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PRODUCTION DATA ON 0.55 eV InGaAs THERMOPHOTOVOLTAIC CELLS

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ABSTRACT

Low bandgap 0.55 eV (2.25 µm cutoff wavelength) indium gallium arsenide ($In_{0.72}Ga_{0.28}As$) thermophotovoltaic (TPV) cells use much more of the long wavelength energy emitted from low temperature (< 1200° C) thermal sources than either Si or GaSb cells. Data are presented on a statistically significant number (2500) of these TPV cells, indicating the performance obtainable in large numbers of cells. This data should be useful in the design and modeling of TPV system performance. At 1.2 A/cm^2 short-circuit current, an average open-circuit voltage of 283 mV is obtained with a 60% fill factor. The peak external quantum efficiency for uncoated cells is 65% and is over 50% from 1.1 to 2.2 µm. Internal quantum efficiency is over 76% in this range assuming an estimated 34% reflectance loss.

OVERVIEW

The main components of a thermophotovoltaic power system include a heat source (which normally has a broad blackbody spectrum, but may also be a selective emitter), photovoltaic cells, and (in cases where the emitter is not selective) an optical filter to reflect photons with energy below the cell bandgap back to the heat source to help maintain its temperature.

This paper describes production data on a certain type (0.55 eV InGaAs) of photovoltaic cell, one of the main components of the TPV system. In this section, we very briefly describe how the heat source temperature and optical filter relate to the cell, and discuss the relative benefits of several cell types (Si, GaSb, InGaAs) now in use with TPV systems. Our goal in this section is to outline why 0.55 eV InGaAs cells may be the best choice for TPV system applications where the heat source is ~ 1200°C or below.

High temperature sources (>2300°C) would allow use of relatively inexpensive, standard Si photovoltaic cells. However, self-contained, high temperature sources are harder to build due to the scarcity of materials which can withstand high temperatures. Therefore, lower temperature sources are being considered for applications such as the ~1100°C radioisotope General Purpose Heat Source [1] for deep space missions, ~1220°C solar thermophotovoltaics [2] with energy storage for commercial power grid use, and small ~1250°C natural gas TPV generators [3] for home use.

All of these applications require a low bandgap cell, since the spectral peak of a 1200°C blackbody falls at 2 µm (see Fig.1). Only 2% of the total 1200°C blackbody energy is from photons with energy above the 1.1 eV bandgap of a Si cell, versus 15% for 0.72 eV GaSb and 35% for 0.55 eV InGaAs cells. Efficient cells with even lower bandgaps are desired, but are unlikely to be available anytime soon.
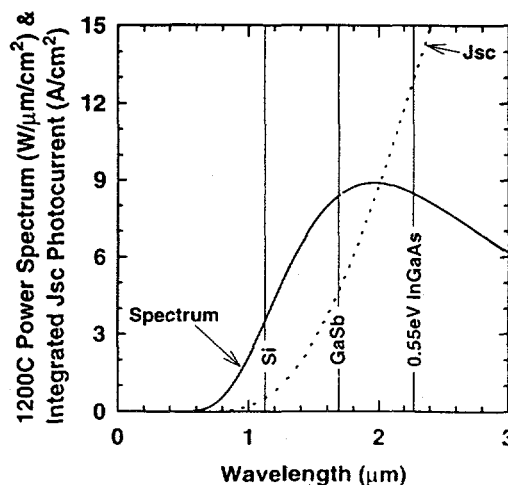
Fig. 1 *Power spectral density in $W/\mu m/cm^2$ and integrated short circuit photocurrent (Jsc) in A/cm^2 for a 1200°C blackbody. Calculated Jsc assumes 100% quantum efficiency for all cell types out to the cutoff wavelength. Horizontal lines mark cutoffs of 1.1 eV Si, 0.72 eV GaSb, and 0.55 eV InGaAs.*

Figure 1 shows that the lower bandgap 2.25 µm cutoff 0.55eV InGaAs cells potentially could have ~3X higher Jsc than 1.7 µm cutoff GaSb cells (12.5 vs 4.5 A/cm^2). However, higher bandgap 0.72 eV GaSb cells can have more photovoltage (500 mV, Voc of best cell in [3]) than the 0.55 eV InGaAs (307 mV, best cell reported here) and GaSb has a higher fill factor (80% vs 67% for best cells in [3] versus those reported here) as well. Overall however, using the above data, about 43% more power per area could be available from the 0.55 eV InGaAs cells than from 0.72 eV GaSb cells under a 1200°C blackbody source.

