PHOTOVOLTAIC CONVERSION OF LASER ENERGY*

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INTRODUCTION

One obvious technique for converting laser to electrical energy is by the use of photovoltaic devices because of our experience with them as solar cells. The efficiency of such devices is dependent on the wavelength and even on the energy density of the laser beam because of temperature effects. In general, though, one would expect useful operation in the range of a few tenths microns to several microns in wavelength, but *not* at 5 or 10μ. The energy density range is estimated to be from any lower level up to about 15 to 20 kW/m^2. With the addition of active cooling, the upper value could be increased considerably.

Photovoltaic devices are attractive for laser conversion for the following reasons: (1) relative ruggedness, (2) efficient light absorption, (3) built-in redundancy leading to high reliability, (4) absence of hazardous materials, (5) present conversion efficiencies of 30 percent with 40 percent feasible, (6) high flexibility in the system design and in transportation and assembly in space because of the small physical size of the devices, and (7) in the case of Schottky barrier devices, ability to match the laser wavelength (within the range mentioned above).

At the first conference held 2 years ago, Professor Martin Wolf presented an excellent tutorial talk on the basics of photovoltaics. The talk was oriented toward silicon technology, and particularly toward p/n homojunction devices, since that technology is presently used in space for solar cells. However, this technology is very limited for laser conversion in that practical maximum efficiencies for silicon (about 40 percent) occur only for a wavelength around 0.9μ. There is presently no high energy laser being developed that will operate in the 0.9-μ range. Operation at shorter wavelengths, and hence, at higher photon energies, will only provide excess heat as explained by Professor Wolf. Only an energy of 1.12 eV, the band gap of silicon at room temperature, corresponding to a wavelength of 1.1μ, is required to generate the electron-hole pairs that will contribute to the output current. However, photons of wavelengths between 0.9 and 1.1μ will not be efficiently utilized either because of the low light absorption in silicon – typical in indirect band gap semiconductors.

If efficient conversion is required at wavelengths shorter than about 1μ, wider band gap semiconductors are required. Indeed, the band gap energy should nearly equal the laser photon energy for maximum efficiency. Since most such semiconductors with a reasonable history of materials technology development are direct gap materials (III-V compounds), light absorption is very high, and the operating wavelength can be very near the absorption edge; that is, the photon

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS 7-100 sponsored by the National Aeronautics and Space Administration.

energy can be just slightly higher than the band gap energy. However, the technology of good p/n junction photovoltaic devices is virtually non-existent for such materials. Another alternative is clearly needed.

An alternative that has been under investigation at JPL is the Schottky barrier (SB) photovoltaic converter. As will be shown, efficiencies to 30 percent at any wavelength in the visible and near infrared region are now attainable with potential for even higher efficiency. Furthermore, the devices can be made in solar cell sizes, such as 4 cm^2 or 9 cm^2, and the semiconductors used (GaAs and $GaAs_{1-X}P_X$) are readily available, as they are commercially grown by vapor epitaxy in very large quantities for the present light-emitting diode market.

PHOTOVOLTAIC CONCEPTS FOR SCHOTTKY BARRIERS

Structure

The structure of the SB converter is shown on the right hand side of figure 2. Physically it is very similar to a conventional solar cell except that the p/n junction is replaced by a simple metal-semiconductor interface. (The oxide layer will be discussed below.) The semiconductor can be nearly any semiconductor depending on the photon energy of the laser; however, the ternary compounds of GaAs containing phosphorous have been chosen because of their relatively high state of development, commercial availability, crystal sizes of 6-10 cm^2, and large scale production potential. The compounds under investigation ($GaAs_{1-X}P_X$, $0 \leqslant X \leqslant 0.5$) are epitaxially grown from the vapor phase on highly doped substrates of GaAs. The latter provide for lower bulk series resistance and for good ohmic back contacts. The photo-active layer need only be several microns thick because of the high light absorption.

