MEMS based Sun Sensor on a Chip

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***Abstract*—A prototype sun sensor has been developed. It consists of a thin slice of silicon coated with a layer of chrome and a layer of gold with hundreds of small pinholes, placed on top of an Active Pixel Sensor (APS) image detector at a distance of 500 microns. Images of the sun are formed on the APS image detector when the sun illuminates the mask. Image processing of the Sun image is performed externally to the chip. Sun angles are derived by determining the precise location of the sun images on the detector – just like a sundial. The envelope of the sun sensor is 10x15x1.5mm, it has a mass of 0.5 gram and the power consumption is 30 mW. The accuracy of the MEMS based sun sensor on a chip is estimated to be 1 arcminute.**

***Index Terms*—APS, attitude determination, camera, MEMS, spacecraft, sun sensor**

I. INTRODUCTION

Sun sensors are widely used in spacecraft attitude determination subsystems to provide a measurement of the sun vector in spacecraft coordinates. Future micro/nano spacecraft and rovers will need to carry sun sensors to determine the pointing direction towards the sun or position determination. Unfortunately, conventional sun sensors are typically too large compared to the size of a micro/nano spacecraft or a small rover. At the Jet Propulsion Laboratory, California Institute of Technology a novel sun sensor on a chip has been developed [1]-[5].

Two categories of conventional sun sensors exist - digital and analog types. The digital sun sensor illuminates different geometric patterns on the detector plane. The presence or absence of light imaged on the plane defines a digital signal that can be translated into the sun angle. In comparison, an analog sun sensor outputs analog currents, from which the sun angles can be derived directly [6]. To enhance the capabilities of these traditional sun sensor devices, a new generation of sun sensors is emerging. These sun sensors utilize an imaging device as the detector plane with a mask placed in front of it. The sun sensor determines sun angles based on the location of the image pattern on the detector plane [7]-[11].

Fundamentally, the MEMS based sun sensor on a chip is a miniaturized pinhole camera. The focal plane is an Active Pixel Sensor (APS) camera on a chip and the optics is a small piece of silicon wafer. APS imagers have in recent years become very popular in the low end of the market for imaging applications [12]. APS chips have the advantage over traditional CCD chips that they are based on regular CMOS technology. This means that additional circuitry such as A/D converter, timing and communication can be integrated on the focal plane itself [13]-[16]. The APS chip that the MEMS based Sun Sensor on a chip is based on has all camera functions integrated on the chip itself [17].

The optics of the miniaturized camera is a small piece of silicon wafer with an evaporated layer of gold on one side with a number of small pinholes in the gold layer. The silicon wafer is mounted 500 microns from the focal plane making the system into a pinhole camera. The Sun is so bright that it will penetrate the silicon wafer where there are pinholes and the rays will form an image. This is basically the same principle as in a sundial. This is sketched in Fig. 1.

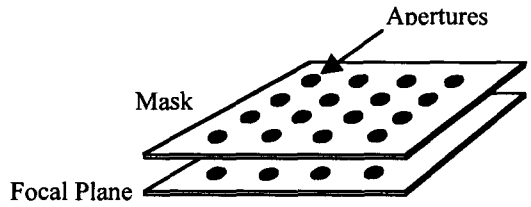


Fig. 1. The micro sun sensor concept

The MEMS based sun sensor on a chip fundamentally consists of 3 parts: 1) mask, 2) spacer and 3) focal plane. This is sketched in Fig. 2. These three parts will be described in details in this paper.

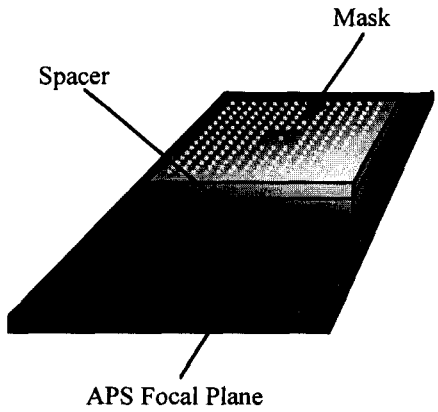


Fig. 2. Sketch of the sun sensor on a chip

II. MEMS MASK

To fabricate masks with hundreds of closely aligned micro size pinholes, MEMS fabrication techniques are required because the MEMS lithography-technique has extremely high precision and is well controlled.

