the etchant is 2% NH_4OH and 98% H_2O_2 , the etching is smoother but slower than for a mixture with 3% NH_4OH and 97% H_2O_2 . We have found the optimum composition, for which the GaAs etch rate is high, selectivity is high, and the etched surface is smooth and flat. Using this optimum composition, we have succeeded in etching away the GaAs substrate from selected portions of a test wafer, while preserving the AlGaAs epitaxial layer on top. It is now possible to remove the GaAs substrate from an MQW layer when an AlGaAs etch-strip layer is grown between the MQW layer and the substrate.

3.2 Optical Waveguiding Experiments in III-V Compound Semiconductor

Waveguides

In order to investigate optical waveguiding, we used the setup shown in

Fig. 3. Either the Nd/YAG laser with output radiation at 1.06 μm or 1.32 μm wavelength or the color center laser pumped by the Nd/YAG laser with output radiation tunable from 1.4 μm to 1.6 μm wavelength is used as the source. The ends of the waveguide samples are cleaved. The laser radiation is end-fire coupled into the waveguide via a focusing lens. The illumination pattern of the output end of the waveguide is imaged onto an infrared vidicon. So far we have seen waveguiding effect in two planar waveguide structure. (A) An GaInAsP layer, 1 μm thick, plus a cap layer of InP, 1 μm thick, grown epitaxially on InP substrate. (B) An AlInAs layer 0.6 μm thick, lattice-matched to and grown epitaxially on InP. More detailed measurement on mode confinement, coupling lens and attenuation rate is currently being carried out.

3.3 The Gate-Controlled Photo Diode

The gate-controlled photodiode (GCPD) is based on two physical phenomena:

1. The photocurrent of a photodiode is dependent on the volume of the depletion region even though the generation of the carriers by optical radiation is taking place in a region much larger than the depletion region;
2. For a MIS structure, the gate voltage V_G could control the depletion layer thickness X_d , and the relationship between X_d and V_G is dependent on factors such as the doping profile, the insulator thickness, etc. Consider the device shown in Fig. 4, the photocurrent I_{ph} is now a function of the product of the optical intensity and the depletion layer thickness D_d which is a function of V_G . Thus it is called a gate-controlled photodiode.

