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GaAs SOLAR CELLS FOR LASER POWER BEAMING

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ABSTRACT

This paper describes efforts to develop GaAs solar cells for coupling to laser beams in the wavelength range of 800 to 840 nm. The work has been motivated primarily by interests in space-to-space power beaming applications. In particular, the Battelle Pacific Northwest Laboratories is conducting studies of the utilization of power beaming for several future space missions. Modeling calculations of GaAs cell performance have been carried out using PC-1D to determine an appropriate design for a p/n cell structure. Epitaxial wafers were grown by MOCVD and cells fabricated at WSU Tri-Cities. Under simulated conditions, an efficiency of 53% was achieved for a cell coupled to 806 nm light at 400 mW/cm².

1. INTRODUCTION

This paper describes efforts to develop GaAs solar cells for coupling to laser beams in the wavelength range of 800 to 840 nm. The work has been motivated primarily by interests in space-to-space power beaming applications. In particular, the Battelle Pacific Northwest Laboratory is conducting studies of the utilization of power beaming for future space missions. However, high efficiency monochromatic GaAs cells will also be useful for numerous applications requiring isolated power and voltage, or transmission of power without electromagnetic interference. This paper considers cell design calculations, cell fabrication, testing procedures with a laser beam, and experimental results for GaAs cells.

When coupled to laser light comprised of photons with an energy equal to the cell material bandgap, a cell can convert the laser beam beam power to electrical power quite efficiently. Before considering the potential efficiency of GaAs cells specifically, it is interesting to consider the efficiency of monochromatic cells over a range of bandgaps. The approach used here is similar to that used to discuss the limiting efficiency of cells coupled to the solar cell spectrum. Figure 1 indicates some of the important considerations. The limiting efficiency is determined by choosing a Q_{ext} of 1.0 ; thus, J_{sc} is set equal to J_{max}.which can be expressed as a fuction of photon energy. If we assume that the monochromatic cell is tuned to the photon energy, then J_{max} is expressed as a function of bandgap. The complete I-V curve is defined if we assume that the current losses are limited by minority carrier injection, and express J₀ as a function of bandgap. The constant indicated in Figure 1 has been selected to agree with the best results we are aware of for GaAs cells, namely, the highest efficiency cells reported by Spire Corporation. Once a value of bandgap is selected, the I-V curve is determined and the maximum power can be calculated . Results for the maximum efficiency of monochromatic cells vs bandgap assuming an input laser beam intensity of 500 mW/cm² are plotted in Figure 2. If we consider GaAs specifically, the limiting efficiency for a 'tuned' cell at 500 mW/cm² is on the order of 70 %. Results for more realistic limiting conditions are given in Table 1. Performance calculations were conducted assuming an incident laser beam intensity of 100 mW/cm² and a wavelength of 806 nm. As indicated, the limiting efficiency for Q_{ext} = 1.0 is 62 % and for Q_{ext} = 0.95 it is 58.8 %. If

one assumes an incident intensity of 400 mW/cm^2 and a wavelength of 840 nm , the corresponding efficiencies are 65% and 62% .

2. ARRAY CONCEPTS

Preliminary considerations have been given to array concepts because of the impact on cell design. It is assumed that passive cooling will be utilized. Thus the input beam intensity is assumed to be in the 100 to 500 mW/cm^2 range. Such an incident intensity condition will result in short circuit current values typical of a concentrated AMO spectrum of $2X$ to $8X$. Thus, it is desirable to have fairly large busbars so that the current can be extracted without significant losses. Figure 3 provides an isometric view of an array concept that is being considered for this application, namely, a hidden busbar arrangement. Triangular reflectors would be bonded to relatively large busbars so that photons normally obscured by the busbars are reflected to active cell area. Based on this approach to array design, the cell collector grid design depicted in Figure 4 was selected. Since an array design is assumed for which photons are not obscured by busbars, cell efficiency is calculated by neglecting busbar area. This method of calculating cell efficiency is equivalent to that used for concentrator cells. Thus, we will refer to a concentrator cell efficiency measurement.

