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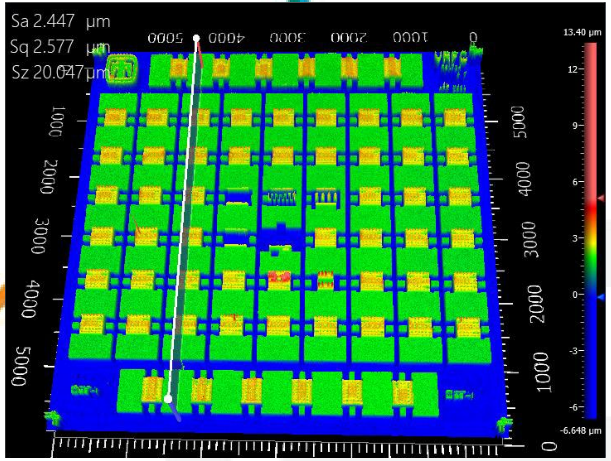
Devices and Experiments for Exploring RF Breakdown in Micrometer-Scale Air Gaps

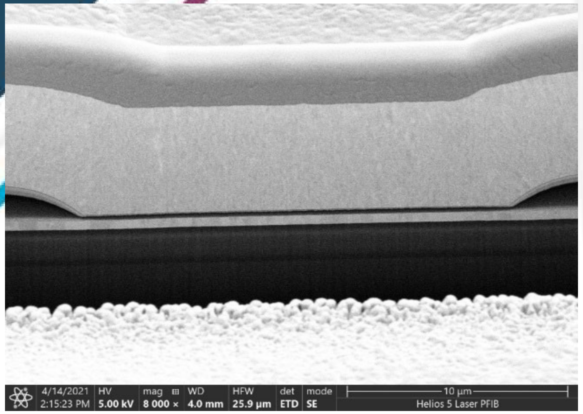
July 13, 2022

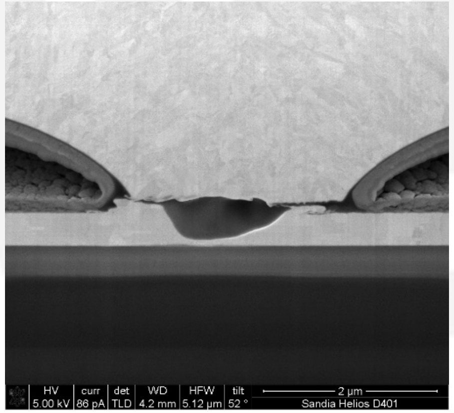
Christopher D. Nordquist, Alexander Ruyack, Matthew Jordan, Jack Kramer, Andrew Bingham, Christopher Moore, Gwendolyn Hummel, Sergio Herrera, Mark Ballance, Adrian Schiess
Sandia National Laboratories, Albuquerque, NM USA

Zach Vander Missen, Steven Pugia, Alden Fisher, Dimitrios Peroulis
Dept. of EECS, Purdue University, West Lafayette IN USA

2022 AP-S/URSI Meeting, Denver, CO USA







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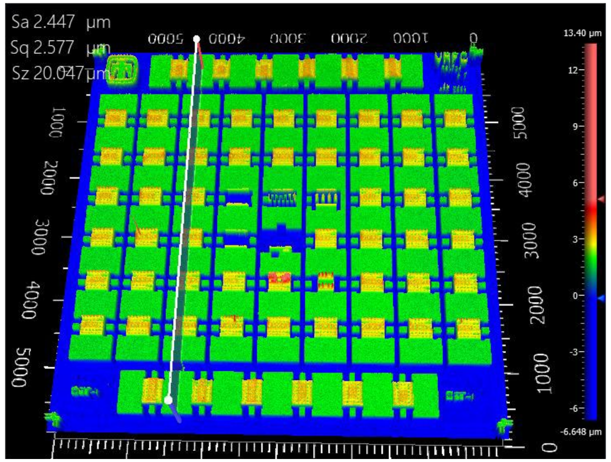
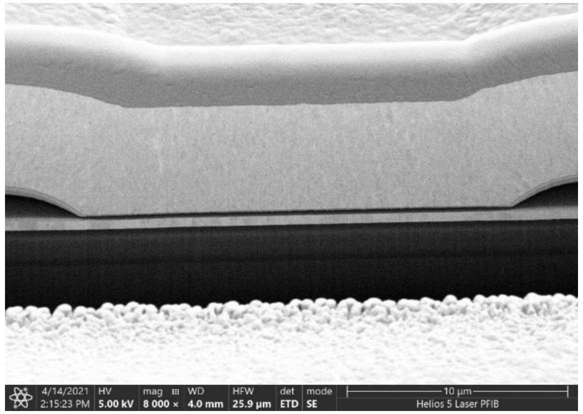
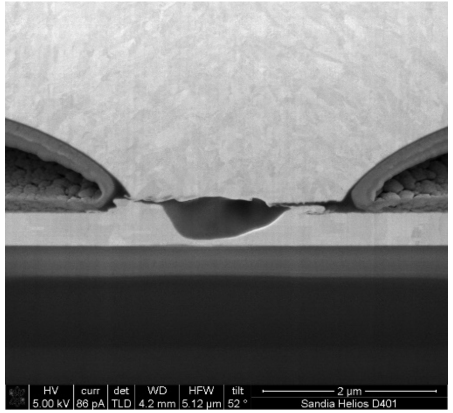
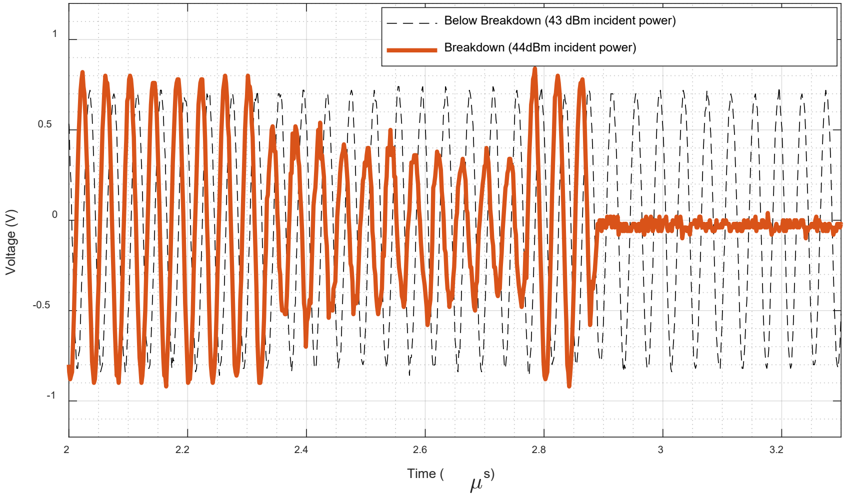
Outline

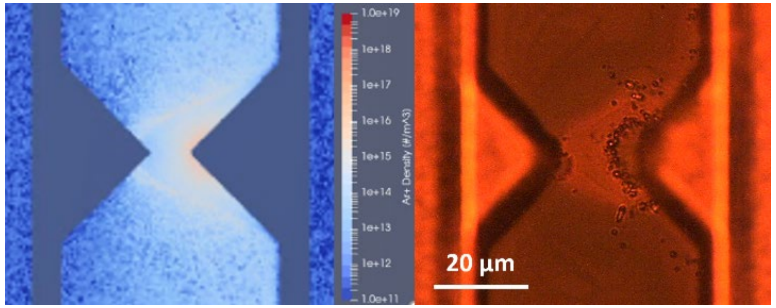
- Introduction – Breakdown in Narrow Gaps & at RF
- Motivation – Fix It Or Feature It
- Device Design and Challenges
- Fabrication – Double Release Process
- DC Test and Screening Results
- RF Power and Time-Domain Results
- Next Steps
- Conclusions





