SENSOSOL: MultiFOV high precision sun sensor

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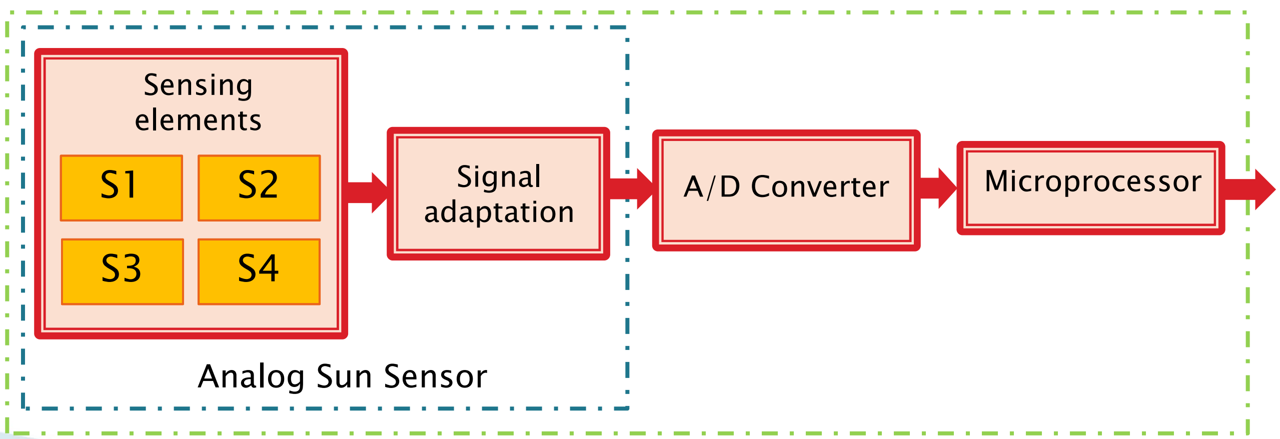
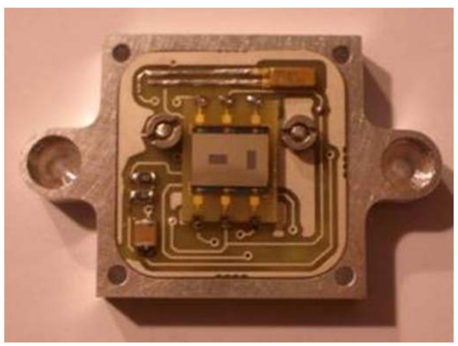
1. INTRODUCTION

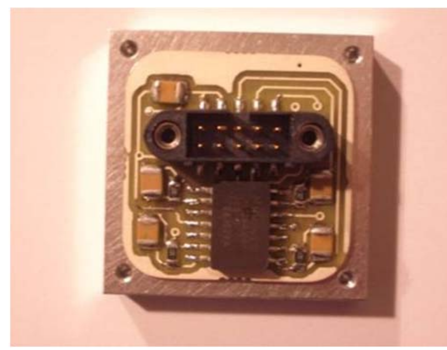
- Sun sensor: measures the incidence angle of sun rays
- Satellital and industrial applications, such as attitude control of satellites and solar power plants
- Classification
  - Analog/digital, coarse/fine
- Analog sun sensors
  - Sensing elements: optical information to current/voltage conversion
  - Amplification stage



1. INTRODUCTION

- The MEMS group of the US has been developing sun sensors for several years
- Vectorsol: a real implementation of analog sun sensor
  - Scientific payload in the Spanish satellite Nanosat 1B, launched in 2009
  - Presented in the ESA-ESTEC in February 2009.





Silicon die:
8.5x7.5 mm^2

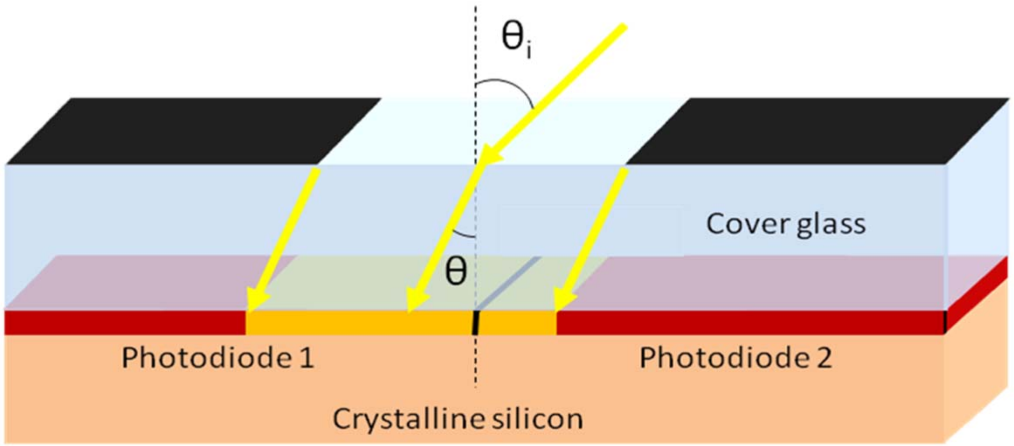
PCB:
25x25 mm^2 aprox.