3. DETAILED MODELING OF GaAs CELL PERFORMANCE

Modeling calculations were conducted for GaAs p-on-n (p/n) solar cells coupled to a monochromatic light for wavelengths ranging from 600 nm to 900 nm , and with incident power covering the range of 100 mW/cm^2 to 500 mW/cm^2 . The basic cell structure is described by Figure 5. The values for the various layer thicknesses are those determined to be optimum for a cell coupled to an 806 nm laser beam. Modeling calculations of cell performance involving variation of layer thicknesses and dopant densities were conducted using the one dimensional code PC-1D, supplemented by the use of computer codes to account for power losses due to sheet resistance and grid finger resistance. Most of the performance calculations have been carried out for a laser wavelength of 806 nm , since initial experimental studies have been based on this wavelength. Figure 6 gives cell efficiency versus emitter depth for a range of emitter-concentration values. The calculated results plotted in Figure 6 assume a collector grid density of 30 cm^{-1} , collector grid fingers that are $10 \mu\text{m}$ wide and $4 \mu\text{m}$ high, and a cell array configuration that provides for photon deflection away from the bus bar (Hidden Busbar Concept). As indicated by Figure 6, the optimum p/n cell design involves a relatively thick emitter, $1.5 \mu\text{m}$ to $2.0 \mu\text{m}$, and doped at a relatively low concentration, $5E17 \text{ cm}^{-3}$. These calculations assume a base dopant concentration of $1E17 \text{ cm}^{-3}$, and front and back surface recombination velocities of $1E4 \text{ cm/sec}$.

Figure 7 describes calculations of monochromatic GaAs cell performance for a range of laser wavelengths (assuming such lasers are available). The limiting performance is based on an assumed external photoresponse of 100% while the results based on the present collector grid assume 1.5% obscuration due to the collector grid, an internal photoresponse of 96% , and a reflectance from the semiconductor surface of 0% .

4. CELL FABRICATION

Cells were fabricated from epi-wafers grown on the WSU MOCVD reactor (SPIRE 500XT). The front surface collector metallization is established using photolithography and liftoff of vapor deposited Au. Maximum transmission is required only at 806 nm . Vapor deposited SiO (1000 \AA) with an index of 1.75 is combined with the 500 \AA AlGaAs window to provide a double AR coating yielding 0% reflection at 806 nm . Cells have been fabricated with dimensions of $0.4 \text{ cm} \times 2.0 \text{ cm}$, as well as with the area indicated in Figure 4.

5. EXPERIMENTAL RESULTS

Best results are shown in Figure 8. The figure gives simulated I-V characteristics for a GaAs cell coupled to a 806 nm laser beam at 400 mW/cm². The I-V characteristics were obtained by first determining the expected short circuit current based on the measured external photoresponse at 806 nm, and then adjusting illumination by an ELH light source to an intensity level such that the appropriate value of short circuit current was achieved. As indicated in Figure 8, this GaAs cell ((91-24-3) converts the laser beam to electrical power with an efficiency of 53.0 %. Internal photoresponse data for a cell made from the same epi wafer as Cell 91-24-3 are given in Figure 9. These data have been fit with theory yielding estimated values for minority carrier parameters are indicated in Figure 9. The minority carrier diffusion lengths are quite satisfactory, but improvements can be made in the values of surface recombination velocity. Results for the external photoresponse of Cell 91-24-3 are given in Figure 10 along with the internal photoresponse data of Figure 9. Note the cell has been tuned to a wavelength near 806 nm. The external photoresponse at 806 nm is 92 %. This value can be improved to 95 % by decreasing the grid line widths and improving the internal photoresponse to 98 %. Experimental results for cell efficiency vs beam intensity at 806 nm are shown in Figure 11. The upper curve describes the limiting efficiency and the middle curve describes the realistic estimate of cell performance based on the present cell design. In order to close the gap between the experimental results and estimated potential cell performance (53.0 % to 59.5 % at 400 mW/cm²), the external photoresponse must be improved to 95 % and improvement must be made in J₀.

6. LASER POWER BEAM TEST BED

Battelle Pacific Northwest Laboratories has established a power beam testing station that utilizes a 10 W, 806 nm AlGaAs laser diode array as a laser source. The testbed is controlled with a Macintosh II ci computer with a National Instruments interface. Analog I/O lines control the voltage to the laser array and monitor the drive current. A detector monitors the laser power and power reflected from the cell under test. Cells under test are placed on a temperature controlled, nickel-coated vacuum chuck. Four point probe contacts are utilized to measure I-V characteristics. The laser beam intensity can be varied from zero to 500 mW/cm², and is uniform over a 3 cm x 4 cm area. Work is underway to insure that the calibration procedure is satisfactory. A schematic diagram of the test setup is shown in Figure 13. A significant effort has been devoted to obtaining a uniform distribution of the laser beam intensity at the cell plane. Figure 14 shows an intensity profile over a 3x4 cm area.

TABLE 1 :
**CALCULATED MONOCHROMATIC GaAs CELL
 EFFICIENCY FOR LASER AT 806 nm & 100 mW/cm²**

Q _{EXT} (%)	J _{SC} (mA/cm ²)	V _{OC} (VOLTS)	FILL FACTOR	EFFICIENCY (%)
100	64.9	1.07	.891	62.0
95.0 ⁽¹⁾	61.7	1.07	.891	58.8

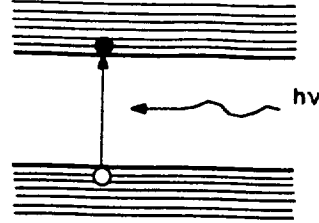
(1) Assumed Internal Photoresponse Is 98 % And Obscuration Due To Collector Grid Is 3 %.