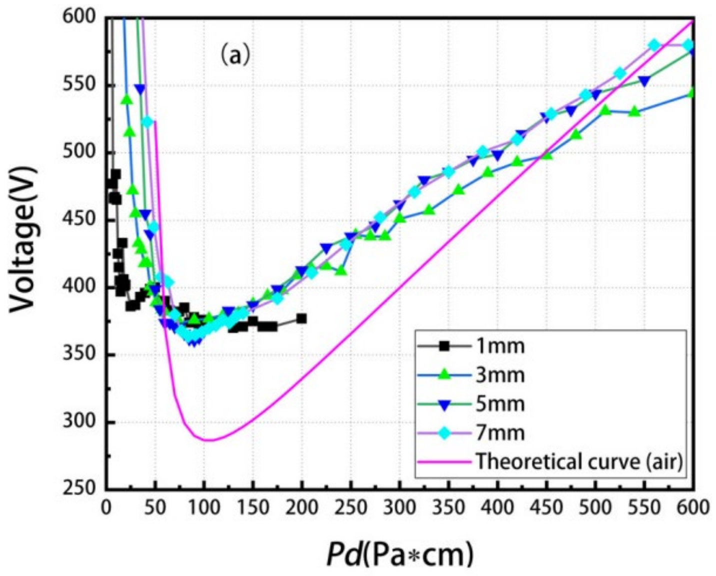






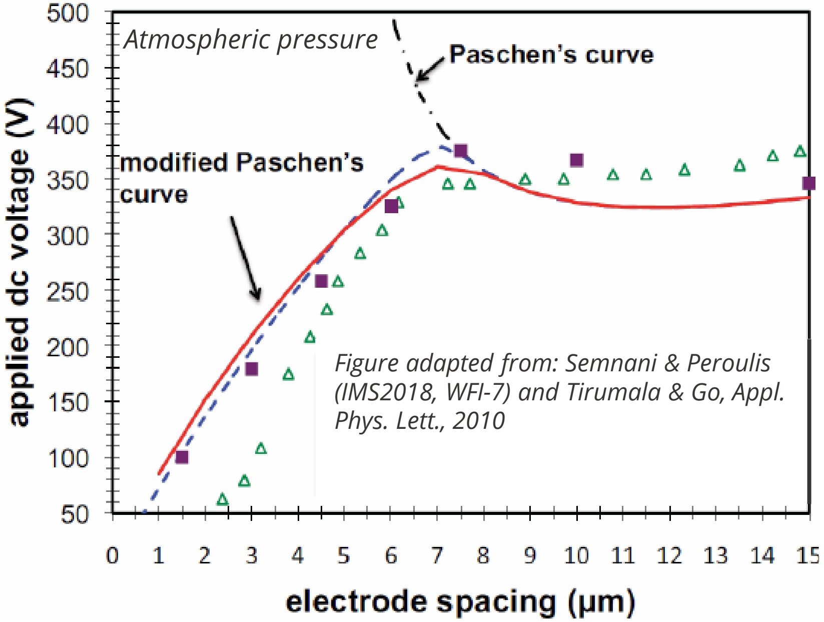
Introduction – Breakdown in Narrow Gaps & at RF

Paschen's Curve

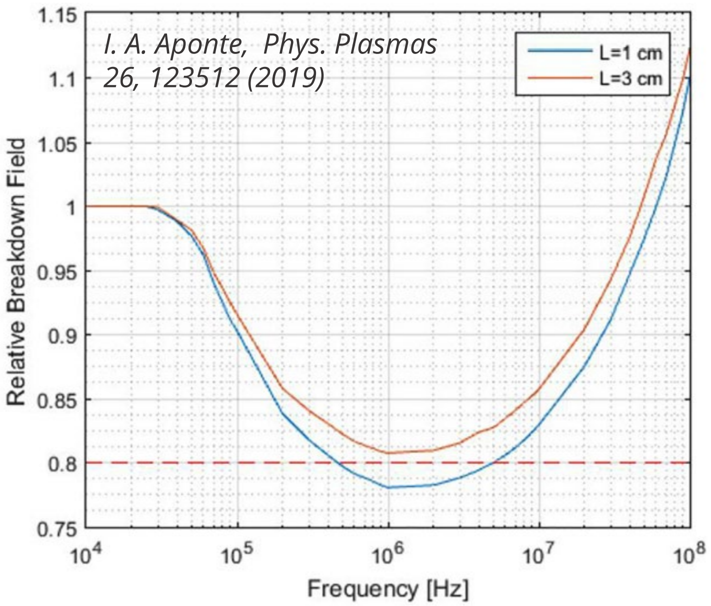


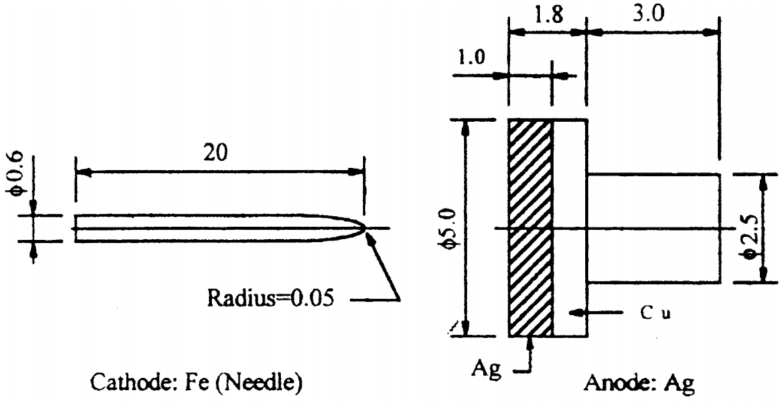
X. Lyu, et al., Phys. Plasmas 27, 123509 (2020)

DC Narrow Gaps

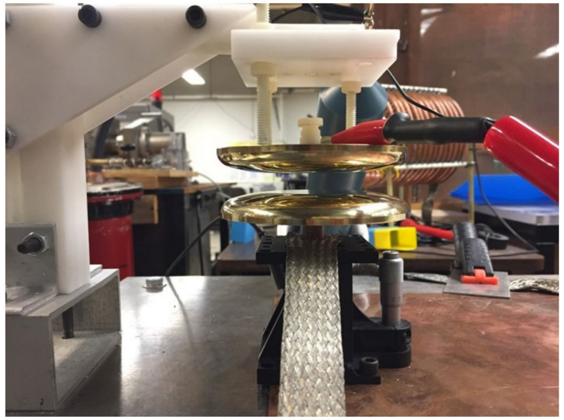


Radiofrequency

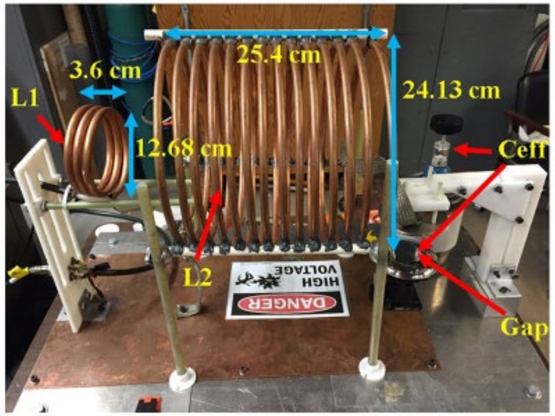




Slade and Taylor, IEEE Trans. Comp. Pack. Tech., 25, 2002.



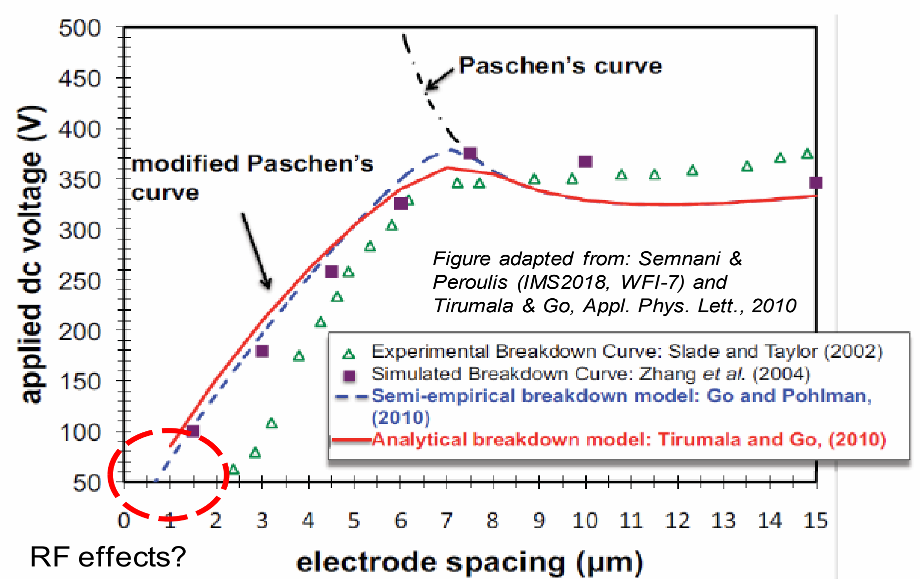
I. A. Aponte, Phys. Plasmas 26, 123512 (2019)

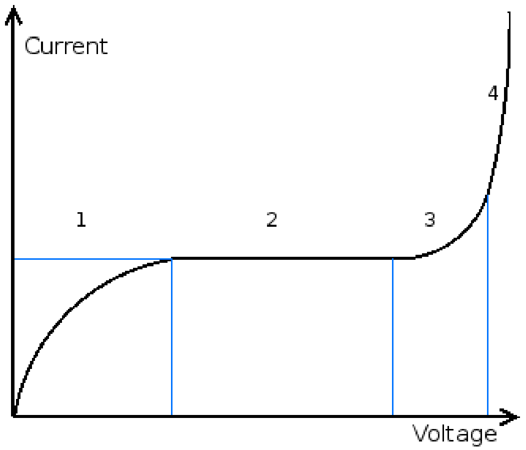


I. A. Aponte, Phys. Plasmas 26, 123512 (2019)

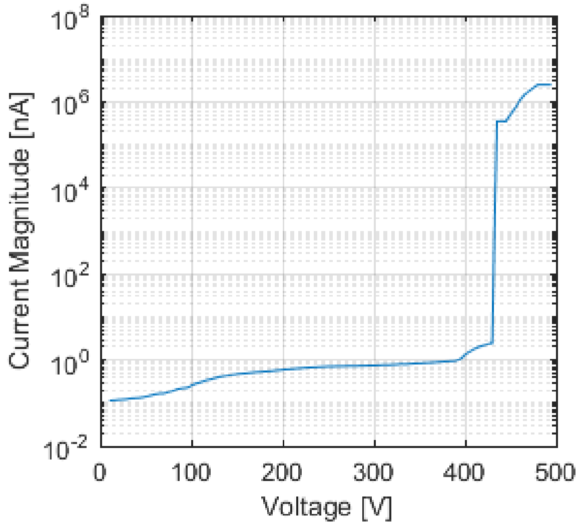
Motivation – "Fix It Or Feature It"

