Micro/Nanotechnology for Picosatellites

SSC08-VII-6

Siegfried W. Janson

August 13, 2008
## Small Satellite Classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Mass Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microsatellite</td>
<td>10-to-100 kg</td>
</tr>
<tr>
<td>Nanosatellite</td>
<td>1-to-10 kg</td>
</tr>
<tr>
<td>Picosatellite</td>
<td>0.1-to-1 kg</td>
</tr>
<tr>
<td>Femtosatellite</td>
<td>10-to-100 g</td>
</tr>
<tr>
<td>Attosatellite</td>
<td>1-to-10 g</td>
</tr>
<tr>
<td>Zeptosatellite</td>
<td>0.1-to-1 g</td>
</tr>
<tr>
<td>Yoctosatellite</td>
<td>10-to-100 mg</td>
</tr>
<tr>
<td>Xennosatellite</td>
<td>1-to-10 mg</td>
</tr>
</tbody>
</table>
**Picosatellite Flight History**

- **Passive Satellites**
- **Active Satellites**

- **Calsphere-1**
- **ERS-5, -6**
- **Calsphere-3, -4, -5, 2-meter Mylar balloon**
- **ODERACS spheres**
- **OPAL picosatellites**
- **Cube-Sats**

**Yearly Deployment Rate**

- **1955**
- **1965**
- **1975**
- **1985**
- **1995**
- **2005**

**THE AEROSPACE CORPORATION**
The Aerospace Corporation Picosatellites

- **Two on OPAL**
  - Ejected February 6, 2000
- **Two on MightySat II.1**
  - Ejected September 7, 2001
- **65-mW transmitter**
  - 150’ dia. receive antenna
- **MEMS payload**
  - RF Switches by Rockwell Scientific
- **10-W-hr primary battery**

- **Tethered together**
  - 100-foot long tether
  - Gold dipoles for increased RCS
- **Smallest active satellites ever flown**
  - 1” x 3” x 4”
  - 275-gram mass

Photo by The Aerospace Corporation
Schematic MOS Transistor

Metal Interconnects

Metal Pitch (this is really small)

Top View

Gate Oxide

Polysilicon Gate

Cross Section

Source Diffusion

Drain Diffusion

Silicon Substrate
# Micro/Nanoelectronics:
The Evolution of a Revolution

<table>
<thead>
<tr>
<th>Year:</th>
<th>Dynamic RAM:</th>
<th>High Volume μPs:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>½-Pitch (nm)</td>
<td>Die Size (mm²)</td>
</tr>
<tr>
<td>2007</td>
<td>65</td>
<td>93</td>
</tr>
<tr>
<td>2008</td>
<td>57</td>
<td>74</td>
</tr>
<tr>
<td>2010</td>
<td>45</td>
<td>93</td>
</tr>
<tr>
<td>2012</td>
<td>36</td>
<td>59</td>
</tr>
<tr>
<td>2015</td>
<td>25</td>
<td>59</td>
</tr>
<tr>
<td>2020</td>
<td>14</td>
<td>74</td>
</tr>
</tbody>
</table>

From the International Technology Roadmap for Semiconductors
Spacecraft Computing Requirements

• Traditional spacecraft requirements
  - Command and telemetry processing: 0.010 MIPS
  - Attitude sensor processing: 0.025 MIPS
  - Attitude determination and control: 0.105 MIPS
  - Power management: 0.005 MIPS
  - Thermal control: 0.003 MIPS
  - Kalman filter: 0.080 MIPS

• Image processing requirements
  - QCIF (174 x 144) encoding @ 10 frame/s: 0.03 - 0.1 GIPS
  - CIF (352 x 288) encoding @ 30 frame/s: 0.5 - 5 GIPS

• Power requirements
  - 1.6 mW for 1 MIPS (Atmel AT91R40807 processor)

2- Hon-Sup Philip Wong et al, “Nanoscale CMOS,” Proceedings of the IEEE, 87 # 4, April 1999
A Really Small Command and Control System

The 80286 microprocessor:
- ~1 MIPS @ 6 MHz
- 134,000 transistors
- 1.5-micron technology
- ~8-mm square

Projections based on ITRS scaling

A small satellite command and control computer, with 1 MB DRAM, can now fit on a sub 1-mm² die.
Custom CMOS

- **The Metal Oxide Semiconductor Implementation Service (MOSIS)**
  - Combines chip designs from multiple users into a single mask set
  - Users split non-recurring costs (like the mask set)
  - CMOS processes: 1.5-\(\mu\)m through 65-nm
  - SiGe BiCMOS processes: 0.5-\(\mu\)m through 0.13-\(\mu\)m
  - ~$1100 for 5 copies of a 2-mm square, 1.5-\(\mu\)m rule design

- **Advantages of Custom CMOS:**
  - Variable size and shape photodetectors for 400 to 1100-nm light
  - Variable size and shape microbolometers using MEMS post-processing
  - Inertial and other sensors are possible using MEMS post-processing
  - Radiation tolerance can be designed into transistors, amplifiers, etc.