QUANTUM EFFICIENCY

The 50X AM0 short wavelength data in Table 2 is basically useful for predicting the photovoltage and fill factor of these cells in a TPV system given a certain photocurrent. However, in order to predict the photocurrent in a TPV application, a system designer would need to know both the TPV cell quantum efficiency (QE) as a function of wavelength and the power spectral density from whatever TPV heat source is planned for use. The external QE for a typical 0.55 eV InGaAs TPV cell is shown in Figure 2. The external QE is above 50% from about 1 to 2.1 μm.
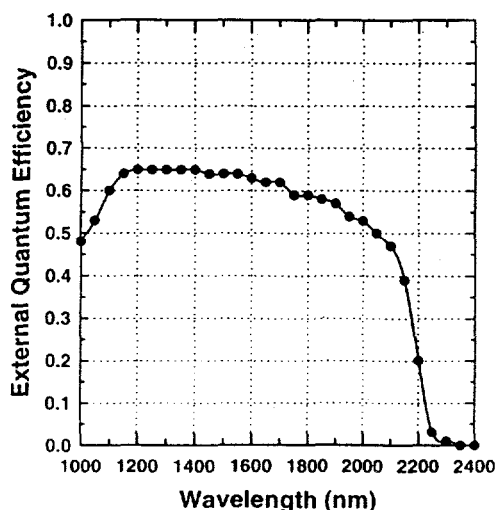

Fig. 2 *Measured external quantum efficiency for 0.55 eV InGaAs cell without any antireflection coating.*

The internal QE is of interest as a measure of the intrinsic cell response, and is simply a correction to the external quantum efficiency to account for the reflectance from the cell surface. We will assume the 0.55 eV InGaAs refractive index (~3.5) is fairly flat with wavelength, so that the normal incidence reflectance in air is estimated as 31%. In addition, the 10% gridline coverage on the cell surface would increase this by 3% to 34%. The peak internal QE is then 98% (vs 65% external), with the internal QE above 76% from 1 to 2.1 μm.

CORRELATION OF Voc AND X-RAY FWHM

The exact indium (In) composition percentage (x) of the $In_xGa_{1-x}As$ cell layers is of great interest since this determines the bandgap energy and cutoff wavelength of the ternary InGaAs material. To determine this quantity, first the material lattice constant is measured with a double-crystal X-ray diffractometer.

Once the lattice constant is known from the position of the X-ray diffractometry peak with respect to the well-known InP wafer peak, a unique composition can be ascribed to the $In_xGa_{1-x}As$ material. The target for this work is the 0.55 eV $In_{0.72}Ga_{0.28}As$ composition. The full-width-half-maximum (FWHM) of this X-ray diffraction peak is popularly considered an indicator of the material quality (broader peaks normally indicate less perfect material).

Table 2 lists the average FWHM of about 200 MOCVD growth runs on both three and two-inch InP wafers. Likewise, the cell open-circuit voltage Voc is fairly sensitive to the dark current, which in turn is sensitive to the material quality (e.g. the number of dislocation defects). It would be a great advantage if the FWHM of the X-ray diffraction peak, which is measured after epitaxial growth but before any material processing, could be used to accurately predict the Voc, a critical cell parameter. This would allow us to eliminate "bad" wafers and process only good wafers, for an appreciable cost saving.

Unfortunately, Figure 3 shows the correlation (or more accurately, the lack of correlation) between the FWHM of the X-ray peak and the Voc. As of the present time, we still do not know for certain why there is so little correlation. We suspect that on many samples the 1 cm wide X-ray "footprint" may cut across several InGaAs regions that, although of the same composition, may have slightly different growth tilts, widening the perceived X-ray peak.
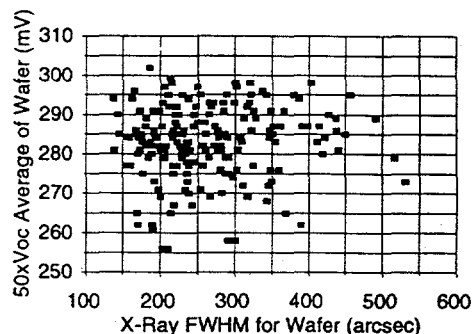
Fig. 3 *Lack of correlation between the cell Voc and the FWHM of the material X-ray diffractometry peak.*

HISTOGRAMS

Histograms of the Voc and FF data for the 2500 cells averaged in Table 2 are shown in Figures 4 and 5, respectively. The data is slightly complicated since what is displayed is the average for all the cells on a wafer, with the majority of wafers being three-inches in diameter with twenty-four cells per wafer, with a significant number of two-inch wafers which had twelve cells per wafer included.