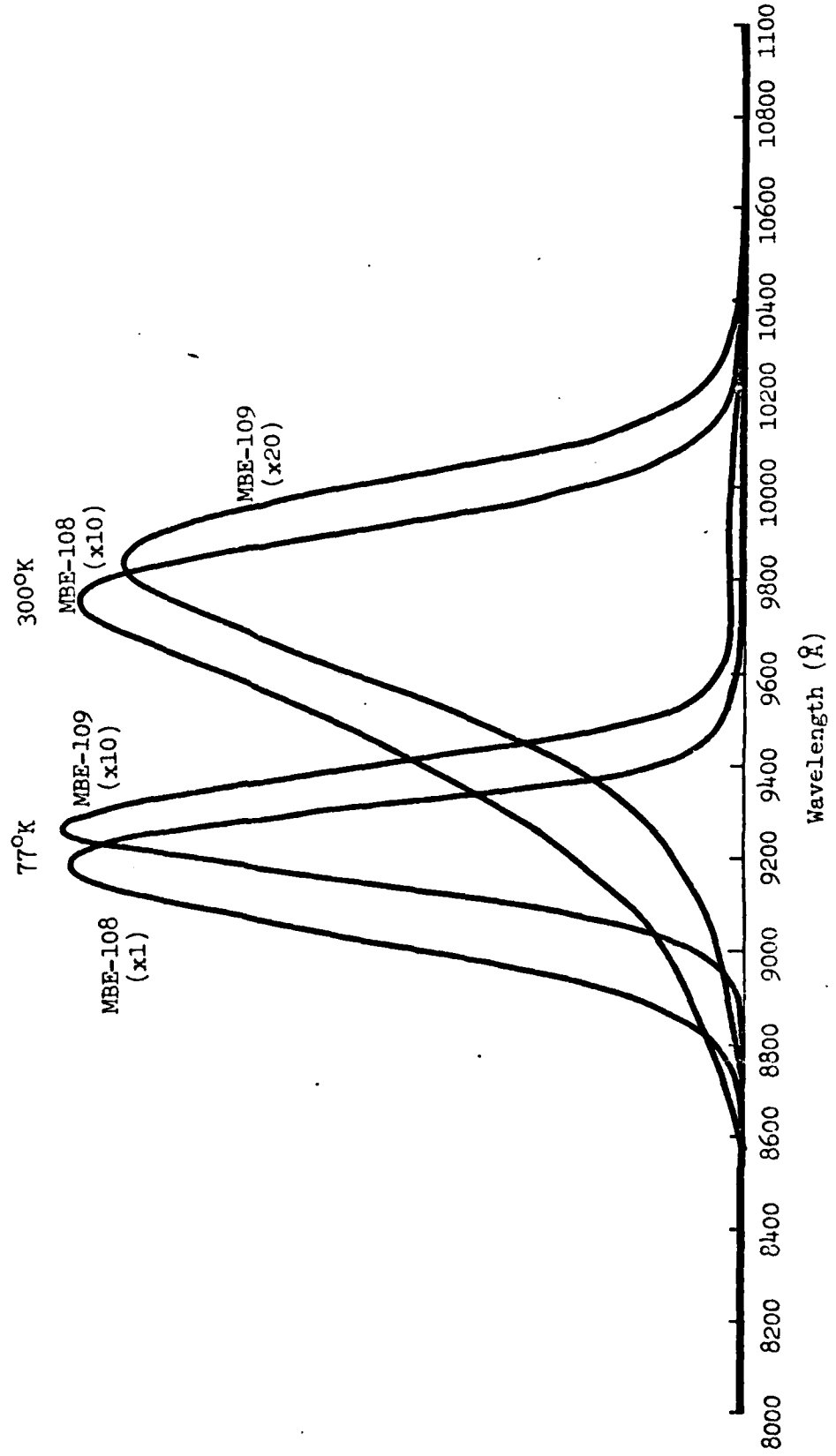
In order to demonstrate this new device concept, a sample with poly-Si

gate and Si substrate has been designed and fabricated, as shown in Fig. 4. The test device consist of a gate oxide of 1000 Å and a field oxide of 1 µm, with 5000 Å thick poly-Si gate. The gate lengths are 75 µm, 35 µm, 25 µm and 15 µm. For an uniform doping profile, $X_d \propto V_G^{1/2}$. Thus $I_{ph} = KV_G^{1/2}P_L$, where P_L is the optical power (or intensity) at λ_1 , and K is a constant. The square root dependence of I_{ph} on V_G has been demonstrated experimentally using a diode laser 0.8 µm wavelength (see Fig. 5). The multiplication property of the device is demonstrated in Fig. 6. The response time of the drive has been measured by displaying on the oscilloscope the photocurrent output as a function of time in response to laser pulses. The response time of the 75 µm gate device is 3 µsec while the response time for the 15 µm gate device is 10 µsec . Experimental and theoretical investigations are currently underway to improve its performance and to analyze its characteristics.

4. References

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4. K. Kene Fick, J. Electrochem. Soc. 129, 2380 (1982).

Figure 2. Photo luminescence spectra of InGaAs and InGaAs/GaAs quantum wells.



