References

1 KIM, H. K., and RA, J. B.: 'An active biquadratic building block without external capacitors', *IEEE Trans.*, 1977, **CAS-24**, pp. 689-694
2 MITRA, A. K., and AATRE, V. K.: 'Low sensitivity high frequency active *R* filters', *IEEE Trans.*, 1976, **CAS-23**, pp. 670-676
3 DRAKE, J. M., and MICHELL, J. A.: 'Continuously tunable sinusoidal *R* oscillators with a minimum number of elements', *Int. J. Electron.*, 1981, **50**, pp. 141-147

0013-5194/82/020096-02$1.50/0

SILICON SOLAR CELLS WITH REDUCED TEMPERATURE SENSITIVITY

Indexing terms: Semiconductor devices and materials, Solar cells

As the open-circuit voltage of silicon solar cells continues to improve, one resulting advantage, not widely appreciated, is reduced temperature sensitivity of device performance. Recently a new type of silicon solar cell has been described which has resulted in a significant increase in open circuit voltage. Experimental results are described for these devices which demonstrate the lowest temperature sensitivity ever reported for silicon cells under unconcentrated sunlight. With further improvements in voltage, it should be possible to approach the relative temperature insensitivity of some high performance GaAs devices.

The energy conversion efficiency of silicon solar cells normally falls by 4000–5000 ppm* for every degree centigrade increase in operating temperature. Gallium arsenide cells are well known to be less sensitive to increasing temperature and, in fact, have a temperature coefficient of performance about half that of silicon cells. Experimental results are described in the present correspondence for a high performance silicon cell which displays a temperature coefficient of performance about halfway between that of conventional silicon cells and gallium arsenide cells. This coefficient is believed to be the lowest ever reported for a silicon cell under unconcentrated sunlight by a substantial margin. The results clearly demonstrate the direction required to obtain further improvements in this area.

The high performance device responsible for this improved performance combines a very shallow N^+P homojunction with a metal-insulator-semiconductor (MIS) heterojunction to give a hybrid MINP structure.[1] The outstanding performance feature of this device is its open-circuit voltage V_{oc}. Open-circuit voltages as high as 678 mV under air mass zero (AM0) illumination at 25°C have been reported with this approach, significantly higher than for any other silicon cell.

Using V_{oc}, the short-circuit current I_{sc} and the fill factor FF to parameterise cell performance, the temperature sensitivity of V_{oc} dominates the performance sensitivity. The ideal temperature sensitivity of V_{oc} is given by[2]

$$\frac{dV_{oc}}{dT} = -\frac{V_{go} - V_{oc} + \gamma kT/q)}{T} \tag{1}$$

T is temperature in absolute units, kT/q is the thermal voltage and γ is a parameter normally lying in the range 1 to 4. V_{go} is the voltage equivalent of the semiconductor bandgap linearly extrapolated from the temperature range of interest to 0 K. For the range 300–400 K, V_{go} has the value of about 1·206 V for silicon and 1·575 V for gallium arsenide.[3]

Since the term involving γ is relatively small, eqn. 1 predicts an essentially linear decrease in V_{oc} with temperature over a limited temperature range. Extremely detailed experimental information on the temperature sensitivity of different silicon cell types is contained in Reference 4. These results confirm the validity of eqn. 1 and the linear variation of V_{oc} over limited temperature ranges. For example, for each of 10 of the 12 silicon device types measured under AM0 (air mass zero) illumination, the five data points in the range 0 to 80°C could be fitted by a linear regression program with a correlation coefficient of magnitude 0·9999 or higher. The extrapolated zero degree V_{oc} ($\simeq V_{go} + kT_{av}/q$) lay in the range 1·229 V to 1·312 V in each of these cases. Results for a gallium arsenide cell type gave a similarly high correlation coefficient with an extrapolated zero degree V_{oc} of 1·582 V.

The important point about eqn. 1 is that it shows that the temperature sensitivity of V_{oc} decreases as the magnitude of V_{oc} increases at any fixed temperature. Hence it predicts a reduced temperature sensitivity for the high performance MINP cells previously described.

The cell short-circuit current (I_{sc}) tends to increase slightly with increasing temperature. This is due to a reduction in the bandgap which increases the absorption coefficient of all wavelengths. This effect is augmented by increases in the minority carrier diffusion length with increasing temperature. Both effects improve the long wavelength response of the cell. Because of its sensitivity to specific cell parameters, it is not possible to derive an expression of equal generality to eqn. 1 for this effect. Experimental results show that I_{sc} increases at a rate of about 300–800 ppm/°C around room temperature under AM0 illumination.

