N91-19211

GaP Betavoltaic Cells as a Power Source*

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Introduction

Since the launch of the very first satellite, photovoltaics has been the most widely used spacecraft power source. Used not only for earth orbiters, but also for a wide range of interplanetary applications such as a Mercury flyby, Venus orbiters, lunar surface power, and Mars orbiters, photovoltaic systems have demonstrated great versatility. However, photovoltaics are limited by the availability of solar illumination. For missions that operate far from the sun and for those with lengthy non illuminated periods, significant system compromises are required. In some cases the use of non PV power sources, such as the RTG (radio-isotope thermoelectric generator), has been implemented. Extending the range of applications of PV to these more difficult situations has been one of the challenges for PV technology development. Much of that effort has addressed methods for reducing photovoltaic system mass and increasing system conversion efficiency.

For many years the workhorse of space photovoltaics, the silicon solar cell, has been reliably used to power heart pacers in the form of betavoltaics [ref. 1]. The beta cell functions analogously to a solar cell, with the radiant energy of the sun replaced by the emitted electron flux. The emitted high energy electrons (beta particles) from the radioactive source traverse the cell material losing energy and thereby creating electron-hole pairs [ref. 2]. Those carriers within a diffusion length of the junction will be swept across contributing a current. An equivalent circuit for the device is identical to that for a solar cell. Such converters are free from the limitations of a solar light source and can operate where conventional photovoltaics are least capable.

During the past decade the use of microelectronic fabrication methods has allowed the fabrication of a diverse variety of advanced solar cell structures. In view of this progress, an investigation was undertaken in order to ascertain if a significant improvement in betavoltaic conversion efficiency could be realized. In particular the use of a GaP device was evaluated experimentally; GaP is an indirect wide-gap semiconductor [ref. 3]. The purpose of this study was to define the power limitations of current GaP beta cells and examine the efficiency and extent of radiation damage in GaP at the energies of interest.

Experimental

The GaP cells used in this study, shown schematically in Figure 1, were fabricated by Astropower Corporation. GaP was chosen as a cell material because of its wide band gap. It has been shown that device efficiency is a function of band gap, with wide-gap materials possessing higher efficiencies [refs. 1-2]. The GaP cells are a 1cm × 1cm p/n structure grown by liquid phase epitaxy. As a comparison to the performance of the GaP beta cells, Si back surface field 2 cm × 2cm n/p solar cells fabricated by ASEC were exposed to identical conditions.

To approximately evaluate cell performance the average beta energy E_β was chosen for two emitters, Ni^{63} ($E_\beta = 20$ KeV, half-life 92 years) and Sr^{90}/Y^{90} ($E_\beta = 200$ KeV/ $E_\beta = 900$ KeV, half-life 28 years and 62 hours respectively). The latter radioactive source Sr^{90} decays to a daughter nucleus Y^{90} which also undergoes beta decay, hence the notation Sr^{90}/Y^{90}. The Jet Propulsion Laboratory Dynamitron electron accelerator was used as the source of monoenergetic incident electrons at 200 KeV and 40 KeV. A flux $\Phi = 2 \times 10^9$ electron/cm²s, equivalent to a 54 mCurie source (1 Curie $= 3.7 \times 10^{10}$ disintegrations/s), was directed on the cells.

Betavoltaic I-V data was collected with a Tektronix 4052 computer interfaced to the experiment during exposure. Cell efficiencies were calculated as the ratio of maximum power output of the cell to incident power of the electrons

$$\eta = P_{max}/P_e$$

where P_e is the product of the electron flux, energy and cell area. All other parameters such as fill factor, open circuit voltage and short circuit current were determined in the usual way.

Results

In Figures 2 and 3 betavoltaic I-V curves are given for GaP beta cells and Si solar cells. The solid lines refer to the initial exposure and the dotted lines represent cell response after an exposure to a total fluence of 2×10^{12} electrons/cm². A summary of the cell characteristics is given in Tables 1-4.

The efficiency of the GaP cells was found to be 9 % at 40 KeV and 5% with exposure to 200 KeV electrons. The reason for the lower device efficiency at 200 KeV is due to the range of the electrons in GaP. At 40 KeV the electrons are stopped within 25 μm, depositing all energy in the active region of the cell. At 200 KeV the incident electrons penetrate approximately 160 μm, depositing a substantial fraction of energy in the substrate, further than a diffusion length (approximately 20 μm) from the depletion region of the cell. A comparison of the GaP cell efficiency to that of Si during exposure demonstrates the effectiveness of GaP over Si in this application. Typical Si heart pacer betavoltaic systems have efficiencies on the order of only 1%.