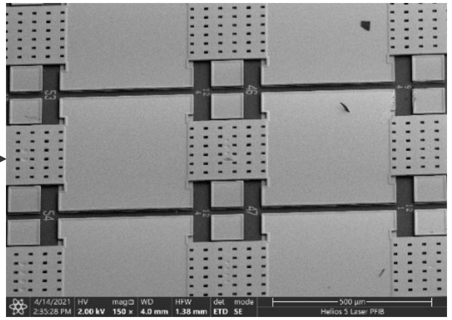
- Encourage Breakdown Where Desired, Mitigate Breakdown When It Isn't
- Narrow gaps and RF frequencies may reduce voltage relative to DC case
  - Synergistic effects could cause lower breakdown





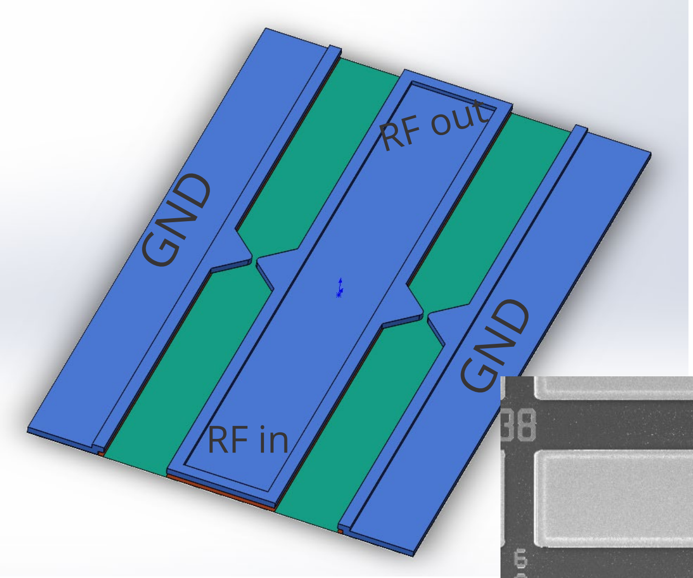
Measurement

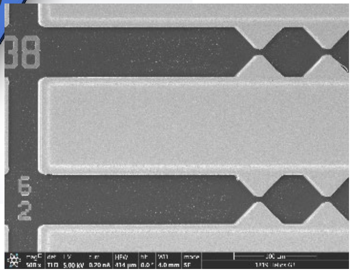




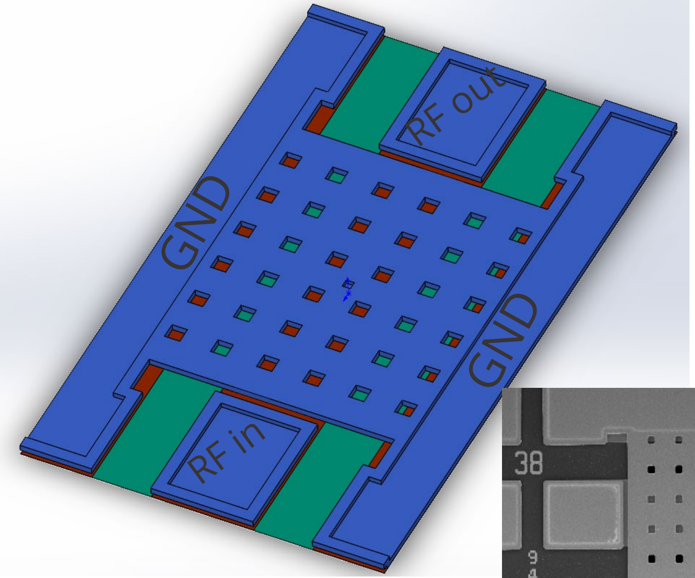
Device Design and Challenges

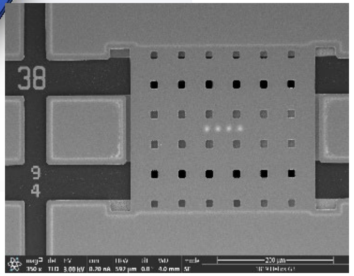
- Challenge: Integrated RF/Narrow gap devices with gaps 0.1 – >20 µm
  - GSG, 50 Ω coplanar waveguide lines, modeled/designed to account for additional capacitance of gaps
  - Horizontal (in-plane) and vertical (out-of-plane) gaps