(2) J₀ = 6.0 x 10⁻²⁰ A/cm². This Value Is An Experimentally Determined Value Based On Spire's Results For GaAs Cells.

MAXIMUM CURRENT

$$J_{max} = q \times [\text{PHOTON FLUX}]$$

$$= \frac{P_{in} \text{ (mW/cm}^2\text{)}}{h\nu \text{ (eV)}} \frac{\text{mA}}{\text{cm}^2}$$



CURRENT-VOLTAGE CHARACTERISTICS

$$J_{sc} = Q_{EXT} \times J_{max}$$

$$J = J_{sc} - J_0 [\exp(V/kT) - 1]$$

$$P_{max} = \text{MAX} (J \cdot V)$$

$$\text{EFFICIENCY} = \frac{100 \times \text{MAX POWER}}{\text{INCIDENT POWER}}$$

FOR LIMITING EFFICIENCY

$$Q_{EXT} = 1.0$$

$$J_0 = 4 \times 10^4 \exp(-E_g/kT) \text{ A/cm}^2$$

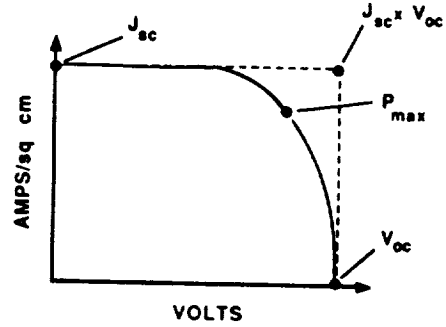


Figure 1. Approach To Calculating The Limiting Efficiency Of Monochromatic Cells.

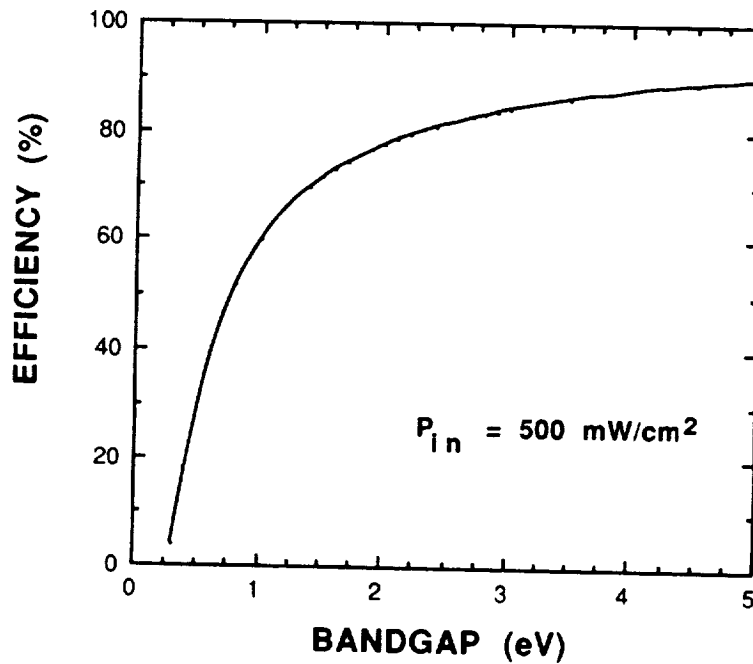


Figure 2. Calculated Efficiency For Monochromatic Cells Coupled To Laser Light Tuned To The Cell Material Bandgap, And Assuming An Input Power Of 500 mW/cm².

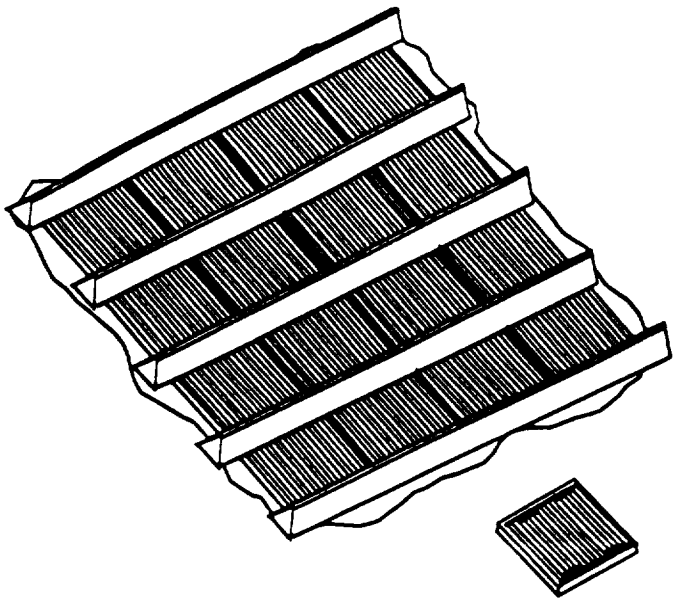


Figure 3. Isometric View Of A Cell Array Utilizing A Hidden Busbar Approach.