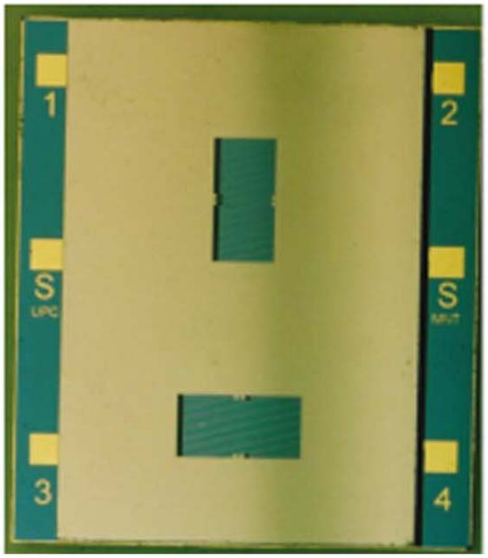
- **Objective of this work**: two improvements proposed
  - Increase of the accuracy.
  - Sensor more compact and robust.

2. VECTORSOL DESCRIPTION

A. Sensing elements

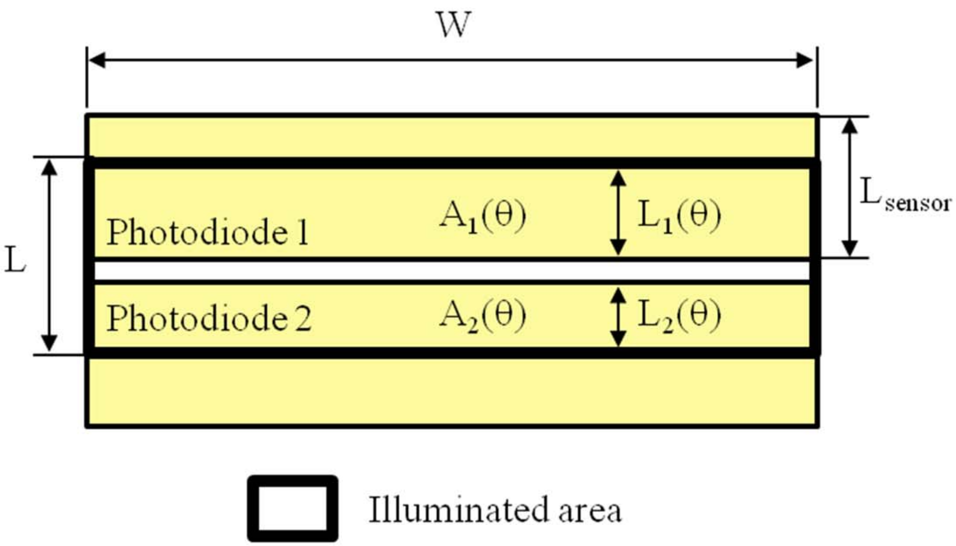
- One axis: pair of photodiodes in silicon bulk. The sun rays reach them through a cover glass layer with an upper window.
- Two pairs of photodiodes are placed orthogonally in order to measure the angle in both axes.





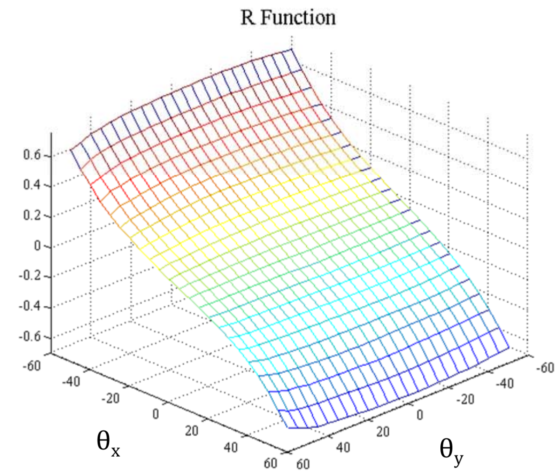
2.VECTORSOL DESCRIPTION

- For each axis, given the illuminated area in the photodiodes it is possible to determine the angle of incidence.



$$R(\theta) = \frac{I_{ph_2} - I_{ph_1}}{I_{ph_2} + I_{ph_1}} = \frac{A_2(\theta) - A_1(\theta)}{A_2(\theta) + A_1(\theta)} = \\ = \frac{L_2(\theta) - L_1(\theta)}{L_2(\theta) + L_1(\theta)}$$

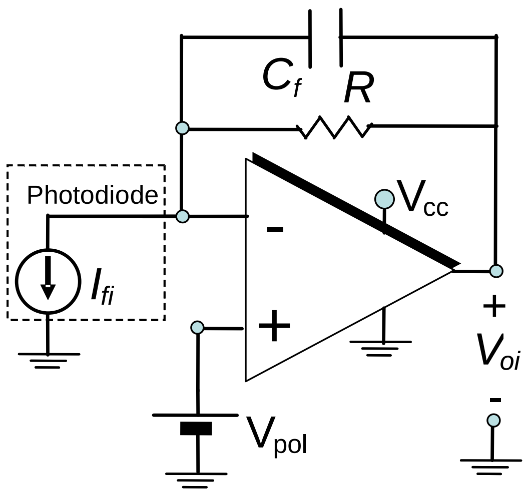
- Example of an experimental *R* function:



2. VECTORSOL DESCRIPTION

B. Signal adaptation circuits

- Consists of a current-to-voltage converter for each photodiode.