Power output of the GaP cells was found to be 3.2 μW and 1.2 μW under exposure to 200 KeV and 40 KeV electrons respectively. The limitation in the power output of the cells is primarily a function of the low incident power on the cells. The electron power at a flux of 2 x 10^9/cm^{2}s is only 65 μW at 200 KeV and 13 μW at 40 KeV. The flux was chosen to represent that from a ideal thin-film source of Ni^{63}, 1 cm x 1 cm in area and 1 micron thick. A thin-film of the radioactive source is necessary to minimize weight and avoid self-absorption of the emitted beta particles by the source material.

To examine degradation of the cells, betavoltaic I-V data was taken after a prolonged exposure of 1000 seconds at the flux of 2 x 10^9/cm^{2}s and compared to the initial data. In addition, standard solar I-V and spectral response data were taken as a diagnostic tool to evaluate the cells for radiation damage. GaP suffers a significant degradation in performance after exposure to 200 KeV electrons at a fluence of 2 x 10^{12}/cm^2. The beta I-V curve shown in Figure 3 shows a 32% decrease in I$_{sc}$. Cell degradation is also shown in Figures 4 and 5. A decrease in spectral response is observed at wavelengths greater than 0.43 μm, while the solar I-V shows a reduced I$_{sc}$ of approximately 25%, consistent with the reduced I$_{sc}$ of the beta I-V shown in Figure 3.

By contrast the exposure at 40 KeV produced no observable damage in GaP. The dotted line of Figure 3b is within the error of the experiment. The solar I-V and spectral response data also show no discernable reduction in device performance. The threshold for electron radiation damage in GaP may then be set in the range 40 KeV < E < 200 KeV.

Given the above data it is useful to discuss a model for a power source based on betavoltaics. A system capable of producing power on the order of a few watts is most practical using a high energy beta emitter such as Sr^{90}/Y^{90}. The fundamental limitation is in the power available from the radioactive source and radiation damage to the cell. Due to the density of nickel and low beta energy the maximum source power ideally achieved with Ni^{63} would be on the order of 10 μW. However, Sr^{90} is much less dense (2.6 gm /cm^3) and represents an order of magnitude increase in the beta particle energy spectrum. It has been shown that if the source thickness for Sr^{90}/Y^{90} is approximately 1/8 the range of the average energy beta particle (200 KeV) self-absorption may be neglected [ref. 4]. Since Sr^{90} is readily available with activities of 75 Curies/gm, a 1 cm x 1cm source 35 μm thick would have an activity of about 1 Curie.

For a system based on Sr^{90}/Y^{90}, an estimate of the power available may be made from the average energy of the two emitted Sr^{90}/Y^{90} betas i.e., 550 KeV. A 1 Curie source will produce roughly 3 mW of power. Assuming an efficiency of 9% a cell output power of 0.3 mW would result. To produce 5 watts of power about 16,000 cells would be required. Excluding packaging this system would weigh about 3 kg and occupy a volume of 700 cm^3. Although not an advantageous system in terms of

specific power it represents a battery capable of delivering several watts of power over a period of 25 to 50 years without recharging.

Even with higher cell efficiencies, which are certainly possible, betavoltaic system specific power will still remain low, especially when compared to typical space PV systems. However, it is not intended that betavoltaics compete directly with photovoltaics. Instead the betavoltaic option is better suited to compete with RTGs or batteries. For the latter case, betavoltaics would best match requirements for a long lived, low power, continuous power source.

A possible solution to the problem of radiation damage is to operate the cell at annealing temperatures. A GaP cell could operate at an elevated temperature due to dissipation of radioactive energy not accessed by the device. If annealing properties are rapid in GaP the cells could operate for extended periods under exposure to the high energy electrons discussed above. However, at this time annealing properties of GaP are not known. The possibility of other radiation hard wide-gap materials has not been investigated and could lead to the use of novel materials for this application.