The cell fill factor FF generally decreases with increasing temperature. Empirical expressions for the fill factor in terms of other cells parameters have recently been described.[5] Using these expressions and assuming that the cell ideality factor[5] n and parasitic series and shunt resistances do not vary strongly with temperature gives the following approximate expression for the temperature sensitivity of the fill factor

$$\frac{1}{FF}\frac{dFF}{dT} \simeq (1 - 1{\cdot}02FF_0)\left[\frac{1}{V_{oc}}\frac{dV_{oc}}{dT} - \frac{1}{T}\right] \tag{2}$$

where FF_0 is the idealised value of the fill factor of the cell in the absence of series resistance effects. The deviation of the above expression from the precise mathematical value is less than about 5% for the normal range of cell $V_{oc}(10 < V_{oc}/[nkT/q] < 50)$.

Eqn. 2 was found to be in reasonable agreement with the experimental results of Reference 4, although it overestimated the magnitude of the temperature sensitivity in some cases. This was attributed to changes in parasitic resistance values with temperature for some cell types.

Both eqns. 1 and 2 highlight the importance of V_{oc} in decreasing the temperature sensitivity of cell efficiency. It was therefore of interest to have an accurate measurement made of the temperature sensitivity of an improved V_{oc} cell at a recognised cell testing centre. This measurement was made using the test facilities within the Photovoltaic Analysis & Evaluation Branch of the Solar Energy Research Institute, Colorado. The device measured was MINP cell N263, which has a V_{oc} of 656

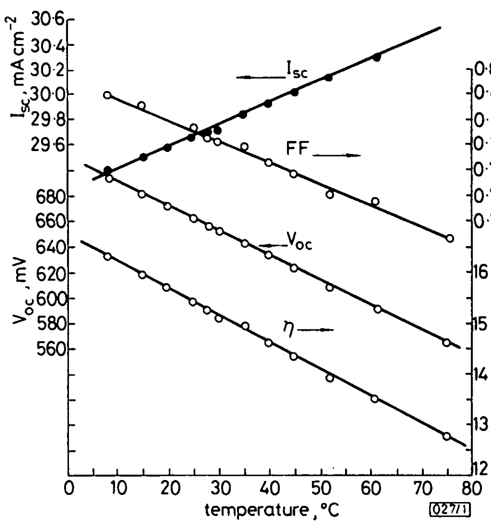

Fig. 1 *Temperature variation of open-circuit voltage V_{oc}, short-circuit current I_{sc}, fill factor FF and efficiency η for high performance MINP silicon cell 263*

* Use of ppm/°C as unit of temperature sensitivity removes ambiguities between relative and absolute units which arise from the dimensionless nature of efficiencies and fill factors

mV at AM1, 28°C. Since V_{oc} at AM0, 25°C would be about 13 mV higher, this cell is within 10 mV of the highest voltage reported for a cell of this type, and hence for any silicon solar cell.

The measured temperature dependence of V_{oc}, I_{sc}, FF and efficiency η are shown in Fig. 1 over the temperature range 8-75°C. All parameters varied approximately linearly with temperature. Linear regression results for the 12 data points are given in Table 1. Note that the 0 K intercept is an extrapolation in each case and does not have direct physical significance.

Table 1 LINEAR REGRESSION RESULTS FOR THE DATA OF FIG. 1

Parameter	0 K intercept	Slope	Correlation coefficient
V_{oc}	1251·0 mV	−1·977 mV/°C	−0·9998
I_{sc}	24·57 mA/cm^2	0·0171 mA/cm^2/°C	0·9983
FF	1·0415	$-8{\cdot}57 \times 10^{-4}$/°C	−0·9963
η	31·40%	−0·0536%/°C	−0·9996

V_{oc} varied at a rate of −1·98 mV/°C with an extrapolated zero degree value of 1·251 V. The latter is close to the median value for the conventional cells of Reference 5 of 1·240 V. Assuming a cell ideality factor of 1·1, the ideal value of the fill factor FF_0 is 0·826. Eqn. 2 then gives an ideal value of the fill factor sensitivity of $-7{\cdot}78 \times 10^{-4}$/°C, only about 9% lower than the experimental value.

The normalised temperature coefficients of N263 at AM1, 28°C are compared in Table 2 to the experimental data of References 4 and 6 at AM0, 25°C. From this Table it is seen that the improved V_{oc} has given cell N263 a marked advantage over other silicon cells with respect to the temperature dependence of V_{oc} and that the temperature dependence of this cell's fill factor is well below the median silicon cell value of Reference 4. In fact, only one of 12 silicon cell types gave a lower value. These results are even more favourable when it is realised that the extra V_{oc} expected under AM0, 25°C measurement (~ 13 mV) gives, from eqns. 1 and 2, a calculated reduction in the magnitude of these dependences of 100 and 30 ppm/°C, respectively. The temperature dependence of I_{sc} for cell N263 is near the median value for the other silicon cells.