C. Calibration process

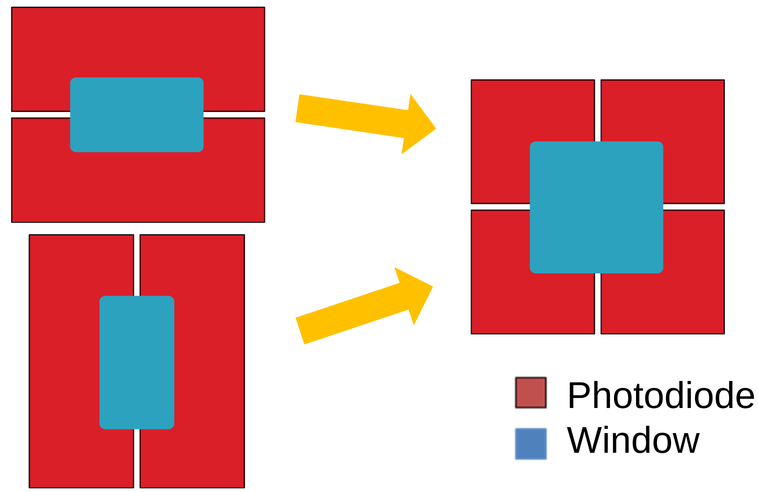
- The device is illuminated with a fixed solar simulator. The rotation is controlled by two motorized rotary stages.
- For each position, *R* function is calculated. By combining both axes, it is possible to obtain the inverse function:

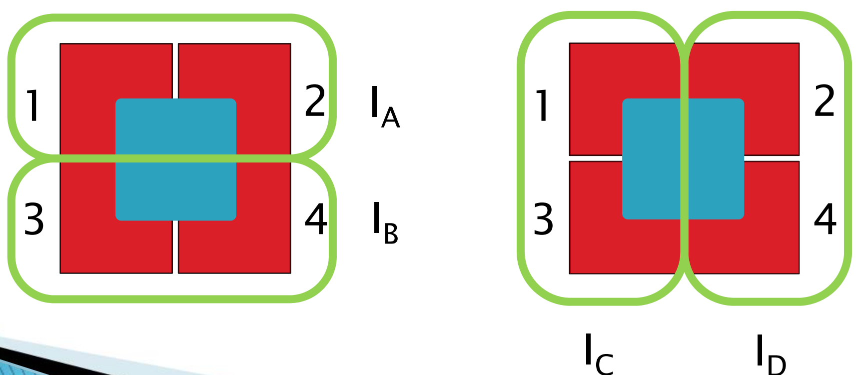
$$R_{1,2} = f(\theta_x, \theta_y) \implies \theta_{x,y} = f^{-1}(R_1, R_2)$$

- During normal operation, the value of *R* is calculated and applied to the inverse function obtaining the angular position.

3.4–Quadrant Design

- New structure
  - Uses a single structure for both axes instead of two separated pairs of photodiodes.
    - Sensor more compact and robust
  - In order to obtain the measures in both axes, the generated currents in the photodiodes are added two by two.

