Paper-based Plasma Sanitizers

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Online Low Temperature Plasma Seminars
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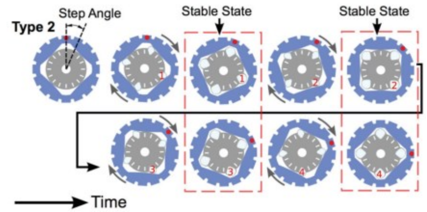
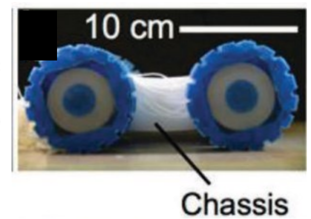
Lab for Machines, Manufacturing, and Mechatronics (Mmm…)

Mazzeo Research Group

Disposable Electronics and Sensors
Soft Robotics
Additive Manufacturing
Structural Health Monitoring



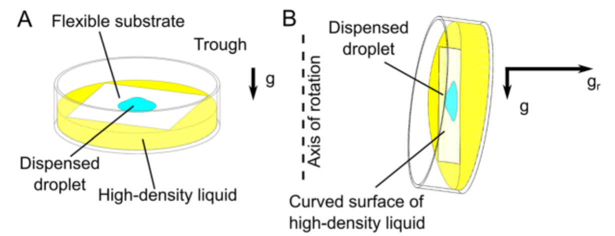


X. Gong. et al., *Adv. Mater.*, 2016.

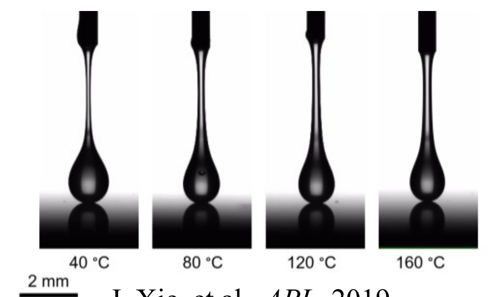
Current Research Activities

- Paper-based skin-like sensing and antimicrobial protection
- Soft, elastomeric structures for electronic, acoustic, hydrodynamic, and aerodynamic coupling
- In-space additive manufacturing of soft and hard materials
- Wireless structural health monitoring for aerospace structures

J. Xie, et al., *Adv. Eng. Mater.*, 2015.

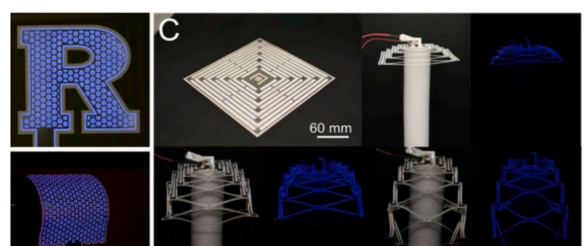


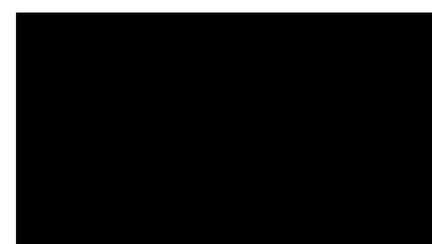
C. Yang, et al., *APL*, 2016.



J. Xie, et al., *APL*, 2019.

X. Zou, et al. *Adv. Elect. Mater.*, 2018.





J. Xie, et al., *PNAS*, 2017.

Paper-based Skin

What is the problem?

- Invent and understand the physics for scalable skin-like sensors.

Significance

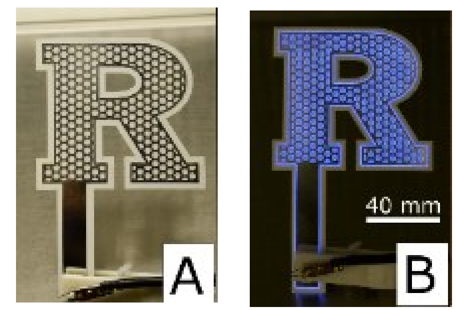
- Overcome the complexity of state-of-the-art, skin-like sensors.
- Large-scale sensors for buildings, vehicles, robotics, and prosthetics

