Influence of atmospheric parameters
on the energy characteristics of a silicon solar battery

A.V. Kozlov, A.V. Yurchenko, and D.A. Pestunov

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Tomsk Polytechnic University

We describe a station for monitoring the operation of solar batteries and present some results obtained. Based on these results we analyze the influence of temperature on the performance characteristics of solar batteries. We have calculated temperature coefficients for the open-circuit voltage, for short-circuit current, and for other parameters as well.

Introduction

Because of the depletion of the world resources of fossil fuels (nonrenewable natural resources), much attention is currently paid to use of solar energy directly converted into the electricity. The conversion is performed with silicon solar cells (SC). These are the main sources of power onboard space vehicles. However, wide use of SC on the earth is constrained by their dearness. The price of the SC is being tried by lowering the costs of production of single-crystal silicon and developing a technology for producing low-price film SC made from amorphous silicon. In both of these cases it is important to know the degradation and energy parameters of the SCs and thus of solar batteries (SB) made using the SCs.

The conversion of solar energy in a SB is accompanied by a heat release (especially at high insolation) and, therefore, the working surface of a SC can be heated to temperatures from 80 to 100°C. This leads to accelerated deterioration of SCs and thus to a decrease of the SB's performance characteristics during their exploitation. The concentration of the defects, which determines the degree of the SC's deterioration, will depend not only on the solar radiation flux incident on the SB, but on the SB temperature[1] as well. For these reasons it is necessary to study the influence of temperature and solar irradiance of silicon SCs on their photoelectric and radiation resistance properties in real conditions.

The authors are engaged in these studies since 1996.

An MC-14-10 silicon solar battery produced at R&D Institute of Semiconductor Devices, Tomsk, was installed at the TOR station of the Institute of Atmospheric Optics. The nominal output power of the battery is 10 W. The measurements have been conducted since 1996 until 2002. The measurement station enabled us to acquire information on temperature, pressure, humidity, wind velocity, solar radiation, and on the short-circuit current of the solar battery. The data collected allowed us to estimate the efficiency of the solar battery. The calculated efficiency is about 13% what is very close to the efficiency of 13.8% measured in laboratory (at $P = 1000$ W/m^2 and $T = 25$°C). Based on these data and data on the total solar radiation, we have estimated the efficiency of the SB operated under field conditions. During a year about 1 165 kWh of solar energy is incident on a square meter of the earth's surface. This means that an MC-14-10 solar battery with the working area of 0.18 m^2 and 13% efficiency produces, on the average, about 28 kWh energy a year.[3,4]

From the array of 38 parameters measured at the TOR station that characterize the state of the atmosphere, we have separated out, based on correlation analysis (coefficient of correlation $K_s \geq 0.3$), those, which affect the operation of SB under the field conditions.[3,4] These parameters are the solar radiation ($K_s = 0.9$), humidity (-0.44), and temperature (0.3).

In addition we have estimated degradation of the short-circuit current (ShCC) of the SB. To do this, we have isolated, from the entire array, data compiled during a year to calculate the ShCC for different irradiance conditions Sr (> 900, 800—900, 700—800, 600—700 W/m^2) at the time from 12 to 14 hours and at the relative humidity from 55 to 65%. Figure 1a shows the dynamics of the ShCC degradation during the test period of six years. The general features of the dynamics observed at different values of humidity are practically the same. Figure 1b depicts the degradation dynamics of the ShCC normalized to its value in the beginning of tests.

It is seen from Fig. 1b that the ShCC decreases with time. Thus, the ShCC has decreased, since 1996 until 2002 by 14%. This is first caused be the defects that appeared in the SB during its operation. In 2002 the containment of the battery broke and it disabled.