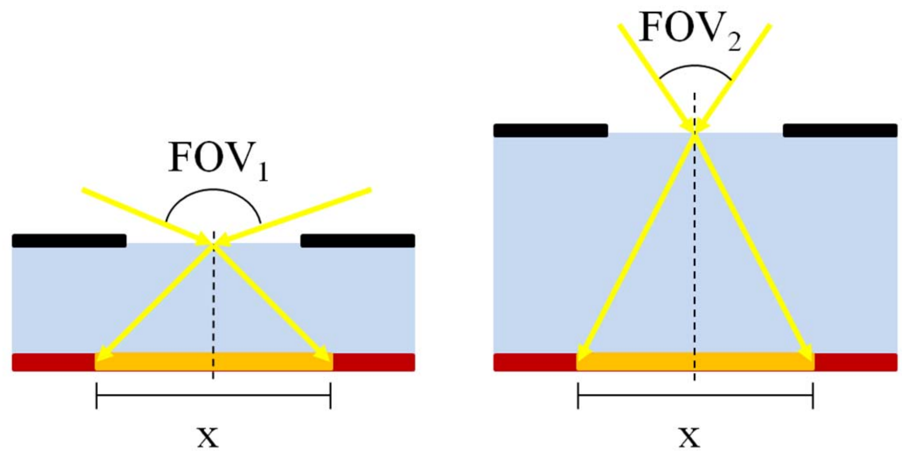




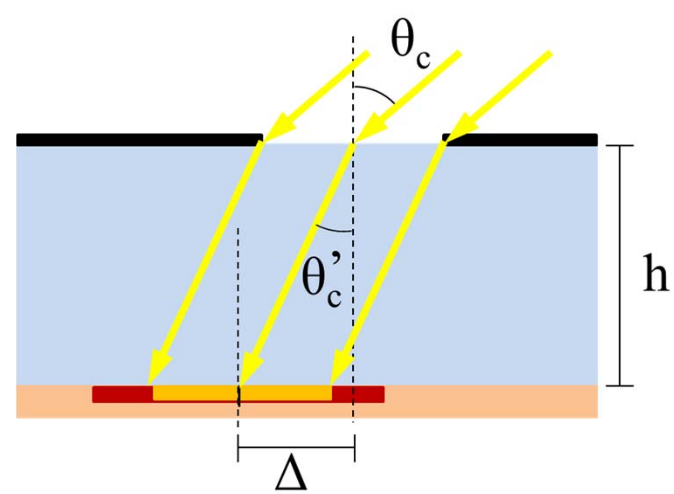
$$I_A = I_1 + I_2$$
$$I_B = I_3 + I_4$$
$$I_C = I_1 + I_3$$
$$I_D = I_2 + I_4$$

3.4-Quadrant Design

- Higher precision
  - By increasing the height of the glass layer, it is possible to manufacture a more accurate sensor.
    - As consequence, FOV is reduced.

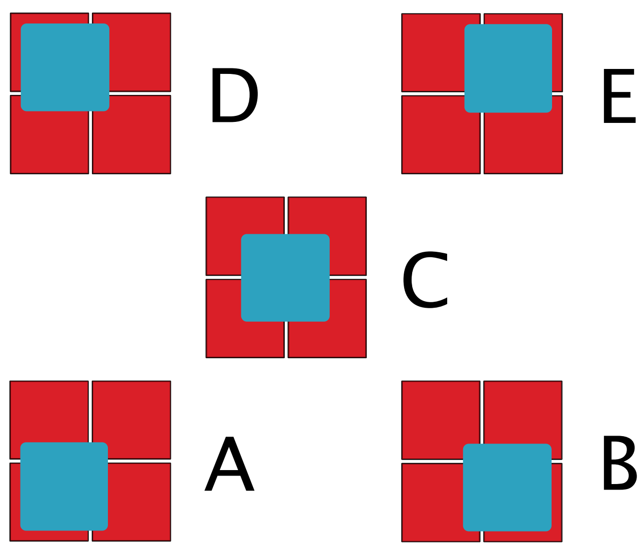


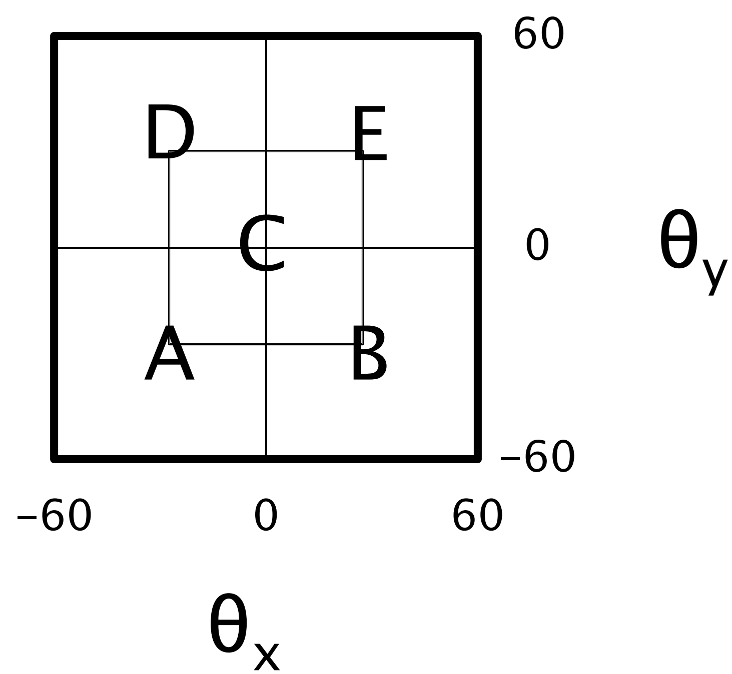
- Subdivision of the FOV
  - In each region, one different sensor provides the measure.
  - To obtain complementary regions of the FOV, the upper window is displaced .



3.4-QUADRANT DESIGN

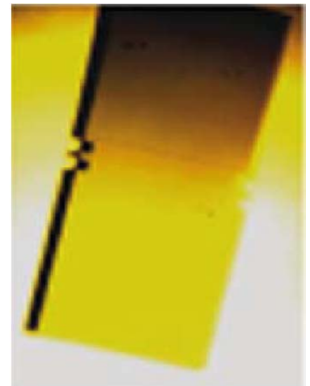
- Complete device design
  - Fine sensor (C): FOV ±35° in both axes.
  - Coarse sensor (A, B, D, E): Each sensor controls one quarter of the complete FOV.



