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A microchip integrated sensor for the monitoring of high concentration photo-voltaic solar modules

F.G. Della Corte[a]*, G. Cocorullo[b], P. Corsonello[b], C. Felini[a], M. Merenda[a], S. Perri[b], G. Borelli[c], M. Carpanelli[c], D. Verdilio[c]

[a]*Università Mediterranea, DIIES, Via Graziella, Reggio Calabria I-89122, Italy*
[b]*Università della Calabria, DIMES, Via P. Bucci 42/c, Rende (CS) I-87036, Italy*
[c]*Becar srl – Gruppo Beghelli, Via della Pace 1 - Monteveglio (BO) I-40050, Italy*

Abstract

A CMOS sensor fabricated in 0.35µm technology, specifically designed for the monitoring of High Concentration Photo-Voltaic (HCPV) modules, is presented. The microchip was designed to monitor temperature and illumination of each solar cell in a module. Temperature is measured by monitoring the base-emitter voltage of two coupled, diode connected, bipolar transistors, while the illumination sensor is an integrated p-n junction photodiode. A custom communication protocol is implemented in the chip to allow the sharing of a two-wire communication resource among the cells.

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Keywords: CMOS sensor, photovoltaics, temperature sensor

1. Introduction

High Concentration PhotoVoltaics (HCPV) is a well known technology showing several advantages compared to standard photovoltaics. It allows to cut the use of semiconductor area, which is interesting in case of high efficiency solar cells made e.g. of expensive semiconductors, or based on complex multi-junction cells [1]. In HCPV systems,

* Corresponding author. Tel.: +39-965-1693463; fax: +39-965-1693463.
E-mail address: francesco.dellacorte@unirc.it

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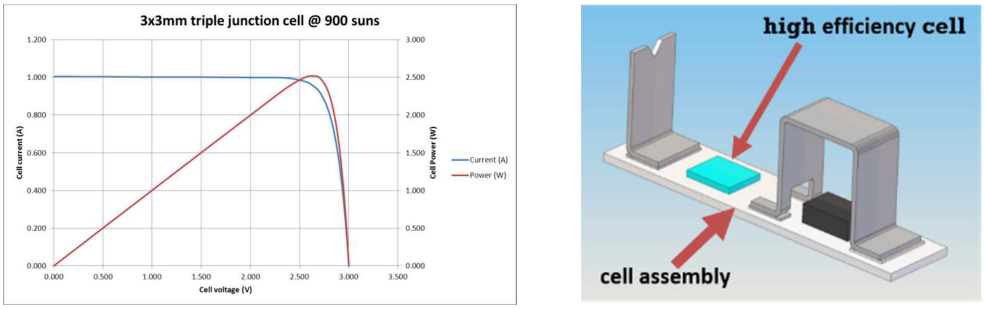
small solar cells convert into electricity a solar radiation that might be as strong as thousands of suns, depending on the concentration optic characteristics, and have therefore to withstand harsh working conditions, especially in terms of temperature and current. As a result, a constant monitoring of the cell key parameters might help prolong their life and optimize the conversion efficiency. In [2] and [3], a virtual instrumentation was used to measure a wide variety of signals with a good accuracy, but the data transfer makes use of a data acquisition board, copper-wired to the cells. A wireless solution has been proposed by [4].

In this paper we present a custom designed microchip to be placed aside each solar cell in a module, to monitor its temperature and illumination. A serial communication scheme was developed to collect data on a master circuit.

2. High Concentration Photo-Voltaic module

Advances in photovoltaic technology have allowed the combination of compound semiconductor materials with differing bandgap energies resulting in higher conversion efficiencies compared to Silicon. Alloys combining Group III and V elements are highy desirable for the wide range of bandgap energies they offer. A multijunction cell is a stack of multiple layers of semiconductors with decreasing bandgaps. Top layers absorb higher-energy photons and are transparent to lower-energy photons that are absorbed by the lower layers of the cell. Cells are available with efficiencies beyond 42% [5]. To fully exploit these cells, sun light should be concentrated by factors up to one thousand times. The typical concentration used in Beghelli systems, based on Fresnel lenses, is 1100×, which means tha the solar irradiation on the multi-junction cell is higher than 900 kW/m^2. Under this illumination conditions the typical response of the cell is shown in the following diagram (Fig 1a), which refers to a 3×3 mm2 cell.



