Lattice-engineered MBE growth of high-indium mole fraction InGaAs for low cost MMICs and (1.3 - 1.55 μm) OEICs*

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ABSTRACT

Using molecular beam epitaxy (MBE) and lattice engineering techniques, the feasibility of combining photonic devices applicable to the 1.3 to 1.55 μm wavelength range and monolithic microwave (or mm-wave) integrated circuits (MMICs) on GaAs is demonstrated. A key factor in the MBE growth is incorporation of an InGaAs active layer having an indium arsenide mole fraction of 0.35 or greater and its lattice compatibility with the underlying semi-insulating GaAs substrate. The InGaAs layer used for the photonic devices, can also serve as the active channel for the high electron mobility transistors (HEMTs) for application in MMICs. Several examples of active and passive photonic devices grown by MBE are presented including an optical ridge waveguide, and a photodetector for detection of light in the 1.3 μm range. The material structure includes a 3-layer AlGaAs/GaAs/AlGaAs optical waveguide and a thin InGaAs absorbing layer situated directly above the optical waveguide. Metal-semiconductor-metal (MSM) photodetectors are formed on the top surface of the InGaAs layer for collection of the photo-induced carriers. The optical ridge waveguide is designed for lateral incidence of the light to enhance the MSM photodetector responsivity. Initial measurements on the optical waveguide and photodetector are presented.

Keywords: MBE, MMIC, InGaAs, photoreceiver, fiber optic links, MSM photodetector, optical waveguide, GaAs, HEMTs

1. INTRODUCTION

Monolithic integration of microwave/mm-wave and photonic devices will be essential for future military as well as commercial broadband communication and radar systems. Optical fiber links used in such systems will require highly efficient electrical to optical and optical to electrical conversion at the transmit and receiver ends, respectively. Today the majority of optical fiber links, both long haul and short haul, employ wavelengths from 1.3 to 1.55 μm to take advantage of the low loss and low dispersion characteristics of fiber operated within this range. Consequently, a key requirement for future optoelectronic integrated circuits (OEICs) is for the photonic devices to be compatible with this range of wavelengths. InGaAs, that can be epitaxially grown on GaAs or InP substrates, can have direct bandgap energies between 1.425 and 0.784 eV for an InAs content ranging from 0% to 50%, respectively. The corresponding optical cutoff wavelengths are 0.86 μm (GaAs) and 1.58 μm. To be compatible with 1.3 μm, requires an InAs mole fraction of 0.35. At this InAs content the lattice constant mismatch with GaAs is around 4%.

It is well known that due to superior carrier transport characteristics, GaAs MMICs, especially for mm-wave applications, typically employ 0.2 InAs mole fraction for the InGaAs channels. These InGaAs channel layers are thin enough (~120 Å) to form a pseudomorphic lattice structure of which the strain of the 2% mismatch is relaxed at the InGaAs/GaAs interface[1]. These pseudomorphic high electron mobility transistor (PHEMT) epi-grown structures provide the superior electronic performance required for mm-wave MMIC applications. To accommodate a 0.35 InAs mole fraction, requires even thinner layers to maintain the dislocation-free strained layer condition. Such thin layers are generally inconsistent with conventionally-constructed photonic devices. In fact, discrete InGaAs lasers and photodetectors for 1.3 μm application are

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generally fabricated on InP substrates due to the more favorable lattice-matched conditions. State-of-the-art (SOA) mm-wave integrated circuits and SOA 1.3 μm and 1.5 μm photonic devices monolithically integrated on GaAs substrates will reduce design and assembly complexity as well as substantially reduce production cost for both military and commercial OEIC components and systems.

Monolithic photoreceivers combining microwave (and/or mm-wave) and optical signal processing functions on a single chip will be an essential component of future broadband, high power fiber-optic links for communication and radar systems. As an example of the potential of MBE-grown material aimed at such application, we describe in this paper TLC's materials and device approach for the development of potentially low cost, high performance monolithic photoreceivers fabricated on GaAs that incorporate metal-semiconductor-metal (MSM) photodetectors, and optical waveguides for 1.3 μm light. The absorbing layer for the photodetectors is an $In_{(0.35)}Ga_{(0.65)}As_{(0.35)}$ layer that can also be used for monolithically integrating PHEMT-based MMICs. The advantage of MBE (in contrast to other epitaxial growth techniques) is its superior material quality and suitability for mm-wave MMICs as well as photonic devices. Strain-relieved lattice-engineered MBE growth also minimizes the thickness of the photonic layers. High MBE growth rate (>2 μm/hr) was also successfully employed to reduce growth time.