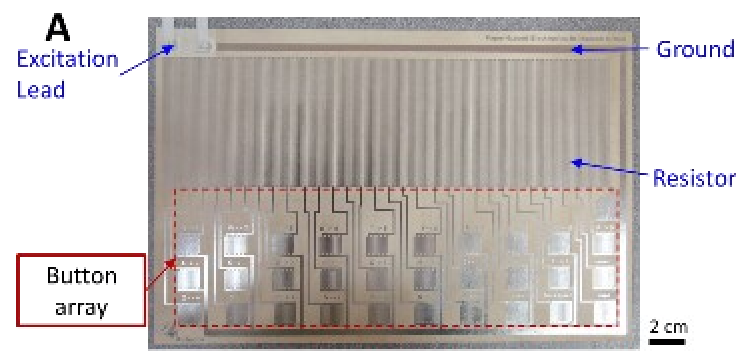
Approach

- Multi-layered devices
- Metallized paper for touch sensors and plasma
- Piezoresistive paper for measuring force

Results

- Ongoing
- Physics and fabrication of separate components





Paper-based Electronics (Papertronics)

Introduction and Description

- "Papertronics" (definition)
  - Paper
    - Multi-scale fibrous material
    - Not just a substrate
  - Electro-chemo-opto-mechanical devices
  - Patterned flow
    - Fluids – heat – light – charges – magnetic fields – forces/stresses

Transformative

- Periodic, tunable morphology
- Understanding, leveraging, and predicting patterned flows
- New processing and manufacturing science (beyond printed electronics)
- Overcome current technical challenges and limits

National Need/Grand Challenge

Topics

What do we expect from skin-like sensing?

- Sensitivity to touch and force
- Spatial mapping
- Flexible substrate
- Stretchable substrate?
  - Skin is elastic to ~10%
  - Yields at 30%
- Scalability
  - Large surfaces
  - Vehicles, buildings, and aerospace structures
  - Interfaces
- Lightweight
- Protection
  - Keeps microbes out
  - Contaminated or sterile environments
- Non-toxic
- Low cost

Flexible and Porous Plasma-based Sanitizers for Antimicrobial Protection

Objective:

- Create a low-cost, flexible, plasma-based device for sanitization
- Understand the relationships between applied high-voltage signals, generated plasma, and effective sanitization
- Establish guidelines for the fabrication of scalable paper-based sanitizers

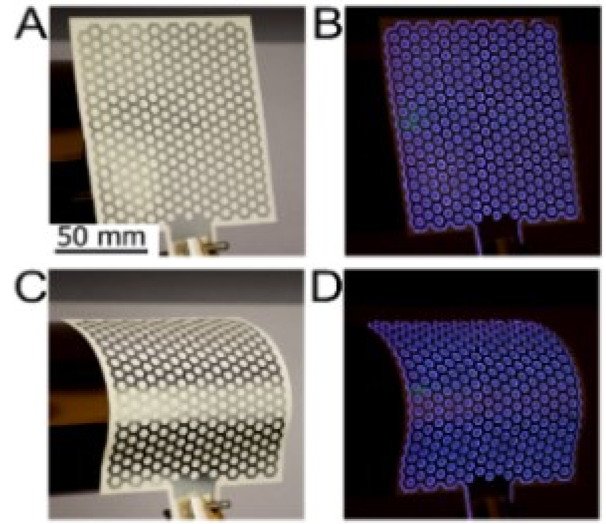
Significance

- Conformity to complex surfaces and objects with crevices
- Reduce infections in contamination-prone areas
- Protective skins for vehicles, humans, and robots
- Future potential for wound healing

Approach

- Laser-based fabrication of metallized paper
- High voltage, low current
- Characterization of deactivation of microbes

Results



J. Xie, Q. Chen, P. Suresh, S. Roy, J. F. White, and A. D. Mazzeo., *PNAS*, 2017.

Broad Impacts of Paper-like Plasma Sanitizers

- What are unmet needs addressed by bendable, paper/fabric-like devices that generate cold plasma?
  - Flexible and conformable to irregularly shaped surfaces
    - Packaged medical instruments (pouches)
    - Handheld electronics (pouches)
    - Food (in-package plasma)
    - Body parts and skin (bandages)
  - At-home care and cleaning
    - Wound healing (low-dose but frequent)
    - Cleaning of surfaces (robotic attachments)
    - Liquid- and refill-free cleaning (bags)
    - Porous substrates and filters (UV-blocked)
- Caution (see Plazlyte/AbTox)