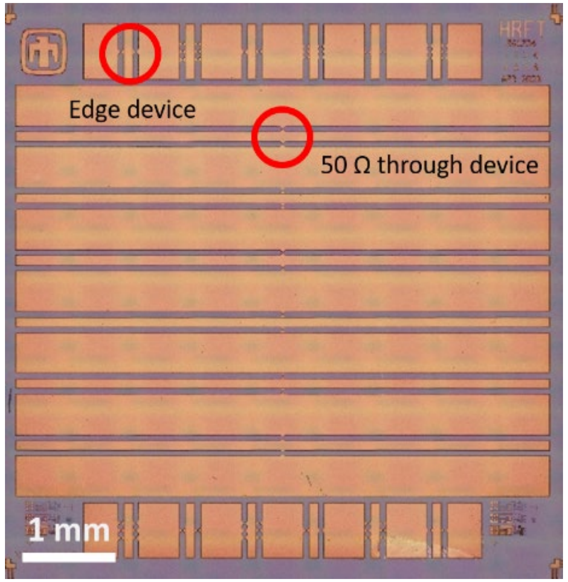


1-24 µm gaps





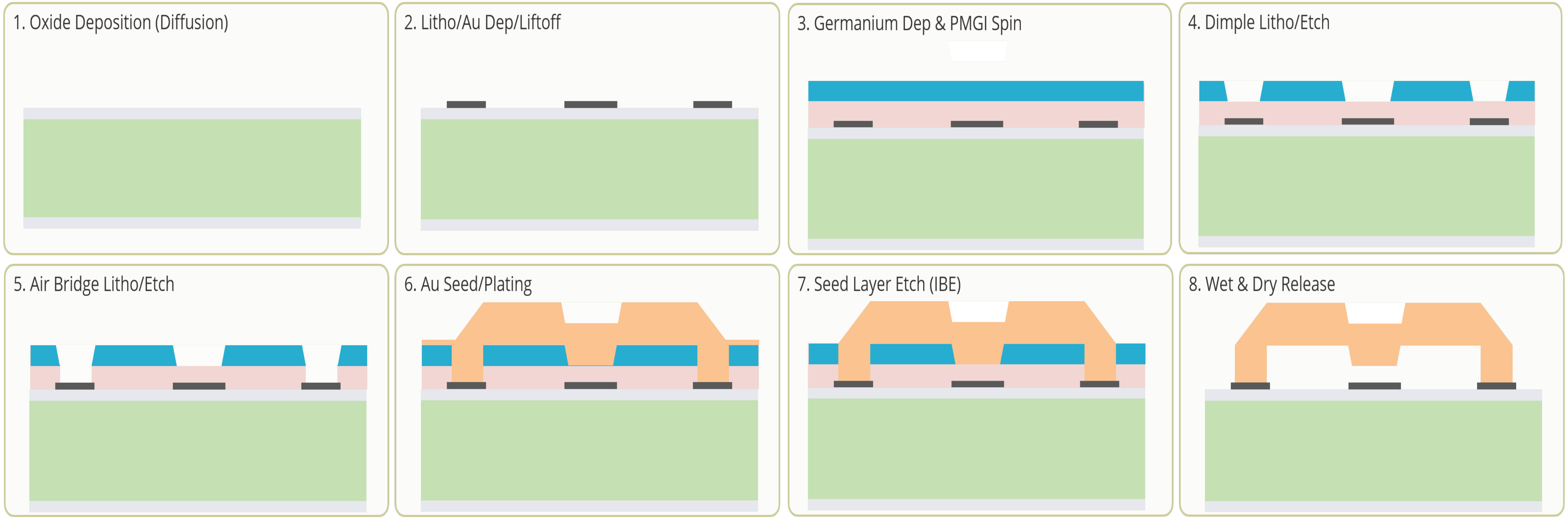
100, 200, 500 nm gaps



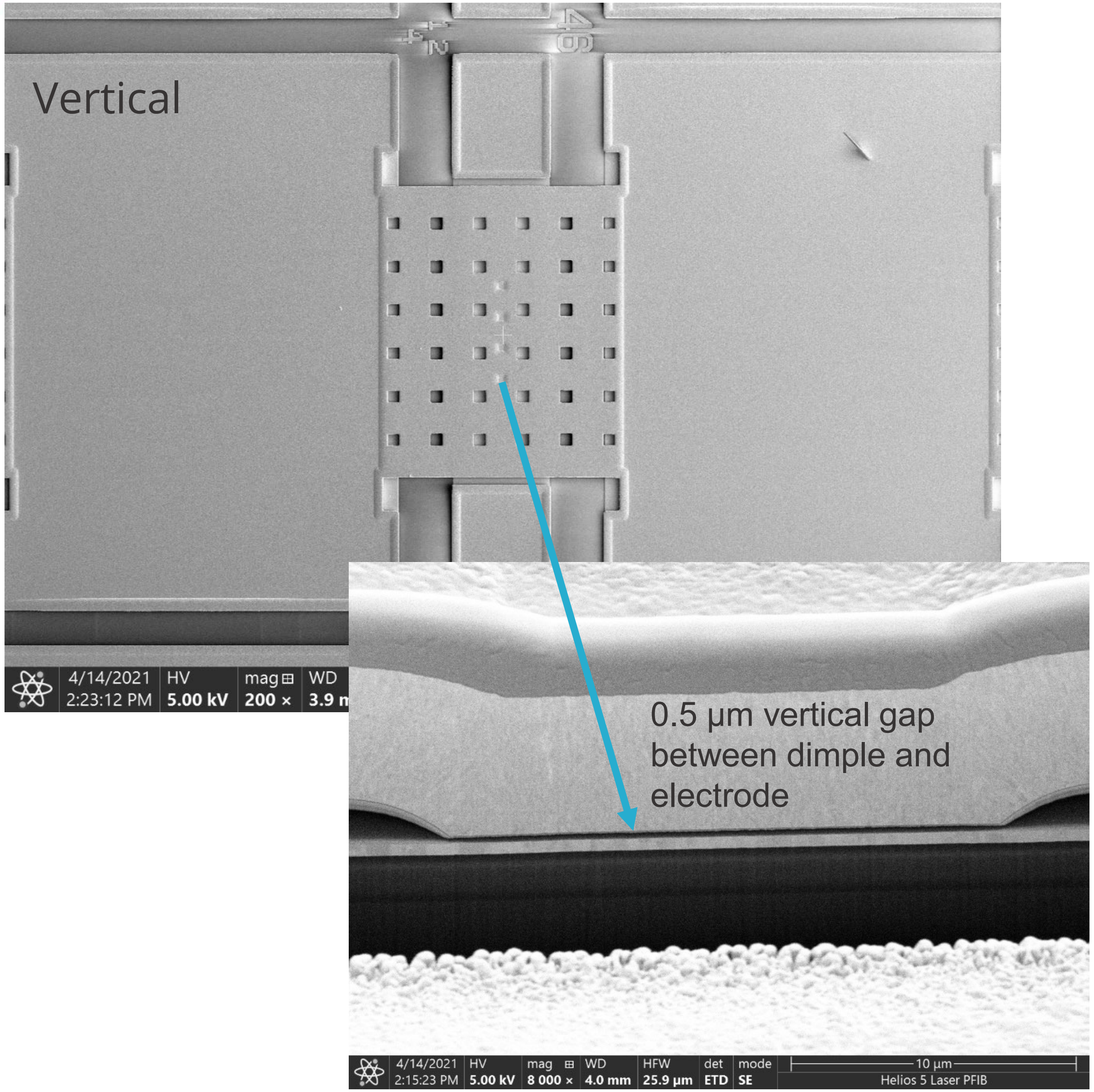
- Other benefits:
  - Microfabricated dimensions for field enhancement investigations
  - Lithographic and fabrication enabled fine control over design-of-experiments

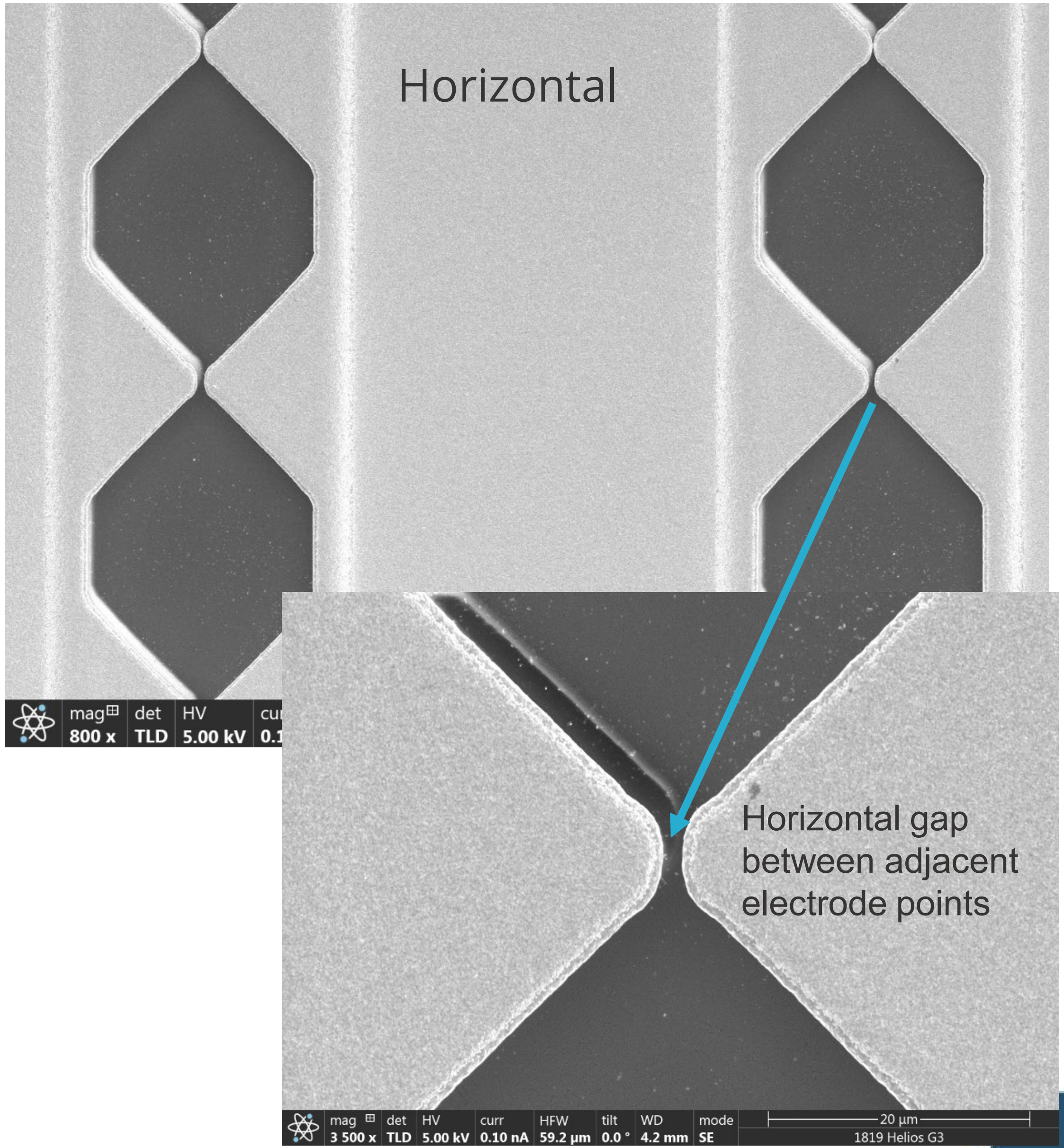
Fabrication – Double Sacrificial Layer

- Vertical and horizontal style devices are co-fabricated using a double release/sacrificial layer process