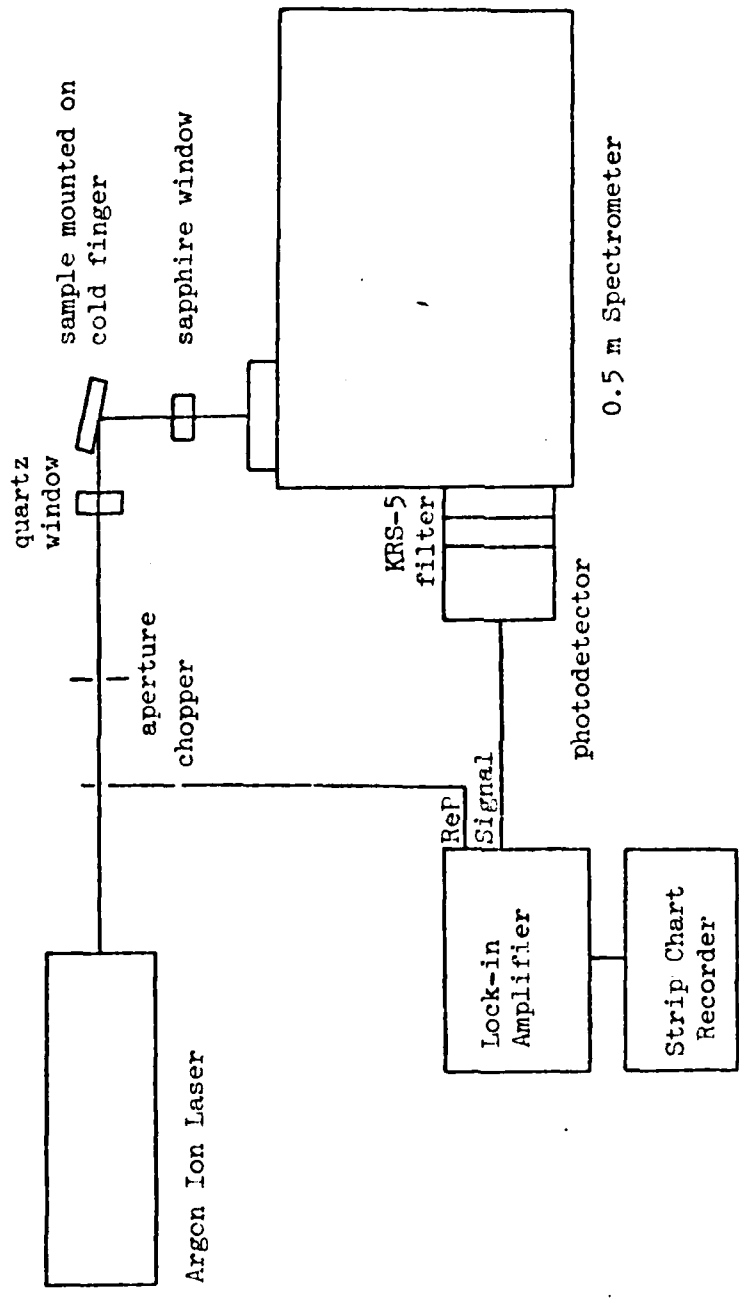


Figure 1. Layout of Photoluminescence Setup.