Conclusions

Maximum power output for the GaP cells of this study was found to be on the order of 1 μW. This resulted from exposure to 200 KeV and 40 KeV electrons at a flux of 2 x 10^9 electrons/cm^{2}s, equivalent to a 54 mCurie source. The efficiencies of the cells ranged from 5% to 9% for 200 KeV and 40 KeV electrons respectively. The lower efficiency at higher energy is due to a substantial fraction of energy deposition in the substrate, further than a diffusion length from the depletion region of the cell. Radiation damage was clearly observed in GaP after exposure to 200 KeV electrons at a fluence of 2 x 10^{12} electrons/cm^2. No discernable damage was observed after exposure to 40 KeV electrons at the same fluence.

Analysis indicates that a GaP betavoltaic system would not be practical if limited to low energy beta sources ($E_\beta \leq$ 100 KeV). The power available would be too low even in the ideal case. By utilizing high activity bet a sources, such as Sr^{90}/Y^{90}, it may be possible to achieve performance that could be suitable for some space power applications. However, to utilize such a source the problem of radiation damage in the beta cell material must be overcome.

References

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Table 1. – GaP Beta I-V Characteristics
Fluence = 2×10^9 electrons/cm^{2}s

cell	E_e(KeV)	$J_{SC}(\mu A/cm^2)$	V_{OC}(V)	FF	Eff(%)
10	200	4.1	1.2	0.65	5
8	40	2.3	1.0	0.51	9

Table 2. – Beta I-V Characteristics GaP
Fluence = 2×10^{12} electrons/cm^{2}s

cell	E_e(KeV)	$J_{SC}(\mu A/cm^2)$	V_{OC}(V)	FF	Eff(%)
10	200	2.7	1.2	0.64	3
8	40	2.3	1.0	0.52	9

Table 3. – Si Beta I-V Characteristics
Fluence = 2×10^9 electrons/cm^2s

cell	E_e(KeV)	J_{SC}($\mu A/cm^2$)	V_{OC}(V)	FF	Eff(%)
119	200	29	128	0.38	2
141	40	8	64	0.25	1

Table 4. – Si Beta I-V Characteristics
Fluence = 2×10^{12} electrons/cm^2s

cell	E_e(KeV)	J_{SC}($\mu A/cm^2$)	V_{OC}(V)	FF	Eff(%)
119	200	28	84	0.33	1
141	40	7	60	0.26	1

GRID LINES ─── ANTI-RECOMBINATION
LAYER

p – GaP ───→

n – GaP

GaP SUBSTRATE

BACK CONTACT

SILVER PAD
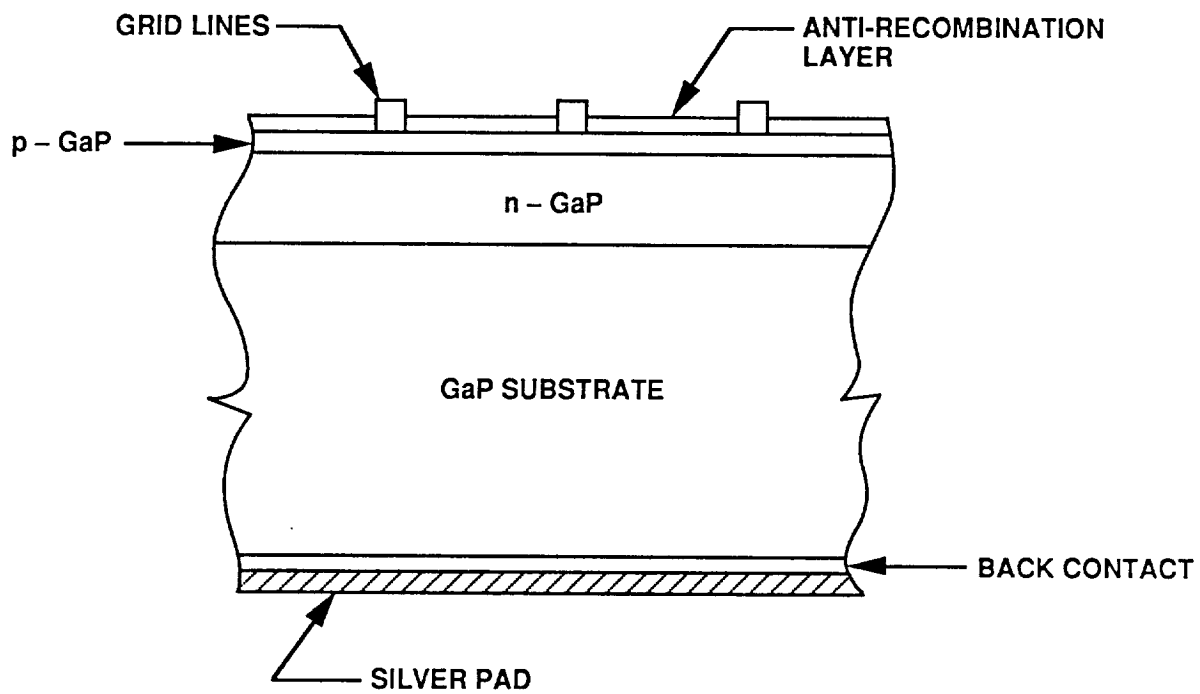
Figure 1. A schematic of the GaP beta cell structure.

