Space Qualification Plan of Optoelectronic and Photonic Devices for Optical Communication Systems

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Purpose

- To characterize newly available photonic devices needed for the future space missions (optical communications with spacecrafts (i.e. International Space Station)/ spectrometers) and develop space qualification guidelines
- To establish a space qualification plan of a newly developed InGaAs Active Pixel PIN Receiver devices, and identify the advantages over the existing state-of-the-art photonic receiver devices
Presentation outline

- Purpose
- Qualification Methodology
- Receivers
- Qualification Variables
- Space Qualification Plan
- Conclusions
- Recommendations
Methodology: Space Qualification of InGaAs/InP Active Pixel Receivers

Mars Exploration Rovers
Deep Space Communications

Process Qualification
Customized InGaAs/InP Die

Product Qualification
Packaged 320x240 Array Part

Correct/Reject

Process Identification Documentation

Product Acceptance

P/F

P

P

F

F

P/F

P/F

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Applications

Tracking System

- Proper Orientation Relative to the Arriving Optical Field.
- Closed Loop tracking Control Systems (Azimuth, Elevation).

Multifunctional Active Spectral Analyzer (MAESA)

- Obtain a wavelength-resolved characteristic spectrum of the target for its identification.
- Obtain temporal and spatial multifunctional information of the same target.
Process Qualification

1. Determine Type of Device
2. Establish TRB
3. Develop Processing Steps
5. Document Design Standard and Processing Procedures
6. Determine Fabricate Technology Vehicle, Circuits, and Parts to be qualified
7. Determine Device Models, Electrical Circuits, and Parts
8. Process Reliability Evaluation
9. Process Qualified
Product Qualification

- External Visual Inspection
- Lot Acceptance Test for Die
- Die mounting and Wire Bonding
- Nondestructive Bond Pull Test
- Pre-ca Visual Inspection
- Serialization and Marking
- Infrared Scan
- Seal Test
- Temperature Cycle/Shock Test
- Vibration/Sock Test
- Particle Impact Noise Detection
- Electrical/Optical Test at High/Low Temperature
- Pre Electrical/Optical
- Burn-in
- Hermetic Seal Test
- Radiographic Inspection
- Final Electrical/Optical
## Typical Packaged Device Screening

<table>
<thead>
<tr>
<th>Test</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nondestructive bond pull</td>
<td>MIL-STD-883, Method 2023</td>
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<tr>
<td>Internal visual inspection</td>
<td>MIL-STD-883, Method 2017</td>
</tr>
<tr>
<td>IR-scan (prior to seal)</td>
<td>JEDEC Document JES2 [7]</td>
</tr>
<tr>
<td>Temperature cycling/</td>
<td>MIL-STD-883, Method 1010/</td>
</tr>
<tr>
<td>Thermal shock</td>
<td>MIL-STD-883, Method 1011</td>
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<tr>
<td>Constant acceleration</td>
<td>MIL-STD-883 Method 2001</td>
</tr>
<tr>
<td>Particle impact noise detection</td>
<td>MIL-STD-883, Method 2020</td>
</tr>
<tr>
<td>Electrical</td>
<td>Customer’s specification</td>
</tr>
<tr>
<td>Burn-in</td>
<td>MIL-STD-883, Method 1015</td>
</tr>
<tr>
<td>Electrical (high/low temp)</td>
<td>Customer’s specification</td>
</tr>
<tr>
<td>Fine leak</td>
<td>MIL-STD-883, Method 1014</td>
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<tr>
<td>Gross leak</td>
<td>MIL-STD-883, Method 1014</td>
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<tr>
<td>Radiographic</td>
<td>MIL-STD-883, Method 2012</td>
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<tr>
<td>External visual</td>
<td>MIL-STD-883, Method 2009</td>
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Space Qualification Plan

• This qualification plan covers the general provisions for photonic devices intended for use in in-situ material analyses/detector system applications.