(a) (b)

Fig 1. (a) typical response of the III-V multijunction cell; (b) cell assembly on alumina substrate

The cell is placed on an alumina substrate (Fig 1Fig 1), in order to reduce the cell assembly heating when it is exposed to huge illumination levels. In Fig. 2b is shown the configuration of a photovoltaic module, where the cells are positioned in an array form. Beside each solar cell there is a μ-chip sensor for monitoring its operating condition

3. Custom CMOS microchip sensor

A block diagram describing the chip organization is shown in Fig 2a. The analog section includes two sensors, namely a temperature sensor and a light sensor. Sensor outputs are first amplified to bring their respective voltages to useful levels, and then digitalised by means of an analog-to-digital converter (ADC). The serial conversion timing is provided by the digital section.

The ADC outputs are then loaded into a parallel-in/serial-output (PISO) 2×8 (or 3×8) bits shift register. Once the measurements are done and the PISO loaded, its content is serialized for transmission at a bit-rate of 3kbit/s.

Many integrated T sensors exploit MOSFETS as the sensing element [6-7], and specifically a proportional-to-absolute-temperature (PTAT) scheme, realized by coupled bipolar junction transistors (BJT) [8-9].

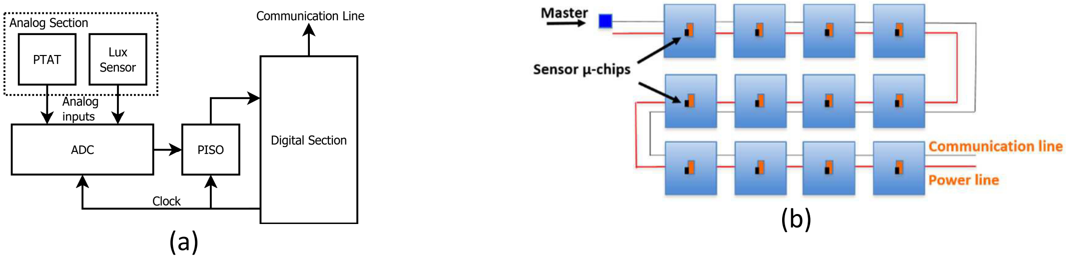


Fig. 2. (a) microchip architecture; (b) schematic of a HCPV module where cell assembly are positioned in array form.

Assuming that for PNP BJTs the collector current is $I_C = I_S e^{V_{EB}/\eta kT}$ with I_s the saturation current of the emitter-base junction, V_{EB} the emitter-base voltage, k the Boltzmann constant, q the electron charge and η the ideality factor, if two identical transistors are biased at currents I_{ref} and I_0 respectively, the difference between the V_{EB} of the two BJTs has a linear dependence on T, according to the following equation, where $\eta = 1$ is assumed:

$$\Delta V_{EB} = V_{EB1} - V_{EB2} = V_t \ln\frac{I_{ref}}{I_s} - V_t \ln\frac{Io}{I_s} = \frac{kT}{q}\ln\left(\frac{I_{ref}}{Io}\right) \quad (1)$$

Two diode-connected BJTs were used (Q1 and Q2 in Fig 3a). Their currents ratio is fixed by the sizes of M1 and M2. In Fig 3b, the differential output of the PTAT in the temperature range from 0 to 100°C is also depicted.

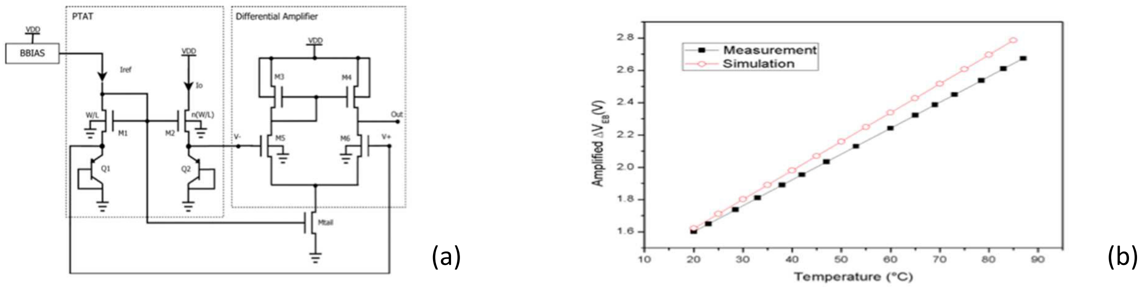


Fig. 3. (a) PTAT sensor with differential amplifier; (b) simulated and measured output characteristics of the temperature sensor.