For the circumstances we had in this experiment we had no possibility of estimating other characteristics of the battery, namely, its open-circuit voltage, output power, and voltage-current characteristic. For these reasons we have assembled a specialized measurement station in 2004 for testing the solar batteries. It enables us to measure the voltage-current characteristic,

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temperature of the SB surface, as well as the air temperature, humidity, and pressure. In March 2005 we have started the new tests of the solar battery.
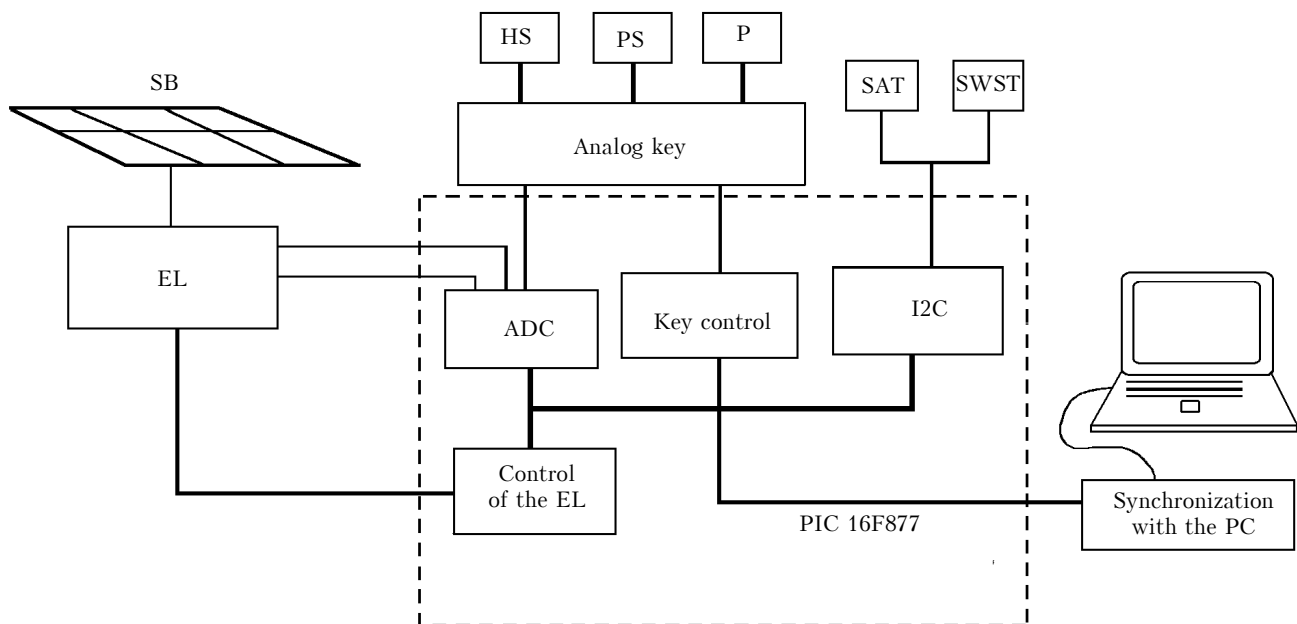

Fig. 1. Dynamics of the short-circuit current measured during 6-year test of a SB: $Sr > 900$ (*1*); $800 < Sr < 900$ (*2*); $700 < Sr < 800$ (*3*); $600 < Sr < 700$ W/m^2 (*4*) (*a*); the averaged relative degradation of the ShCC (*b*).

Station for monitoring of the solar battery operation

The equipment set of the station comprises the solar battery to be tested, block of measuring devices, sensors of air temperature (SAT), sensors of the SB's working surface temperature (SWST), humidity sensors (HS), pressure sensors (PS), pyranometer (P) that measures total solar radiation, and a computer with a specialized software package developed for this complex. All sensors are connected with the measuring block. The sensors of humidity, pressure and the pyranometer yield analog output signals and, therefore, an ADC is used to digitize these signals prior to entering them into the computer. All the analog sensors are connected to the same via an analog key. Multiplexing of the data exchange between the computer and sensors is controlled by the computer. Temperature sensors have digital output signals, which are transmitted to the computer via an I2C bus. The measuring block of the station has an electric circuitry of the electronic load (EL), which sets the electric current of the SB. The voltage and current set are measured with the ADC. Measurement of the electric current set is necessary for monitoring the operation of the electronic load. Then the measuring block sends the data to the computer (see Fig. 2). Table 1 gives the information on the station performance parameters.