• The qualification plan should include optical as well as electrical for all the photonic devices such as:
  – laser diodes (single/multiple modes)
  – PIN receiver diodes and transistors
  – fibers (single/multiple mode)
  – Index guides: p-InP/n-InGaAs/p-InP
  – Opto-couplers
  – Optical amplifiers
  – Optical switches
Optical Receivers

• Devices
  – Photo-gate
  – Photodiode
  – Avalanche Photodiodes

• Readout Circuits
  – Amplify
  – Switching
  – 2-D Data processes
# The State-of-the-Art Detectors

<table>
<thead>
<tr>
<th></th>
<th>Si APD</th>
<th>Ge-APD</th>
<th>InGaA/InP APD</th>
<th>InGaAs-PD/FET</th>
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</thead>
<tbody>
<tr>
<td>$\lambda$ (microns)</td>
<td>0.5-1.0</td>
<td>0.8 - 1.5</td>
<td>1.25</td>
<td>1.0 -1.7</td>
</tr>
<tr>
<td>$\eta_{\text{max}}$</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>$i_d$ (A)</td>
<td>1.00E-11</td>
<td>1.00E-06</td>
<td>1.00E-09</td>
<td>1.00E-09</td>
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<tr>
<td>$C_j$ (pF)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
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<tr>
<td>$F$</td>
<td>300</td>
<td>70</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>$\tau_r$ (ns)</td>
<td>0.15</td>
<td></td>
<td>0.16</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Active Pixel Sensor (APS)
Single Stage Buried Channel Junction CCD
Active Pixel Sensors
A Typical Monolithic Integration

- Planarizing Polyimide
- N Contacts
- P Contacts
- Grown-In P Layer
- Grown-In N Channel
- InGaAs Detector
- Zn Diffused P Region
- First Plated Gold Plug
- Second Plated Gold Plug
- BCB Insulating Layer
- Metal Inter-connect Lines

Semi-Insulating InP Substrate
Key Reliability Factors

- Major critical variables to qualify the receiver are:
  - Detectivity ($D^* = 10^{12} \text{cm(Hz)}^{1/2}/\text{W}$ at a temperature of 200K)
  - Lifetime
  - Operating Temperature (-100 – 125°C, 10°C/half life)
  - Bias Current/Voltage
  - Output power
  - Data Rates: 50Mb/s
  - Spectral width (0.5 ~ 2.5 µm)

- Dislocations
- Metal diffusion
- Inner material Degradations
- Point Defects
- Crystal structures vacancies
- AlGaAs/GaAs>InGaAs(P)/InP
- 110 Crystal axis
- Impurity level of the material
- Workmanship/reproducibility
- Radiation Damages
- Total Ionizing Dose (25K Rad)
- Replacement Damage (>25K Rad)
- Single Event Upsets (75MeV/mg/cm²)
- Single Event Latch ups
- Single Event Burn outs
- Modulation Transfer Functions
- Surface Degradations
- Facet oxidation/slow
- Aluminum/inhibit diffusion: AlGaAs/GaAs
- Output power: 200mW
- Catastrophic optical damage/fast
- Facet melting: AlGaAs>InGaAs/InP
- Bandgap shrinking: non-absorbing mirror (<0.1 MW/cm²)
- Alloy electrodes
- Metal diffusion
- AuZnNi: Dark spot defects
- Schottky type electrode: TiPtAu
- Bonding parts
- Soft solders: In, Sn, and Au rich solders/sudden failures
- Hard solders: Au rich solders/reduce instability
- Optical degradation/Modes
- Lifetime
Summary of Lifetime

• Monolithic Integration
  – Front Illumination Possible
  – Remove the Hybridization
  – Low-power, Low-cost, and Miniaturization Possible
• Active Pixel Smart Control
  – Direct Addressing
  – Remove the Needs of Multiplexers
  – Fast Data Processing
• Two-dimensional APS
  – Dual Function Imaging Possible
  – Spectrometer/Laser Image Detection and Ranging
  – Real-time Data Processing Possible
Modulation Transfer Function

- In-situ evaluation of advanced active pixel focal plane arrays by Modulation Transfer Function in different stages of imager system developments is necessary for an ideal design of different sensors and their signal processing.
- Understanding the tradeoff between different figures of merit will enable designers to achieve the most efficient array design for specific missions.
Modulation Transfer Functions

• Modulation Transfer Function
• Active Imaging Focal Plane Arrays
• Cross talks
• Advanced Photodiode Active Pixel Test Chip
• Optical probing system
• Results
Modulation Transfer Function (MTF)

\[ MTF = MTF_{\text{optical}} \times MTF_{\text{pixel}}. \]

Ideal imaging system MTF is given by the product of the optical diffraction limited MTF of the optics and the ideal MTF of the pixel.