Appropriately designed, i.e., lattice-engineered pseudomorphic InGaAs material grown on GaAs with 0.35 InAs mole fraction can detect vertically incident light at wavelengths longer than is possible with GaAs[2]. However, due to the thin layer (a necessary condition to maintain a dislocation-free lattice) the detection efficiency (responsivity) is degraded because of a reduced carrier collection volume. To improve photodetector responsivity without degrading its high speed characteristics or its ability to be fabricated on a GaAs substrate, a monolithically integrated AlGaAs/GaAs/AlGaAs optical waveguide is used directly beneath the InGaAs absorbing layer[3,4]. This waveguide is designed to couple laterally-incident light into the absorbing layer over an extended interaction length thereby increasing the effective collection volume. This approach for the development of efficient and very broadband photoreceivers has been recently demonstrated by Lin, et al.[5] using a buried optical guide beneath a GaAs absorbing layer. This scheme, however, restricts the wavelength to 0.86 μm. The primary motivation for operation at the longer wavelengths and the use of an InGaAs active layer grown on a GaAs substrate is to reduce OEIC cost by taking full advantage of the already established optical fiber infrastructure at 1.3 and 1.55 μm and the relatively mature GaAs-based MMIC technology. Potential applications for this technology include broadband photoreceivers for microwave/optical systems including large phased array antennas, telecommunication systems, digital OEICs, local area networks (LANs) and home area networks (HANs).

2. MBE DESIGN CONSIDERATIONS AND EPITAXIAL GROWTH

There are two major issues associated with the epitaxial material growth of the InGaAs absorbing layers grown on GaAs substrates. First, is the requirement that the InAs mole fraction (MF) of the InGaAs absorbing layer must be at least 0.35 for it to be sensitive to 1.3 μm light. The second issue is associated with the fact that the underlying AlGaAs/GaAs/AlGaAs optical waveguide structure, having a lattice constant essentially that of GaAs, must be in close proximity to the absorbing layer to minimize optical loss and achieve high detector responsivity. Any intervening layer must be as thin as possible. On the other hand, since the lattice constant of $In_{(0.35)}Ga_{(0.65)}As_{(0.35)}$ differs from GaAs by 4% a thicker, not thinner, transition layer is typically required to prevent misfit dislocations and maintain device-quality material[2].

In this work a solution to these conflicting epitaxial growth requirements was found through a systematic set of MBE growth runs and material evaluations that led to a device-quality material structure consistent with the requirements of an $In_{(0.35)}Ga_{(0.65)}As_{(0.35)}$ absorbing layer and a thin transition layer (U.S. and international patents pending). All of the MBE growth runs were done using 3-inch wafers. To verify the quality of the critical interfaces, several standard material structures (for which TLC has extensive data) were first grown on top of the optical waveguide structure, including an AlGaAs/InGaAs PHEMT (InAs MF = 0.2) and an InAlAs/InGaAs HEMT (InAs MF 0.35). The PHEMT structure was grown directly on top of the 3-layer, 7-μm thick AlGaAs/GaAs/AlGaAs optical waveguide (instead of the normal GaAs buffer layer) resulting in nominal PHEMT material characteristics. The HEMT layers were succesfully grown for the first time over an AlAs transition layer. The transition layer thickness was decreased from 1-2 μm (standard practice) to less than 0.5 μm for the sake of enhancing the photodetector responsivity. The HEMT 300°K and 77°K mobilities were measured to be 5850 and 15170 cm/V-s, respectively, with the corresponding sheet carrier density of $\geq 2.0 \times 10^{12}$ cm^{-2}. These results indicate only minor degradation of the electronic characteristics. Finally, to allow formation of a good quality Schottky metal contact, a thin (barrier) layer of InAlAs lattice-matched to the InGaAs layer was grown on the top surface of the overall material structure. Figure 1 shows a simplified schematic of the final epitaxial structure on which were fabricated the optical ridge waveguides and the MSM photodetectors.