The MEMS mask is shown in Fig. 3.

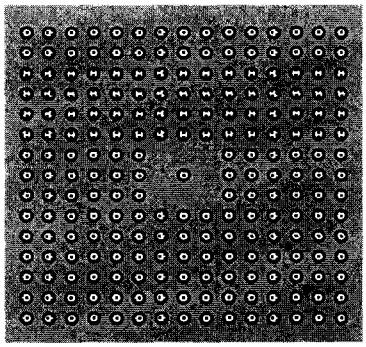


Fig. 3. The MEMS pinhole mask layout

The sunlight is transmitted though the mask and the pinholes and impinge on the APS chip

III. SPACER

The silicon mask itself cannot be mounted on the focal plane itself because of the high refractive index of silicon. The objective of the spacer is therefore to separate the pinholes from the focal plane with a gap (low refractive index). The spacer is 7 x 7 mm and it is made of a 500 microns thick silicon wafer. It is coated with 0.2 microns of gold so it is opaque to sunlight. It is sketched in Fig. 4.

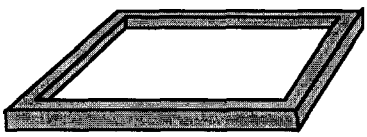


Fig. 4. Sketch of the spacer

IV. APS DETECTOR

The Versatile Integrated Digital Imager (VIDI) 512 is a complete CMOS imaging system on a chip [17]. The VIDI contains a 512 x 512 imaging array, 512 A/D converters (one for each column), D/A converters that control the internal reference voltages, currents, and a digital control block. The minimum VIDI interface consists of 5 wires: V_{dd}, Ground, Serial Data Input, Serial Data Output, and Clock. The imager configuration is programmed through the serial input port. The configuration determines the pixel timing and ADC signals that are generated internally. After the imager is configured, a single command through the serial input port will cause image data to be taken. The images can be output in the form of serial or parallel data or with a pair of differential analog voltages. The image serial output is SPI compatible to ease interface compatibility between the VIDI and external data collection hardware. There is a power down mode that shuts down all the internal circuitry except for the serial input port so power consumption can be minimized when the camera is not in use. The imager can be programmed to perform an internal column voltage offset correction to minimize column fixed pattern noise.

The imager is a 512 by 512 photodiode pixel array. It can randomly access any window in the array, from 1 pixel x 1 pixel all the way to 512 pixels x 512 pixels in any rectangular shape. Integration can be set as low as one row read time to $2.1 \cdot 10^9$ row times. The window size and integration time are set with configuration registers.

A summary of the VIDI specifications is given in Table 1.

Table 1. Summary of measured parameter values for VIDI

Characteristics	Values
Technology	CMOS, 0.5 m
Outputs	Analog & Digital
Format	512 x 512
Pixel Size	12 m x 12 m
Responsivity	4 V/photon
Quantum efficiency	42% (peak @ 550 nm)
Dark Current	300 pA/cm^2
Noise	40 e$^-$
ADC resolution	10 bits (9.3 bits effective)
Power	10 mW @ 30 FPS

A picture of the MEMS based sun sensor on a chip is shown in Fig. 5. The mass of the unbounded MEMS based sun sensor on a chip is ~0.5 grams and the envelope is 10mm x 15mm x 1.5 mm.

Fig. 5. Photo of the MEMS based sun sensor on a chip. For size comparison a penny is also shown

V. ALGORITHMS

In an image captured from the micro sun sensor, a pattern of 217 apertures is typically observed as shown in Fig. 6. The position of this pattern on the focal plane changes as a

function of sun angle. In order to calculate the sun angles, the positions of the aperture centroids on the focal plane have to be determined. This type of image processing is routinely done in star trackers [18-19], where the centroids of bright spots (stars) are found in an image. The image is sifted for pixels that are above a given threshold. Once such a pixel is detected, a region of interest (ROI) window is aligned with the detected pixel in the center. The average pixel value on the border is calculated as shown in Fig. 7 and subtracted from all pixels in the ROI.