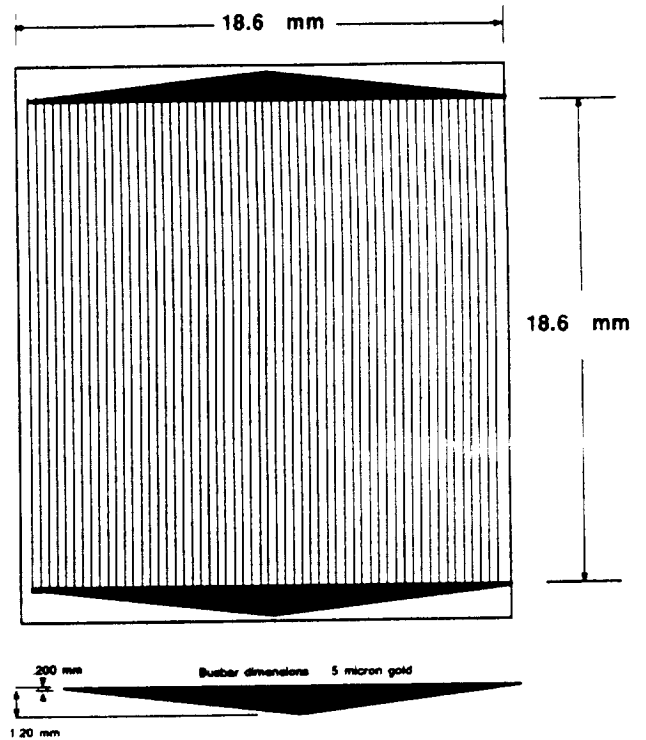


Figure 4. Collector Grid Design Used For GaAs Cells Grown And Fabricated By WSU.

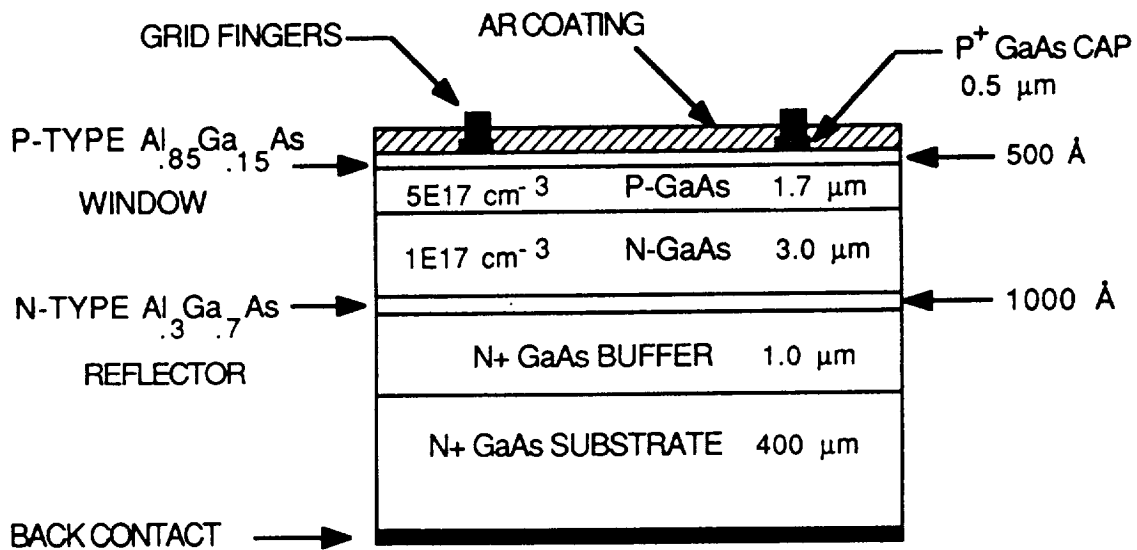


Figure 5. Optimum Cell Structure For p/n GaAs Cells Coupled To Laser Light At 806 nm.