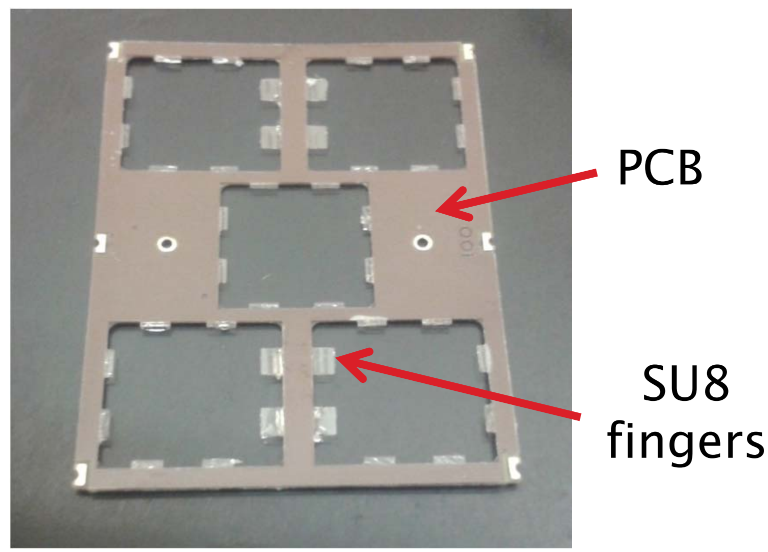


4.Fabrication

- Alignment and glue bonding between cover glass and silicon
- Until now: optical alignment using marks
  - Tedious process
  - Non repetitive alignment errors
    - Displacement (~200μm)
    - Rotation (~1.3º)



- New process
  - Manufacturing of an alignment frame using MEMS and SU8 techniques
  - Improvement of the alignment error
    - ~20μm on displacement, and rotation better than 0.05º

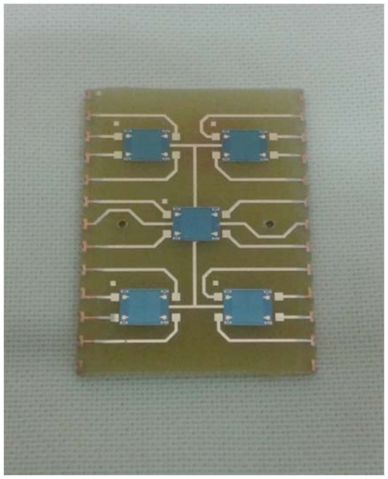


4.FABRICATION

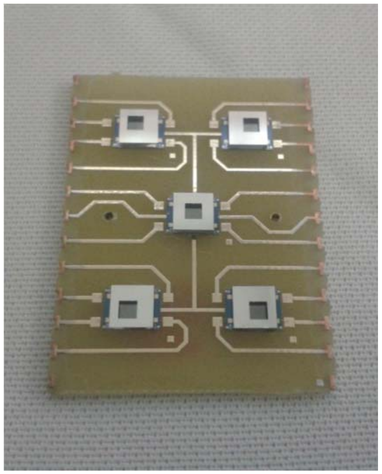
- Fabrication steps
  1. PCB
  2. Frame 1 placement
  3. Silicon dice conductive epoxy bonding
  4. Frame 1 removal
  5. Wire bonding
  6. Frame 2 placement
  7. Borofloat epoxy bonding
  8. Frame 2 removal and PCB gap bonding
  9. Frame 3 placement
  10. Cover glass epoxy bonding
  11. Frame 3 removal
  12. PCB gap bonding

4. FABRICATION

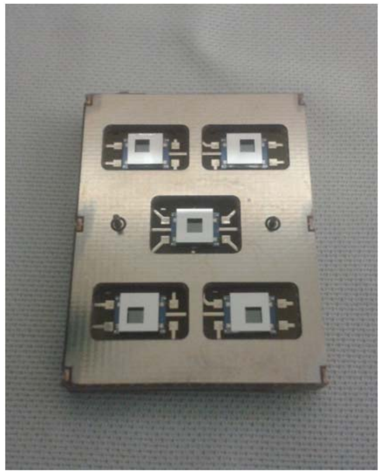
- Fabrication steps



- PCB
- Silicon dice



- PCB
- Silicon dice
- Borofloat



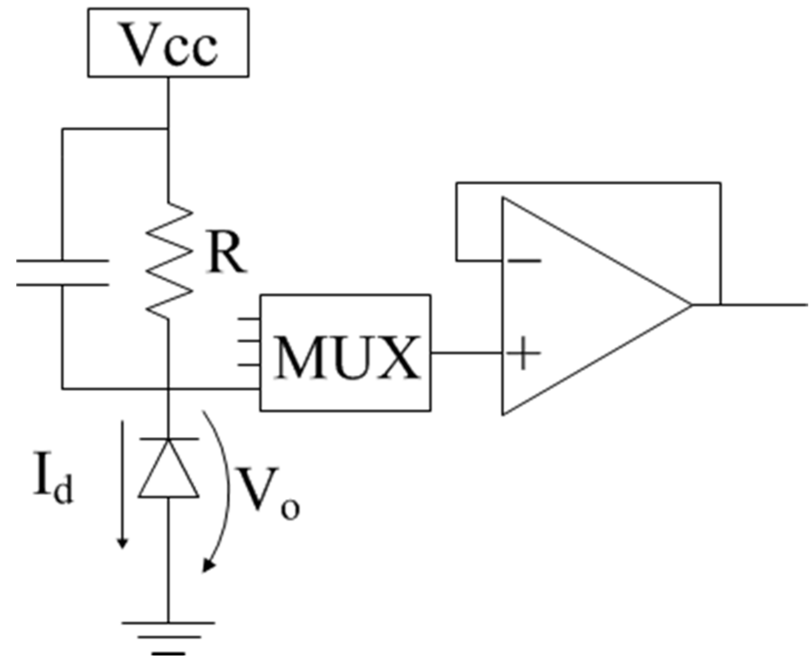
- PCB
- Silicon dice
- Borofloat
- PCB gap