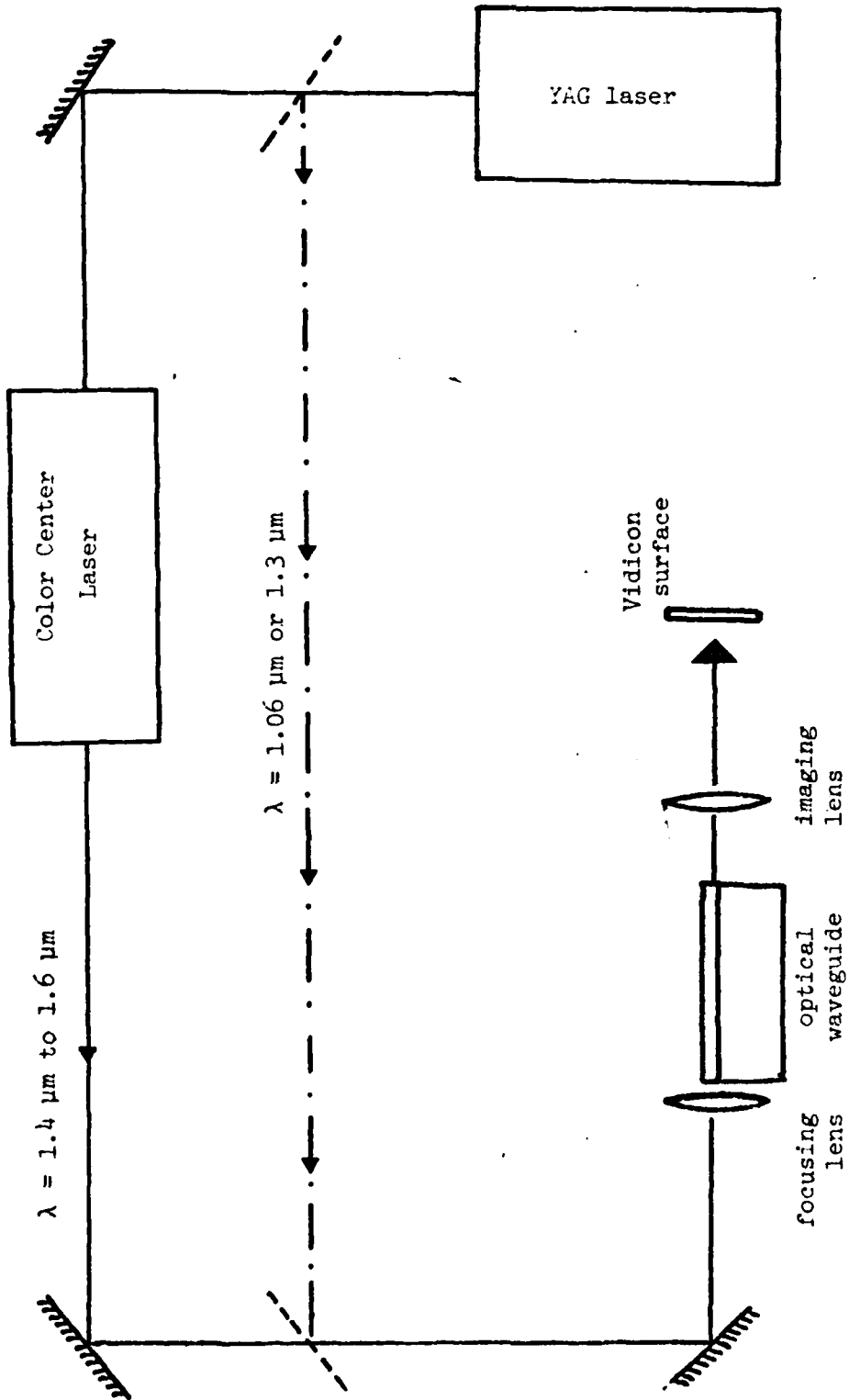


Figure 3. Schematic of the waveguide evaluation setup.