3. EXPERIMENTAL DEVICE RESULTS

To verify the quality of the epitaxial material from a device perspective, the MBE wafers containing the integrated HEMT and optical waveguide structures as well as specially prepared wafers containing specific isolated structures were used to fabricate a variety of test structures including MSM photodetectors and optical ridge waveguides. Their fabrication and subsequent evaluation is described next.

3.1 Optical ridge waveguides

Special wafers containing only the waveguide structure (consisting of a 4 μm AlGaAs lower cladding, a 2 μm GaAs guide layer, and a 1 μm AlGaAs upper cladding) were used to fabricate the ridge waveguides. The AlAs MF in the clad layers was 0.05. All three layers were nominally undoped. While it is well known that low loss ridge waveguide can be successfully fabricated by metal-organic chemical vapor deposition (MOCVD), it is not clear that waveguide structures of comparable quality can be grown by MBE. One issue is the relatively thick layers required for these waveguide structures. For practical manufacturing reasons this necessitates accelerated growth rates (>330 Å/min). Consequently, it is important to evaluate the quality of the optical layers grown under these high growth rate conditions.

For the input and output guides the critical issue is to achieve low loss and single mode propagation. Single mode is required both for optimum operation of the detector as well as for applications involving monolithically integrated devices such as modulators and switches. Simulations of the "4,2,1" μm AlGaAs cladding and GaAs guide layers described above predict single mode propagation for waveguide widths less than around 5.5 μm. To experimentally verify their optical performance a series of test patterns consisting of a set of straight ridge waveguides having constant width and up to 2 cm long were fabricated on the optical guide wafer. The widths ranged from 1 μm to 10 μm. Reactive ion beam etching (RIBE) was used to etch down through the guiding layer, reaching slightly into the lower clad layer (a total of about 3 μm). A schematic of the isolated ridge waveguide structure is shown in Figure 2a. Figure 2b shows an SEM photomicrograph of the RIBE-fabricated ridge waveguide.

A special optical bench setup based on the Fabry-Perot resonance method is used to measure the attenuation of the nearly 2 cm long ridge waveguides. The wafer sample containing the guide is cleaved at both ends to form the resonator. An ultra-stable solid state laser transmits through this resonator and the optical transmission is observed using a standard photodetector. The sample is then slightly heated (a few degrees). Due to the resulting dimensional change, the resonator standing wave pattern shifts as does the optical transmission. From the maxima and minima of the transmission data the modal attenuation is determined by a computer fitting routine. Based on the measurement of several waveguide samples the results, shown in Figure 3, indicate typical insertion loss of around 1.3 to 2 dB per cm for single mode propagation of 1.3 μm light. The lowest loss for single mode propagation occurs at a waveguide width of around 4 μm. These results are very encouraging for an MBE-grown structure, and more significantly, the insertion loss is well within the range of practical application in advanced optoelectronic/MMIC integrated circuits.

3.2 MSM photodetectors

For evaluating the InGaAs photodetector structures a set of MSM photodetector (i.e., back-to-back Schottky diodes) designs were developed and an optical mask set generated and fabricated. For lateral guided incidence the optical guide passes directly beneath and perpendicular to the interdigitated metal fingers. The light absorbing InGaAs layer is restricted to the area of the fingers. The basic pattern used for all designs consists of 1 micron interdigitated metal fingers, 10 um long, spaced 4 μm apart. Away from the finger area the active area is etched off the top of the waveguide. The input and output guides are 4 μm wide to ensure single mode propagation. In addition to the detectors designed for lateral incidence a set of test structure detectors were designed for vertical illumination. The same 1 x 4 finger width and spacing is used over the total active area of 40 x 50 μm^2. These devices were used for the initial measurements of the photodetector structures using vertical illumination to verify basic operation and responsivity over the 1.26 to 1.33 um wavelength range.
Evaluation of the detectors using lateral, guided illumination has not yet been completed.