BETAVOLTAIC I-V Si

(a) $\Phi = 2 \times 10^9/cm^2 s$ $E = 200\,KeV$ Cell 119
— t = 0 sec
---- t = 1000 sec

(b) $\Phi = 2 \times 10^9/cm^2 s$ $E = 40\,KeV$ Cell 141
— t = 0 sec
---- t = 1000 sec

I (mA)

Voltage (V)
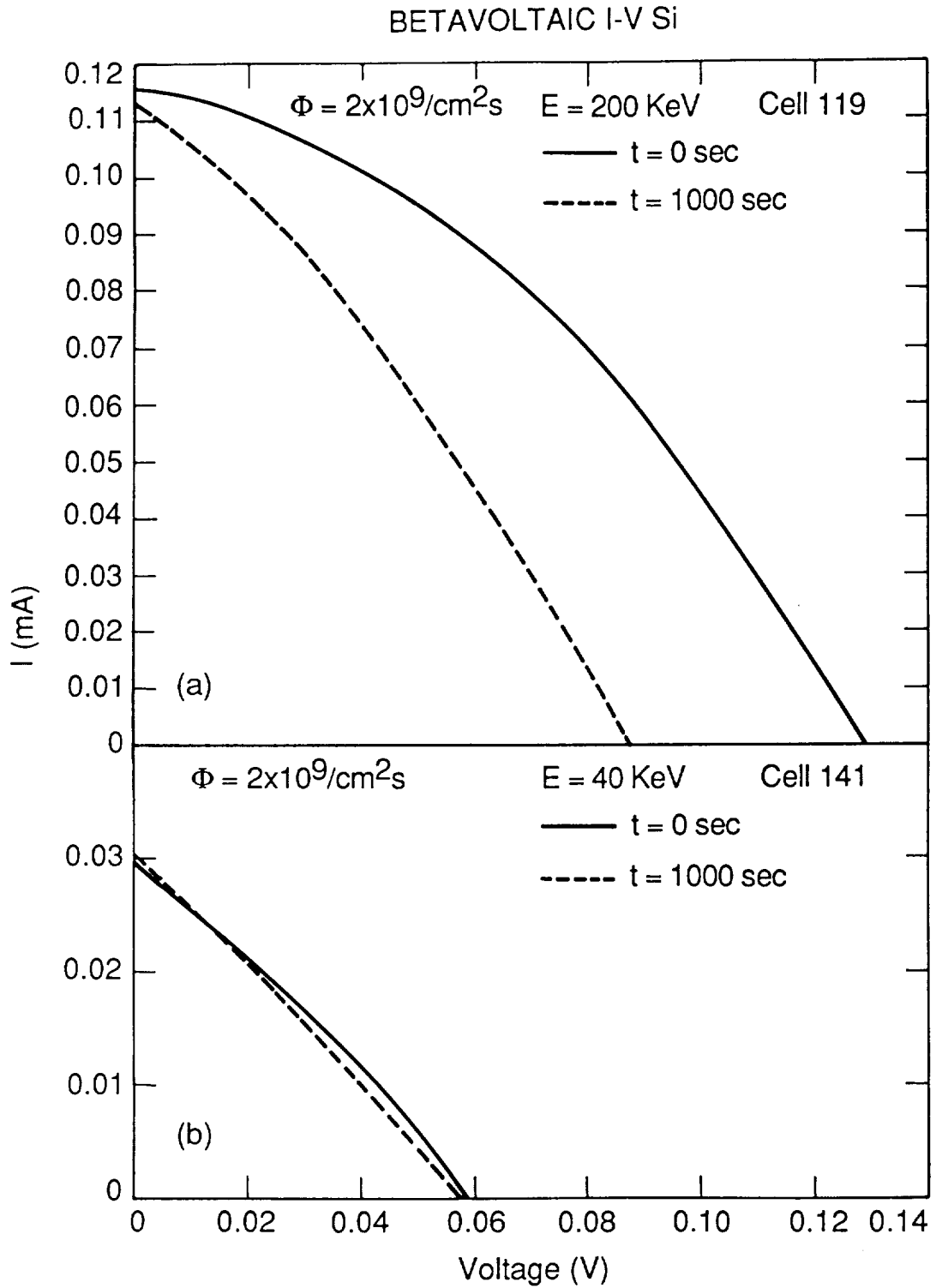
Figure 2. Betavoltaic I-V of Si solar cells for (a) 200 KeV and (b) 40 KeV electron exposures at a flux of 2 x 10^9 electrons/cm^{2}s.
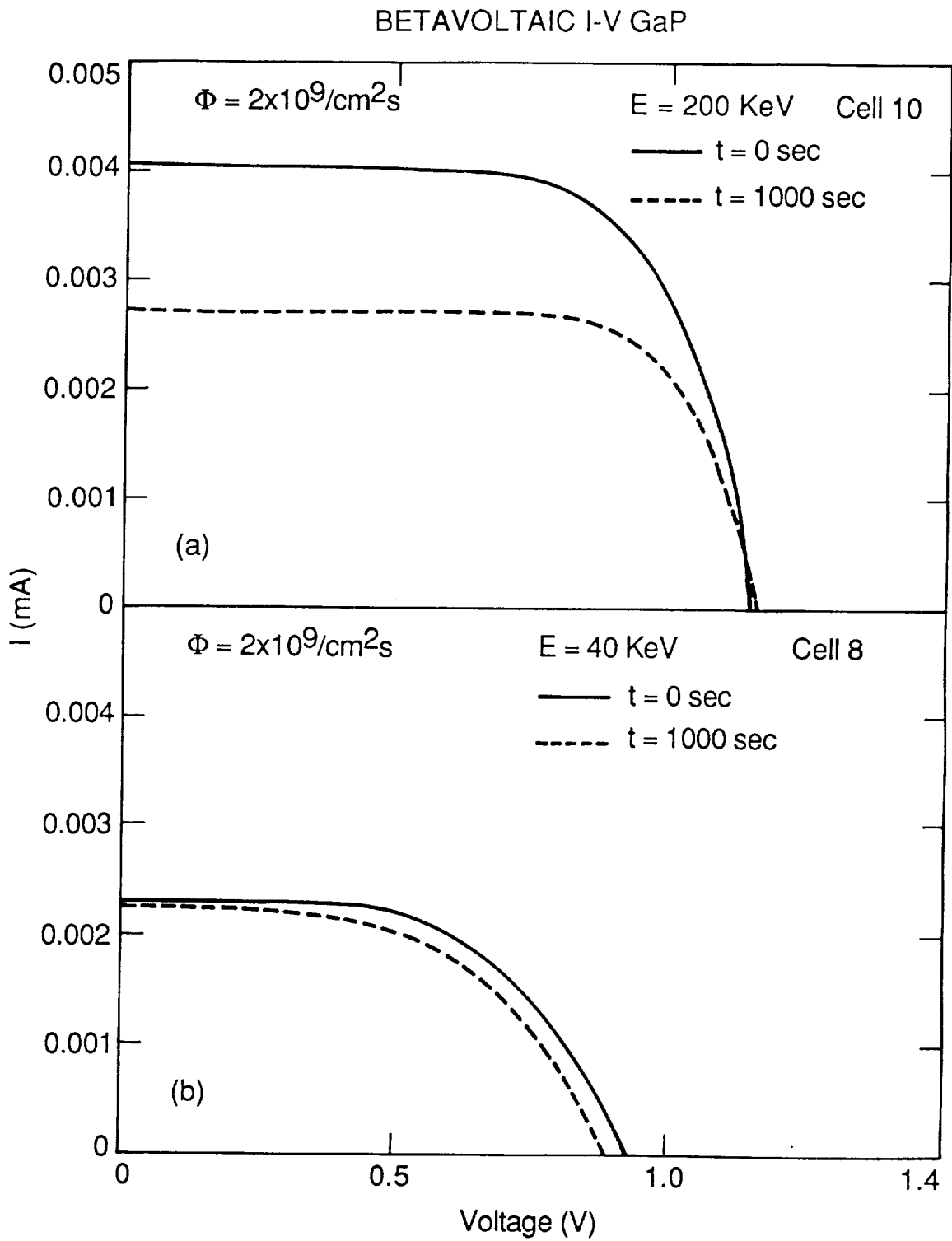
BETAVOLTAIC I-V GaP