The semi-transparent metal film currently being used is an evaporated 60Å-thick gold film. The grid contact has been a thicker film of gold – soon to be changed to another metal for soldering ease. The antireflection coating is presently Ta_2O_5. All fabrication steps can be done sequentially in one vacuum evaporation station without breaking vacuum. Neither the AR coating nor grid contact have been optimized to date.

A number of advantages of the SB approach as compared to p/n junctions are given in figure 2. As we shall see, the current output of SB devices is substantially better than a junction solar cell for a given wavelength and intensity, but the voltage output is inherently lower. Two approaches to improve the voltage will be discussed later.

Current Output

The basic mechanism of all photovoltaic devices is the absorption of photons of sufficient energy to generate electron-hole pairs – usually one pair per photon. Professor Wolf's talk at the last conference described some of the loss mechanisms in the collection efficiency (η_c) which prevent the current generated from being equal to the maximum possible current ($q N_{ph}$), where q is the electronic charge and N_{ph} the photon density. Figure 3 shows the generation of the hole-electron pair for a direct-gap semiconductor such as GaAs. For photon energies above the band

gap, the excess energy is converted to heat by lattice interactions. The amount of light generated current (J_L) for a given power input (P_{in}) is given by

$$\frac{J_L}{P_{in}} = \frac{q}{hc} \lambda \eta_c , \tag{1a}$$

$$\frac{J_L}{P_{in}} \left(\frac{\text{amps}}{\text{Watt}}\right) = 0.80 \ \lambda \ (\text{microns}) \ \eta_c \left(\frac{\text{electrons}}{\text{photon}}\right), \tag{1b}$$

where h is Planck's constant, and c the velocity of light. Figure 4 shows the relationship between P_{in} and J_L for various collection efficiencies. Typical values of η_c, the number of electrons collected per photon absorbed, are from 0.7 to 0.9 in an SB device. For example, with a wavelength of 0.5 μ and a power of 10 kW/m^2, the output current density would be about 300 to 350 mA/cm^2 with no reflection losses.

The simplest model for current generation (ref. 1) leads to the expression for J_L given in figure 5, where $\phi \equiv N_{ph}$ (absorbed), α is the absorption coefficient, W is the space charge region width (see figure 1), and L_p the hole (minority carrier) diffusion length. The last term in the expression for J_L is negligible. Experimental measurements of the spectral response do not agree well with this expression, particularly at short wavelengths, probably due to recombination in the inversion layer (in figure 1, $0 < X < \lambda$). This effect should decrease with increasing doping concentration since both λ and W decrease in width. Devices are now being made to verify this. In any case, such expressions for current density or collection efficiency are only valid for photons absorbed in the semiconductor. The wavelength dependence for the transmission of light through the metal film for the thicknesses utilized is not that well known to be able to calculate exactly the density of photons transmitted into the semiconductor.

On the basis of some computer calculations, it is believed that the amount of absorption in the 60-Å gold film is about 10 percent, with another 5-10 percent lost because of the grid structure. Despite these losses, the output current of the SB cells is generally better than that in junction devices, particularly at short wavelengths. Figure 6 shows some results of the calculated optical characteristics, which have primarily been used to determine the antireflection coating requirements.

In summary, the expected current densities from SB cells are those obtained from equations (1a and 1b) or from figure 4 using a value of ~ 0.8 for η_c. These current densities are satisfactory, especially for GaAs which has good values of minority carrier diffusion length (L_p). Little improvement can be expected except by decreasing the metal film thickness or grid area, neither of which is compatible with higher laser intensities.

Voltage Output

Improvements in conversion efficiency can only come from increases in the voltage output. This parameter, in particular the open-circuit voltage V_{oc}, is determined by the magnitude of the dark diode current density J_D. Referring to figure 5, the expression for J_D is for an ideal or near-ideal metal-semiconductor contact. For doping densities below about 5×10^{16} cm^{-3}, field

emission or tunneling are negligible, and J_D is determined by the barrier height ϕ_B since the current is by thermionic emission over the barrier. The constant A* is the modified Richardson's constant, $A^* = m^*/m_o \times A_o$, where $A_o = 120\ A/^oK^2/cm^2$, and m^*/m_o is the ratio of effective-to-free electron mass; R_s is the series resistance and k the Boltzmann constant. The empirical factor n describes non-ideal behavior due to image forces, field-tunneling, and interfacial layers.