Photodetector fabrication includes 50Å Ti/800Å Au fingers deposited directly onto the InAlAs top surface. Figure 4 shows a SEM photomicrograph of the fabricated 40 x 50 μm^2 MSM photodetector. As discussed above, the InGaAs photodetectors are fabricated with the underlying optical waveguide layers. Although the waveguide structure was not used for light injection (lateral incidence), its presence below the absorbing layer verifies detector operation under vertical incidence with the basic materials configuration expected for optimized prototype OEICs.

For the experimental measurements a solid state tunable laser coupled to an optical fiber was used to direct light onto the interdigitated metal fingers of the photodetector. The beam was confined to the area of the metal fingers and its intensity as well as its wavelength adjusted from less than 100 μW to 400 μW and from 1.26 μm to 1.33 μm, respectively. Figure 5 shows the measured dark current-voltage characteristic. Excellent symmetry in the reverse-biased back-to-back diode characteristic, including a breakdown voltage approaching 80 V and a dark current of tenths of a μA are obtained. The photodetector can be biased over a wide voltage range, and typically is operated at around 40 V to maximize responsivity. Figures 6a, b, and c, show the detector's I-V characteristic for 1.27 μm, 1.3 μm and 1.33 μm illumination, respectively over the intensity range 0 (dark conditions with room lights turned off) to 400 μW of optical power and a bias range from -40 to +40 V. The measured characteristics are well behaved with the photocurrent well above the negligible dark current for all non-zero intensities tested. The detector's responsivity for 1.27 μm illumination and 40 V bias is 0.05 A/W. It is important to bear in mind that the relatively low responsivity is attributed to the short absorption distance resulting from the vertical incidence mode of operation. With lateral, on-chip guided incidence and an optimized materials structure, the responsivity is expected to be greatly enhanced. Finally, Figure 10 shows the measured detector's dependence on optical wavelength. It is clear from these measurements that the characteristics are not optimized for the 1.3 μm region and that further material and detector design improvements are necessary. Nevertheless, these initial results are encouraging and provide a basis for the realization of a high responsivity, 1.3 μm photodetector fabricated on a GaAs substrate.

4. CONCLUSIONS

The above results confirm the basic feasibility of the simultaneous HEMT, optical waveguide, and optical detector capabilities of this MBE-grown heterostructure material. The InGaAs material with a high indium mole fraction (0.35) has been successfully grown on a GaAs substrate and used as the absorption layer for long wavelength photodetectors. This same layer is also designed to be used as the active layer in a HEMT-based MMIC which can be fabricated on the same die. Optical loss measurements of the 3-layer ridge waveguide indicate that the performance is more than adequate to meet the requirements of on-chip optical waveguides for future OEICs. Furthermore, accelerated growth techniques have been successfully employed for the relatively thick (~3 μm) MBE-grown, 3-layer AlGaAs/GaAs/AlGaAs waveguide structure. The latter point being essential if this approach is to be commercially viable. Although the overall material structure has not yet been optimized for 1.3 μm detection, successful fabrication of functional InGaAs MSM photodetectors on top of the optical waveguide structure and GaAs substrate has been demonstrated. These detectors exhibit nominal photodetector characteristics in the 1.27 to 1.33 μm range, albeit with relatively low responsivity due to the vertical mode of illumination.

For the future, it is expected that with guided wave detection (lateral incidence) photodetector responsivity will be greatly increased. Coupled with a velocity-matched traveling wave structure for the detector design[5] and a HEMT-based MMIC postamplifier, this MBE materials approach promises to be the basis for the development of low cost monolithic photoreceivers for broadband microwave-(or mm-wave) modulated light operating in the 1.3 μm to 1.55 μm range. Typical applications include remoting of phased array antennas, broadband wireless telecommunications for HANs and LANs, and military radar. The basic approach can be used to integrate other photonic devices including laser structures.