The software package developed for the PC of this complex. The array of results measured with this complex is the voltage-current characteristic of the solar battery, its temperature, as well as the temperature, humidity, and pressure of the air, and the power of solar radiation. The results are stored in a file, which is then used in analysis. The software used enables one to set the duration and frequency of measurements.
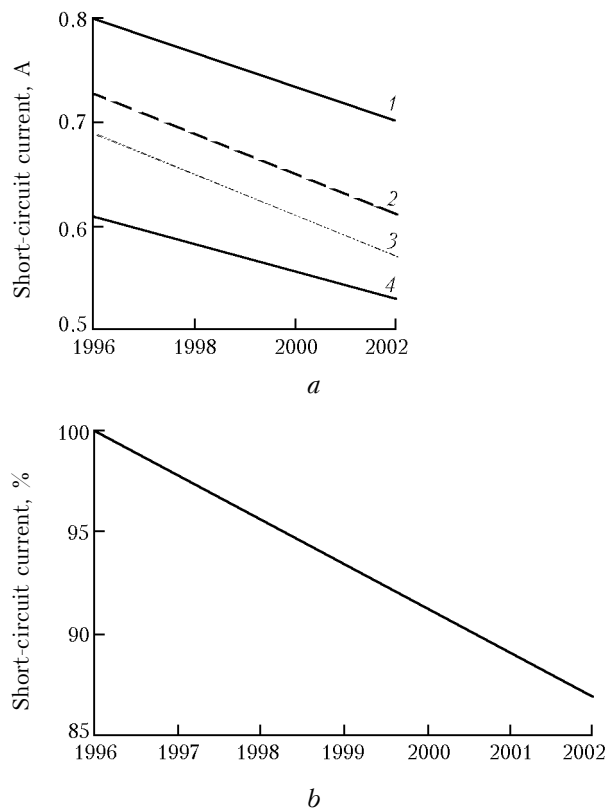
Fig. 2. Block-diagram of the station.

Table 1. Performance parameters of the station

Parameter	Value/region	Error
Characteristics of the solar battery measured		
Open-circuit voltage, V	0...20	± 0.3
Short-circuit current, A	0.1...2.5	± 0.05
Temperature of the working surface, °C	−50...+125	± 0.5
Measured parameters of the ambient air		
Temperature°C	−50...+125	± 0.5
Relative humidity, %	0...100	± 2
Air pressure, mmHg	700...800	± 5
Solar irradiance, W/m^2	0...1300	—
Other parameters of the mobile station		
Voltage of the power supply (line), V	220	
Consumed current, A	1	
DC power supply voltage, V	18...24	
Height, mm	90	
Width, mm	275	
Length, mm	195	

The mobile version of the station is capable of conducting measurements in real time using eight solar batteries each having power from 10 to 50 W.

Results of solar battery tests at the monitoring station

The station has been operated in the following way. The measurement cycle starts in the beginning of every hour. Then the voltage-current characteristic (VCC) of the SB and the temperature of the air are recorded in a 1-minute interval and the working point of the VCC is calculated. After 15 minutes the measurements are interrupted until the beginning of the next hour. As a result each measurement cycle yields a one-dimensional array of data comprising 15 elements. Then this array is averaged and the result obtained is stored in a data file. The data file containing the short-circuit current below 0.1 A is canceled. Such data correspond to twilight or nighttime conditions and thus are not interesting for this study. Figure 3 shows the dependences of the open-circuit voltage of the battery, its efficiency, short-circuit current of the battery on the working temperature. Dashed lines in the figures denote the theoretical behavior of the parameters.

