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P/N In(Al) GaAs MULTIJUNCTION LASER POWER CONVERTERS

Steven Wojtczuk and Themis Parodos
Spire Corporation
Bedford, Massachusetts

and

Gilbert Walker
NASA Langley Research Center
Hampton, Virginia

SUMMARY

Eight In(Al)GaAs PN junctions grown epitaxially on a semi-insulating wafer were monolithically integrated in series to boost the ~0.4V photovoltage per typical In(Al)GaAs junction to over 3 volts for the 1 cm² laser power converter (LPC) chip. This is the first report of a multijunction LPC for the 1.3 to 1.5 μm wavelength range. This wavelength range is optimum for laser power transmission over low-loss single-mode silica optical fiber, and is also useful with high efficiency 1.315 μm iodine lasers in free-space power transmission.

Advantages of multijunction LPC designs include the need for less circuitry for power re-conditioning and the potential for lower I²R power loss. As an example, these LPC's have a responsivity of ~1 amp/watt. With a single junction LPC, 100 watts/cm² incident power would lead to about 100 A/cm² short-circuit current at ~0.4V open-circuit voltage. One disadvantage is the large current would lead to a large I²R loss which would lower the fill factor so that 40 watts/cm² output would not be obtained. Another is that few circuits are designed to work at 0.4 volts, so DC-DC power conversion circuitry would be necessary to raise the voltage to a reasonable level. The multijunction LPC being developed in this program is a step toward solving these problems. In the above example, an eight-junction LPC would have eight times the voltage, ~3V, so that DC-DC power conversion may not be needed in many instances. In addition, the multijunction LPC would have 1/8 the current of a single-junction LPC, for only 1/64 the I²R loss if the series resistance is the same.

Working monolithic multijunction laser power converters (LPCs) were made in two different compositions of the In_xAl_yGa_{1-x-y}As semiconductor alloy, In_{0.53}Ga_{0.47}As (0.74 eV) and In_{0.5}Al_{0.1}Ga_{0.4}As (0.87 eV). The final 0.8 cm² LPCs had output voltages of about 3 volts and output currents up to about one-half amp. Maximum 1.3 μm power conversion efficiencies were ~22%. One key advantage of multijunction LPCs is that they have higher output voltages, so that less DC-DC power conversion circuitry is needed in applications.

INTRODUCTION

Laser power converters (LPCs) efficiently transform the optical power of a laser beam into electrical power (ref. 1). Myriad applications exist for this technology:

Powering planetary "rover" vehicles - The original goal of this program was to develop an efficient converter of 1.315 μm light that would be supplied by a high-power solar-pumped iodide laser (ref. 2) in orbit around a planet. This laser would be aimed at a "rover" vehicle on the planet's surface, so that heavy batteries or other vehicular power sources would not be needed.

Powering orbital transfer vehicles - Powerful ground-based lasers could deliver more optical power to an array of LPCs on a space platform than sunlight could deliver optical power on an array of

solar cells of similar weight to the LPC array (ref. 3). As an additional advantage, because the LPC system is optimized to the single laser wavelength, it will also be more efficient at converting the laser light than a solar cell array would be at converting the multiple-wavelength sunlight.

Safe explosive fuses - Explosives for both commercial and military uses are often detonated remotely by an electrical signal sent over wires to a blasting cap attached to the explosives. The wires can act as antennae, and a passing radio transmitter (*e.g.* a CB radio) can induce a voltage which prematurely detonates the explosive, with unfortunate consequences. If the wires are replaced by optical fiber, the system becomes immune to this hazard. LPCs are used to convert the light signal sent over the fiber into electricity to trigger the explosion safely.

Powering remote sites - The $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ LPCs developed in this Phase II are ideally suited for use with low-loss silica optical fiber transmission systems. Such optical fiber has an attenuation minimum at 1.5 μm (power lost is only 0.2 decibels per kilometer). Undersea cable telecommunications repeater stations power is one possible application.