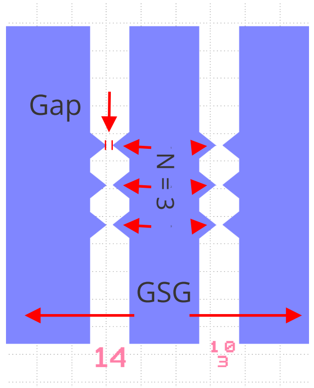


Fabrication – Results

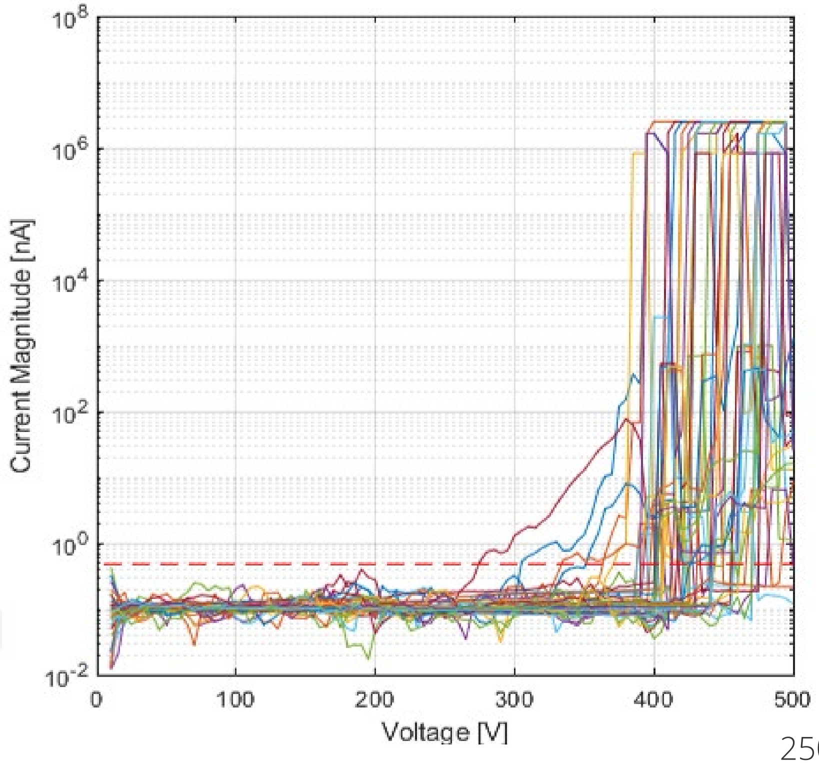




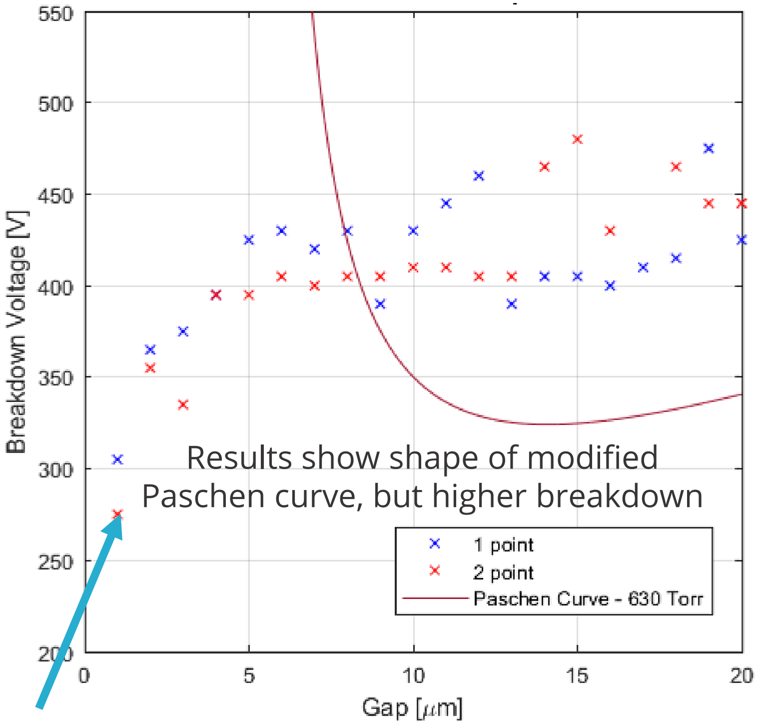
DC Screening Results – Horizontal Devices



- Example data from **horizontal** device die
  - measured using Keithley 6487 Picoammeter & custom python script