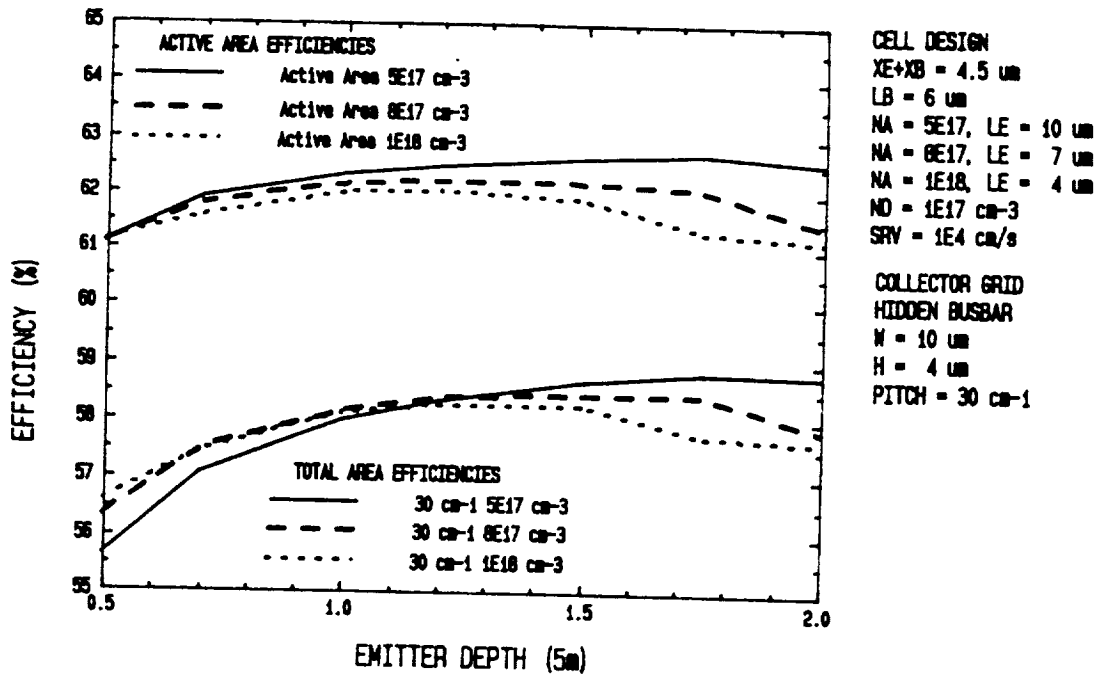


Figure 6. Calculated Efficiency vs Emitter Depth, And Emitter Doping, For a p/n GaAs Cell Coupled To 806 nm Light At 400 mW/cm².

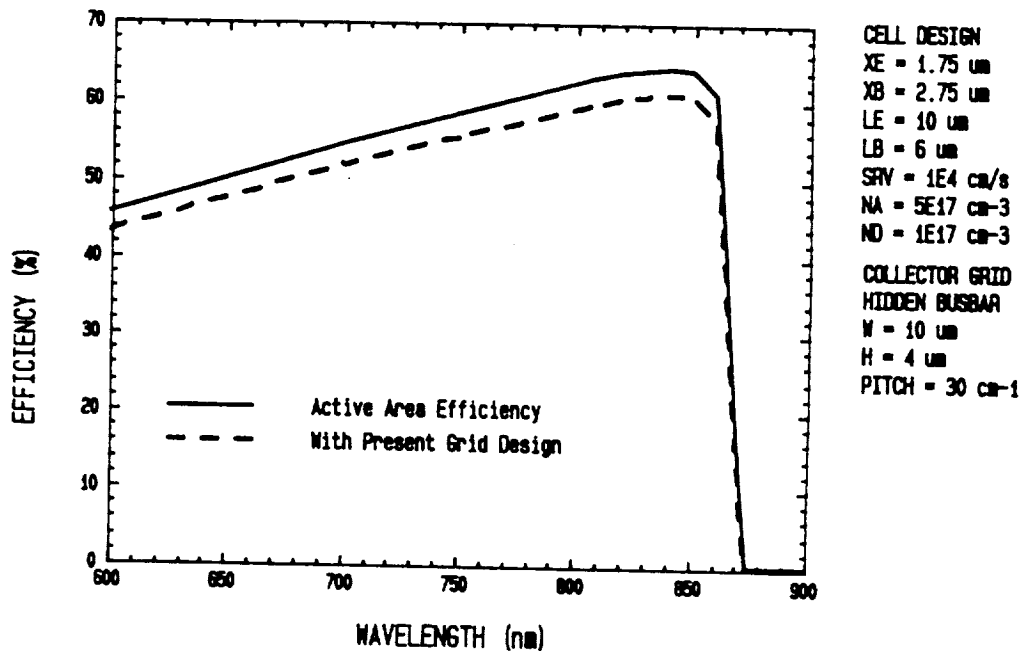


Figure 7. Calculated Efficiency vs Laser Wavelength For A p/n GaAs Cell. The Incident Beam Intensity Is Assumed To Be 400 mW/cm².