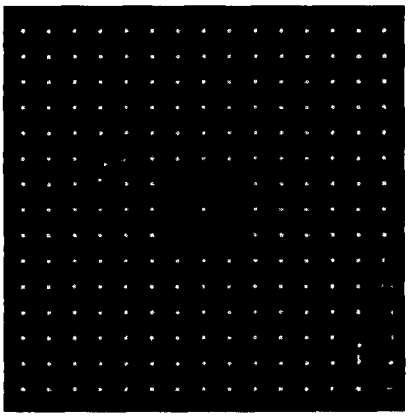
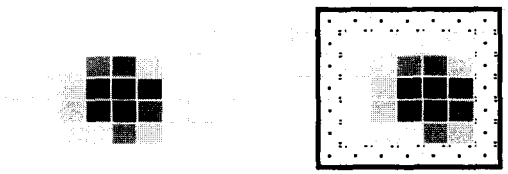


Fig. 6. Sketch of a typical Sun image



= Border

Fig. 7. The region of interest (ROI), and the border of the ROI of a detected bright spot

The brightness in units of A/D converter numbers (DN) and the centroid (x_{cm}, y_{cm}) are calculated from the background-subtracted pixels in the ROI.

$$DN = \sum_{i=ROIstart,i}^{ROIend,i} \sum_{j=ROIstart,j}^{ROIend,j} image(i,j)$$

$$x_{cm} = \sum_{i=ROIstart,i}^{ROIend,i} \sum_{j=ROIstart,j}^{ROIend,j} \frac{i \cdot image(i,j)}{DN}$$

$$y_{cm} = \sum_{i=ROIstart,i}^{ROIend,i} \sum_{j=ROIstart,j}^{ROIend,j} \frac{j \cdot image(i,j)}{DN}$$

The next step in the algorithmic flow is to transform the (x,y) centroids into Sun angles. A simple pinhole camera model is used. The pinhole camera model includes the distance from the pinhole to the focal plane (F) and the intersection of the optical axis and the focal plane (x_0,y_0). It is possible to transform from centroid coordinates into a unit vector centered at the pinhole and pointing towards the Sun utilizing the following equation [20]:

$$\begin{pmatrix} i \\ j \\ k \end{pmatrix} = \begin{pmatrix} \cos(atan2(x-x_0, y-y_0)) \cdot \cos(\frac{\pi}{2} - atan(\sqrt{\left(\frac{x-x_0}{F}\right)^2 + \left(\frac{y-y_0}{F}\right)^2})) \\ \sin(atan2(x-x_0, y-y_0)) \cdot \cos(\frac{\pi}{2} - atan(\sqrt{\left(\frac{x-x_0}{F}\right)^2 + \left(\frac{y-y_0}{F}\right)^2})) \\ \sin(\frac{\pi}{2} - atan(\sqrt{\left(\frac{x-x_0}{F}\right)^2 + \left(\frac{y-y_0}{F}\right)^2})) \end{pmatrix}$$

Where atan2 is four-quadrant inverse tangent and (i,j,k) is the unit vector starting at the pinhole and pointing towards the Sun.

The 217 pinholes are all individual and an individual calibration has been done for each of them (for details on the calibration refer to [5]). 217 different unit vectors pointing towards the Sun is calculated (one for each pinhole). The next step is to "average" these 217 vectors. A theory for calculating "average vectors" is given in e.g. [21]. A simple way to calculate an average vector is to use the Nather-Mead Simplex method. This method is described in this paper.