- Final device

4. FABRICATION

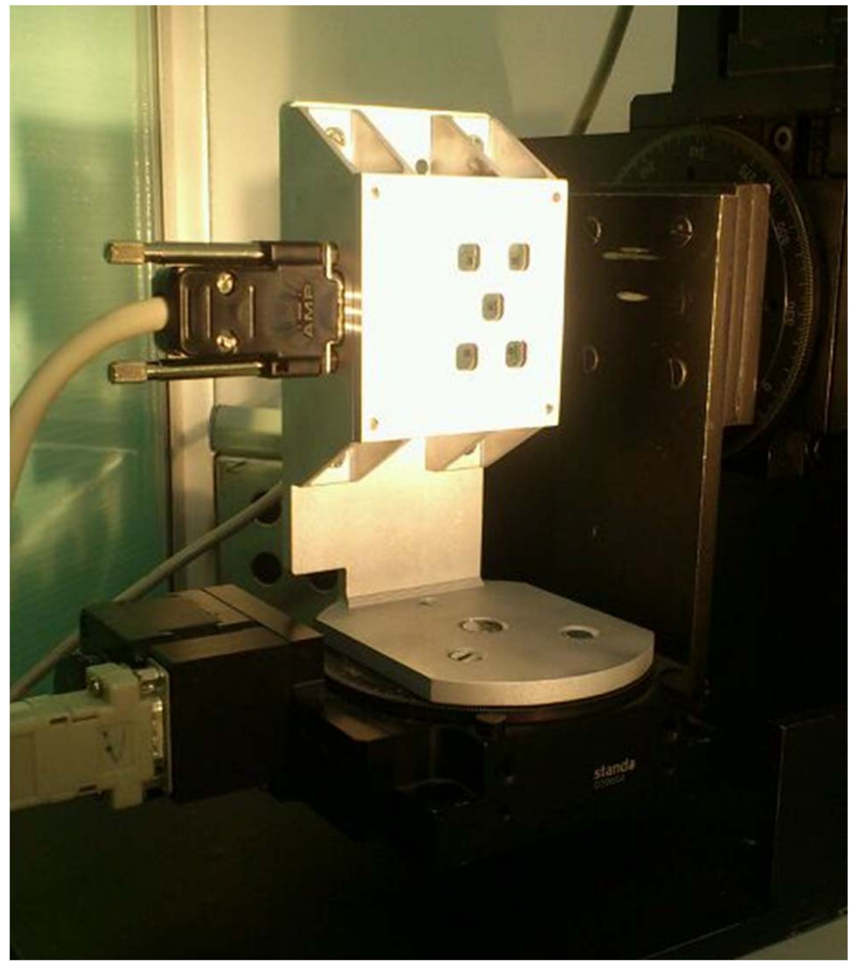
- Signal adaptation circuits
  - Due to the elevated number of photodiodes, the signals of the sensors are multiplexed.
  - Operational amplifier is used as a voltage follower.
  - Relationship between generated photocurrent (I_d) and output voltage (V_o):