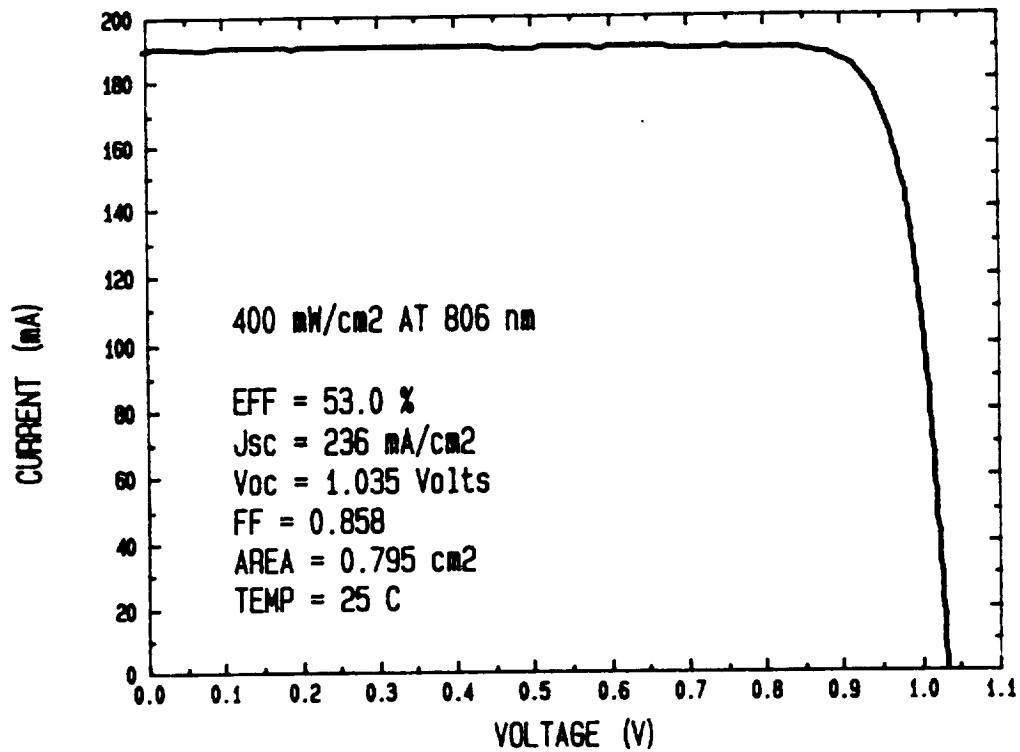


Figure 8. Simulated I-V Characteristics For p/n GaAs Cell 91-24-3 Coupled To 806 nm Light At 400 mW/cm². The GaAs Cell Was Grown And Fabricated At WSU Tri-Cities.

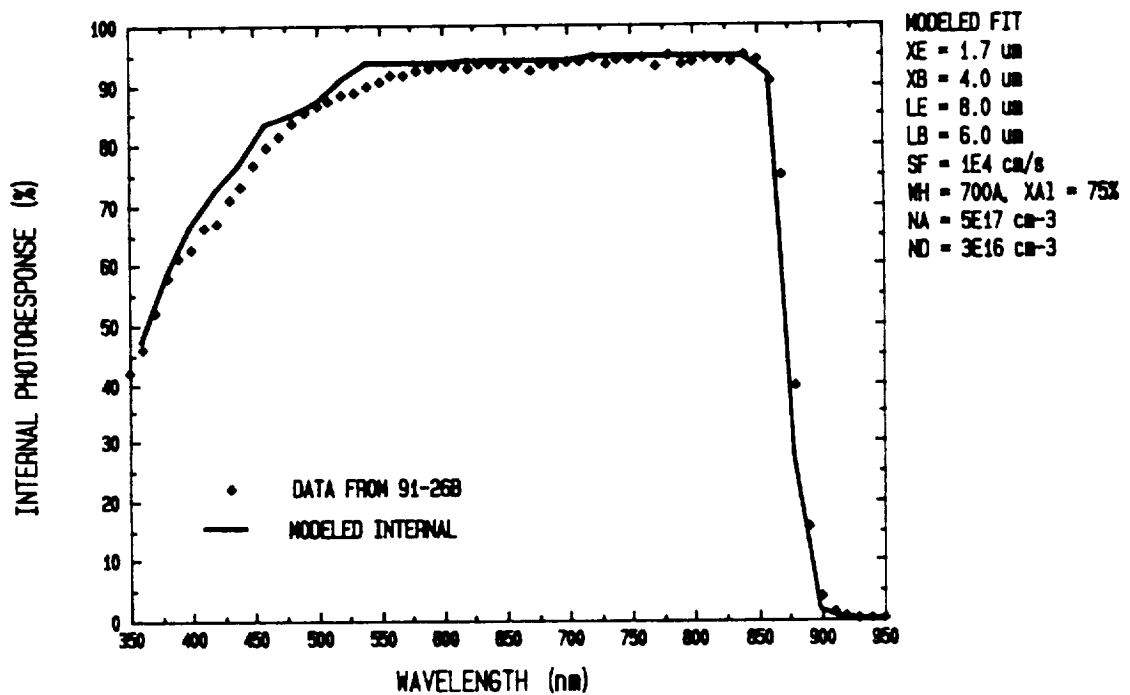


Figure 9. Internal Photoresponse Measured For A GaAs Cell Fabricated From The Same Epi-Wafer As Cell 91-24-3. Minority Carrier Parameters Determined From Fitting The Photoresponse Data Are Indicated.