Upon setting the current J equal to zero, the expression for V_{oc} in figure 5 follows. We see that for a fixed light intensity, and hence, fixed J_L, V_{oc} is linearly dependent on n and logarithmically on J_D. An obvious means of increasing V_{oc} is by raising ϕ_B. Since the barrier height is approximately two-thirds of the band gap for many n – type semiconductors, this increase in V_{oc} can, and indeed is, raised by using higher band gap materials. Figure 7 shows this effect assuming a modest value for n of 1.1. Unfortunately for laser energy conversion, the wavelength must be decreased correspondingly so as to assure absorption in the semiconductor. But for a given power density, the total number of photons decreases as the wavelength decreases according to

$$N_{ph} = \frac{\lambda}{hc} P_{in} \tag{2}$$

Consequently, the amount of current generated drops, even as the voltage rises, and we find that the conversion efficiency remains approximately the same. The means of varying the band gap, and hence, the barrier height, is simply done by adding phosphorous or aluminum to GaAs (figure 8). Since Schottky barriers can be made with equal ease on any of these ternary compounds, the increase in band gap to "tailor" the converter to any specific laser with about the *same* efficiency is one of the major features of the SB cell. Figure 9 gives the spectral response, or actually η_c, measured for three ternary compounds. We see that the peak of response, as expected, does shift to shorter wavelengths as the phosphorous content is increased. Thus, for example, the ideal converter material for matching the copper vapor laser under development at JPL ($\lambda = 5106$Å) is $GaAs_{1-X}P_X$ with X about 0.4.

In summary, increasing the voltage output by raising the semiconductor band gap does not increase the efficiency due to the drop in current (assuming that the laser wavelength is kept near the equivalent band-gap wavelength). To further increase the efficiency, which is about 20 percent for the "ideal" SB cell (n = 1.0), other concepts must be utilized.

ADVANCED CONCEPTS

Multilayer Schottky Barrier Cell

We have seen that raising the semiconductor band gap, and hence, the barrier height, increases the voltage output. However, for monochromatic light, we are limited by the fact that the energy of the band gap can not exceed the photon energy. For polychromatic light, such as sunlight, the increase in band gap will decrease the current because of reduced light absorption.

A concept such as that shown in figure 10 is currently under development on another program to obtain the higher voltage without a major drop in current. The top layer upon which the Schottky barrier is made has a band gap of about 2 eV and is epitaxially grown on GaAs which has a

band gap of 1.42 eV. Photons which are not absorbed in the top layer are absorbed in the GaAs. Because of the difference in band gaps, there will be a 0.5-eV barrier for the minority carriers (holes) to surmount or penetrate if they are to be collected at the surface. For this reason, the top layer thickness should ideally be not larger than the width of the space charge region W, in which case, the built-in electric field should improve the hole transport by thermionic-field emission. Since GaAsP compounds require a region of graded composition to minimize the effect of dissimilar lattice constants with GaAs, the top layer semiconductor was chosen to be $Al_XGa_{1-X}As$ which has a much better lattice match with GaAs. Unfortunately, AlGaAs is presently grown only by liquid epitaxy. This process does not give as smooth a surface as vapor phase epitaxy, and does not allow for large areas or large quantity production. Suitable devices with the required physical characteristics have not been grown to date. In any case, the major interest in such a device, if successfully grown, will be for broad-band light, that is, sunlight energy conversion, since these would be only limited improvements for laser energy conversion.