Power for telephones - Telephone lines superimpose weak voice signals on a steady 48V DC potential. This potential is used to power the phone ringer, *etc.* When optical fiber comes into the home, LPCs will most likely come with it to mimic the present system. A steady high intensity laser beam present on the fiber would be superimposed with weaker optical voice signals; the LPC would supply power to the phone ringer.

This program (ref. 4) was undertaken since efficient photovoltaic converters did not exist for use with 1.3 μm light. For example, silicon (Si) and gallium arsenide (GaAs) solar cells, the most popular types, have semiconductor bandgaps too high to absorb any of the 1.3 μm laser light. The 0.94 eV photon energy is smaller than the 1.1 eV bandgap of silicon or the 1.4 eV bandgap of gallium arsenide and passes through these materials without absorption. The quaternary (four-component alloy) compound semiconductor indium aluminum gallium arsenide $\text{In}_x\text{Al}_y\text{Ga}_{1-x-y}\text{As}$ was selected as the cell epitaxial material because it had three desirable characteristics:

- 1) The bandgap was tunable in the range from 0.36 eV to 2.2 eV. Material with any bandgap in this range could be obtained by epitaxially growing the right material composition.
- 2) A small subset of material compositions, with bandgaps ranging from 0.74 eV to 1.52 eV, was available having the same crystal lattice constant as an available wafer, indium phosphide (InP). This would allow defect-free (*i.e.* dislocation-free) material to be grown with better performance than would otherwise be possible.
- 3) The $\text{In}_x\text{Al}_y\text{Ga}_{1-x-y}\text{As}$ system is a (periodic table) group III-III-III-V material. Because there is only one group V hydride, arsine, the material composition should theoretically be easier to control than, for example, InGaAsP, a group III-III-V-V with much the same bandgap range as $\text{In}_x\text{Al}_y\text{Ga}_{1-x-y}\text{As}$. When growing $\text{In}_x\text{Al}_y\text{Ga}_{1-x-y}\text{As}$, there can be a great excess of the group V arsine gas present; it does not have to be tightly controlled. Since the three group III materials (indium, aluminum, gallium) should incorporate into the growing epitaxial film similarly, the composition should be easy to adjust.

LASER POWER CONVERTER EPILAYER STRUCTURE

Table I shows the epilayer structure for the LPCs. Both $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and $\text{In}_{0.5}\text{Al}_{0.1}\text{Ga}_{0.4}\text{As}$ LPCs used the same overall structure shown in Table I, the only difference being the $\text{In}_x\text{Al}_y\text{Ga}_{1-x-y}\text{As}$ composition. The epitaxial layers were grown in a Spire 100S low-pressure metalorganic chemical vapor deposition (MOCVD) reactor at a temperature of 690°C, using trimethylindium, triethylgallium,

trimethylaluminum, and arsine. Dimethylzinc and silane were the P and N type dopants, respectively. The 690°C growth temperature was a compromise between better $\text{In}_x\text{Al}_y\text{Ga}_{1-x-y}\text{As}$ material lifetime (better at higher temperatures due less aluminum bonding with oxygen) and better compositional uniformity (better at low temperatures since indium has a low vapor pressure).

Table I *P-on-N laser power converter epilayer structure.*

| Layer | Material | Doping cm^{-3} | Thickness μm | Comments |
|----------------------|------------|-------------------------|-------------------------|--|
| Emitter | In(Al)GaAs | P, 10^{19} (max) | 0.3 | > Thickness tradeoff - QE (thin better) vs. low series resistance (thick better) > InGaAs is a good contact layer |
| Base | In(Al)GaAs | N, 2×10^{17} | 2.5 | > ~3 absorption lengths thick; absorbs 95% of 1.3 μm light > ~4 hole diffusion lengths thick |
| B.S. Field Etch Stop | InP | N, 10^{19} (max) | 0.1 | > Minority carrier mirror enhances QE > InGaAs mesa etch does not etch InP |
| Buried Layer | InGaAs | N, 10^{19} (max) | 3 | > Thick, hi-doped to lower I^2R loss > Bottom contact layer |
| Substrate | InP | Semi-insulating | 500 | > Fe-doped semi-insulating wafer to isolate the LPC multi-junctions |

LASER POWER CONVERTER FABRICATION

The laser power converters (LPC) we have fabricated are a series connection on a semi-insulating InP wafer of In(Al)GaAs P on N mesa photodiodes. Similar devices for 800 nm use have been made on semi-insulating GaAs (ref. 5). The main challenge in multijunction LPC fabrication was establishing a process to interconnect the individual junctions.