For circular aperture, the diffraction-limited MTF of the optics is circular symmetric. Its one dimensional profile can be given as:

\[ MTF_{\text{optical}}(f/f_c) = \frac{2}{\pi} \left\{ \cos^{-1}(f/f_c) - \frac{f}{f_c} \left[ 1 - \left( \frac{f}{f_c} \right)^2 \right]^{1/2} \right\}, \]

for all \( f_c \leq f \) and zero otherwise.

The cutoff frequency \( f_c \) is related as \( 1/(f/#) \). The ideal pixel MTF is the magnitude of the Fourier transform of a rectangular function of width \( W \) or height of the active area of the pixel can be expressed as:

\[ MTF_{\text{pixel}}(f) = |\sin(\pi f W) / \pi f W|. \]

The real pixel MTF is depend upon many variables such as charge transfer efficiency (CTE), cross talk, pixel fill factor, pixel shape, and readout electronics including time delay integration (TDI) techniques.
Ideal MTF

Normalized Response

Optical Limit

Pixel MTF

FF = 54 %

Ideal MTF

f / f nyquist

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Discrete Fourier Transformations for Modulation Transfer Function (MTF)

\[ X_d(k \Delta f) = \Delta t \sum_{n=0}^{N-1} x(n \Delta t) \exp \{ -j 2\pi k \Delta f n \Delta t \} \]

where

- **N**: number of samples being considered,
- **\( \Delta t \)**: the time between samples,
- **\( \Delta f \)**: the sample interval in the frequency domain,
- **\( n \)**: the time sample index,
- **\( k \)**: the index for the computed set of discrete frequency domain,
- **\( j \)**: \((-1)^{1/2}\).
Typical crosstalk among the eight nearest neighbor pixels is 5.1%
Block diagram of the Microelectronic Advanced Laser Scanner

PC CONTROL AND DISPLAY

BIT MAPPER

LASER

NEUTRAL DENSITY FILTER

MONITOR

ENERGY METER

BEAM SPLITTER

DUT CHIP

MICROMANIPULATOR
DICE APD CHIP PIXEL ARRAY
Active test pixel arrays used for the MTF measurements
Procedure of the MTF Measurements

- A Single image containing an edge was stored for location of the edge.
- Utilizing the linear regression line fitting, the edge spread function (ESF) was determined as:

\[
F(x) = D + \frac{A}{\exp\left\{\frac{(B-x)}{C}\right\} + 1}
\]

where A, B, C, and D are constants.

- Calculate the line spread function (LSF) by differentiate the ESF.
- Perform the discrete Fourier transformation (DFT) of the LSF for MTF of the one-dimensional focal plane array. The real part of the DFT is the MTF.
Edge Spread Function

Intensity (Arb. Unit) vs. Pixels

- Intensity values range from 0 to 2,000.
- Pixels range from 0 to 35.

Graph shows data points representing intensity against pixel count.
Modulation Transfer Function

J13MTFHR
Fill Factor = 54 %

Normalized Response

f / f nyquist
Modulation Transfer Function

J13MTFVR
Fill Factor = 23 %

Calculated

Measured
Modulation Transfer Function

104MTFHR
Fill Factor = 74 %
Modulation Transfer Function

Normalized Response

104MTFVR
Fill Factor = 54 %

Calculated
Measured

f / f nyquist

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Summary of the MTF

- The performance of active pixel focal plane arrays is characterized by estimating their spatial frequency responses. A modified knife-edge technique that estimates 1-dimensional system MTF profiles is used.
- Advantages of the technique include the need for only a single image to perform the measurement in each direction and the fact that moving parts and high-precision alignment are not necessary.
- Various silicon active pixel sensor array responses that are not affected by the charge transfer efficiency (CTE) were measured and compared with calculated MTF profiles in both the horizontal and vertical directions.
- Calculated ideal pixel MTF of the different fill factor was compared with measured MTF and overall pixel crosstalk effects. Furthermore, it was demonstrated that the technique can be utilized as a timely evaluation technique of the focal plane array pixel design.
Conclusions

- General overview of Space qualification of Optoelectronic and Photonic Devices for space optical communications/Spectrometer was described.
- Efforts were concentrated to generate the needed general guideline of the optical reliability concerns.
- Ultimate goal for this effort is to gradually establish enough data to develop a space qualification plan of newly developed photonic specific parts.
- A numerical model to assess the lifetime and MTF as qualification variables
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