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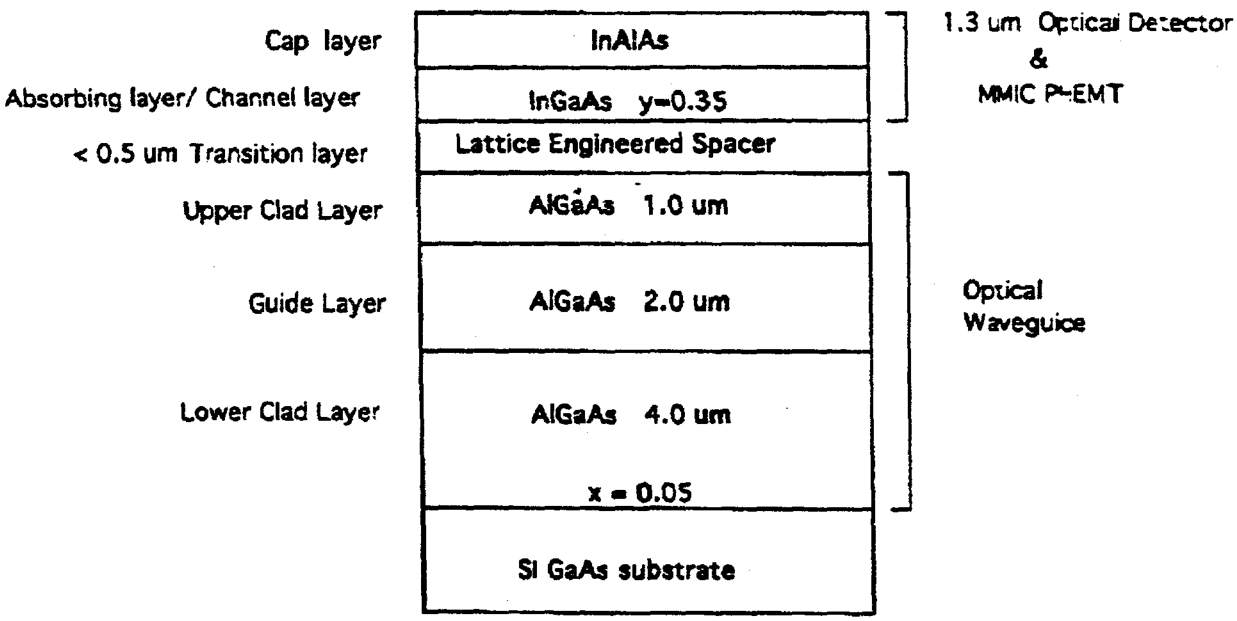
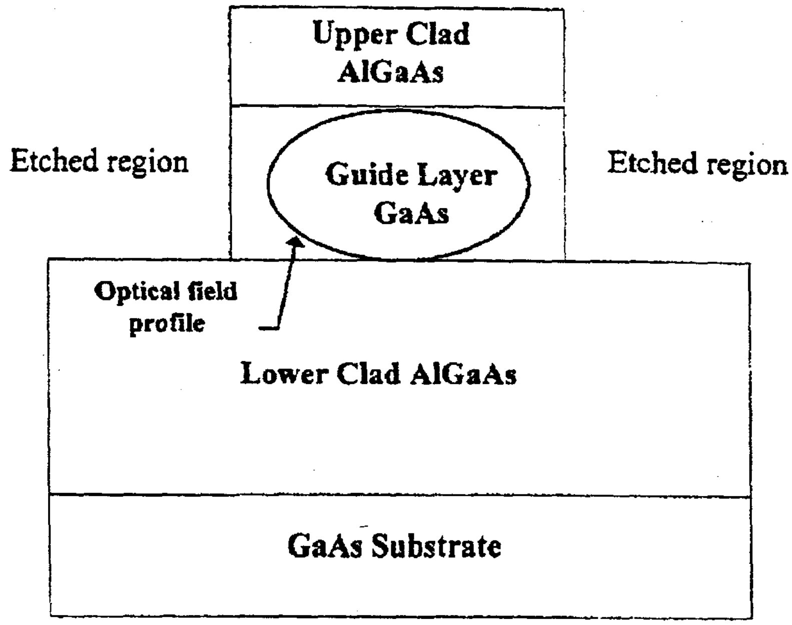
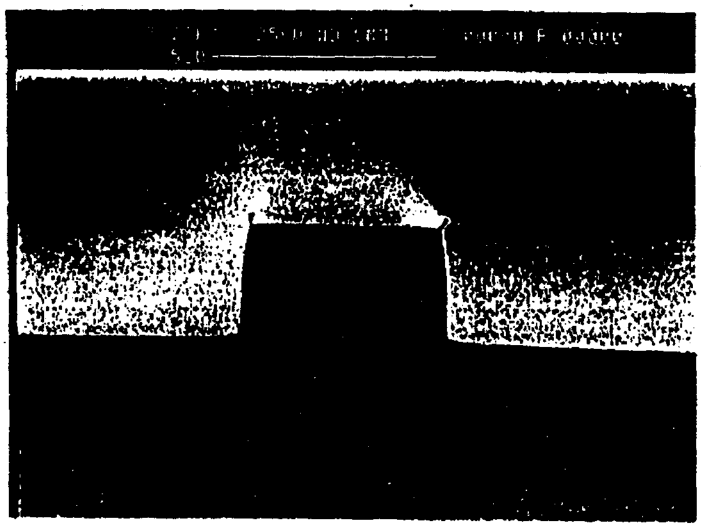