$$V_o = V_{cc} - I_d \cdot R$$



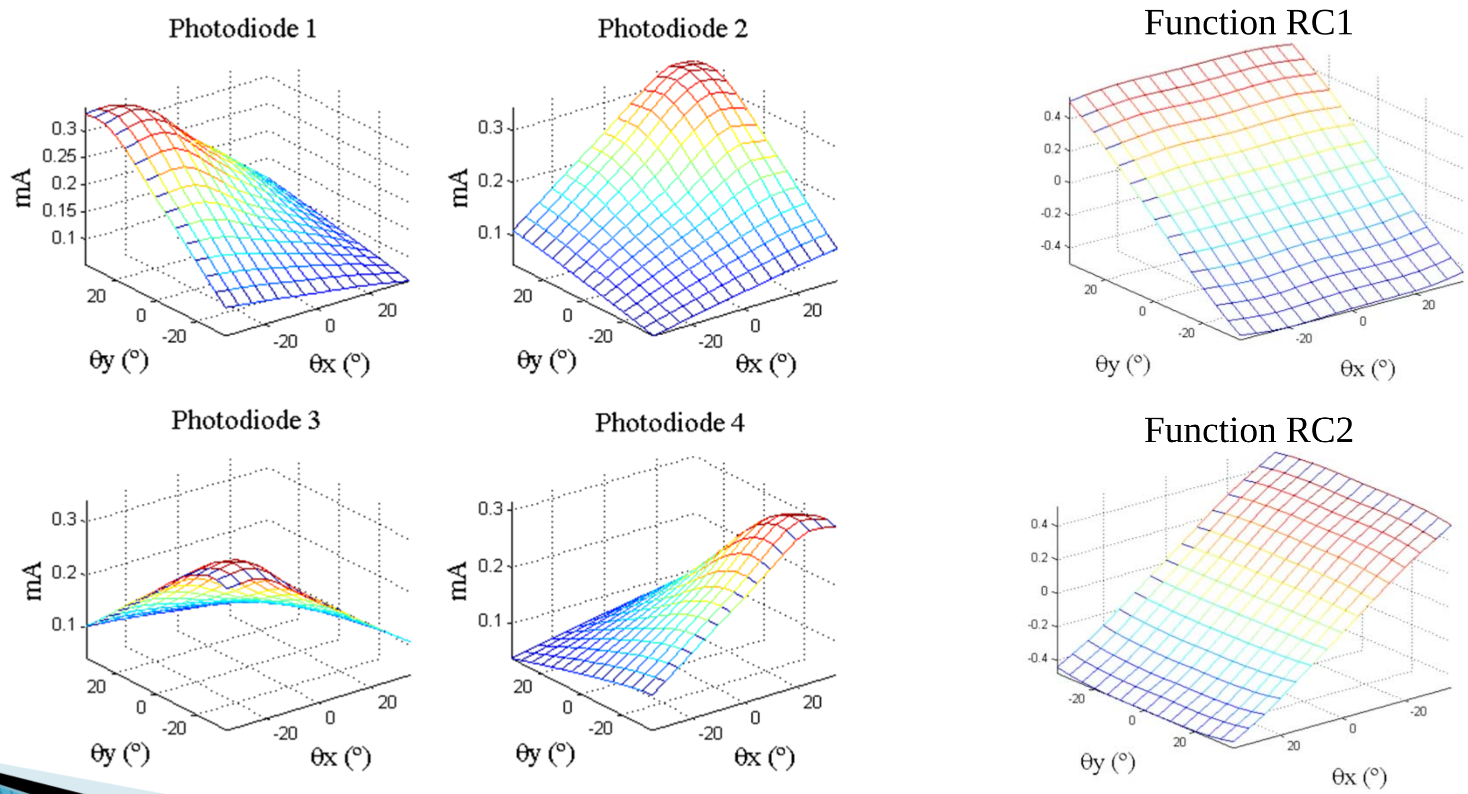
4.FABRICATION

- Complete device
  - The sensor and the electronics are encapsulated using an aluminum shell.



5. Experimental Results

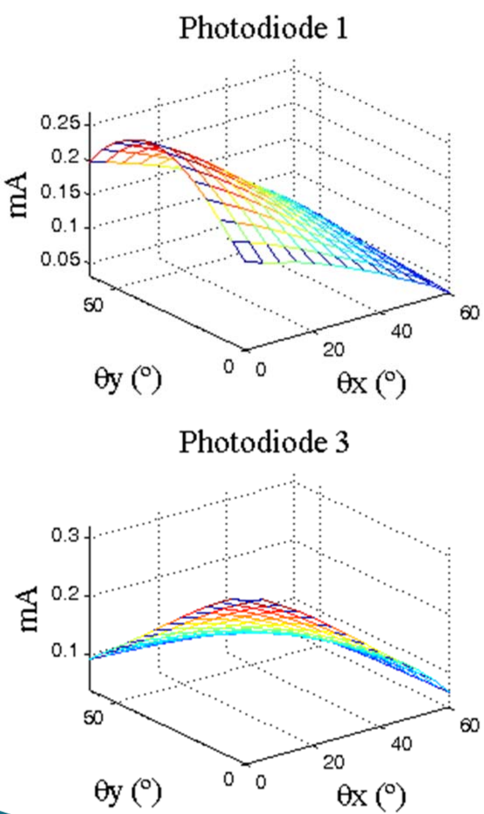
- Calibration
  - [-60º,60º] with 5º step in both axes.
  - The generated current is obtained for each position and the R functions are calculated.

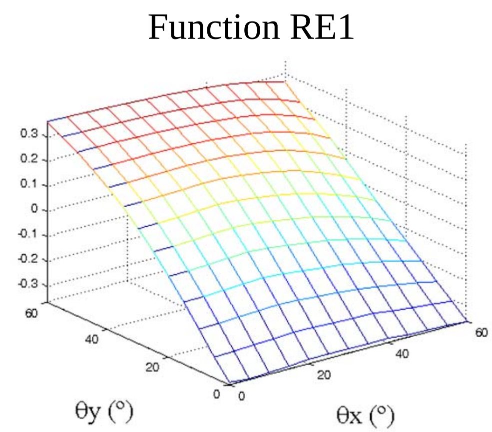


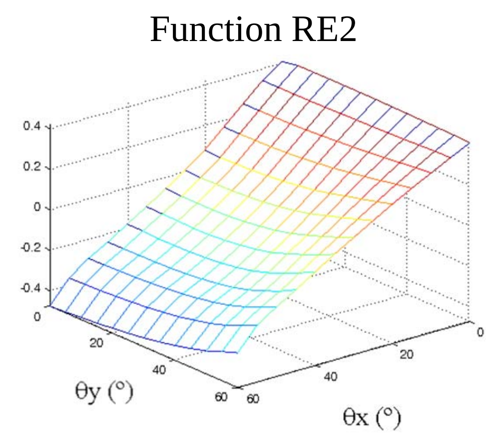
Sensor C [-35º,35º]