As follows from Fig. 3 the open-circuit voltage of the battery decreases by 14% as temperature increases from 5 to 40°C ($\Delta T = 35$°C), and the efficiency falls down from 13 to 8%. The difference between the SB temperature and the temperature of the ambient air was from 10 to 20°C. In the previous experiments[3,4] temperature of the solar battery was not measured and, therefore, the dependence of these parameters of the solar battery on temperature could not be studied correctly. According to data obtained in this experiment one can state that the temperature coefficient of the open-circuit voltage, $\Delta U_{ocv}/\Delta T = -75$ mV/°C, that of the short-circuit current is $\Delta I_{scc}/\Delta T = 5$ mA/°C, and of the peak power $\Delta W/\Delta T = 0.177$ W/°C; the temperature coefficient of the efficiency is $\Delta\eta/\Delta T = -0.2$%/°C.
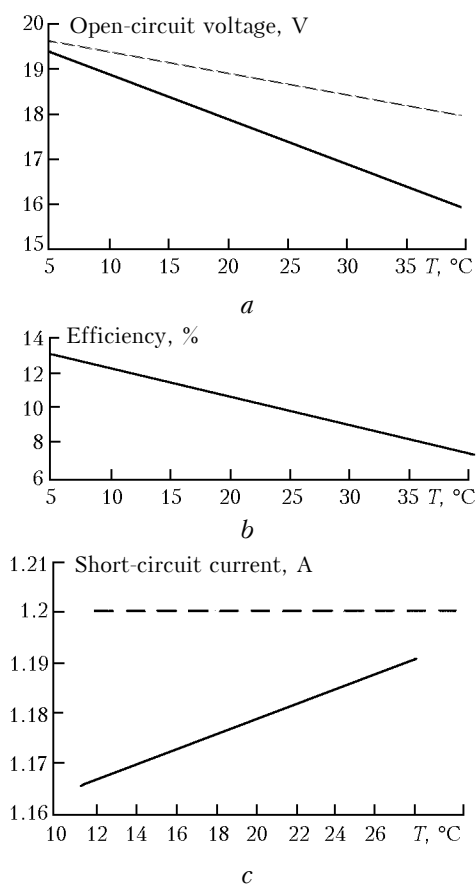
Fig. 3. Dependences of the solar battery's parameters on the working temperature: open-circuit voltage (*a*); efficiency (*b*); short-circuit current (*c*).

The increase of the short-circuit current at increasing temperature is explained by the absorption of light. The matter is that the increase of SB temperature is accompanied by a shift of the SB's absorption band edge, due to narrowing of the forbidden zone of the crystal and to the increase of the number of pairs generated in a volume. The latter

factor causes an increase in the short-circuit current. On the other hand, the coefficient of light absorption changes with the increasing temperature. As a result the short-circuit current grows with the temperature growth (see Fig. 3*c*).

As known from the theory,[5] the VCC of silicon photocells is quite well described by the following equation:

$$I(U,T) = I_{\mathrm{ph}} - I_{\mathrm{s}}(T)\exp\left[\left(\frac{qU}{kT}\right) - 1\right], \qquad (1)$$

where I_{ph} is the photocurrent, I_{s} is the reverse current of the photocell, T is the temperature of the SB in K, q is the electron charge.

The temperature dependence calculated by this formula is shown in Fig. 3 by the dashed curve. It is seen that qualitatively the theoretical and measured dependences are similar.

The decrease of the open-circuit voltage at the temperature growth is related to the changes in the concentration of the charge carriers and in the width of the forbidden zone of the crystal. In the general case, the open-circuit voltage is defined by the relationship

$$U_{\mathrm{ocv}} \sim \ln\frac{I_{\mathrm{scc}}}{I_{\mathrm{s}}}, \qquad (2)$$

according to which U_{ocv} should grow at the increasing I_{scc}. Narrowing of the forbidden zone at increasing temperature causes an increase in the reverse current (I_{s}). A sharp growth of the I_{s} through the $p{-}n$-junction leads to a decrease in the open-circuit voltage, thus minimizing the positive effect of the short-circuit current growth. The increase of temperature decreases the duty factor of the VCC, because of the increase in the reverse current. The decrease in the open-circuit voltage and in the duty factor of the

VCC are the main cause of the SB's output power and efficiency deterioration.

Conclusion

Station for monitoring of the operation of solar batteries has been developed and tested during 3 months. The station is intended for use as a stationary setup as well as a compact mobile device for measurements under field conditions.

The tests of the station enabled us to determine the temperature coefficients of the open-circuit voltage, short-circuit current, peak power, and of the efficiency of solar batteries.

It was found from the measurement data compiled in March—May of 2005 that the difference between the temperature of the SB's surface and temperature of the ambient air can reach 20°C. In summer the temperature difference should reach higher values.

Acknowledgments

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