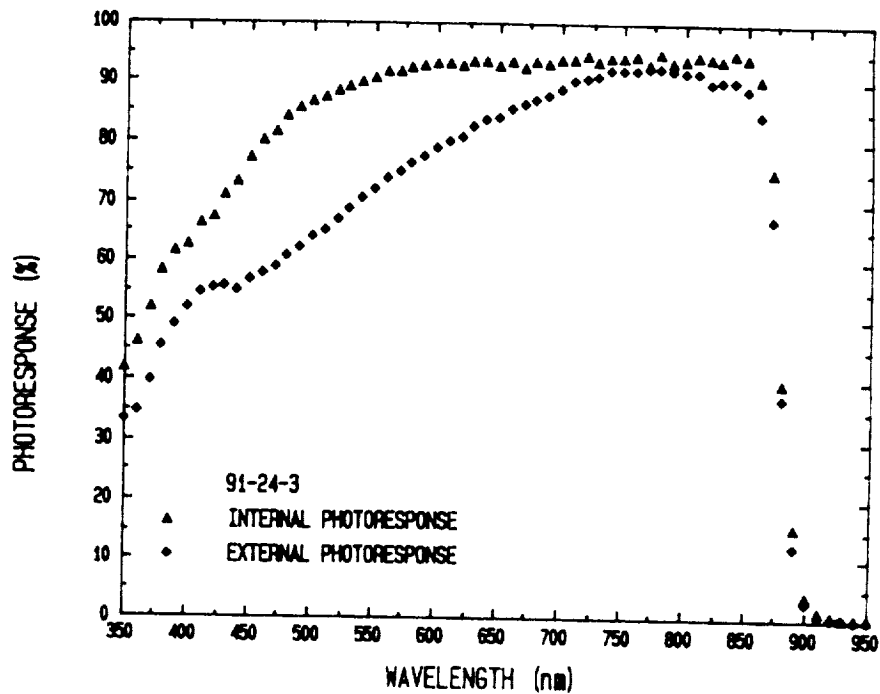


Figure 10. External Photoreponse And Internal Photoreponse Data For 53 % Cell (91-24-3). An AR Coating Of 1000 Å Of SiO Was Used To Tune The Cell To The 800 To 850 nm Wavelength Range.

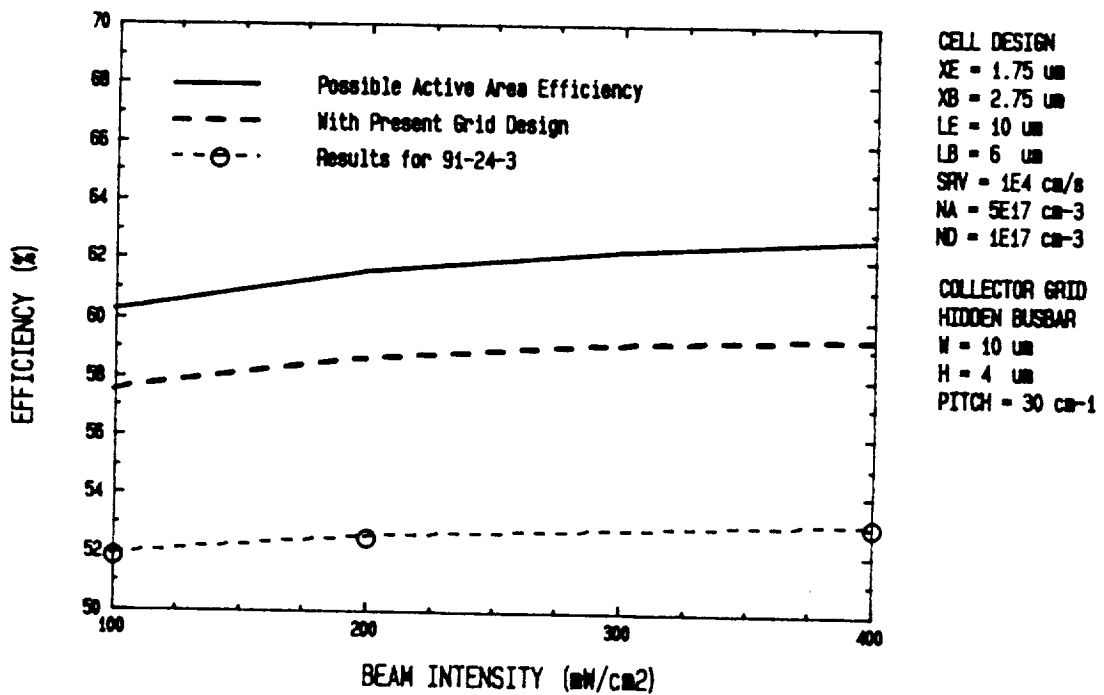


Figure 11. Experimental And Theoretical Results For Efficiency vs Laser Beam Intensity. Experimental Results Are Simulated Measurements As Discussed In Text,.