- **Disadvantages of Custom CMOS:**
  - Design mistakes can be costly
  - Some processes are available only every 3 months
  - You can’t use their packaging service for optical detectors
Custom CMOS: Design Your Own Sun Sensors

- 1.2-micron CMOS
- 5 copies for ~$1100
- 2.2-mm die size

1-Axis interdigital sensor  1-Axis binary sensor  2-Axis 10 x 10 imager

Photos by The Aerospace Corporation
Custom CMOS: Design Your Own Microbolometers

- 1.2-micron CMOS
- 5 copies for ~$1100
- 2.2-mm die size
- Post-processing chemical etch required

6 x 6 thermocouple array

6 x 6 thermocouple array

12 x 12 diode array

Photos by The Aerospace Corporation
## Commercial Imagers for Picosatellites

- **Active pixel CMOS imagers are now cheap**  
  - Expensive CCD technology rarely needed
- **Image compression chips are available**
- **Megapixel imagers are common**

### Imager Specifications

<table>
<thead>
<tr>
<th>Device</th>
<th>Array Size</th>
<th>Pixel Size (µm)</th>
<th>Package</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OmniVision OV7141</td>
<td>640 x 480</td>
<td>5.6 x 5.6</td>
<td>28-pin CLCC</td>
<td>40 @ 30 frame/s</td>
</tr>
<tr>
<td>OmniVision OV3630</td>
<td>2048 x 1536</td>
<td>2.2 x 2.2</td>
<td>6.1 x 6.3-mm</td>
<td>110 @ 15 frame/s</td>
</tr>
<tr>
<td>Micron MT9V011</td>
<td>640 x 480</td>
<td>5.6 x 5.6</td>
<td>28-pin LCC</td>
<td>70 @ 30 frame/s</td>
</tr>
<tr>
<td>Micron MT9D131</td>
<td>1600 x 1200</td>
<td>2.8 x 2.8</td>
<td>48-pin CLCC</td>
<td>348 @ 15 frame/s</td>
</tr>
<tr>
<td>Micron MT9P031</td>
<td>2592 x 1944</td>
<td>2.2 x 2.2</td>
<td>48-pin iLCC</td>
<td>381 @ 14 frame/s</td>
</tr>
<tr>
<td>STMicroelectronics VS6724</td>
<td>1600 x 1200</td>
<td>2.2 x 2.2</td>
<td>7.8-mm square</td>
<td>300 @ 30 frame/s</td>
</tr>
<tr>
<td>Kodak KAC-9628</td>
<td>648 x 488</td>
<td>7.5 x 7.5</td>
<td>48-pin CLCC</td>
<td>168 @ 30 frame/s</td>
</tr>
<tr>
<td>Kodak KAC-01301</td>
<td>1284 x 1028</td>
<td>2.7 x 2.7</td>
<td>48-pin CLCC</td>
<td>100 @ 16 frame/s</td>
</tr>
</tbody>
</table>
Near Infrared Imaging with a CMOS Camera

- CMOS cameras respond to light between 300 and 1100-nm
- Visible light ranges from ~400 to 700-nm
- Remaining 700 to 1100-nm near-IR range can be useful
  - Vegetation is very bright
- Even color imagers can see 700 to 1100-nm range

Normal camera view  Camera with RT-830 filter

Photos by The Aerospace Corporation
CMOS Imagers for Star Trackers

- Cannon EOS-20D
- 18-mm f/3.5 lens
  - 5.1-mm effective aperture
- 2-second exposure
- CMOS Star Camera:
  - 1” diameter optic
  - 0.1-s exposure time
  - Stars to 4th magnitude

Photo by The Aerospace Corporation
Simple Sun Sensor for a CubeSat

• Apertured position sensitive detector (PSD)
  - Hamamatsu S7848 detector (4.8 x 4.1 x 1.8-mm)
  - PSD area is 2-mm square
  - 200-micron diameter aperture
  - 500-micron aperture-PSD separation

• Simple, robust concept
  - Flown on AMSAT Phase 3D satellite
  - Will fly on AMSAT Eagle and KiwiSat

• BK-7 glass window in this design
  - Radiation shielding
  - UV light cutoff below 350-nm wavelength (protects plastic from UV degradation)
Simple Sun Sensor for a CubeSat