AMOS Solar Cell

A major advance in increasing the efficiency of both laser and solar energy Schottky barrier converters has recently been made at JPL. With an addition of a controlled amount of oxide layer between the semi-transparent metal film and the semiconductor, as shown in figure 1, the open-circuit voltage was found to increase by as much as 50 percent. Figure 11 shows a comparison between two cells under water-filtered tungsten lighting – one without the oxide and the other with (called AMOS – *A*ntireflection coated *M*etal-*O*xide-*S*emiconductor). The oxide process also works on GaAsP compounds and figure 12 shows a light I-V characteristic for laser illumination at 5154Å. This cell has an efficiency of 30 percent when AR-coated. The enhanced effect occurs at all light intensities investigated, and cells have been operated at current densities of nearly 0.4 A/cm^2, or over 10 times the current density of a silicon solar cell in space.

The oxide layers reported on here were thermally grown in air at temperatures between 100° and 200°C. The oxide films are apparently patchy and nonuniform, thus the ultimate enhancement in efficiency has not been obtained. Increasing the oxide thickness increases the value of the empirical factor n, through at the same time it increases the value of the pre-exponential part of J_D. The diode current departs from purely thermionic emission as the thickness increases, thus tending to lower the increase in voltage. The *net* effect though, is to substantially raise the voltage to some unknown limit, before which the series resistance of the oxide film degrades the curve factor of the light I-V curve. This occurs at about 50-Å thickness depending on the light intensity level being used.

An explanation for such a marked effect is not completely understood at this time, but undoubtedly is related to the density of surface states at the oxide-semiconductor interface. The presence of an interfacial layer modifies the transmission coefficient of the barrier, and hence, the value of J_D at a given bias. Since there will be a bias dependent voltage drop across the insulating layer, there will also be a reduced dependence of the semiconductor surface potential on bias leading to an increased value of n in the expression for J_D. The degree of the effect on the value of n depends on whether the interface states are in better communication with the metal or with the semiconductor. The analysis of the interfacial effect on n for dark current-voltage curves was first reported by Card and Rhoderick (ref. 2), who showed that increasing the oxide thickness (on silicon) increases the communication between the interface states and the semiconductor, and in

turn, increases the value of n. We have been able to double the value of n, although the aforementioned increase in the pre-exponential term limits the corresponding increase in voltage to some degree.

Our current effort is to improve and optimize the oxidation process and to better understand the underlying physics of the enhanced effect, with a goal of 40 percent efficiency at any wavelength in the visible.

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2. Card, A. C.; and Rhoderick E. H.: Studies of Tunnel MOS Diodes I. Interface Effects in Silicon Schottky Diodes, J. Phys. D: Appl. Phys., Vol. 4, no. 10, 1 Oct. 1971, p. 1589-1601.

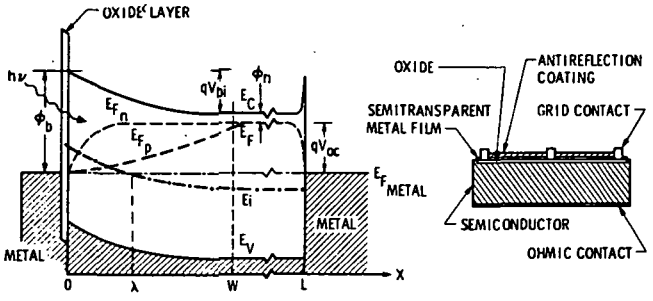

Figure 1.– AMOS solar cell.

- ADVANTAGES OF BARRIER CELLS
  - LOW TEMPERATURE FABRICATION
  - HIGH CONTROL OF CHARACTERISTICS
  - LOW COST BARRIER FABRICATION
  - CARRIERS GENERATED IN SPACE-CHARGE REGION
  - ELIMINATES PROBLEM OF SHALLOW JUNCTIONS
  - ELIMINATES PROBLEM OF SURFACE RECOMBINATION
  - COMPATIBLE WITH POLYCRYSTALLINE FILMS
- REQUIREMENTS OF METAL FILM
  - HIGH LIGHT TRANSMISSION
  - LOW SHEET RESISTANCE
  - STABLE
  - HIGH BARRIER HEIGHT
  - COMPATIBILITY WITH A-R COATING

Figure 2.– Schottky barrier cells.