One advantage of GaSb cells is that they have no epitaxial growth costs, since GaSb cells use PN junctions formed by dopant diffusion into GaSb wafers. However, GaSb is currently available only in 2-inch diameter wafers, while the 3-inch diameter InP wafers used for InGaAs cells have twice the area, resulting in twice as many InGaAs cells per processed wafer. InP wafers are available from several competitive vendors due to communications industry need for 1.5 μm detectors and lasers, while GaSb wafer development is limited by the smaller GaSb TPV market.

Finally, a good optical filter [4] or reflector [5] is crucial for all cell types. Even for the InGaAs cell, 65% of the total 1200°C blackbody energy is from photons too low in energy to create electron-hole pairs in the cell. These photons would be wasted heating the cell if the filter did not reflect these photons back to the heat source. Less demanding, easier-to-realize, filters may be possible with the lower bandgap 0.55 eV InGaAs since this cell uses more of the blackbody spectrum. In contrast, higher bandgap cells may need a more complex filter to reflect over a wider band.

FABRICATION OUTLINE

The material used for the 0.55 eV cells was epitaxially grown on InP wafers in a commercial Spire 100S metal organic chemical vapor deposition (MOCVD) reactor [6]. The epilayer structure (Table 1) was a fairly standard N-on-P design except for proprietary composition, higher bandgap, back surface field and window layers used to minimize the recombination velocity at the back and front cell interfaces. Cell layers were grown lattice-mismatched to the supporting indium phosphide (InP) P-type substrate wafer. A conventional multistep $In_xGa_{1-x}As$ grading layer was used between the wafer and the cell to reduce dislocation defects. In a comparative test, this grading layer increased the observed open-circuit photovoltage by about 100% (from 150 to 300 mV) from a control test structure which had a simple InGaAs buffer layer instead of the grade.

Table 1 *Epilayer Structure of 0.55 eV Cell*

~ 200 Å N++ higher bandgap window
~ 2500 Å N+ In(72%)Ga(28%)As emitter
~ 3 μm P- In(72%)Ga(28%)As base
~ 5000 Å P+ higher bandgap back surface field
~ 4 μm In(x)Ga(1-x)As step grading layer P+ In(72%)Ga(28%)As to P+ In(53%)Ga(47%)As
~ 5000Å P+ InP buffer layer
~ 25 mil P+ InP wafer

Standard back contacts, front grid metal, and wet etching process steps were used to fabricate cells. Final cells were 1 cm by 1 cm in size with a shadow loss of about 10% for the busbar and 10% for the front contact gridlines.

ILLUMINATED I-V DATA

When the cells were illuminated to get an average 1.2 A/cm^2 short-circuit current density (Jsc), an average open-circuit photovoltage (Voc) of 283 mV (best cell 307mV) and average fill factor (FF) of 60% (best cell 67%) resulted. The Voc, Jsc, and FF shown in Table 2 represent the average of over 2500 cell measurements. This 1.2 A/cm^2 test current is not the maximum current (up to 5 A/cm^2 could be used, with some fill factor degradation due to ohmic loss).

Table 2 *Average (Standard Deviation) Data from 2500 InGaAs 0.55 eV Cells (50X AM0)*

Indium %	Voc mV	Voc/Eg %	FWHM arcsec	Jsc A/cm^2	FF %
71.6 (0.7)	283 (9)	51 (2)	262 (79)	1.2 (0.1)	60 (3)

Table 2 data were measured under 50 sun air mass zero (AM0) "white-light" illumination. AM0 light was used since it is well-defined and powerful sources are readily available. This data are directly applicable for determining Voc and FF for TPV applications if the heat source used in the TPV system generates the same photocurrent from the TPV cell as listed in Table 2. The rated Voc (283 mV) and FF (60%) will be obtained whether the spectral content of the illumination is predominantly short (AM0) or long (e.g., a 1200°C blackbody) as long as the incident light drives the cell to 1.2 A/cm^2, since the dark current (which affects the Voc) and the series resistance (which affects the FF) are spectrum-independent.