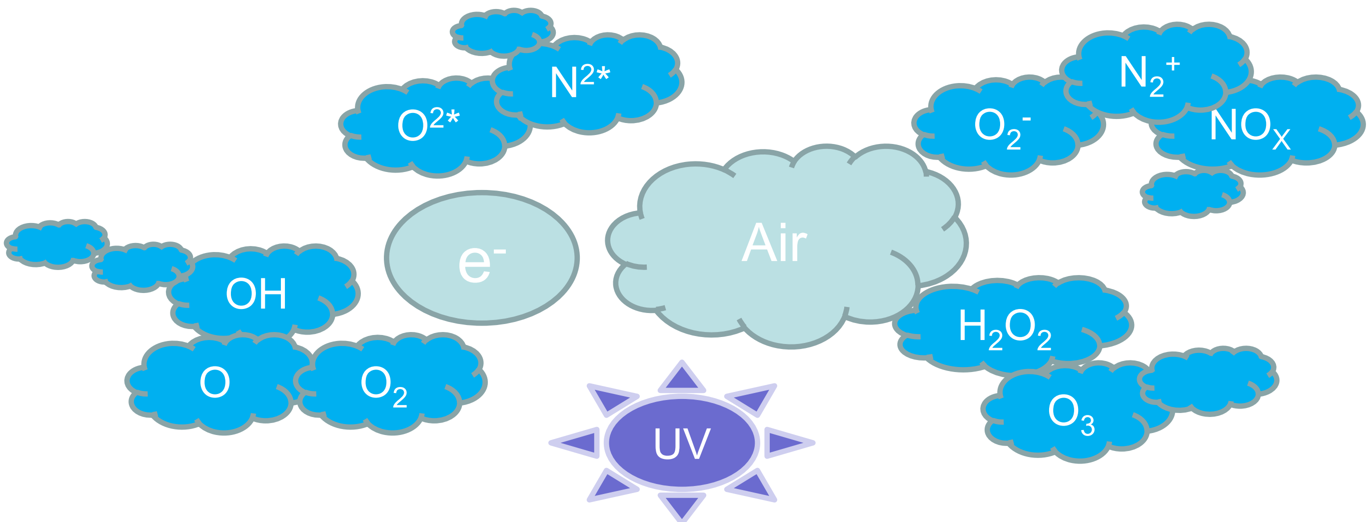
T. Maisch, … G. Morfill, and J. L. Zimmermann, *PLoS One*, 2012.

NY Times., 2010.

PlasmaDerm Flex

Plasma-based Inactivation of Microbes

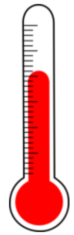
- Plasma
  - Ionized gas
  - a quasi-neutral collection of electrons, positive ions, and neutrals capable of collective behavior



- Inactivation of microbes through multiple mechanisms (synergistically)
  - Free radicals with oxidation
  - Electron ionization/bombardment (more prevalent in vacuum)
  - Hydrodynamic ablation
  - UV radiative effects

Background

- Sterilization: more rigorous than disinfection, sanitization
- Limitations of conventional sterilization technology



Permanent damage and alter material properties
High pressures: 103 kPa; high temperatures: 120-140 °C
Exposure time ~ 30 minutes

EtO, Glutaraldehyde, formaldehyde, Peracetic acid
Damage fiber optics, electronics
Introduce toxicity

Gamma radiation, X-Rays
Needs well-trained personnel to handle
Costly

The “Start”

300 Hz- 4 kHz, 5 kV
Helium (1 atm)
10-minute discharge
Inactivation of ~10^5
Pseudomanas fluorescens

Multijet plasma generator
Pulsed RF discharge in air
20 msec for sterilization and deodorization

P. Koulik, S. Begounov, and S. Goloviatinskii, *Plasma chemistry and plasma processing,* 1999.

M. Laroussi, *IEEE Transactions on Plasma Science* (1996)

Sources of Plasma for Deactivation of Microbes

HV

Plasma jet

Gas

Plasma jet

Inductively Coupled Plasma (ICP)
(Kylian, 2006)

Atmospheric Pressure Plasma Jet (APPJ)
(Cheng et al., 2005)

Dielectric Barrier Discharge
(Tanino et al., 2007)