The first step in fabrication was isolation of the individual mesas required to form the LPCs. A positive photoresist process was used to pattern the mesas. Care was taken to insure the mask was aligned to the substrate such that any orientation dependent etches would result in profiles which could easily be covered by subsequent thin film depositions. A 3:4:1 $\text{H}_3\text{PO}_4\text{:H}_2\text{O}_2\text{:DI}$ etch, selective to In(Al)GaAs, was used to remove the junction layers to the InP etch-stop. Typical etch rates were 400 Å/s. Etching to completion was achieved by observing a color change while the samples were immersed in the solution. Continuing for an additional 10s beyond this point insured total removal of the In(Al)GaAs junction layers. With the same photoresist in place, a 10s HCl dip removed the InP etch stop exposing the N^+ In(Al)GaAs buried layer. To complete isolation of the mesas, the 3:4:1 $\text{H}_3\text{PO}_4\text{:H}_2\text{O}_2\text{:DI}$ etch was used to remove the InGaAs buried layer down to the semi-insulating InP substrate. Since the etch is selective, a protruding overhang of the InP etch-stop resulted as the 3:4:1 solution removed the In(Al)GaAs. To insure continuity of the films to follow, we used a 5s HCl dip to remove the InP. Initially we were concerned that this final dip would undercut the InGaAs buried layer, however, examination of several cleaved cross sections proved that there was no undercut. In fact we found a transition between the InGaAs and InP which was favorable for film continuity.

Once the mesas had been formed, the next step was exposure of the N^+ InGaAs buried layer to form the back contact. Once again, positive resist was used. Care was taken to insure coverage of the mesa edges. The 3:4:1 solution was used to remove the junction layers to the etch stop and an HCl dip removed the InP.

A 2000Å of Si_3N_4 was deposited on the wafers by plasma assisted chemical vapor deposition (PACVD). The Si_3N_4 was then patterned to cover one side of the interconnect from the P^{++} top contact to the bottom of the via. The BHF used to pattern the Si_3N_4 undercut the photoresist and reduced the width of the final pattern. Therefore to correct for the undercut, we adjusted alignment of the Si_3N_4 etch mask to insure coverage of the step. In addition, the BHF bubbled vigorously as it etched the Si_3N_4 . Any bubbles which adhered to the surface acted as masks, leaving some Si_3N_4 underneath as the film etched. To minimize the amount of Si_3N_4 residue caused by the bubbles, we removed them at the midpoint of the etch using flowing DI water. Upon completion of this process, both the N and P sides of the junctions were ready for metallization.

Based on supporting experimental data indicating good contact resistance, we chose to use the same metal system for ohmic contact to both the N and P type materials. Image reversal photolithography and lift-off was used to pattern the 3 μm thick metallization.

The last step in LPC fabrication was deposition and patterning of the anti-reflection (AR) coating. A single-layer, quarter-wave PACVD Si_3N_4 film tuned for minimum reflectance at 1.315 μm was deposited on the wafers. A final photolithographic step removed the Si_3N_4 from the bonding regions. Figure 1 shows a top view of a completed two-inch wafer. Figure 2a shows a single multijunction LPC and Figure 2b shows one of the test sites. Figures 3a shows details of the grid lines too fine to see in Figure 2a, and Figure 3b shows details of the interconnect.