Figure 1. Schematic representation of MBE layers including an InGaAs active layer used for monolithic HEMTs and long wavelength photodetectors grown on top of GaAs.



(a)



(b)

Figure 2. Low loss 4 μm-wide optical waveguide fabricated by MBE
(a) schematic
(b) scanning electron microscope (SEM) photomicrograph

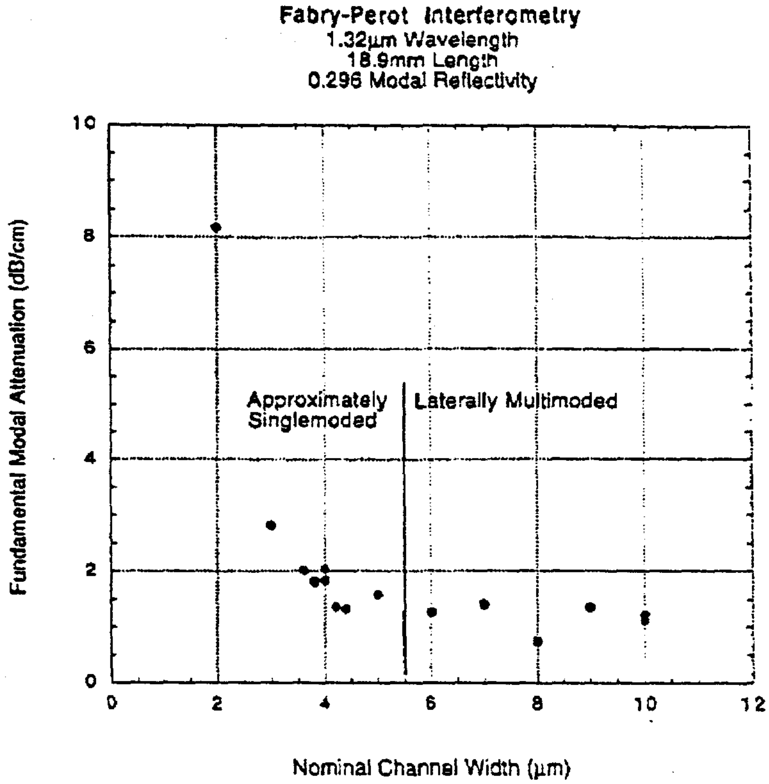


Figure 3. Measured optical waveguide loss: For a 4 um wide ridge typical losses are between 1.3 and 2 dB per cm.

Figure 4. SEM Photomicrograph of a 40 x 50 μm^2 photodetector for 1.3 μm light fabricated on a GaAs substrate

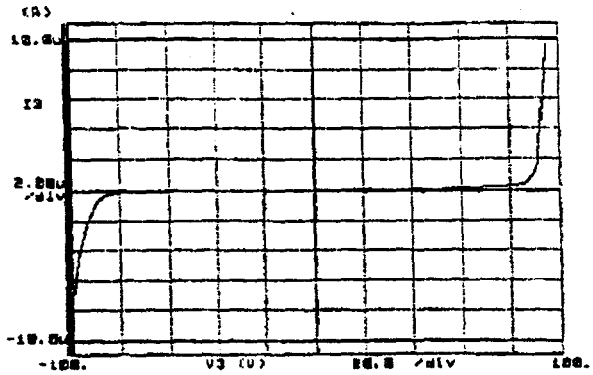


Figure 5. Dark current I-V characteristic for MSM photodetector of Figure 4: Breakdown voltage is nearly 80 V.