Microwave-induced Argon Plasma
(Park et al., 2003)

Cold Plasma Sterilization

Atmospheric DBD

Rapid
Deactivation of
Bacillus Spores

M. Laroussi and F. Leipold. *Int. J. of Mass Spec.*, 2004.

Floating electrode DBD

sterilization of living tissue with *Staphylococcus*, *Streptococcus*, and yeast: 6 log reduction in 5s

G. Fridman, et al. *Plasma processes and polymers, 2008.*

Plasma-activated water

Inactivation of *E. Aerogenes*

I. Joshi, D. Salvi, D. W. Schaffner, M. V. Karwe. *J. of food protection, 2018*

Cold Plasma Sterilization

1kHz,10kV$_{pp}$

Atmospheric DBD to reduce HAI

30 s treatment

Atmospheric DBD on different surfaces

G.Stearothermophilus spores

T. G. Klämpfl, et al. *Appl. Environ. Microbiol.*, 2012

Wound Healing

Tumour Ablation by Cold Plasma Jet

PlasmaDerm® VU-175 2010

Before

After

Bernhardt, Thoralf, et al. *Oxidative medicine and cellular longevity* (2019).

Keidar, M., et al. *British journal of cancer* (2011)

Flexible Plasma Generator-Background

Tracing paper with well-dispersed single-walled carbon nanotubes (CNT) or an LBL-assembled $(CNT/PVA)_{30}$ film on a 5-m parylene