$$\frac{J_l}{P_{in}}\left(\frac{\text{amps}}{\text{watt}}\right) = 0.8\ \eta_c\left(\frac{\text{electrons}}{\text{photon}}\right)\lambda\ (\mu)$$

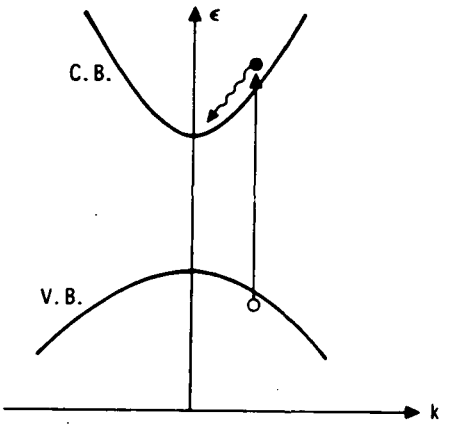

Figure 3.– Current generation.

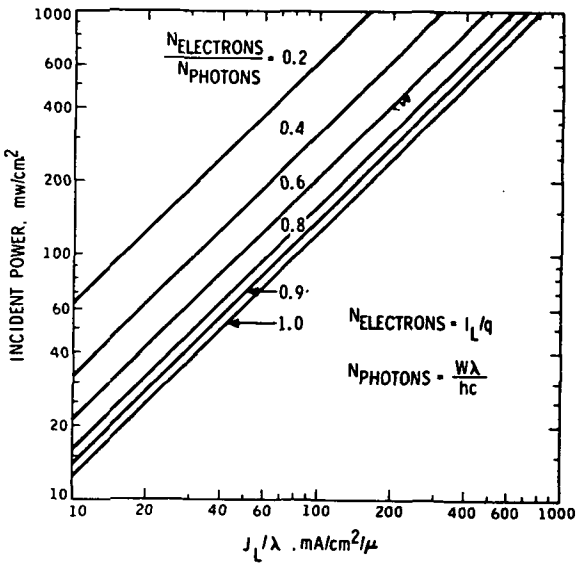

Figure 4.– Determination of collection efficiency.

$$J = J_D - J_L$$

$$J_L = -q\phi\left\{1 - \exp\left[-\alpha W(V)\right]/1+\alpha L_p\right\} - \frac{qD_p}{L_p} p_o \left[\exp(-qV/kT)-1\right]$$

$$J_D = A^* T^2 \exp(-\phi_B/kT) \exp\left[q(V-IR_s)/nkT - 1\right]$$

$$V_{oc} = nkT/q\left[\ell n (J_L/J_D) + 1\right]$$

Figure 5.– Solar cell equations.

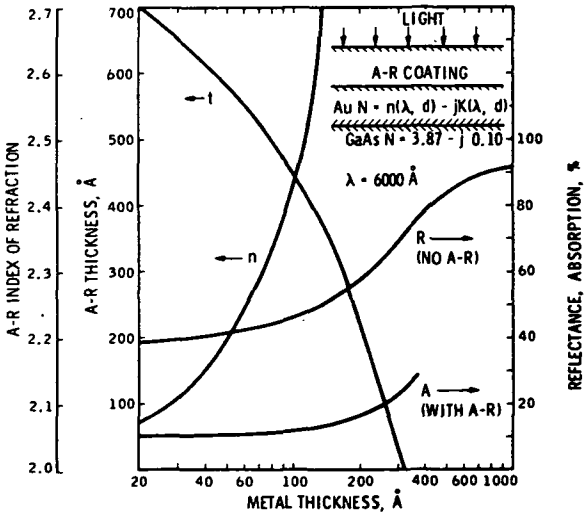

Figure 6.– Optical characteristics.