5. EXPERIMENTAL RESULTS

- Calibration







Sensor E [0,60º]

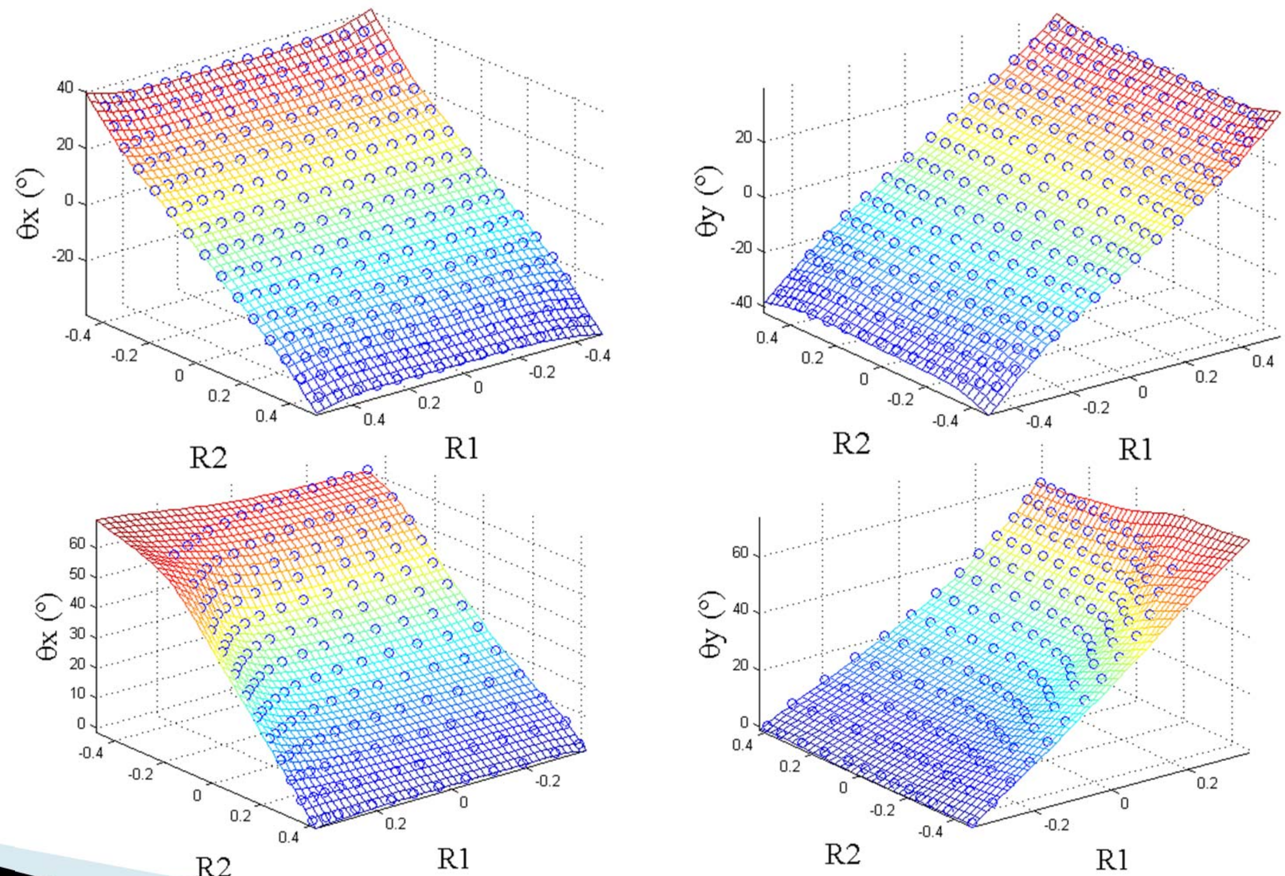
5. Experimental Results

- Inverse function
  - The inverse functions are obtained by combining the *R* functions in both axes.

Sensor C

$$\theta_{x,y} = f(R_1, R_2)$$

Sensor E



5. Experimental Results

- Inverse function
  - During normal operation, the value of *R* is calculated and applied to the inverse function in order to obtain the angular position.
  - A verification process is required: 100 random positions are measured and compared with the real angle of incidence, providing us the value of 3σ.

Sensor	3σ (º)
C	0.15º
A, B, D, E	0.45º

7.Conclusions

- Design of a high precision sun sensor for satellite applications.
- Improving the accuracy implies reduction of the FOV.
  - MultiFOV design.
  - 5 sensors will measure the entire FOV.
- New fabrication process using SU8 alignment frames.
  - Reduces the alignment error between PCB, silicon and borofloat.
- Experimental results
  - Calibration and evaluation of the device have been done.
  - Accuracy better than 0.2° has been obtained for fine sensor (ten times better than Vectorsol), and better than 0.5° for coarse sensor.

QUESTIONS?

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THANKS FOR YOUR ATTENTION!