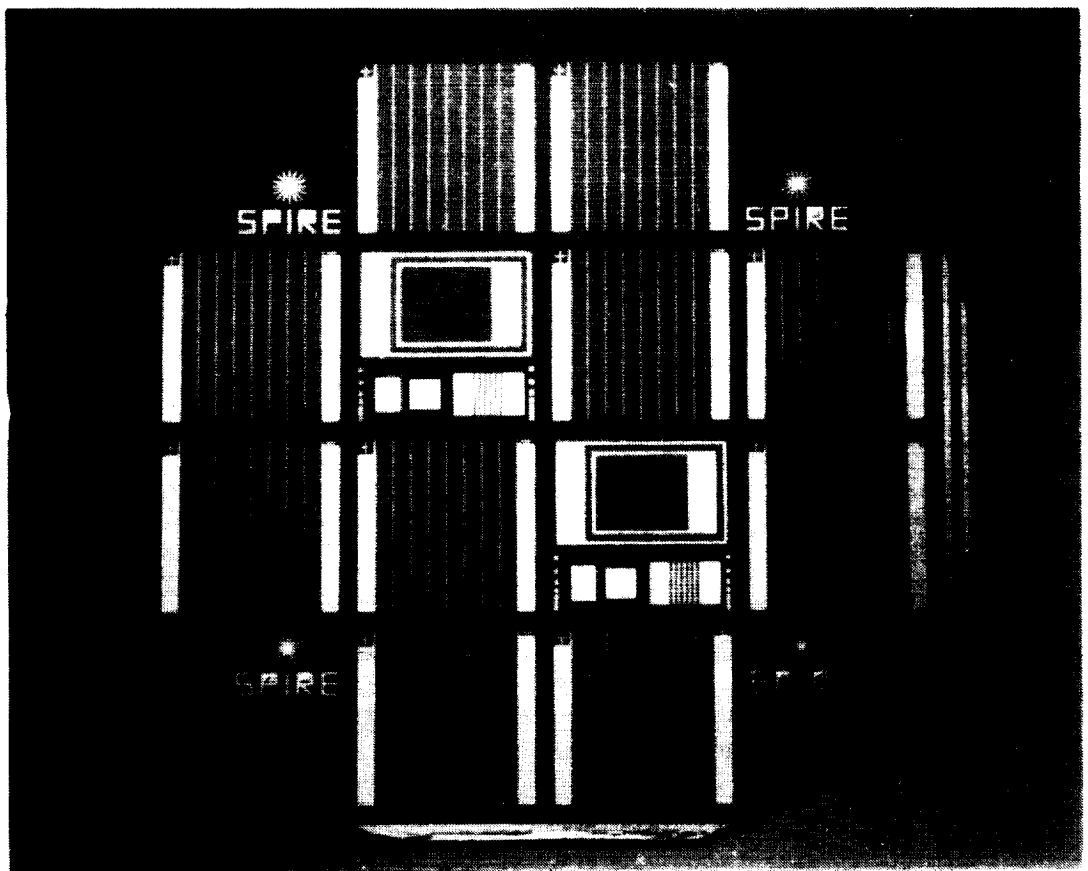
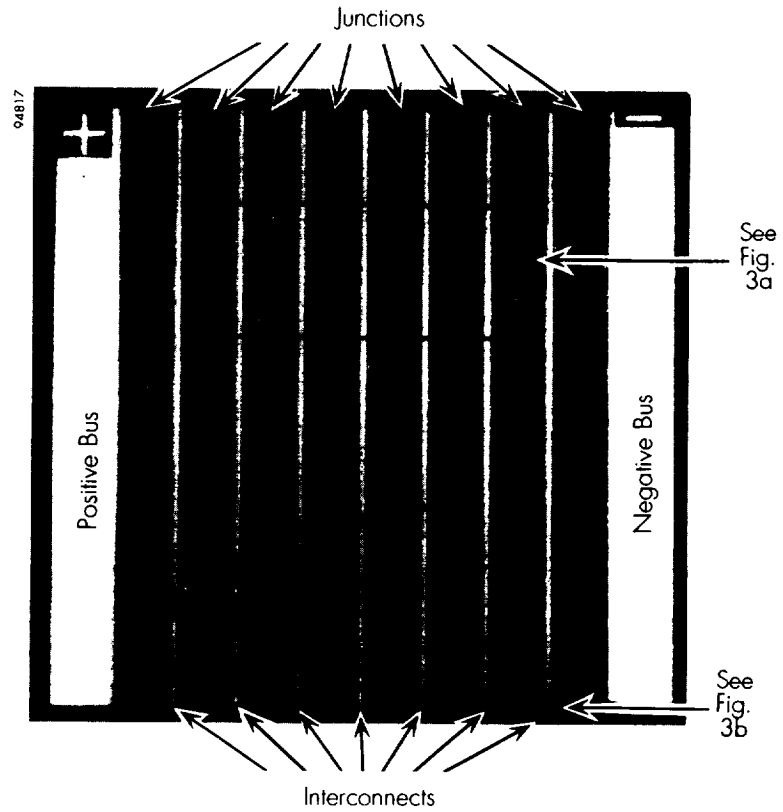


