Print with Molecular Precision
Space Foundry at a glance

- NASA Ames Research Center Spinoff

**Business:** Printed electronics product manufacturing

**Value Proposition:** Dry printing of conductors & dielectrics

- Three granted patents - several filed

- Funded by – NASA SBIR Phase I-III (active) (Marshall Space Flight Center & Ames Research Center)

- Revenue generating through equipment sales (30% of total fund inflow)
Technology Origin

NASA Ames Research Center: 2012-2017

- Biosensors
- Biomining
- Printed Electronics
- Plasma Jet
- Sterilization

Jessica Koehne
Meyya Meyyappan

CIF 2014; AES 2015
CIF 2016; NIAC 2016
SIF 2017; GCD-2017
DDF-2017
Emerging Printed Electronics Market

Embedded & conformal electronics creating new capabilities

In Space Manufacturing

Aerospace & Defense
Hypersonics & Radomes

Wearables/ AR/VR

In mold electronics

Need for direct write technologies that allows printing on platforms that are not conducive for traditional processing
Printed Electronics Industry Problems

- **Ink**
  - Heavy reliance on ink quality - shelf life, oxidation state
  - Prohibitively expensive ink formulations

- **Process**
  - Multiple equipment set for multiple steps (pretreatment, annealing)
  - Multiple process steps for every single material

- **Adhesion issues**

- **Printing of Copper on to other substrates** - Holy Grail

- **Environmental issues** - liquid waste, nanoparticles, toxicity
Plasma Jet Printing Technology

State of the art printers

- Dry printing & no curing
- Reduces processing steps & materials cost
- Uses aqueous ink solution (reduces supply chain issues)
- Inks have long shelf life, no nanoparticles, no liquid waste
- Recover water from the ink
- Gravity independent

Environmental friendly - green chemistry process
Role of Atmospheric Pressure Plasma

• Activation of the material to be printed and the surface to be coated
• Enhance the adhesion
• Precise control over thickness and morphology
• Ability to tailor material properties in-situ
• To facilitate plasma polymerization in the case of organics & inorganics
# Materials Printed

- Dry printing of copper, silver, gold, platinum, and other transition metals
- Can print on 3D objects, planar & flexible substrates, curved & rough surfaces

<table>
<thead>
<tr>
<th>Conductors</th>
<th>Insulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Silicon dioxide</td>
</tr>
<tr>
<td>Silver</td>
<td>Variable K dielectrics</td>
</tr>
<tr>
<td>Gold</td>
<td>Copper oxide</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semiconductors</th>
<th>Organics</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>CNT</td>
</tr>
<tr>
<td>ZnO</td>
<td>Reduced graphene oxide</td>
</tr>
<tr>
<td>SnO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>P3HT</td>
</tr>
</tbody>
</table>

Substrates: Poly imide, glass, poly carbonate, PET, acrylate, ultem, composites, resin used for 3D printing, silicon, alumina (ceramic), FR4, teflon.
Business Model

Equipment sales:
- Desktop Printer

OEM Integration

Printed Service:
- Dry metal printing (Copper & Silver)
- Proprietary particle-free ink

Market Segments:
- Aerospace & Defense
- In space manufacturing
- Wearables (Medical, AR/VR)

- Small market size
- Go to market strategy to capture larger market
- Get insight of customer pain points
- Customers create new applications

Large market size and opportunity
Need strategic partnering
Space Foundry has **two** distinct approach & hardware/process for printing metal traces

- **Commercial print head**: Currently being sold
  - uses off the shelf nanoparticle inks
  - Inks that are compatible with aerosol jet printing will work

- **Custom print head**: Under development & not released yet
  - uses particle-free ink synthesized in-house with minimal synthesis step
  - Cost < 100X of nanoparticle inks
  - Water based ink with no complex solvents
  - Recover water from the ink while printing
  - Works with range of metals Cu, Ag, Au and can possibly be extended to alloys
  - Long shelf life
Plasma Printers at Customer Location

- Sandia National Lab
- Boise State University
- UCL, UK
- University of Auckland
- NASA Ames Research Center
- NASA Marshall Space Flight Center
- Nextflex
- Idaho National Lab
Robotic arm Integration