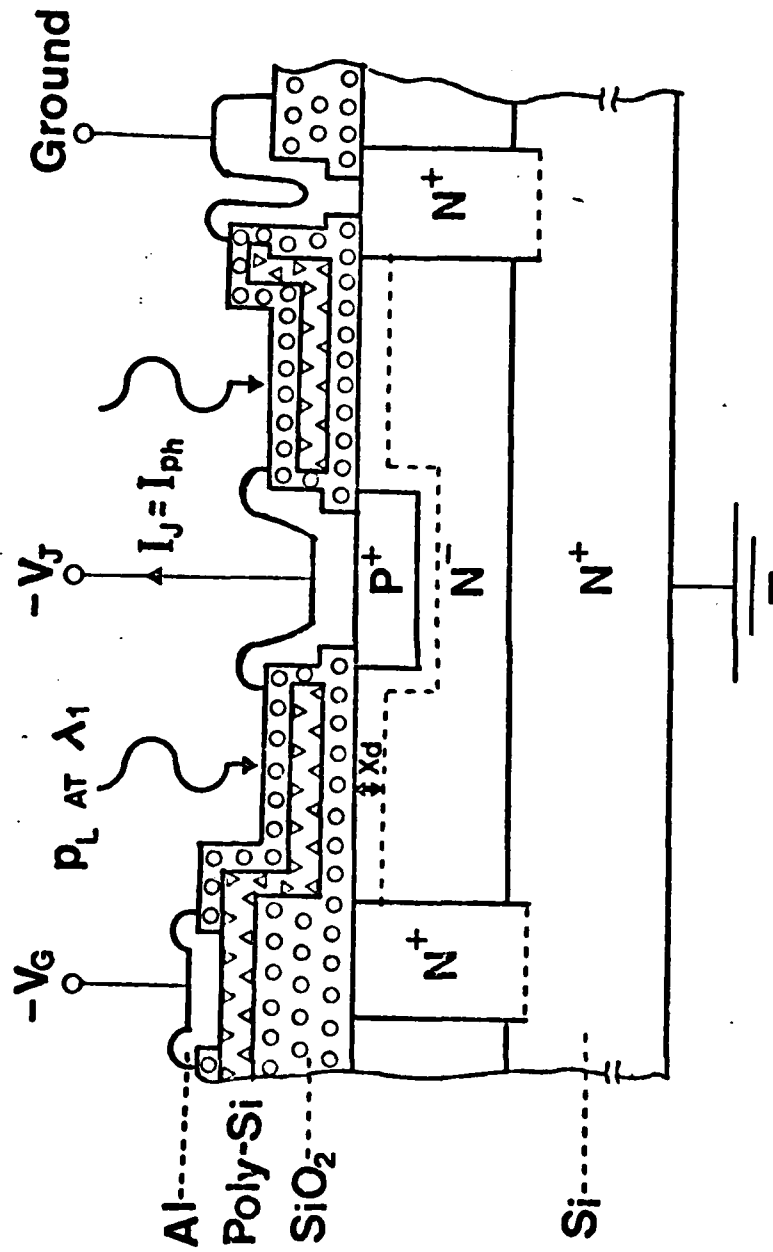
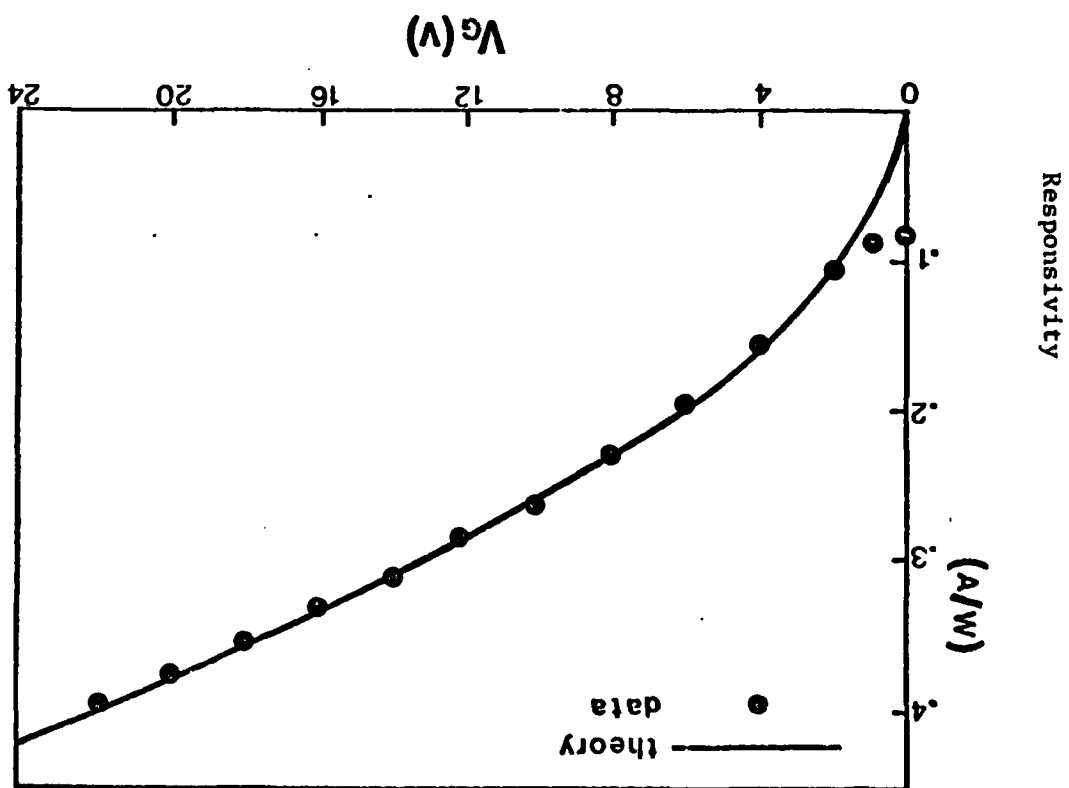


Figure 4. Illustration of the gate-controlled photodiode.