Figure 1 *Two-inch InP wafer with ten LPCs and two test sites. These square devices are designed for uniform illumination over the photoarea from a distant laser. LPCs for optical fibers or for free-space transmission with small diameter laser beams should have pie-shaped circular photoareas.*

2a)



2b)

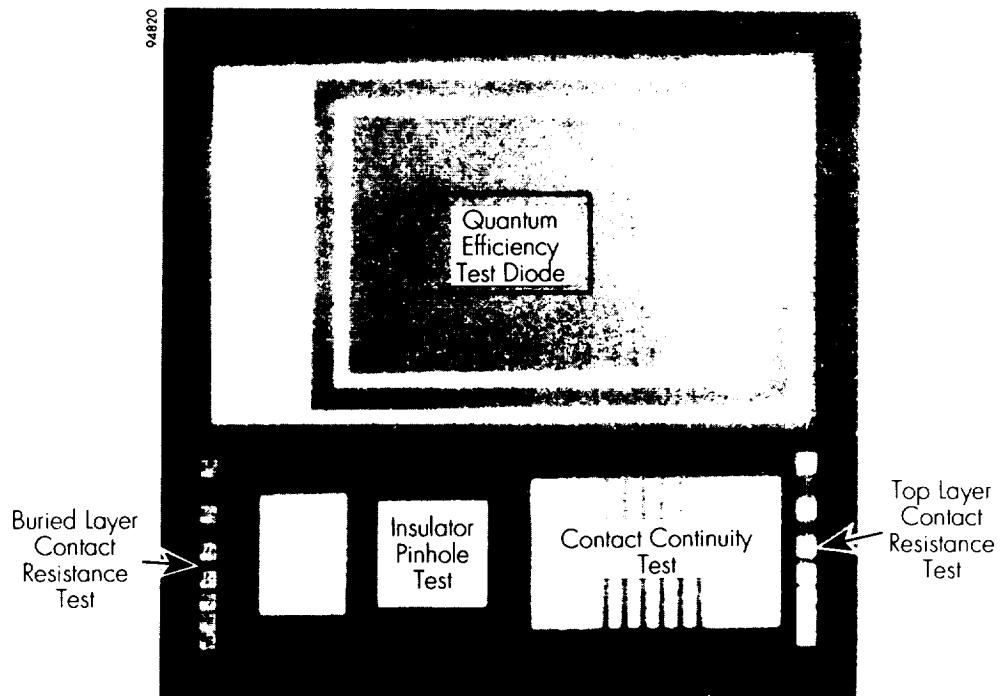
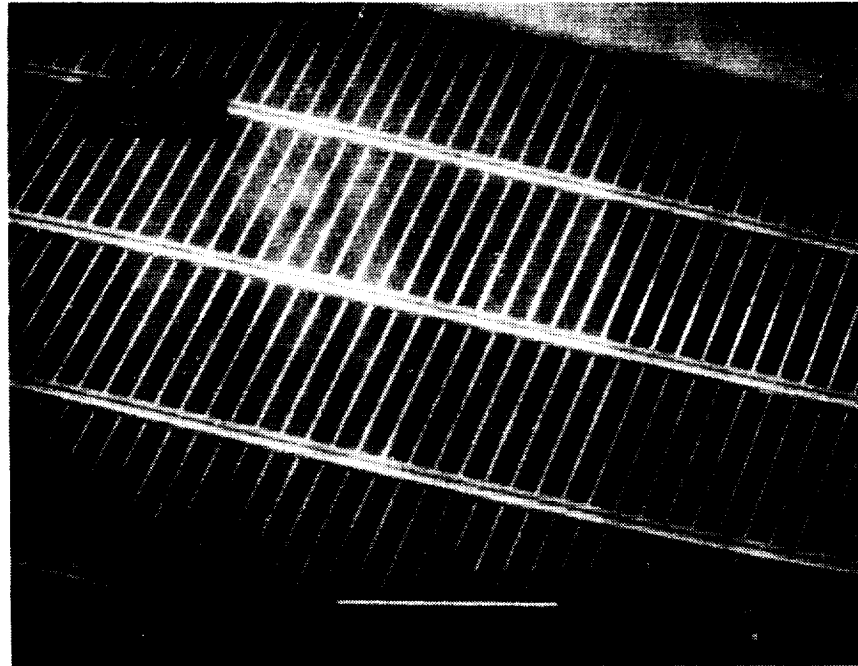