The data in Table 2 can be extended to other photocurrent levels since the Voc at these higher illuminations was observed to be approximately diffusion-dark-current limited with an ideality factor close to unity. If, for example, a TPV system designer expects to supply enough illumination so that the Jsc in Table 2 is tripled to 3.6 A/cm^2, the photovoltage can be roughly estimated to be 26mV*log(3) or 29 mV higher than the value in Table 2. The fill factor can be taken to be roughly constant for currents from about 0.5 to 4 A/cm^2. This procedure for estimates only works for photocurrents in this restricted range. For lower photocurrents, the procedure is invalid due to a bias-varying ideality factor much greater than unity. For higher photocurrents, the procedure breaks down because the fill factor can no longer be considered constant due to the higher I^2R ohmic power loss.
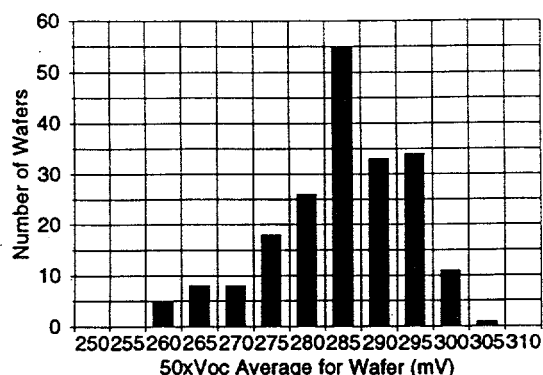
Fig. 4   *Histogram of the open-circuit voltage of 2500 0.55eV InGaAs cells (see text).*
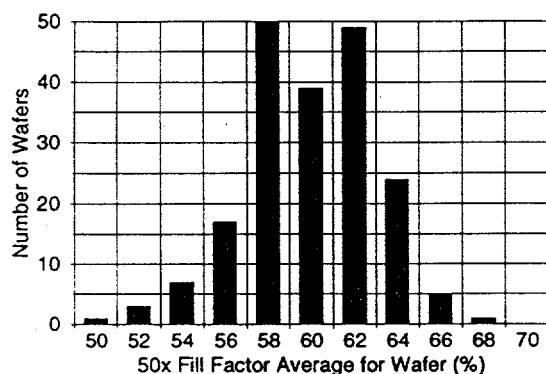

Fig. 5   *Histogram of the fill-factor of 2500 0.55eV InGaAs cells (see text).*

SUMMARY

In this paper, we presented some basic information on the average performance (based on 2500 cell measurements) of 0.55 eV InGaAs thermophotovoltaic (TPV) cells that a TPV system designer would need to know. A typical quantum efficiency is presented (Figure 2), so that the photocurrent can be estimated if the heat source spectral density is known. Table 2 gives the typical average open-circuit photovoltage and fill factor that could be expected, and methods of extending this data to cover expected photocurrents in the 0.5 to 4 A/cm^2 range is discussed. With these three parameters, the cell electrical output is predictable. Additional model data [7], including

dark current and series resistance, are available for similar cells. Overall yields for these 0.55 eV InGaAs cells (~70% for 2500 cm^2 of cells) were lower than that reported for about one-tenth the number of 0.6eV InGaAs cells [8]. In our process, most yield loss occurred when the fragile InP wafers were sawed into cells. We are currently improving the sawing technique and investigating other methods for separating cells.