The average vector is the vector with the smallest squared angular distance to all other vectors. The azimuth angle (_) and elevation angle (_) of the average vector can be converted into Cartesian coordinates with the usual equations [6]:

$$x_c = \sin\delta \cdot \cos\alpha \qquad y_c = \sin\delta \cdot \sin\alpha \qquad z_c = \cos\delta$$

The angular distance between a given vector i and the average vector is:

$$\phi_i = a\cos(x_c \cdot x_i + y_c \cdot y_i + z_c \cdot z_i)$$

$$cost = \sum_{i=1}^{217} \phi_i^2$$

We now want to find the azimuth angle (_) and elevation angle (_) that minimizes:

It is simple to find the set of (_, _) that will result in the minimum cost using Matlab's fminsearch function, which utilizes the Nelder-Mead Simplex algorithm for gradient descent search, or the Microsoft Excel solver function. The solution is the average vector of the measurements.

Assuming that the 217 pinholes are independent, then the accuracy of the average vector towards the Sun will be improved by a factor of sqrt(217)=14.7 relative to the accuracy of a single aperture.

VI. COELOSTAT TESTING

JPL's Coelostat Simulator facility was used to test the MEMS based sun sensor on a chip. The facility contains a coelostat, which is simply a "sun tracker". The heliostat consists of a mirror mounted on an axis parallel to the earth rotation axis. The sun light bounces off this mirror and onto another mirror that corrects for small changes in declination primarily due to refraction in the atmosphere and directs the light onto the device under test. The light bundle will always come from the same direction. A picture of the coelostat is shown in Fig. 8.

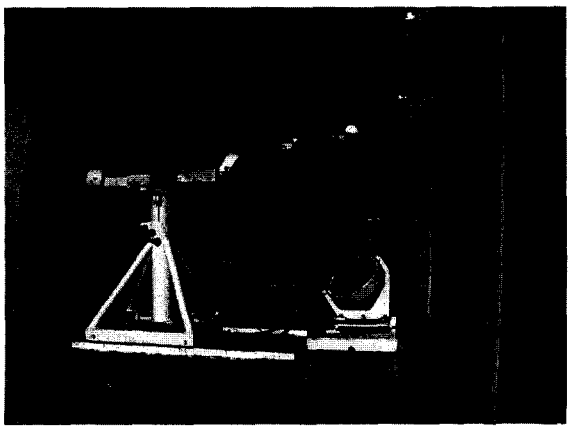


Fig. 8. The coelostat at JPL.

A 2-axis gimbal holding the MEMS based micro sun sensor on a chip is rotated though a large number of different angles and images are recorded. Based on all these measurements, it is possible to derive the relationship between the centroids and the sun angles as described previous. It is basically an over-determined set of equations, where hundreds of measurements are used to determine F, x0 and y0. A picture of the 2-axis gimbal with the MEMS based micro sun sensor on a chip is shown in Fig. 9. For a detailed discussion and the equations for doing this calibration is discussed in [5]. The accuracy of the sun sensor on a chip is 1 arcminute.

VII. SUMMARY

A new type of sun sensor based on MEMS technology has been described in this paper. A tiny gold and chrome plated silicon wafer is bonded on top of a spacer that is bonded to the APS chip. The APS chip contains all camera functions on the chip. The mask consists of 217 pinholes. The sun angle can be determined based on the position of the aperture centroids – just like a sundial.

Fig. 9. The 2-axis gimbal used to calibrate the MEMS based sun sensor on a chip

The centroid of the apertures is calculated with algorithms similar to those utilized in star trackers. Calibrations show that the accuracy is better than 1 arcminute utilizing multiple apertures.

The MEMS mask and the focal plane have been packaged together. The mass of the MEMS based sun sensor on a chip is 0.5 grams. Such an miniaturization is unprecedented and represents orders of magnitude improvement over current state-of-the-art sun sensors.

ACKNOWLEDGEMENTS

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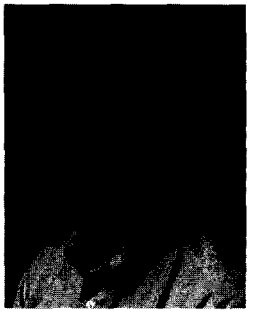

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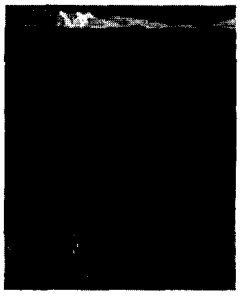

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