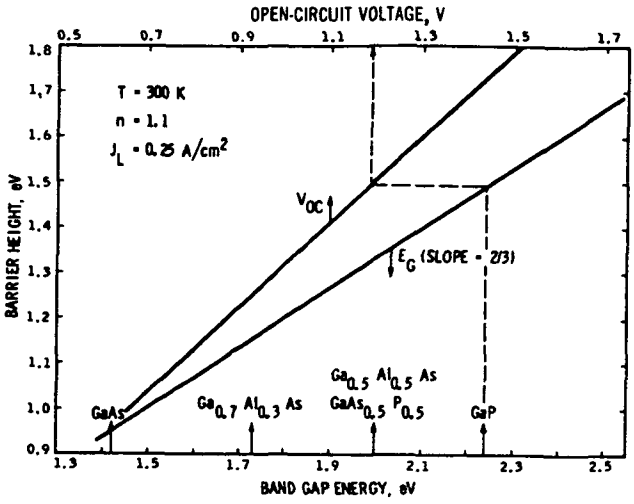

Figure 7.– Effect of higher band gaps.

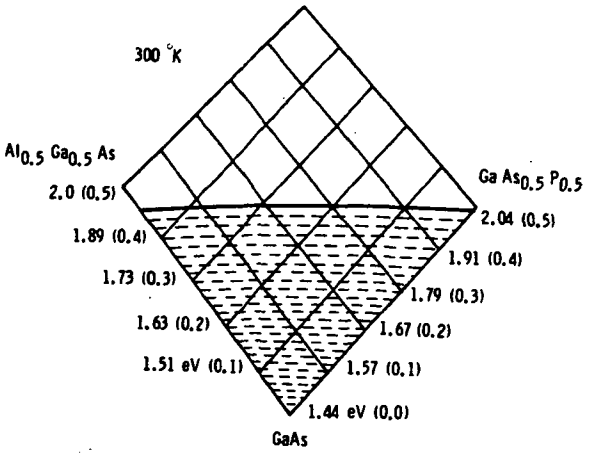

Figure 8.– Ternary compounds of Ga As.

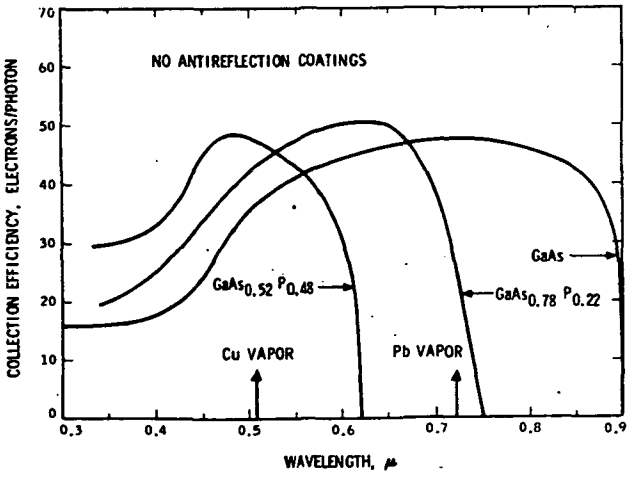

Figure 9.– Absolute spectral response.

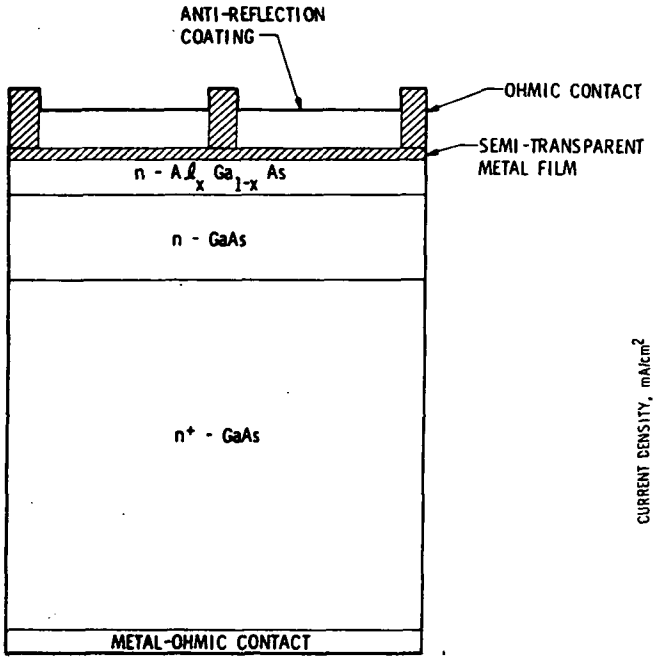

Figure 10.– Multilayer Schottky barrier solar cell.