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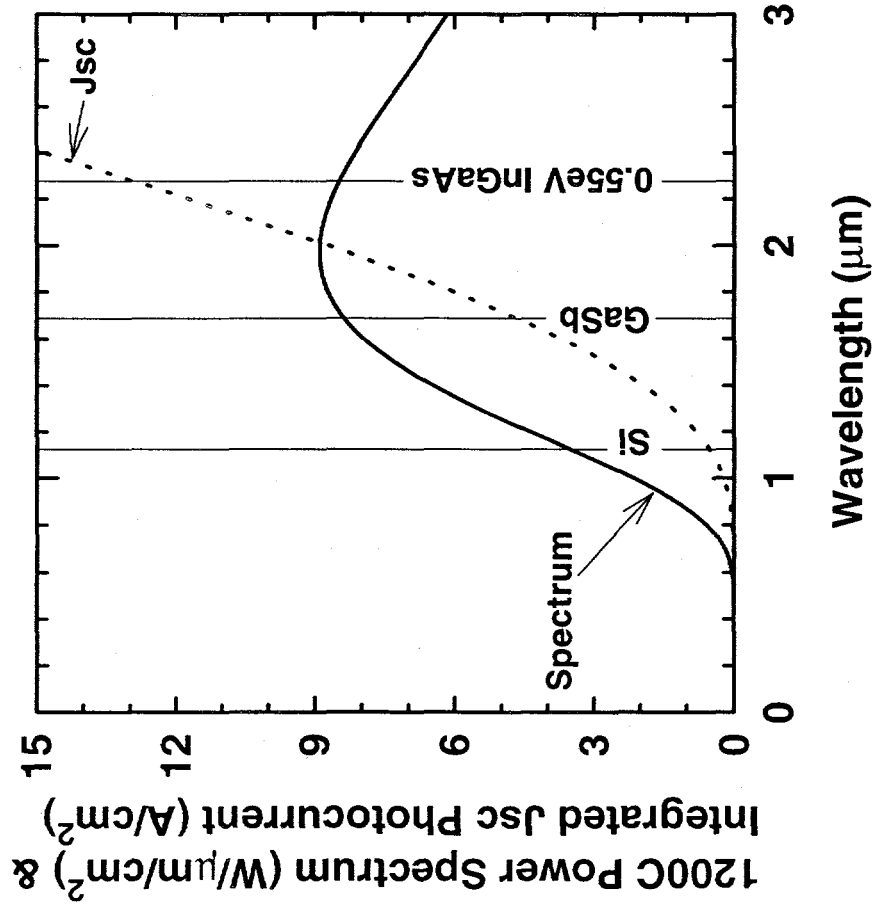
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Why 0.55 eV InGaAs cells?

- Lower bandgap cells use more spectrum

- Trade-off in Voc and FF versus Jsc

- However, overall, more power from InGaAs for low temperature sources

Epilayer Structure of 0.55 eV Cell

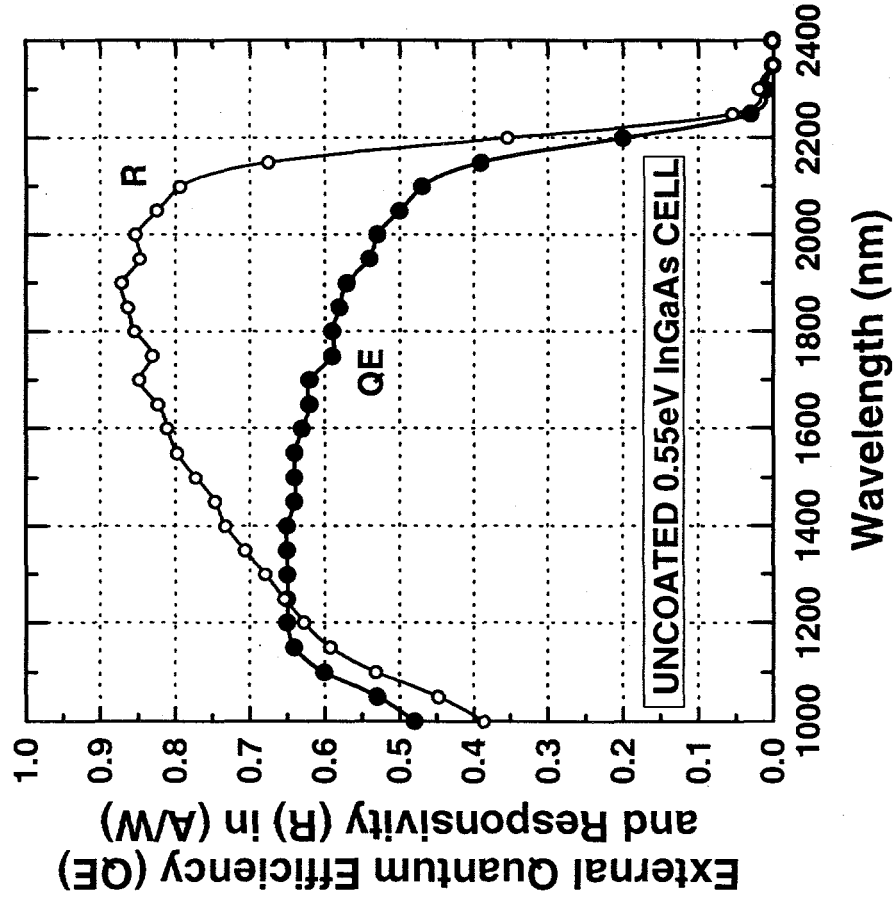| |
|---|
| ~ 0.02um N++ higher bandgap window |
| ~0.25um N+ In(72%)Ga(28%)As emitter |
| ~3um P- In(72%)Ga(28%)As base |
| ~0.5um P+ higher bandgap back surface field |
| ~4um P+ step grading layer In(72%)Ga(28%)As to In(53%)Ga(47%)As |
| ~0.5um P+ InP buffer layer |
| ~25mil P+ InP wafer |