Figure 3. Betavoltaic I-V for GaP beta cells for (a) 200 KeV and (b) 40 KeV electron exposures at a flux of 2 x 10⁹ electons/cm²s.
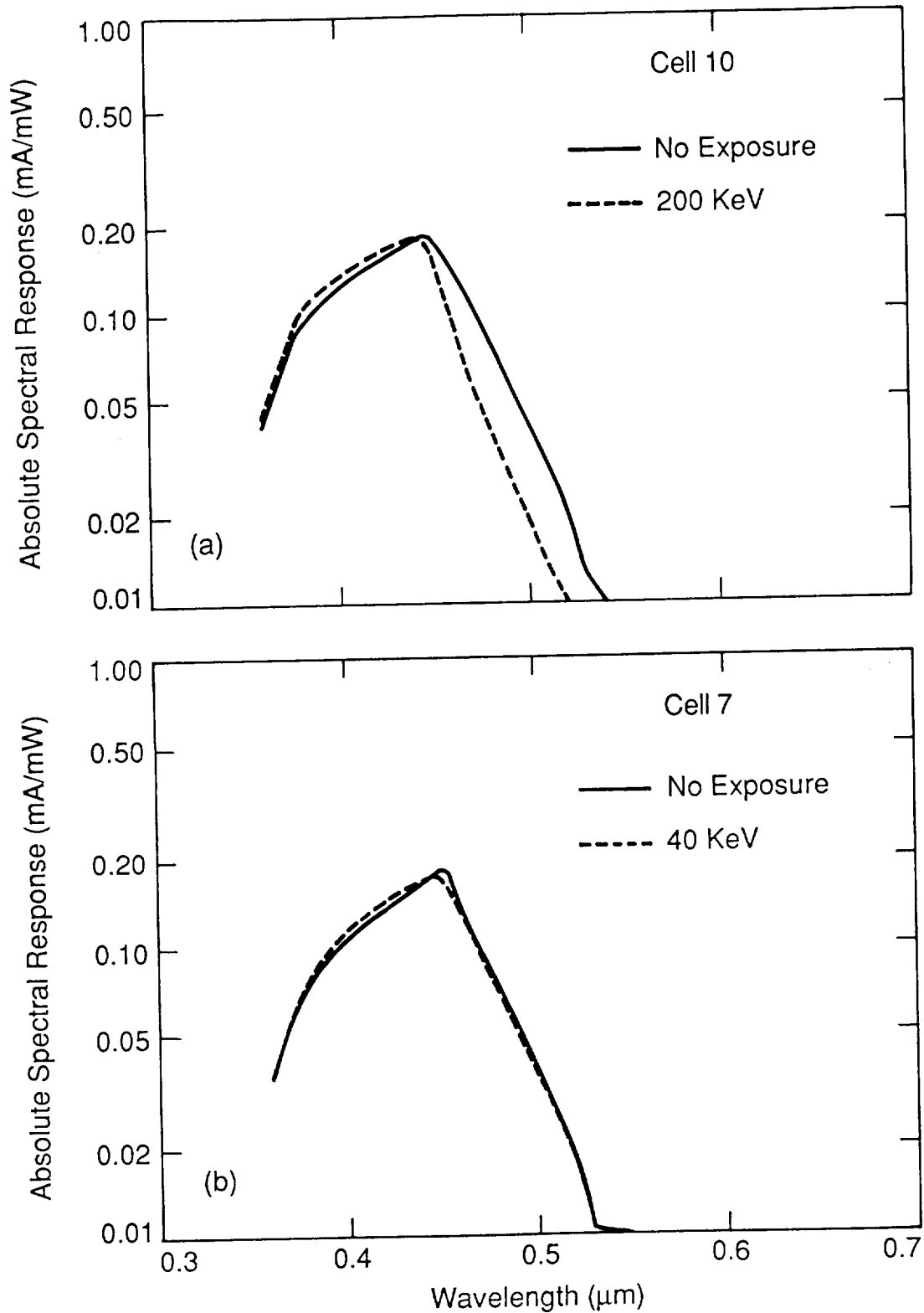
SPECTRAL RESPONSE GaP