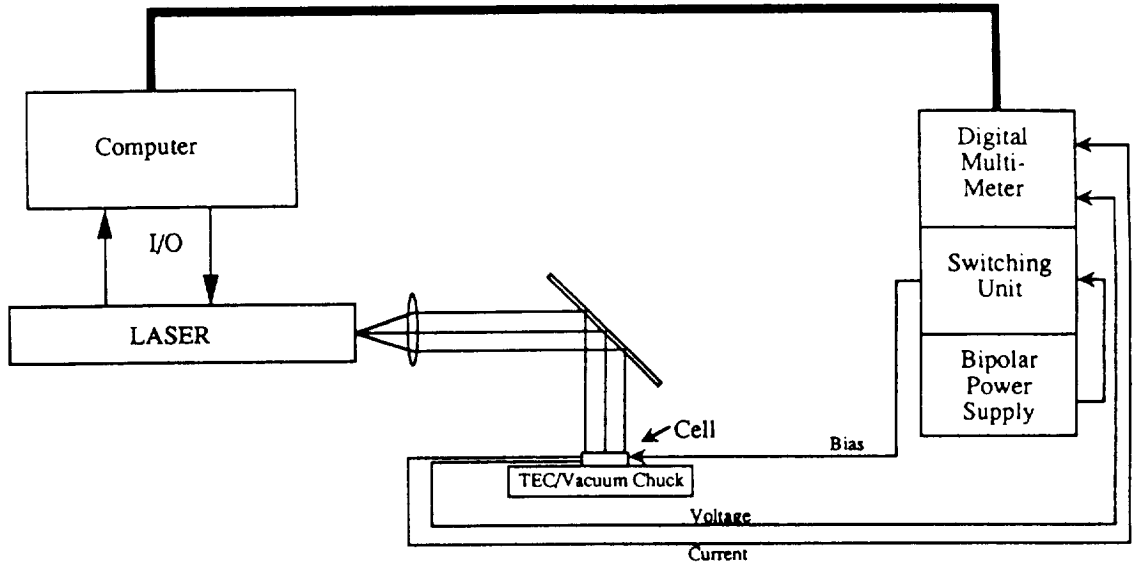


Figure 12. Schematic Of Battelle Northwest Laboratory's Arrangement For A Laser Beaming Test Bed.

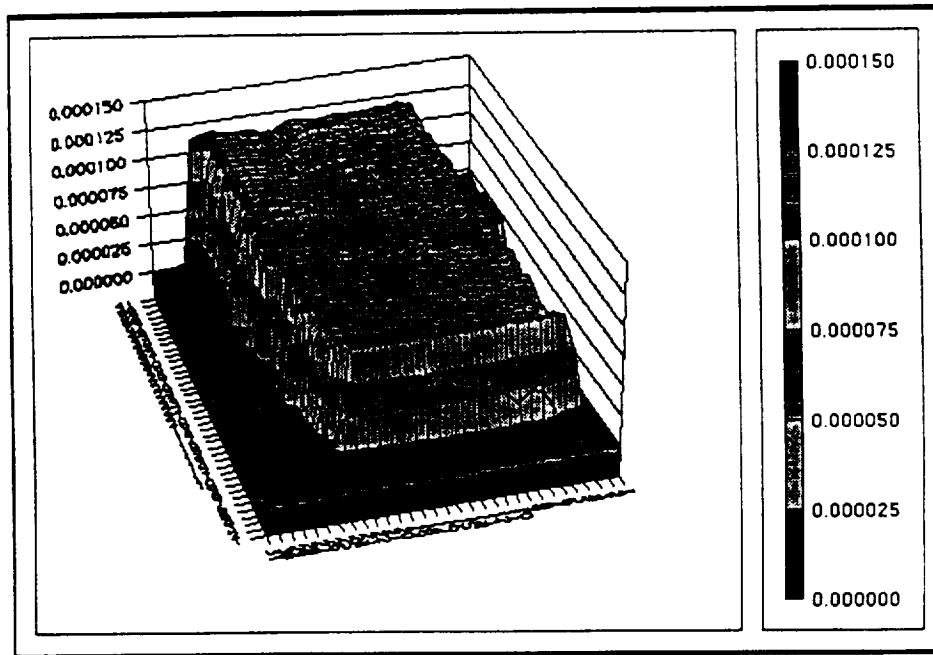


Figure 13. Laser Intensity Profile Over A 3x4 cm Area At Cell Test Plane.