Measured Quantum Efficiency

Surface reflectance is ~31% (n ~ 3.5)

Grid reflectance is ~3% (10% shadow)

Internal Quantum Efficiency is >76% from 1.1 to 2.2 um

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External Quantum Efficiency (QE) and Responsivity (R) in (A/W)

Wavelength (nm)

R

QE

UNCOATED 0.55eV InGaAs CELL

Average (Std. Dev.) Data of 2500 Cells

For an average test Jsc of 1.2 A/cm2 (0.1):

(max Jsc ~ 4 to 5 A/cm2, limited by FF)

- Voc   283 mV (9)   Best cell 307 mV
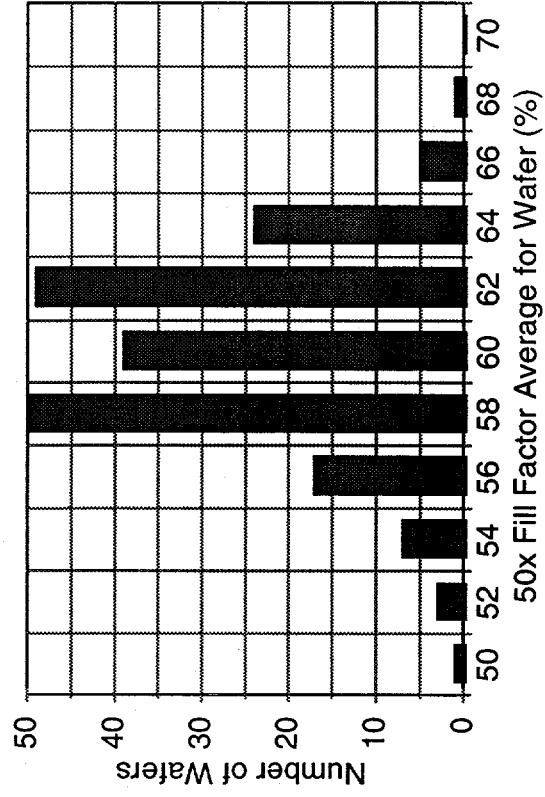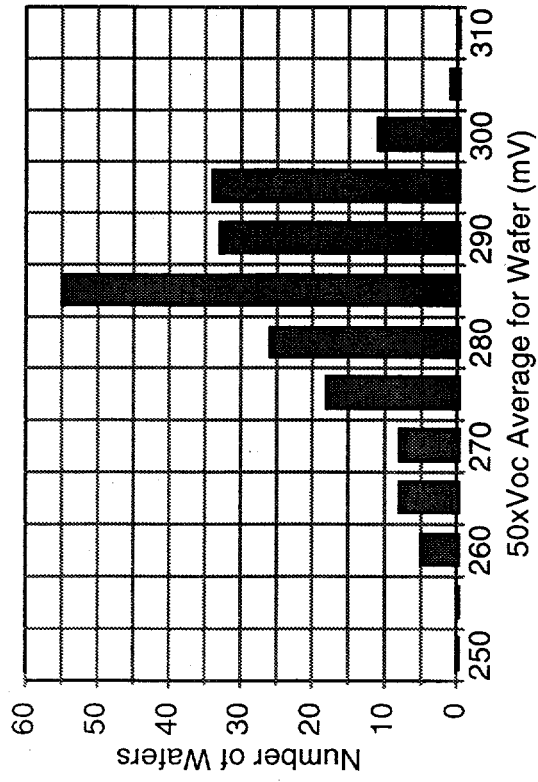- FF   60% (3)   Best cell 67%

Average x=71.6 (0.7) for In(x)Ga(1-x)As cells

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Histograms

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Summary

- We have presented data that should enable a TPV system designer to predict output power if the heat source spectral density is known

- Estimation procedure:
  - Integrate QE with design spectrum to get Jsc
  - ratio design Jsc to test Jsc to correct test Voc
  - assume constant FF (within ~10% 0.4-4A/cm2)

- Avg qVoc (283mV) to Eg (550 meV) ratio of 51% is extremely good for lattice-mismatched cells

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