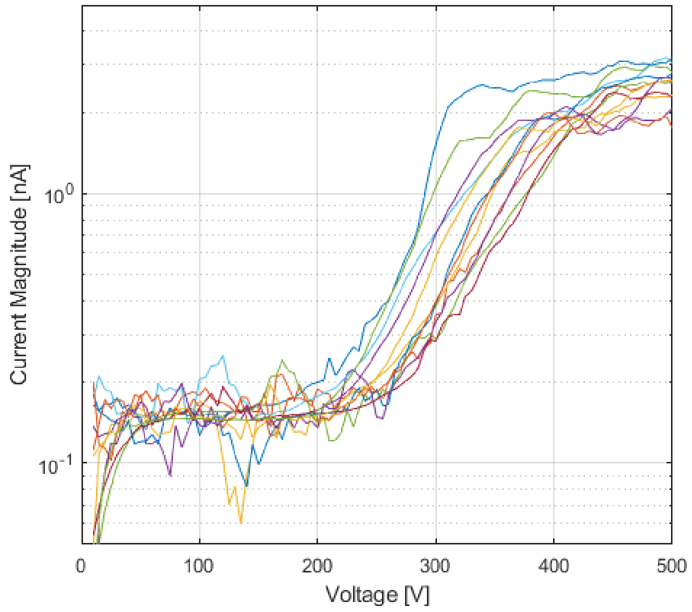


IV curves each correspond to a separate device



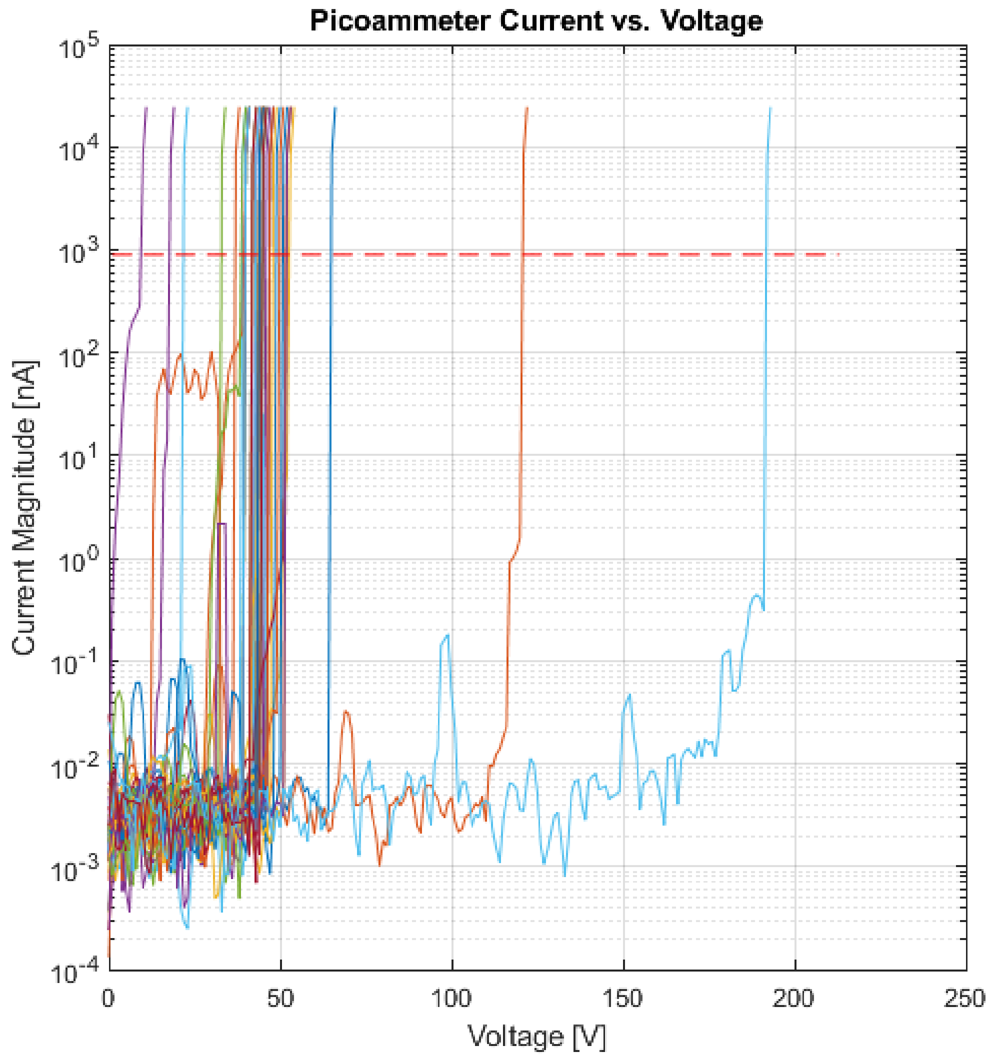
250 V_{peak} is ~625 Watts in 50 Ω

Onset of breakdown vs. plasma gap

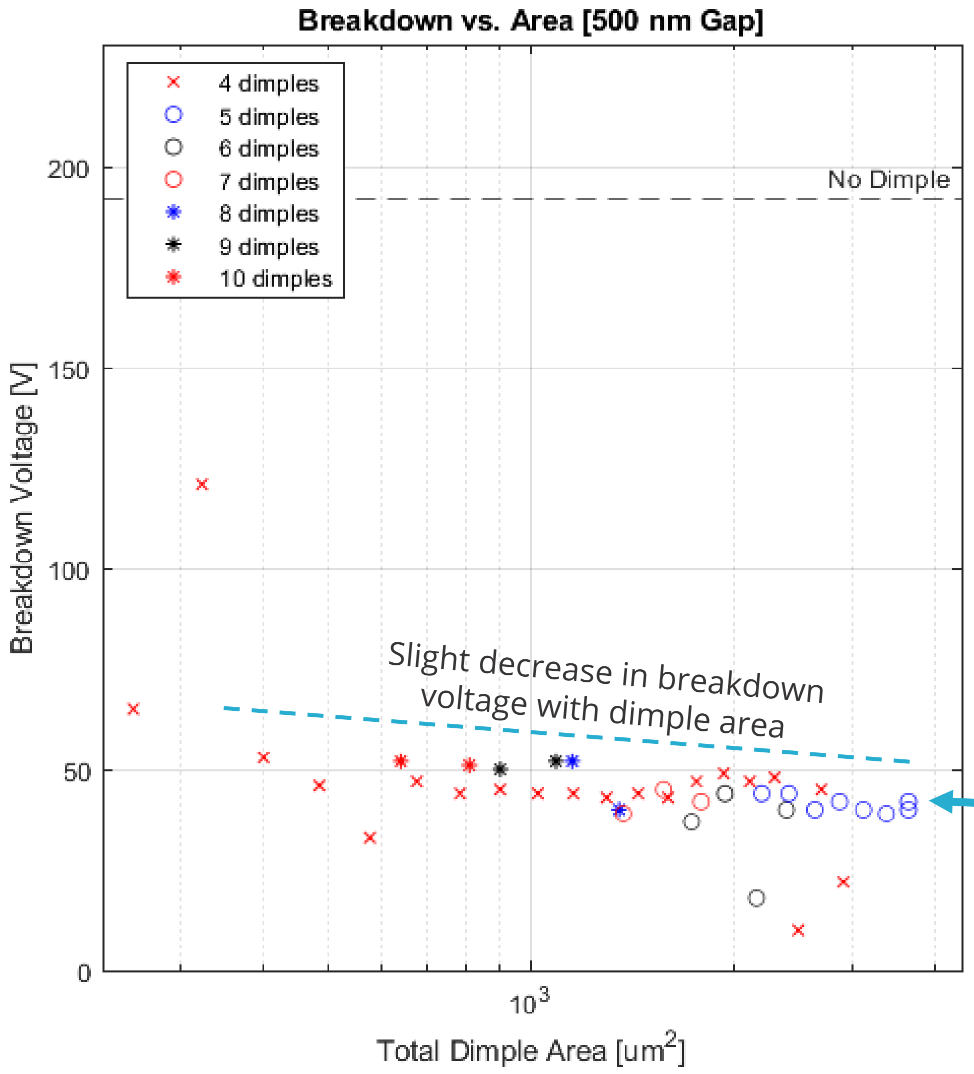


Field emission in vacuum – threshold fields of 15-30 MV/m

DC Screening Results – Vertical Devices



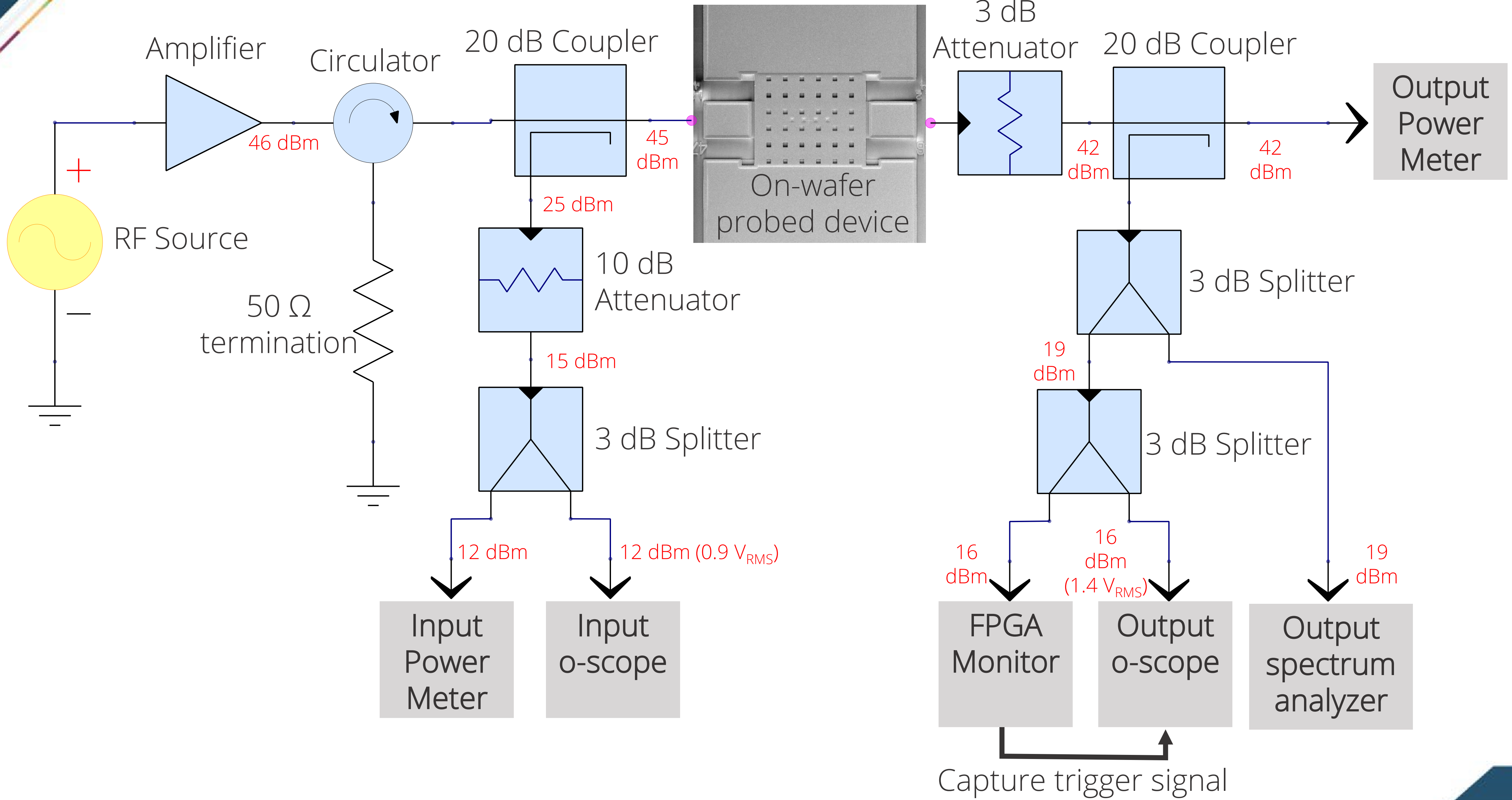
IV curves each correspond to ~60 separate devices on die