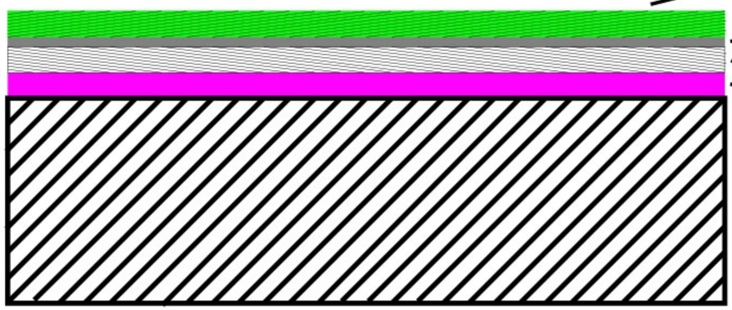
Scale bar -1 cm

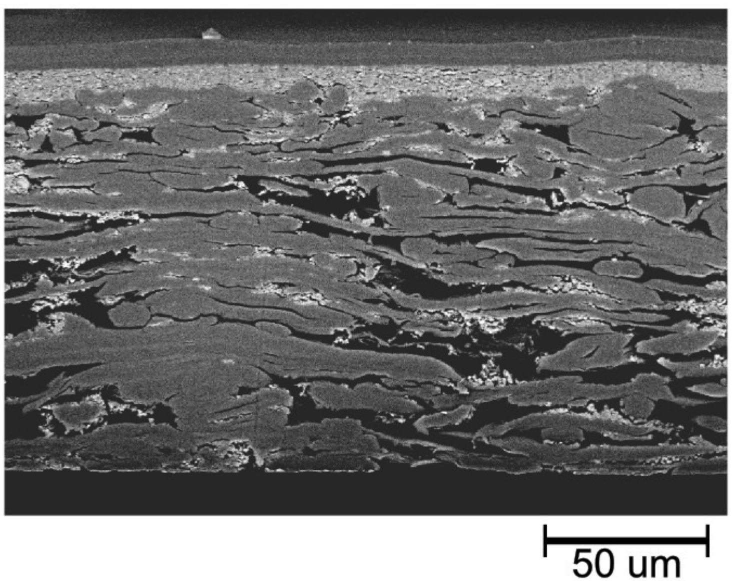
25% strain in Argon filled glass tube

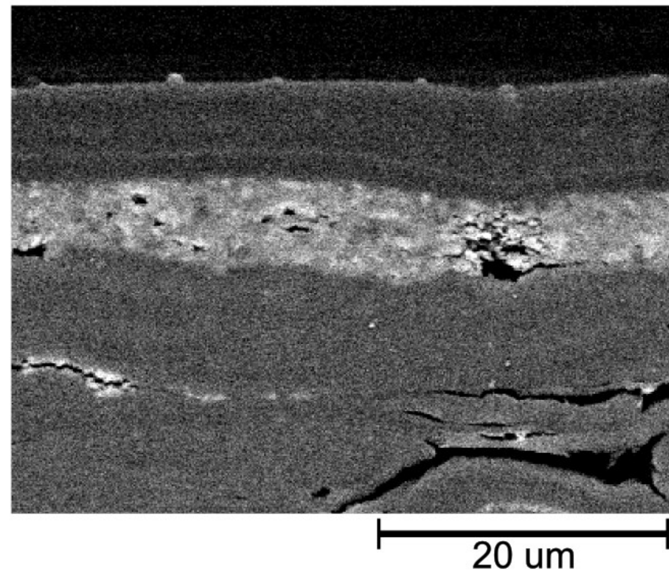
Scale bar -1 cm

Shyu, Terry C., et al. *Nature materials,* 2015.

Metallized Paper







- Simplicity
- Roll-to-roll processing
- Low-cost

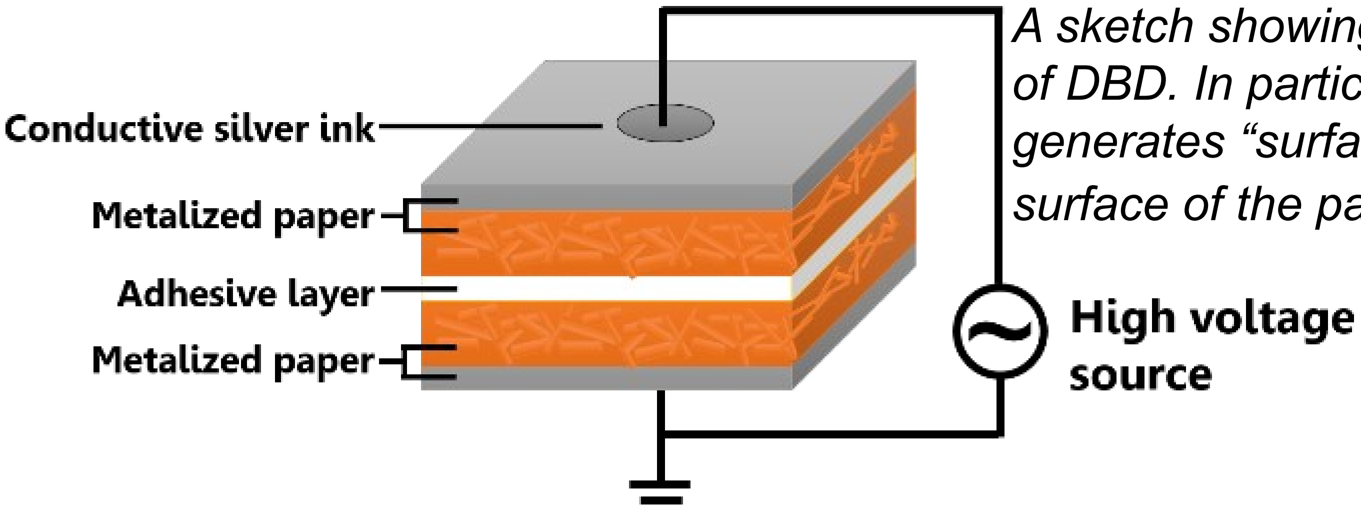
A. D. Mazzeo, et al. *Advanced Materials*, 2012.

Alarmed Box

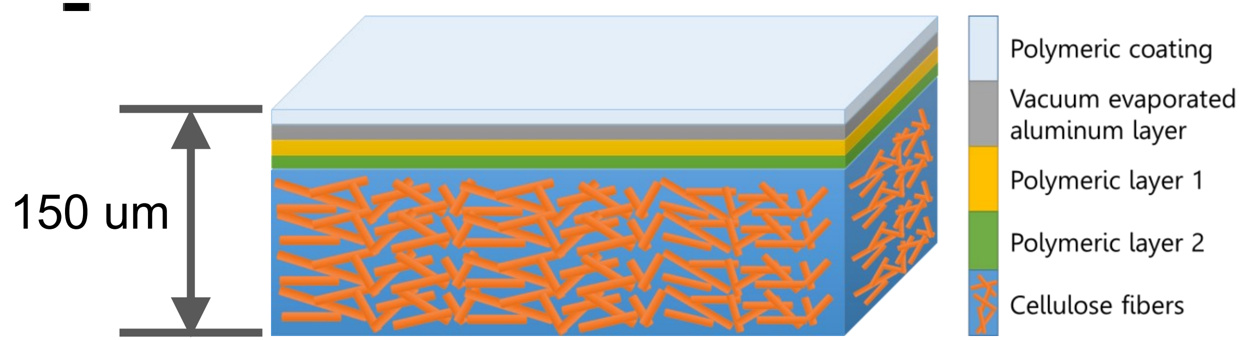
A. D. Mazzeo, et al. *Advanced Materials*, 2012.