- Sun sensor and single infrared detector on same board
- PC board size is 3.3 x 2.5-cm

PSD with Aperture Plate  
Sun and Earth Sensor PC Board
Sun Sensor for a CubeSat: Ground Data

- Tested at AM0 conditions
  - SpectraLabs X-25 simulator
- Total range: +/- 50°
- Linear range: +/- 30°
  - Plastic index of refraction important beyond 30° inc.
  - Raw accuracy: +/- 2°
Micro/Nano/Picosatellite Attitude Sensors

• **Sun sensors:**
  - PSD-based sensors can be small and simple.
  - Custom CMOS sensors can have better performance, but will cost more.
  - CMOS imager-based sensors will have best performance when coupled with algorithms that perform Earth light rejection and centroid analysis.

• **Earth and horizon sensors:**
  - Single temperature sensors operating in the 5 to 12-micron range exist.
  - Microbolometer infrared detectors are available for a few thousand dollars.
  - Custom CMOS microbolometer arrays can be made for a few hundred dollars (recurring costs assuming 5 copies at $1100 total).

• **Magnetic field sensors:**
  - Giant magnetoresistive sensors readily available, sensitive, and cheap.
  - Picosatellite magnetometers usually swamped by nearby currents and batteries.

• **MEMS rate sensors:**
  - Noise density of 0.05°/s/Hz^{1/2} available; e.g., from Analog Devices.
  - MEMS sensors are O.K. for several minutes, but not for navigation.
# COTS MEMS Rate Gyro Performance Levels

<table>
<thead>
<tr>
<th>Provider</th>
<th>Model</th>
<th>Max. Rate (deg/s)</th>
<th>Noise (deg/sec/Hz(^{1/2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Devices</td>
<td>ADXRS150</td>
<td>150</td>
<td>0.05</td>
</tr>
<tr>
<td>Analog Devices</td>
<td>ADIS16255</td>
<td>80 to 320</td>
<td>0.05</td>
</tr>
<tr>
<td>Silicon Sensing Sys.</td>
<td>CRS02</td>
<td>300</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>CRS03-02</td>
<td>100</td>
<td>0.05 (3-10 Hz)</td>
</tr>
<tr>
<td></td>
<td>CRS04</td>
<td>150</td>
<td>1.2</td>
</tr>
<tr>
<td>Kionix</td>
<td>KGF01-075</td>
<td>75</td>
<td>0.14</td>
</tr>
</tbody>
</table>
The Analog Devices ADXL202/210 Accelerometers

- Integrated 2-axis Accelerometers
  - ADXL202: +/- 2 g range
  - ADXL210: +/- 10 g range

- Low Power
  - 3 to 5.25 V
  - Less than 0.6 mA

- Wide Frequency Response
  - DC to 5 kHz

- Low Noise
  - 500 μg/(Hz)^{1/2} noise floor

- Analog and Digital Outputs

- Good for monitoring thrusters

Photo by The Aerospace Corporation
MEMS Accelerometers Monitored STS-93 Flight

Silicon Designs 1010J & 1210J
Capacitive MEMS Accelerometers

ASIC
Sensor

Photo by The Aerospace Corporation

Photo courtesy of NASA

Z-Axis Acceleration (g’s)

Launch

Orbit Correction

Simplex #1 Burn
1-engine OMS
10 seconds

Z-axis
Y-axis
X-axis

Time (EDT, seconds)

1800 1900 2000 2100 2200 2300 2400

0 0.5 1 1.5 2 2.5 3

Z-Axis Acceleration (g’s)

Time (UTC, seconds)

25740 25760 25780 25800 25820 25840 25860

0 0.005 0.01 0.015 0.02

Acceleration (g’s)
Summary

• Until the year 2000, only 2 active picosatellites were launched
  - Most picosatellites were passive objects

• The picosatellite era started with Stanford’s OPAL satellite
  - Six picosatellites ejected in 2000
  - Two picosatellites ejected in 2001
  - CubeSats dominate starting in 2003

• Evolving micro/nanoelectronics and MEMS enabled intelligent picosatellites

• Digital micro/nanoelectronics is not really a problem for picosatellites
  - Microprocessor performance of ~1000 MIPS/W is available
  - Gigabytes of data can be stored in a 1-cm² memory card

• Miniaturized attitude sensors are needed for capable picosatellites
  - Pointing of sensors and optics
  - Pointing of medium to high gain antennas to increase downlink rates

• These sensors are either available or can be custom-fabricated using CMOS prototyping services
Acknowledgements

I gratefully acknowledge The Aerospace Corporation’s Independent Research and Development program and its former Corporate Research Initiative in MEMS and Microtechnology for funding the development of CMOS-based sensors.