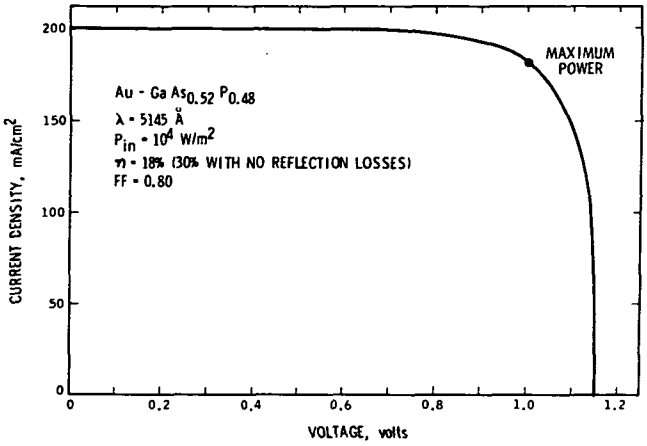

Figure 12.– Light 1-V characteristic.

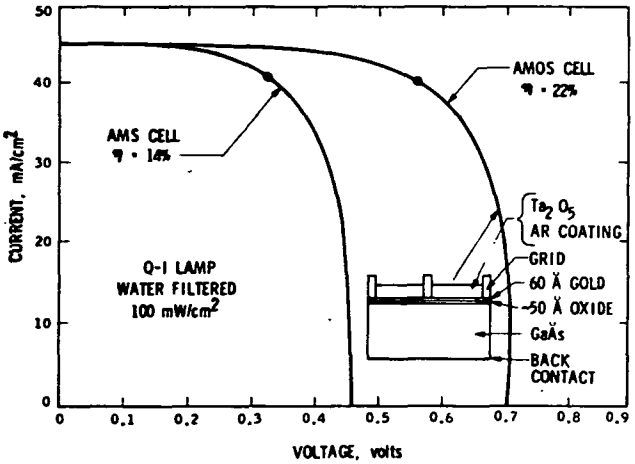

Figure 11.– AMOS solar cell.

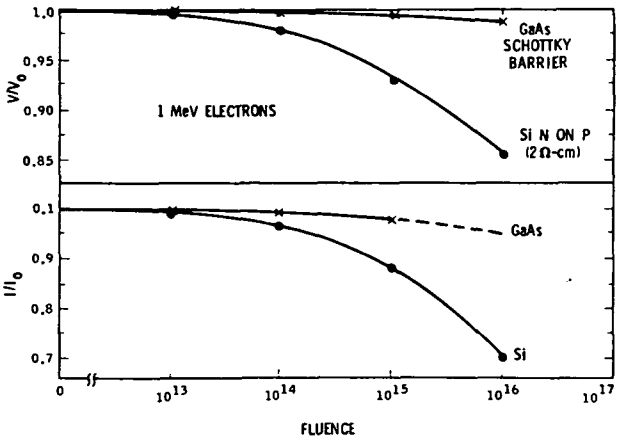

Figure 13.– Radiation resistance.

DISCUSSION

Ned Rasor, Rasor Associates – I assume all these results were recorded at room temperature?

Dick Stirn: Yes.

Ned Rasor: I wonder if you could mention how high you could go and not get well out of this performance range.