Allows printing on 3D objects eliminating the complex curing step

“Nextflex” logo printed using TiO2 ink
## Printed Service - Applications

<table>
<thead>
<tr>
<th>Priorities</th>
<th>Market Sector</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market 1</td>
<td>Aerospace &amp; Defense, (current focus)</td>
<td>Conformal Antenna, Frequency selective surfaces (FSS)</td>
</tr>
<tr>
<td>Market 2</td>
<td>IOT, AR/VR, Medical</td>
<td>Flexible electronics</td>
</tr>
</tbody>
</table>

Plasma jet printing to enable embedded antenna on large 3 dimensional structures like fighter jets and predator drones
Space Foundry’s Goal in Space Economy

To become an indispensable supply chain for metallization in space

LEO Commercialization

Lunar Manufacturing
In Space Manufacturing

Potential ISS Installation in early 2025
• Continued LEO presence and develop applications
• In early stage discussion with other space players
Currently aiming to create a library of materials and cartridge development

Potential Applications:
• Phased array antenna
• Metallization and interconnects for solar panel manufacturing
• Alloy manufacturing
• Meta materials

Lunar based manufacturing - Interconnects for solar panel & solvent less regolith processing
NASA ODME

Energy Generation
- Solar Panel

Energy Storage
- Supercapacitor, battery

Sensors
- Gas Sensor
- Bio Sensor

Integrated Circuit
- Logic
- Memory

Display
- Lighting

Communication
- Antenna

Printer/Material
Sustainable In-Space Opportunities

Varda Space

Space factories for Earth-bound products
BRINGING A GRAVITY-OFF SWITCH TO MANUFACTURING
LET'S BUILD

Axiom Space

Orbital Reef

NASA OSAM 2

DARPA Nomad
Printed Copper using proprietary ink

Aqueous based particle-free proprietary ink

7mm X 7mm pad

Copper resistivity: ~60X bulk
To achieve: <10X bulk
X Band Antenna on Kapton

Copper and silver X band and wifi antenna printed on Kapton

Silver on Kapton

Copper on Kapton
Plasma Jet Printed Silver

Silver printed on Kapton

7mm X 7mm pad
Copper & Silver Prints

Copper on teflon

Spacing between lines ~ 400 microns

Line width <1mm

Silver on kapton

~ 200 microns

8mm
Silver X Band Antenna on Alumina

Characterized by our customer

**Space Foundry Printed Antenna Characterization**

- X Band patch antenna (10.0 GHz design, measured 10.9 GHz, good resonance)
- Space Foundry printed on alumina
- Connectorized with card edge coax connector
- Sample not tested, shorted and asymmetric
- Gap to edge filled with Ag epoxy

**VSWR vs Frequency**

10.9 GHz
Plasma Printed Copper Resistivity

Resistivity & Conductivity of plasma printed copper:
(as printed with no external annealing step)

<table>
<thead>
<tr>
<th>Bulk Copper</th>
<th>Plasma Printed Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity = 5.96*10^7 S/m</td>
<td>Conductivity = 9.4*10^5 S/m</td>
</tr>
<tr>
<td>Resistivity $\rho_{Cu} = 1.70*10^{-8}$ Ωm</td>
<td>Resistivity $\rho = 1.06*10^{-6}$ Ωm</td>
</tr>
<tr>
<td>$\rho_{Cu} = 1.70$ µΩcm</td>
<td>$\rho = \sim 106$ µΩcm</td>
</tr>
</tbody>
</table>

$\rho_{plasma}/\rho_{bulk} = 106$ µΩcm/1.70 µΩcm = 63
Print Thickness

Plasma printed copper and silver thickness depends on print speed & number of passes.

Print speeds vary from 0.25mm/sec to 1mm/sec.

Thickness depends on print speed, number of passes, gas flow ratios.