Figure 5. The responsivity of GCPD as a function of V_G .



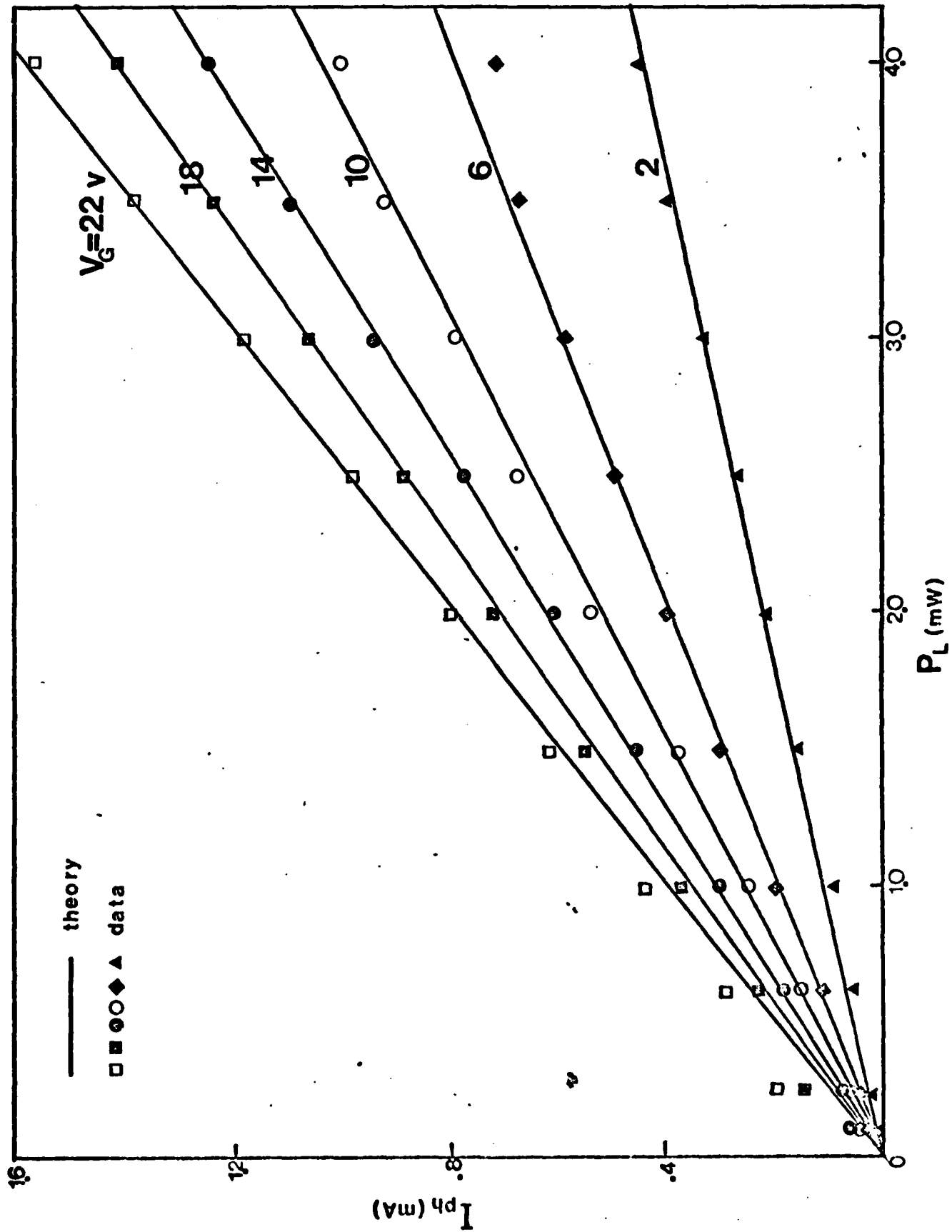


Figure 6. I_{ph} as a function of V_G and P_L for 75 μm gate length.

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