Dick Stirn: That's a very pertinent question, of course, and I did mean to mention that at the beginning but overlooked it. All photovoltaic devices, of course, have this problem. It comes in the reverse saturation current since there is a temperature dependence. As one increases temperature, the output drops. In silicon its like 2 mV/°C and that corresponds in sunlight to about 2 mW/°C. Normally with PN junction devices as you go up in band gap this improves, the source of this reverse saturation current in a junction is related to the diffusion current and that's related to the band gap, But, unfortunately, for a Schottky barrier device it's thermionic current and who knows what with the oxide layer AMOS cell. We don't know for sure since we haven't yet investigated its temperature dependence. But for the thermionic emission, of course, that has different temperature characteristics and in practice its turning out to be comparable to that of silicon. So even though we are working with a higher band gap, the temperature characteristics are similar to silicon and we would expect to see that kind of decrease. So we predict that its going to be about 2 mV/°C loss and you can carry that as far as you like. The big question is how high these will be operated at, of course. That's hard to say – it depends on the system we are finally going to talk about. Certainly, even if we could shield the cells from the sun by orientation or with a narrow band filter, this would help a lot. A solar panel stabilizes at about 60°C. How well heat sinked these are and radiate to outer space will determine their temperature.

Mark Wrighton, M. I. T. – What is the highest absolute current you have been able to achieve?

Dick Stirn: We haven't particularly shot for that; we haven't even ran the laser at full power. We are just putting on AR coatings which will remove a 40 percent loss. Dr. Lundholm was there the other day. What was it – gallium arsenide that we stuck on which did have an AR coat? I remember that we were running about 0.5 A/cm^2 I think with the laser we have now, we can run up to 1 A/cm^2.

Joe Horwath, Lockheed – It is well known that the quantum efficiency for light generation from gallium arsenide can be dramatically improved by lowering the temperature to, for example, 77°K. Have you, in fact, lowered your temperatures to see what the efficiencies become?

Dick Stirn: I don't think the collection efficiencies will change much with temperature; of course you are referring to the inverse processes. But for electrical output, the inverse process – conversion – the current is relatively insensitive to temperature. What will happen is the voltage will go up. Thus the inverse of what Ned Rasor mentioned will happen – the voltage will increase by 2 mV/°C down until other processes take over. Thus the efficiency goes up even higher.

Joe Horwath, Lockheed – But there is no, abrupt nonlinear type effect?

Dick Stirn: Not that I am aware of; physically I can't see of any.

Dick Pantell, Stanford – The use of AR coatings means that you have to be concerned about orientation.

Dick Stirn: That's true – we always assume normal incidence. In the system they would be on panels which you assume will be oriented for the beam so the cosine of the angle, even for 20°, will be small.

Dick Pantell, Stanford – But with interference multilayer films this will be quite sensitive – much more sensitive than a cosine law.

Dick Stirn: No, we will use a very simple layer AR coating, and this should not be very orientation-sensitive.

Joe She, Colorado State University – I guess these Schottky barrier devices are only applicable to wavelengths shorter than 0.9 μ? Could you comment on the possibility of extension to longer wavelengths?

Dick Stirn: They are not very attractive. The same is true with PN junctions. The problem is that the voltage is dropping. As you go to lower and lower band gaps the reverse saturation current keeps increasing just as if you were going up in temperature. For larger than 1 μ of course, you would have to leave silicon. And the band gap and Schottky Barrier will be small, so that the voltage output will be small. This oxide might help, but you still will only have about one-half volt output.

Joe Horwath, Lockheed – Except for gallium arsenide phosphide, I really don't see that the economics of the system are ever going to be in favor of Schottky barrier devices of the type you mentioned as opposed to the silicon devices.

Dick Stirn: Are you talking about terrestrial use or space use where in the latter case you can tolerate a high cost for performance? The present Schottky substrates are about five times that of silicon; with mass production they tell me this can be lowered to two and one-half times. As long as you brought that up – let me mention that one of the reasons for working on Schottky barriers is that the approach should lend itself to polycrystalline thin films, unlike other photovoltaic devices. We are going to look into this for the terrestrial solar energy program in the very near future. Because the Schottky is made by a low temperature process, without too much loss in efficiency this could be adapted to a polycrystalline thin film which will cut down the cost tremendously.