Figure 2 a) Multijunction 1 cm^2 LPC (0.8 cm^2 photoarea); b) test site containing large single-junction photodiode for QE measurement, contact resistance test patterns for both the top (P) and bottom (N) contact layers, and an insulator test pattern.

3a)



3b)

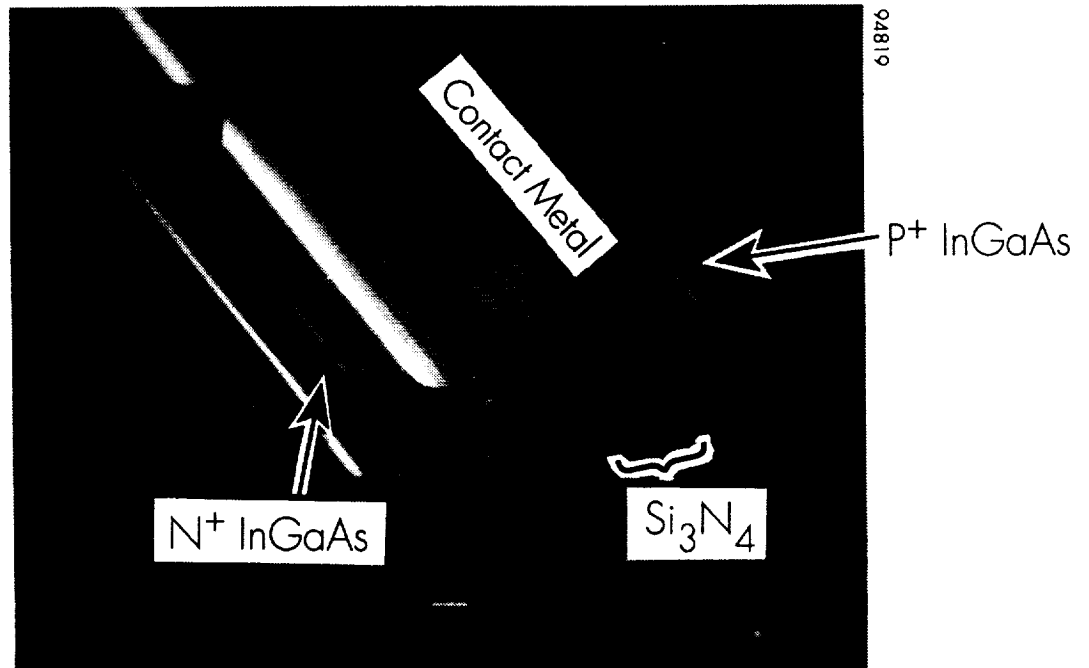


Figure 3

a) SEM detail of top contact 5 μm gridlines (100 μm centers) too fine to see in Fig. 2a.
b) SEM detail of 100 μm wide metal interconnect from bottom N^+ In(Al)GaAs layer of one junction over a silicon-nitride-protected mesa edge onto the upper P^+ InGaAs layer of the next junction. The number of junctions per cm for the LPC is limited by this "dead" interconnect area to about 10 per cm (100 μm dead to 900 μm active width).