Table 2 SUMMARY DATA ON NORMALISED TEMPERATURE COEFFICIENTS IN (ppm)/°C FORMINP CELL, CURRENT SILICON SPACE CELLS AND GaAs CELLS

	MINP N263* (AM1, 28°C)	Silicon space cells† (AM0, 25°C)	GaAs cells[4,6] (AM0, 25°C)
$-\frac{1}{V_{oc}}\frac{dV_{oc}}{dT}$	3010	3490–4510 (3690)	2040–2160
$\frac{1}{I_{sc}}\frac{dI_{sc}}{dT}$	580	380–710 (520)	520–710
$-\frac{1}{FF}\frac{dFF}{dT}$	1090	1000–1600 (1460)	610–1000
$-\frac{1}{\eta}\frac{d\eta}{dT}$	3510	4070–5350 (4470)	1950–2640

* Obtained from data of Table 1
† Range of values for the 12 silicon cell types reported in Reference 4. Median value is shown in brackets

As a result of the low values of the V_{oc} and FF dependences of cell N263, the magnitude of the measured temperature coefficient of efficiency of 3500 ppm/°C (estimated 3400 ppm/°C at AM0, 25°C) is markedly lower than the normal silicon cell coefficient of about 4500 ppm/°C. It is believed to be the lowest ever measured for a silicon cell under concentrated sunlight by a clear margin. In fact, it lies about halfway between the normal silicon cell value and reported values for gallium arsenide cells of 2000–2600 ppm/°C. If a silicon MINP cell of 700 mV open-circuit voltage is successfully developed, its temperature coefficient of efficiency would be expected, on the basis of eqns. 1 and 2, to drop in magnitude below 3000 ppm/°C, approaching the upper range of values observed for gallium arsenide cells.

This work was completed while one of us (MAG) was on a Special Studies Program at the Solar Energy Research Institute, Colorado. He would like to thank Dr. L. L. Kazmerski for making this possible. The financial assistance of the Solar Energy Research Institute and the Australian National Energy Research Development & Demonstration Council is gratefully acknowledged.

M. A. GREEN†
K. EMERY

Solar Energy Research Institute
Golden, Colorado, USA

A. W. BLAKERS

Solar Photovoltaic Laboratory
University of New South Wales
Kensington, Australia 2033

8th December 1981

† Permanent address: Solar Photovoltaic Laboratory, University of New South Wales, Kensington, Australia 2033

References

1 GREEN, M. A., BLAKERS, A., WILLISON, M., SZPITALAK, T., KELLER, E., GUAJA, E., and HART, P.: 'The MINP solar cell—A new high voltage, high efficiency silicon cell'. Conf. record, 15th IEEE photovoltaic specialists conf., Orlando, p. 1405; BLAKERS, A. W., and GREEN, M. A.: '678 mV open-circuit voltage silicon solar cells', *Appl. Phys. Lett.*, 1981, **39**, p. 483
2 GREEN, M. A.: 'Solar cells: Operating principles, technology, and system applications' (Prentice-Hall, 1982, p. 91
3 SZE, S. M.: 'Physics of semiconductor devices' (Wiley, 1969), p. 24
4 ANSPAUGH, B. E., CASAD, T. A., BECKERT, D. M., DOWNING, R. G., MIYAHIRA, T. F., and WEISS, R. S. (Eds.): 'Characterization of solar cells for space applications'. Jet Propulsion Laboratory Publication 78-15
5 GREEN, M. A.: 'Solar cell fill factors: General graph and empirical expressions', *Solid-State Electron.*, 1981, **24**, p. 788
6 WALKER, G. H., CONWAY, E. J., HONG, K. H., and HEINBOCKEL, J. H.: 'High temperature properties of GaA/As/GaAs heteroface solar cells'. Conf. record, 14th IEEE photovoltaic specialist conf., San Diego, 1980, p. 1098

0013-5194/82/020097-02$1.50/0

1·55 μm OPTICAL TRANSMISSION EXPERIMENTS AT 2 Gbit/s USING 51·5 km DISPERSION-FREE FIBRE

Indexing terms: Optical fibres, Optical transmission

The high sensitivity of a Ge APD optical receiver, and dispersion-free fibres at a minimum loss wavelength of 1·55 μm, made it possible to achieve 51·5 km optical signal transmission at 2 Gbit/s. The optical receiving level was −31·4 dBm at a 10^{-9} error rate, and the degradation caused by fibre dispersion was only 0·6 dB. A data-rate repeater-spacing product of 103 (Gbit/s)km was achieved at 1·55 μm.

Introduction: Since silica optical fibres have minimum loss at 1·55 μm wavelength, optical transmission systems utilising 1·55 μm optical devices are expected to provide the longest repeater spacing.[1,2] Conventionally designed single-mode fibres, however, have a maximum transmission bandwidth near 1·3 μm wavelength. High-speed optical pulse transmission systems have, so far, been more easily realised at 1·3 μm than at 1·55 μm. A 1·3 μm optical transmission experiment with a data-rate repeater-spacing product of 88·6 (Gbit/s)km has already been reported.[3] This result clarified that long-wavelength optical transmission systems show promise for use in future telecom-