Figure 4. Spectral response of GaP beta cells before and after exposure to (a) 200 KeV and (b) 40 KeV electrons to a total fluence of 2×10^{12} electrons/cm^{2}s.
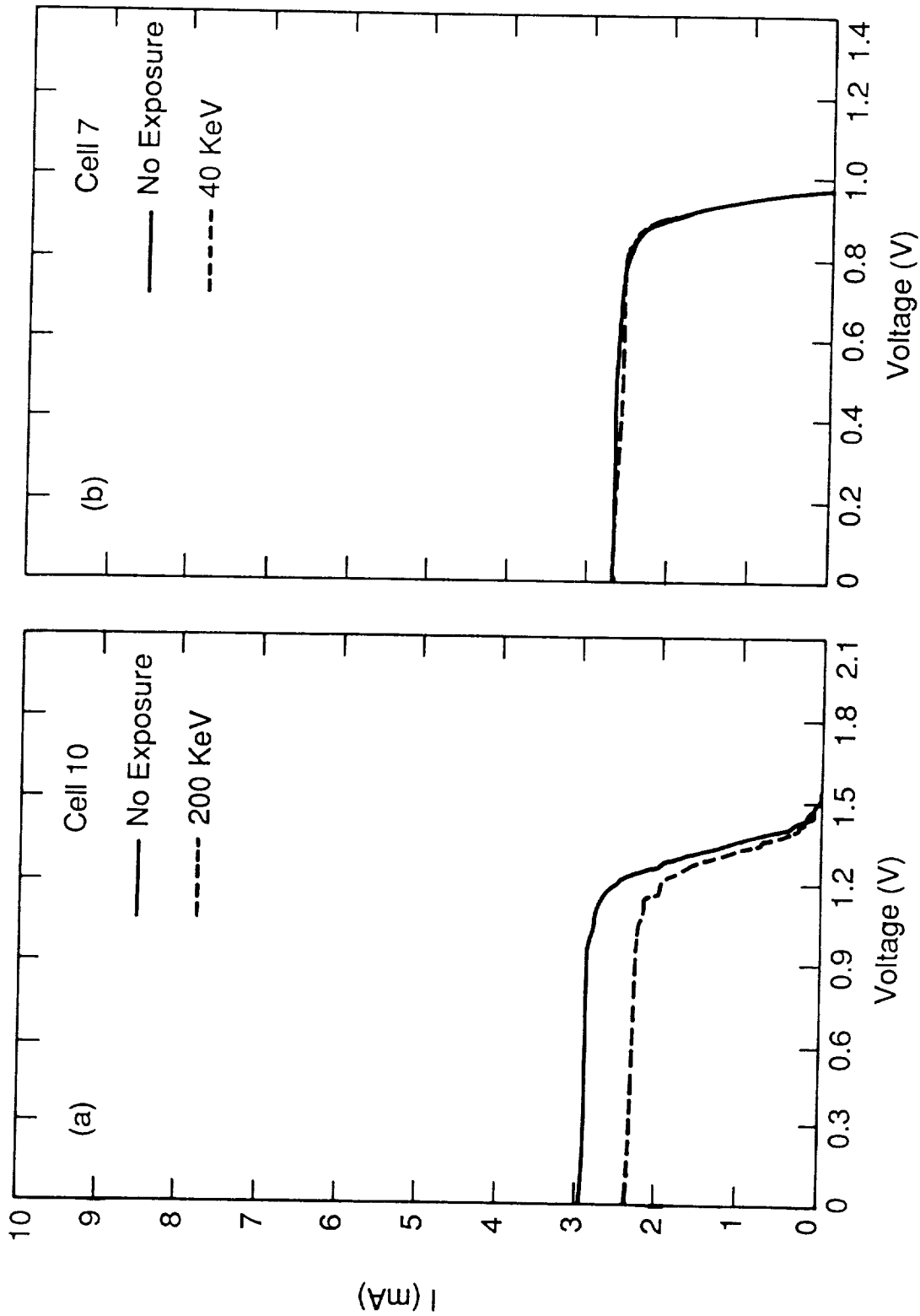
SOLAR I-V GaP

Figure 5. Solar I-V data of GaP beta cells before and after exposure to (a) 200 KeV and (b) 40 KeV electrons to a fluence of 2×10^{12} electrons/cm^{2}s.