MEASUREMENTS

Figure 4 shows measured absolute quantum efficiencies of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and $\text{In}_{0.5}\text{Al}_{0.1}\text{Ga}_{0.4}\text{As}$ single junction test diodes.

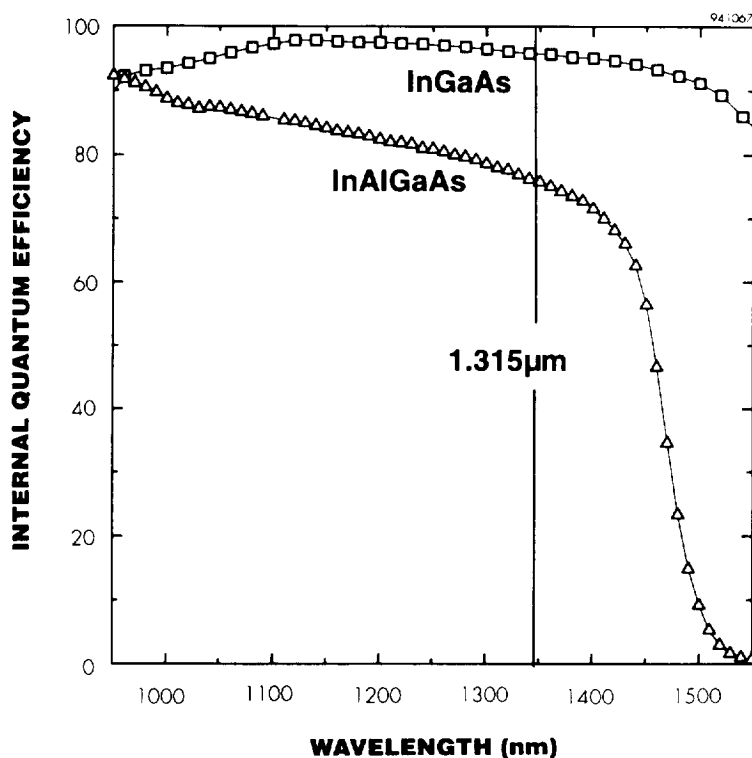


Figure 4 Quantum efficiency of 0.74 eV InGaAs and 0.85 eV InAlGaAs test diodes. The InGaAs results are typical, but InAlGaAs results vary considerably depending on lattice-mismatch and MOCVD reactor growth conditions; the InAlGaAs device here is from a better MOCVD growth run.

In general, the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ devices performed better than the In(Al)GaAs LPCs, even though the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ LPCs bandgap was not as favorable for this application. The quaternary In(Al)GaAs devices are harder to lattice-match during epitaxial growth repeatably than the ternary InGaAs devices. In addition, the aluminum in the InAlGaAs devices scavenges oxygen very readily. In general, quantum efficiencies were considerably lower for In(Al)GaAs LPCs than for InGaAs LPCs. The dark currents for In(Al)GaAs LPCs were often better than the InGaAs devices, presumably because of the higher bandgap, and the photovoltages were as good or slightly better than InGaAs devices; however, the lower photocurrent and quantum efficiency of the In(Al)GaAs devices always meant the InGaAs devices were better performers.