Dielectric Barrier Discharge (DBD)

- AC voltage (1kV~100kV, >1 kHz), atmospheric pressure, room temperature
- Dielectric layers allow for plasma discharge to reach material surface

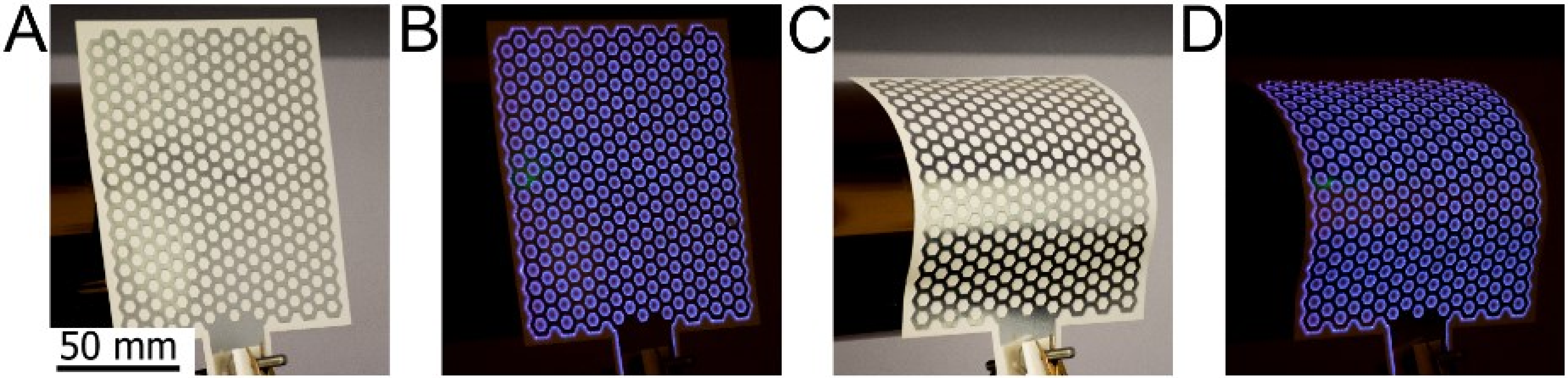


A sketch showing the working principle of DBD. In particular, this configuration generates "surface plasma" on the surface of the paper.



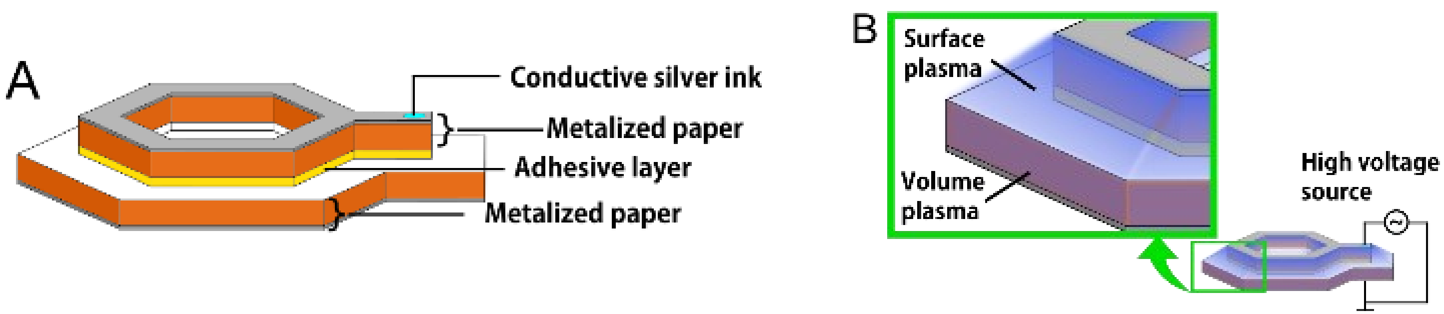
The structure of the metalized paper for making the flexible plasma sterilizer.