40 V_{peak} is ~16 Watts in 50 Ω

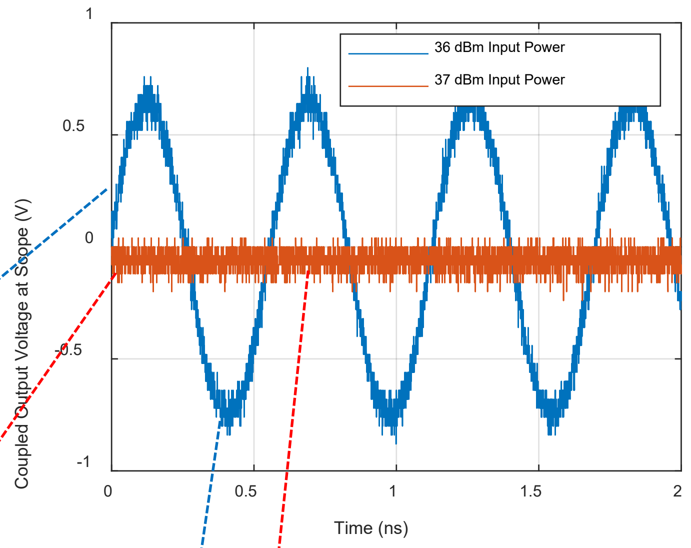
Onset of breakdown vs. dimple area

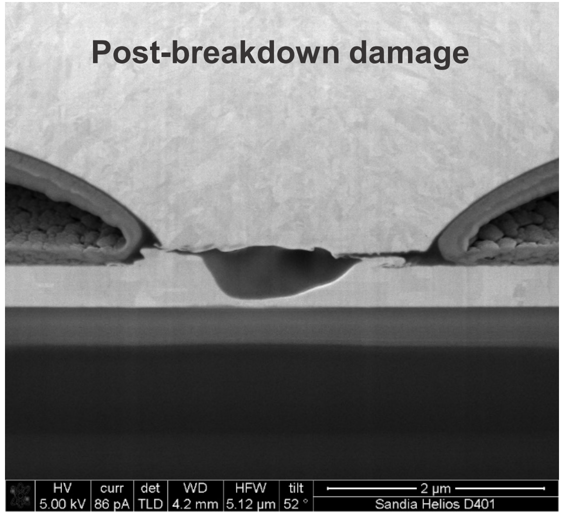
RF Test Setup

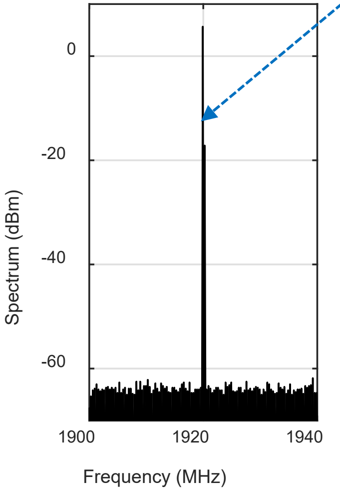


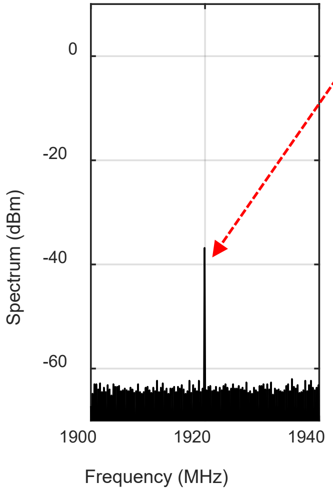
Initial RF Test Results

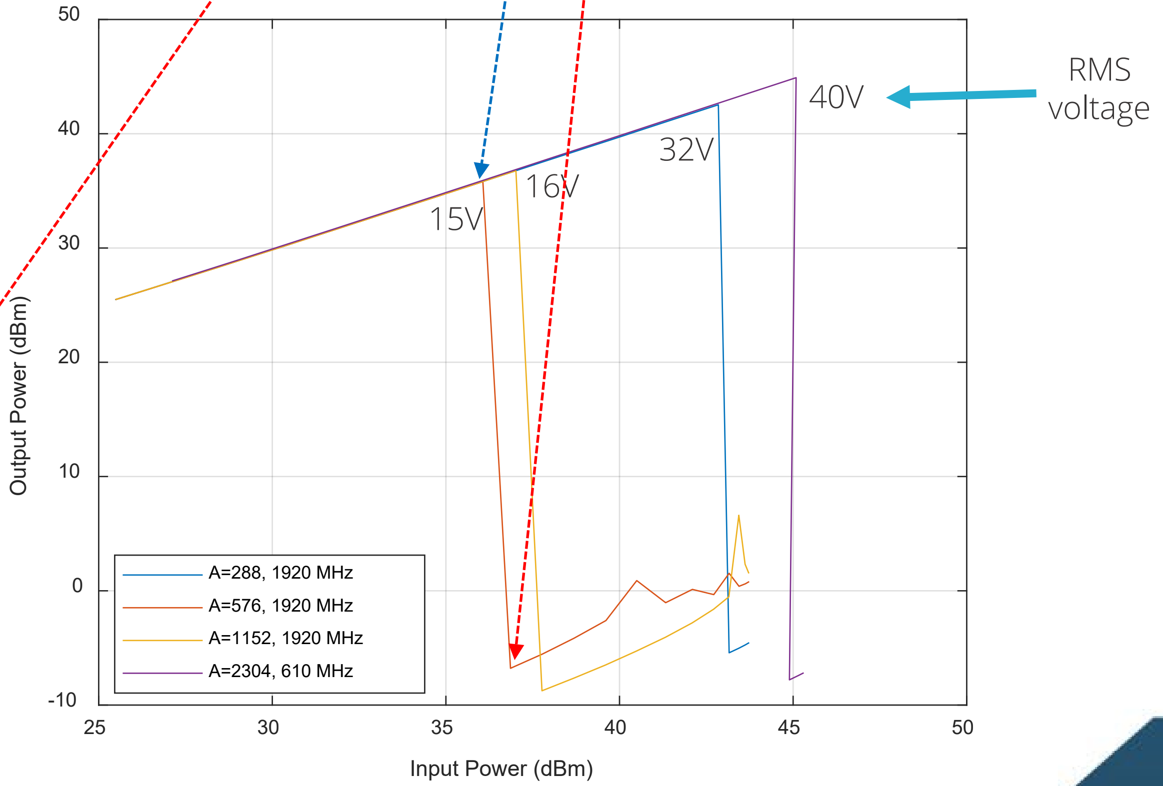
- Initial test results at small range of areas and frequencies.
- Preliminary observations based on limited dataset:
  - Breakdown decreases with increasing area
  - Breakdown decreases with increasing frequency
- Breakdown is permanent in all cases: arcing vs. alpha regime (P & T)
- Plan to repeat experiment with more frequencies and areas.





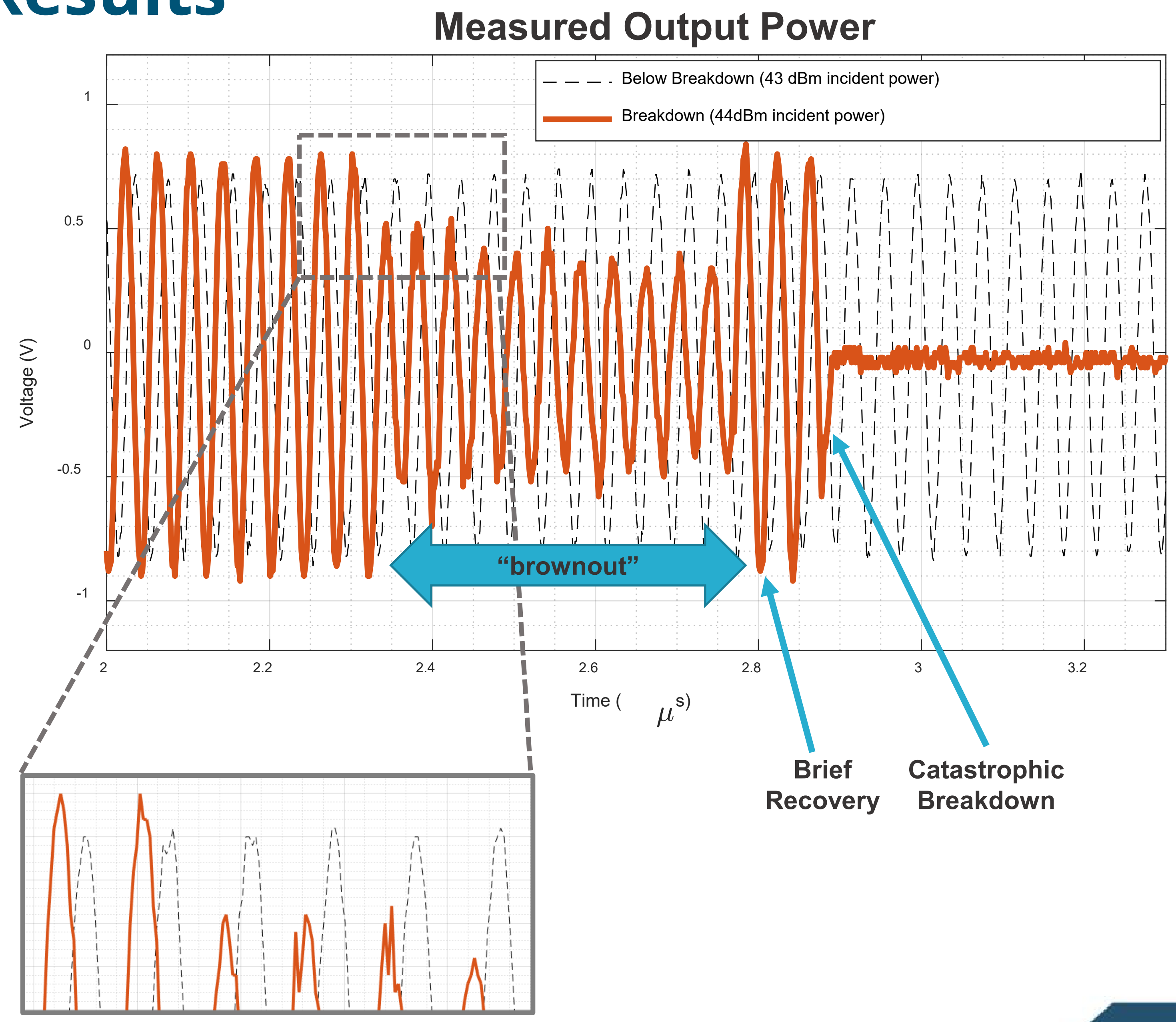






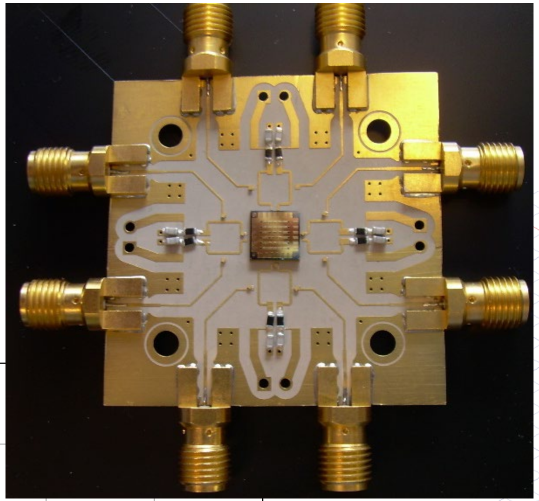
Time Domain RF Results

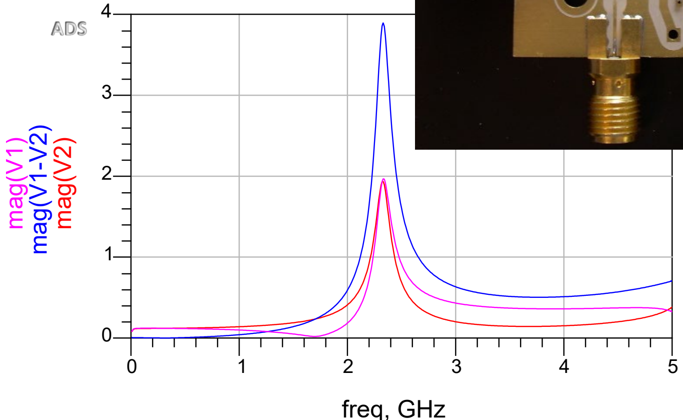
- Use real-time data capture to determine temporal nature of RF breakdown
- FPGA compares device output to a mask, and triggers scope upon deviations
- Scope captures portion of the waveform before and after breakdown
- Observations:
  - Some "brownouts" where power drops by a few dB for a few cycles (~200 nanoseconds)
  - Catastrophic breakdown happens quickly, within a cycle
  - Timescales are consistent with arcing
  - Possibly some additional "arcing" at the waveform peaks when approaching breakdown
  - More work to be done here