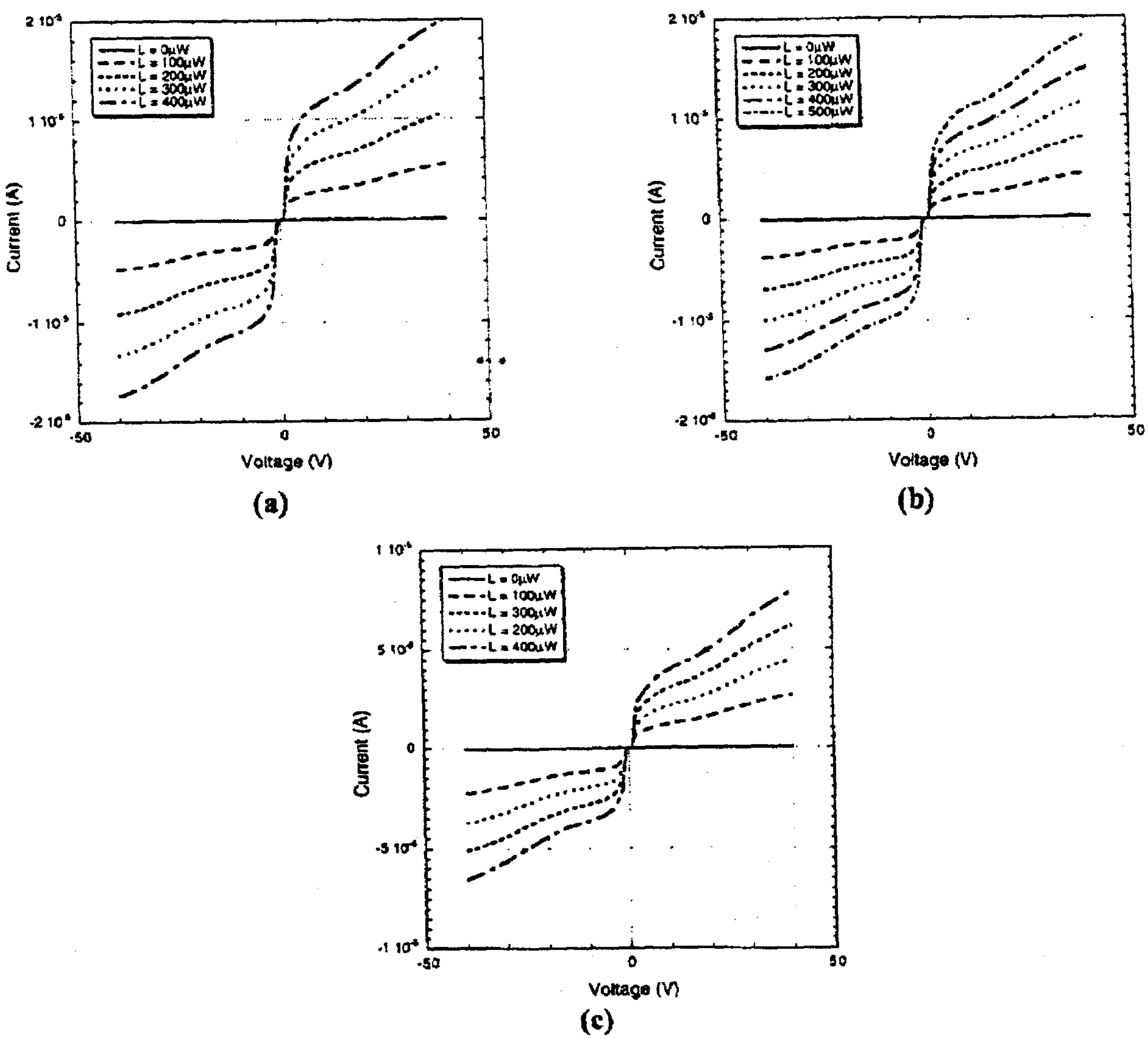


Figure 6. Photodetector I-V's for 3 different wavelengths and different optical powers: (a) 1.27 μm (b) 1.3 μm (c) 1.33 μm (vert. scale = 10 μA/div., (a) & (b); 5 μA/div., (c))