Figure 5 below shows two illuminated I-V curves of an eight junction $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ LPC. An equivalent 1.3 μm single wavelength power density is shown for each curve. The measurements were actually taken with a solar simulator (concentrated white light). We now explain how we arrived at an equivalent 1.3 μm light power density with the simulator. The devices were illuminated and driven to an arbitrary photocurrent. The 1.3 μm quantum efficiency measured previously (similar to Figure 4) from the test site single junction diode is used to determine how much 1.3 μm light would need to be incident on the LPC to produce the simulator photocurrent:

$$\text{Equivalent } 1.3 \mu \text{ power} = \frac{hc}{q\lambda\eta} * (\text{simulator photocurrent})$$

where h is Planck's constant (J/s), c is light's velocity (m/s), q is the electron charge (C), λ is 1.3×10^{-6} m, and η is the $1.3 \mu\text{m}$ quantum efficiency from the test site diode for the wafer. The above formula is a simple re-arrangement of the standard formula for the photocurrent from a photodetector. The dead interconnect area (10%) and gridline shadow loss (5%) of the LPC, which is not present or part of the test site diode, is included in this calculation. This is the power density indicated on the graph. The open-circuit voltage and fill-factor are exactly the same for either white light or single $1.3 \mu\text{m}$ wavelength illumination as long as the total photocurrent is exactly the same, as it is by definition here.

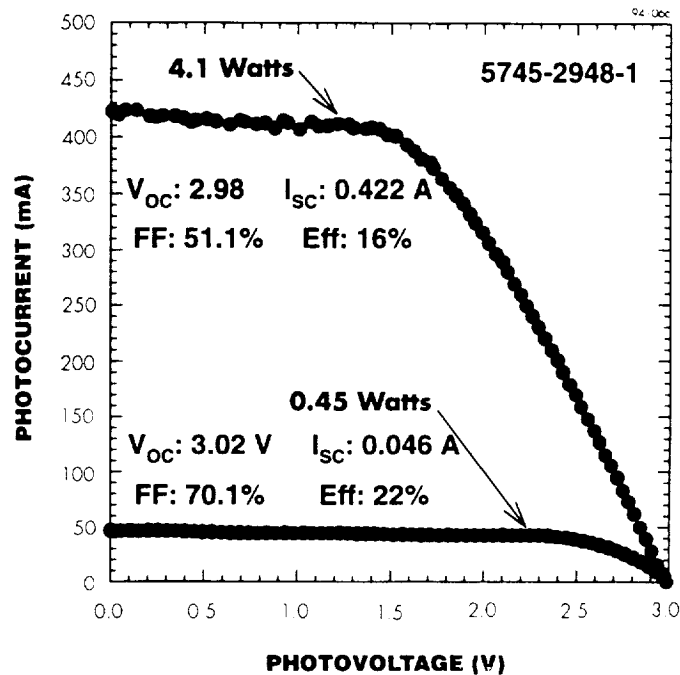


Figure 5 *I-V curves of an eight-junction $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ laser power converter under two $1.3 \mu\text{m}$ equivalent illumination levels. At higher photocurrents the device becomes series resistance limited*

CONCLUSIONS

We have demonstrated working monolithic multijunction (eight-junction) $\text{In}_x\text{Al}_y\text{Ga}_{1-x-y}\text{As}$ LPCs with $1.3 \mu\text{m}$ power efficiencies up to 22%. Although the (0.85 eV) $\text{In}_{0.5}\text{Al}_{0.1}\text{Ga}_{0.4}\text{As}$ LPCs should have been superior to the (0.74 eV) $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ LPCs for converting $1.315 \mu\text{m}$ light (0.94 eV), additional material dislocation defects and oxygen recombination sites limit the current performance of the more complex $\text{In}_{0.5}\text{Al}_{0.1}\text{Ga}_{0.4}\text{As}$ LPCs. The simpler $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ LPCs in all cases had better power conversion efficiencies. LPCs of both types are currently limited by series resistance to incident optical power densities below 10 W/cm^2 . Some additional redesign of the contact grid and emitter and buried layers may result in some improvement of the series resistance. However, to improve the operating power density by an order of magnitude, more junctions are needed to lower the photocurrent and I^2R loss. Additional development of photolithographic processing of non-planar devices is needed in order to successfully pattern the photoresist in the small trenches between LPC junctions.

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