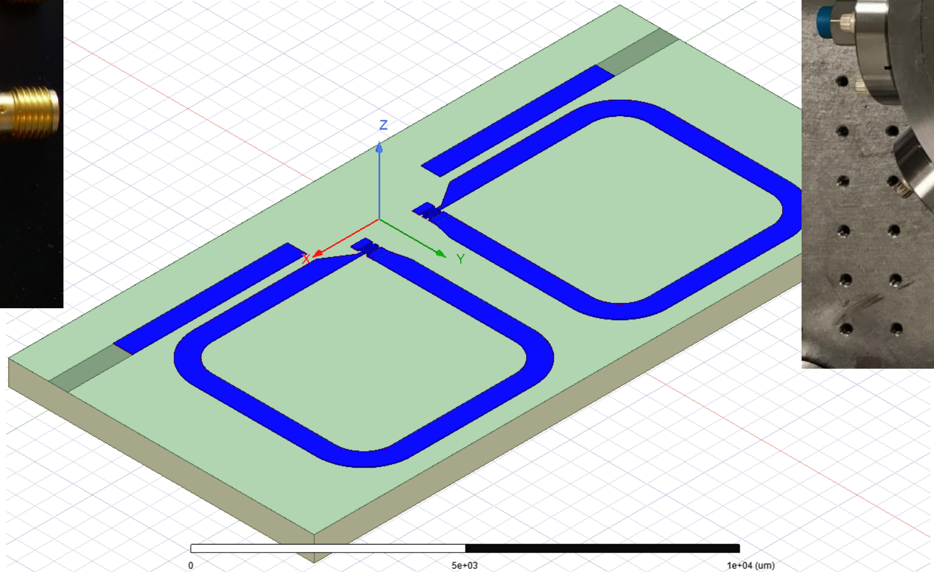


Next Steps

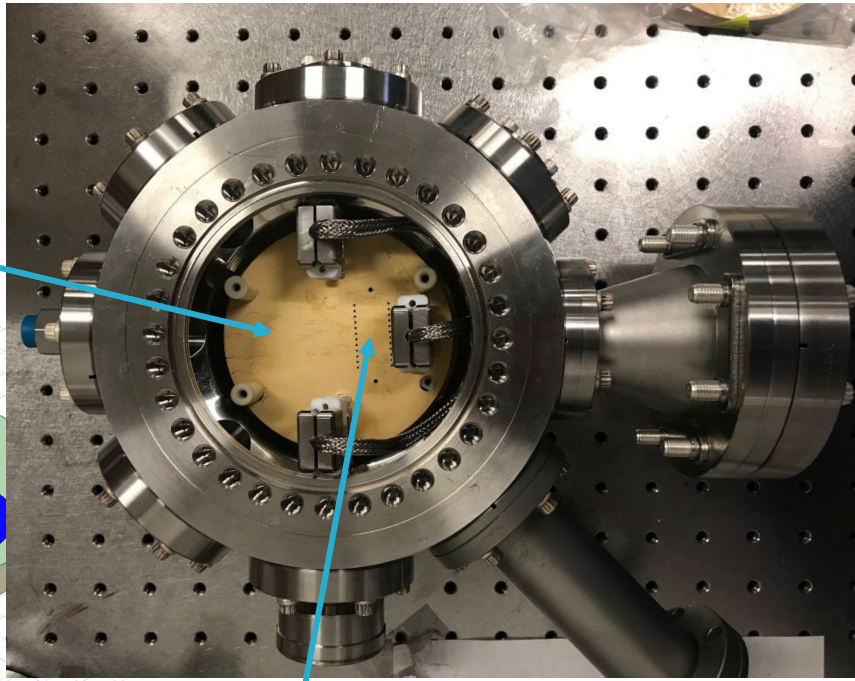
- Additional measurements at varied frequencies and dimple areas in air.
- Correlate modeled and measured results.
- Measurements in vacuum and other environments (move from arcing to alpha regime)
- Integration into resonators, filters, antennas, and other devices.
- Application of results into other technologies and areas.







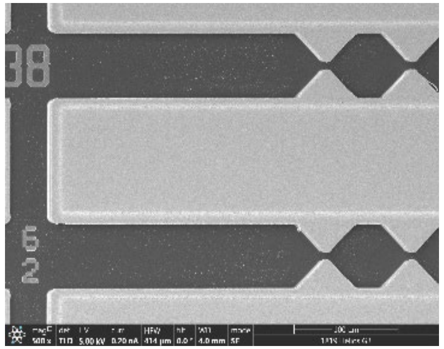
RF daughterboard
(4 DUTs) location

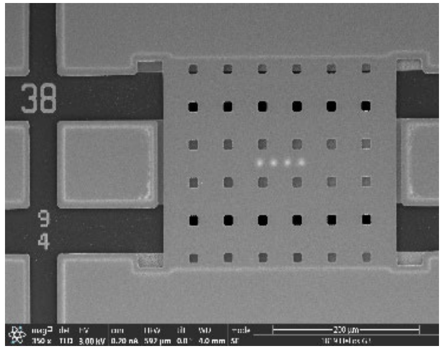


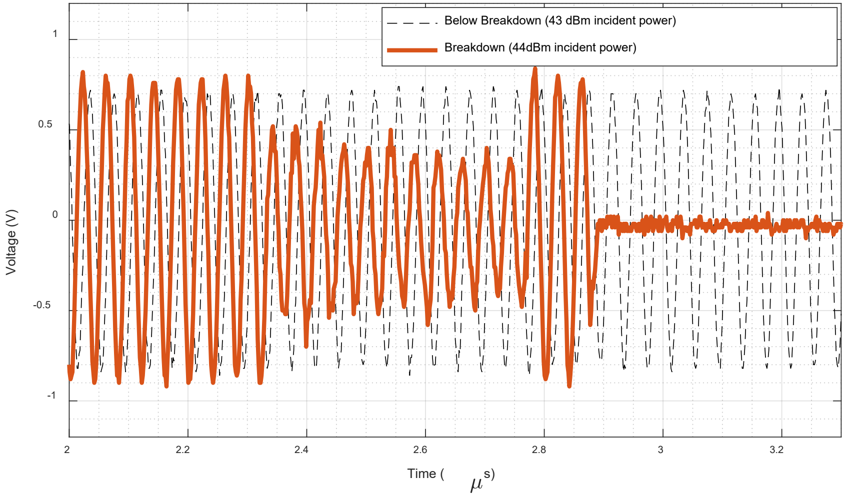
24-pin DIP package
(20 DUTs) goes here

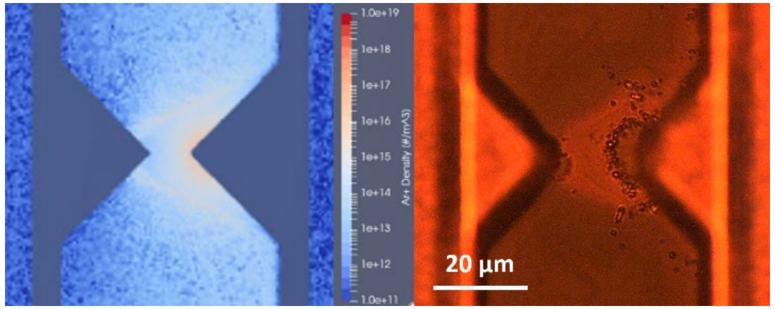
Conclusions

- Making progress towards understanding narrow-gap breakdown at RF frequencies.
- Microfabricated devices use a dual sacrificial layer process to enable a systematic study of breakdown in narrow gaps.
- DC and RF breakdown <50 V observed for 500 nm gaps – field emission instead of avalanche.
- RF digital capture enables time-domain study of the breakdown signatures, and enables capture of dynamic and intermittent effects.
- Simulation complements effort to improve understanding of narrow-gap breakdown physics.
- Obtaining sufficient device current, reliable breakdown, and survivability remain as key challenges for exploiting these effects in real devices – move from arcing to less damaging regimes.









Acknowledgements

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Sandia National Laboratories

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