Thickness varies from 3 - 15 microns per pass depending on speed, gas flow etc.,
Vertical growth

Silver Vertical pillars (7mm in height)
Materials Processing in Microgravity
Microgravity Printing Demo

NASA Flight Opportunities Program

[Diagram showing altitude vs. maneuver time with key points: 45° Nose High, Zero-g, 45° Nose Low, 350 Kias, and 1.8g at different altitudes.]
Plasma Jet Printer
• PLC based fully automated process
• G code & M code
Flight Demo

[Images of astronauts in zero-gravity environments performing equipment manipulation tasks]

[Images of equipment and astronauts in a simulated space environment]
Wiring problem
We realized that manual intervention to print is not going to work
Decided to use accelerometer based triggering of PLCs
G code and M code to fully control the print
Hardware that needed to be fixed after 1st flight
### 2 Parabolas: Sequence of Triggers/Commands

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
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</thead>
<tbody>
<tr>
<td>Parking</td>
<td>Printhead moves to parking position (dump site) ~4mm from print site and wet gas valve sends gas to printhead.</td>
</tr>
<tr>
<td>Wait for 1.2 G</td>
<td>When accelerometer detects 1.6G or higher it signals a 2G event is occurring and now listens for 1.2 G.</td>
</tr>
<tr>
<td>Print head move</td>
<td>Wet gas valve sends gas to exhaust -&gt; printhead moves to print site - wet gas valve sends gas to printhead. 3.5 seconds total.</td>
</tr>
<tr>
<td>Printing</td>
<td>Print Pattern in &lt;22 sec</td>
</tr>
</tbody>
</table>
2nd Flight - Fluid delivery failure

Positive pressure build up in fluid delivery

Aerosol chamber

Peristaltic Pump

Ink Out

Ink In

Atomizer

Aerosol chamber

Ink supply connected here (not shown)
Partial Success - able to get few good prints
Droplet formation in between prints
(Unacceptable)
Decided to have additional filters/valves
Flight 4: Successful Prints

Interdigitated Patterns

Continues Line
1g - 2g - 0g - 2g - 1g

WiFi Antenna printed with 2 passes

<- Bottom Tip
# Variation in G & printing

<table>
<thead>
<tr>
<th>Parab 1 Line</th>
<th>Parab 2 Line</th>
<th>Parab 3 Line</th>
<th>Parab 4 Line</th>
<th>Parab 5 Line</th>
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<tbody>
<tr>
<td>n15s</td>
<td>1.320716</td>
<td>7.997965</td>
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<td>n21s</td>
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<td>n25s</td>
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<tr>
<td>n26s</td>
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<td>n27s</td>
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<td>n28s</td>
<td>0.4125009</td>
<td>7.9996</td>
<td>7.9996</td>
<td>7.99856</td>
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<tr>
<td>n29s</td>
<td>0.4245496</td>
<td>7.999765</td>
<td>7.9996</td>
<td>7.9996</td>
</tr>
</tbody>
</table>

**Colors:**
- RED : Martian G
- Orange : Lunar G
- GREEN : Printing

Variation in G & printing
### Variation in G & printing

**YELLOW : Near 0 G Conditions**

**GREEN : Printing**

<table>
<thead>
<tr>
<th>Par 9 Pad</th>
<th>Par 10 Pad</th>
<th>Par 26 3mm line</th>
<th>Par 27 3mm line</th>
<th>Par 29 2x2mm</th>
</tr>
</thead>
</table>
| Tips of 3mm lines not printed in 0 G so SEM scans done in center.
Microstructure Analysis

Zero g

1 g
Microstructure Analysis

Zero g

1 g

100 nm

100 nm
Silver particles that are globular in 1g appear more stretched in 0g, probably due to surface tension, resulting in a well connected network.
• Resistivity of bulk Silver: 1.6 $\mu\Omega$ cm
• Resistivity of samples printed in microgravity: 13.4 $\mu\Omega$ cm
• 8X higher than bulk silver resistivity
Antenna Characterization
Wifi Antenna Printed in Zero G

![Graph showing S11 and S21 vs. frequency](image)

- S11 SF Ant.
- S21

Resistivity of printed silver ~10x pure silver
Antenna and sensor components get plasma jet printed in microgravity

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