The integrated illumination sensor is a p-n photodiode, formed the P-type substrate and N-type well of CMOS technology (Fig 4a). This structure could be figured out as a micro solar cell that converts the photon flux impinging on its active surface into current signal. The outmost metal layer (metal one) was used to build fingers that collect the photocurrent to the anode. A trans-impedance amplifier (TIA) was also integrated, by means of an operational amplifier, to convert the photodiode output current into a voltage signal (Fig 4b).

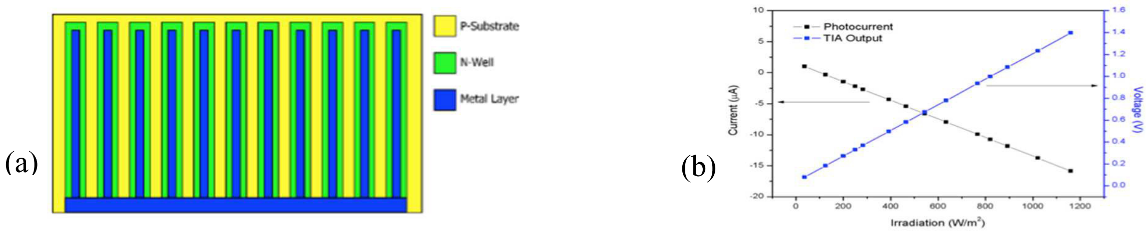


Fig. 4. (a) schematic reperesentation of the integrated photodiode; (b) photodiode output characteristics before and and after amplification.

The digital section of the microchip include the communication circuit, based on a custom designed protocol, shown in Fig 5a. It is assumed that the module consists of n cells, each having its own micro-chip μc_i (with $i=1,...,n$). The master chip is a CY8C29466 microcontroller. The "operative unit" receives digitalised data of the analog section and communicates with the master chip using the clock signal locally generated by a ring oscillator.
It is worth pointing out that each μc_i can operate in two different states: during the active state the μc_i communicates with the master chip; at the end of the data transfer μc_i enters its passive state and thus serves just as a pass-through device to make the communication between the micro-chip μc_{i+1} and the master chip possible.

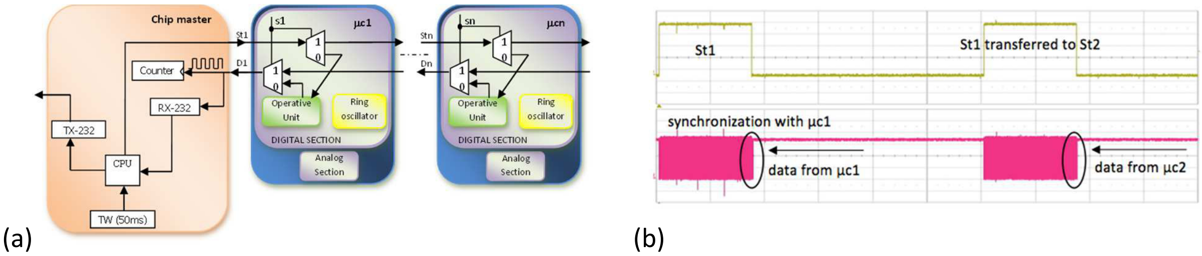


Fig. 5. (a) schematic representation of the communication chain ; (b) sample timing diagram between two microchips and the master chip.

4. Results

A sample communication frame between the master chip and the two microchips μc_1 and μc_2 is shown in Fig 5b. The steps required to successfully monitor the entire module are summarized in the following:

1. at the beginning, a power-on-reset takes place and the signals s_1,..., s_n are set to 1;
2. the master chip initiates the communication with μc_1 sending a rising start signal on the St_1 line;
3. through the D1 line, μc_1 sends to the master chip the clock signal locally generated by its own ring oscillator and the master chip measures the actual clock frequency;
4. through the St_1 line the master chip enables the data transfer and μc_1 serially sends its data;
5. when all the bits have been sent, μc_1 automatically enters the passive state, setting the signal s_1 to 0.

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