Functionality and Flexibility

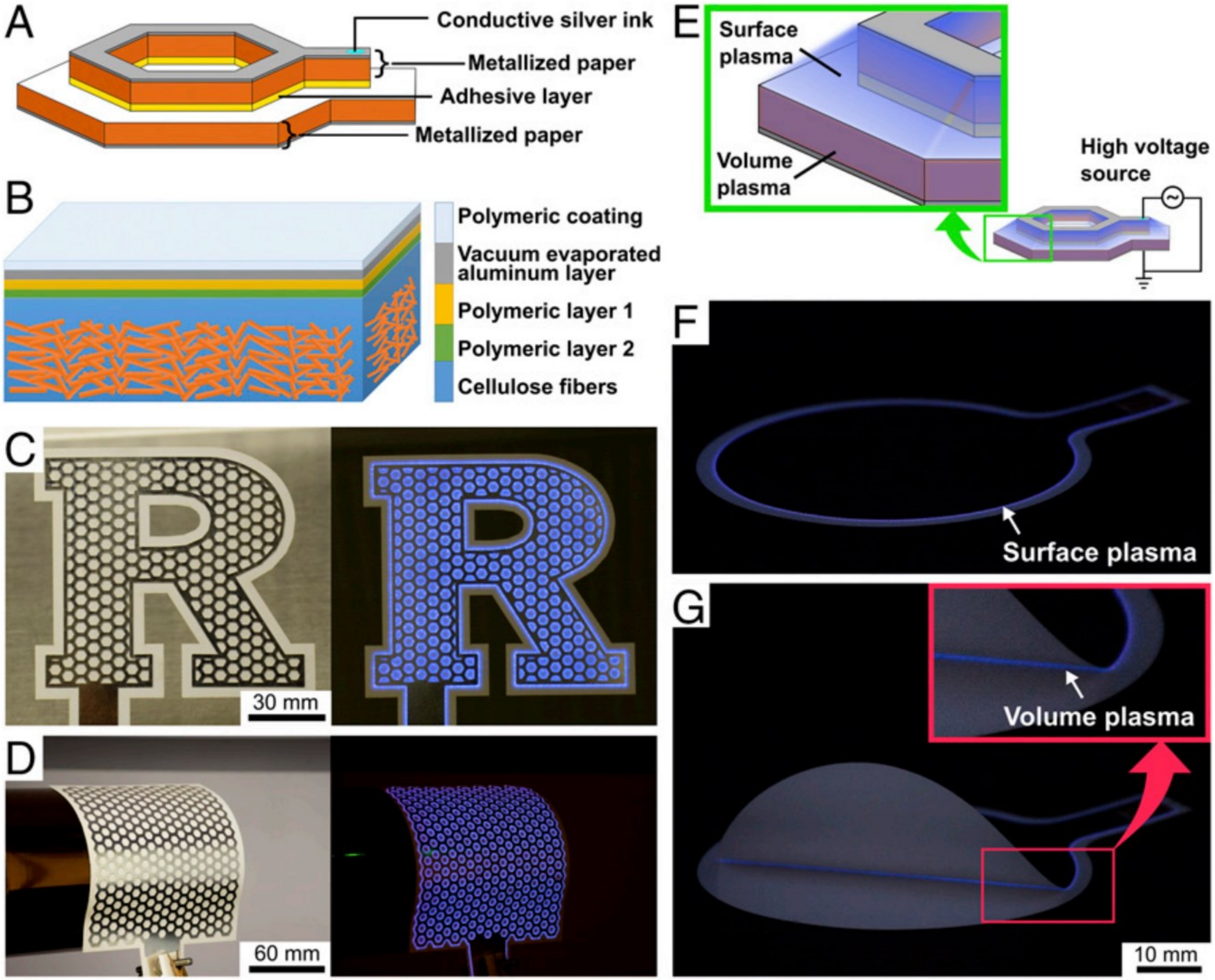


A flexible plasma generator made from etched metallized paper in straight and bent states. The plasma glows with the application of high voltage.

Paper-based device: Volume plasma and surface plasma



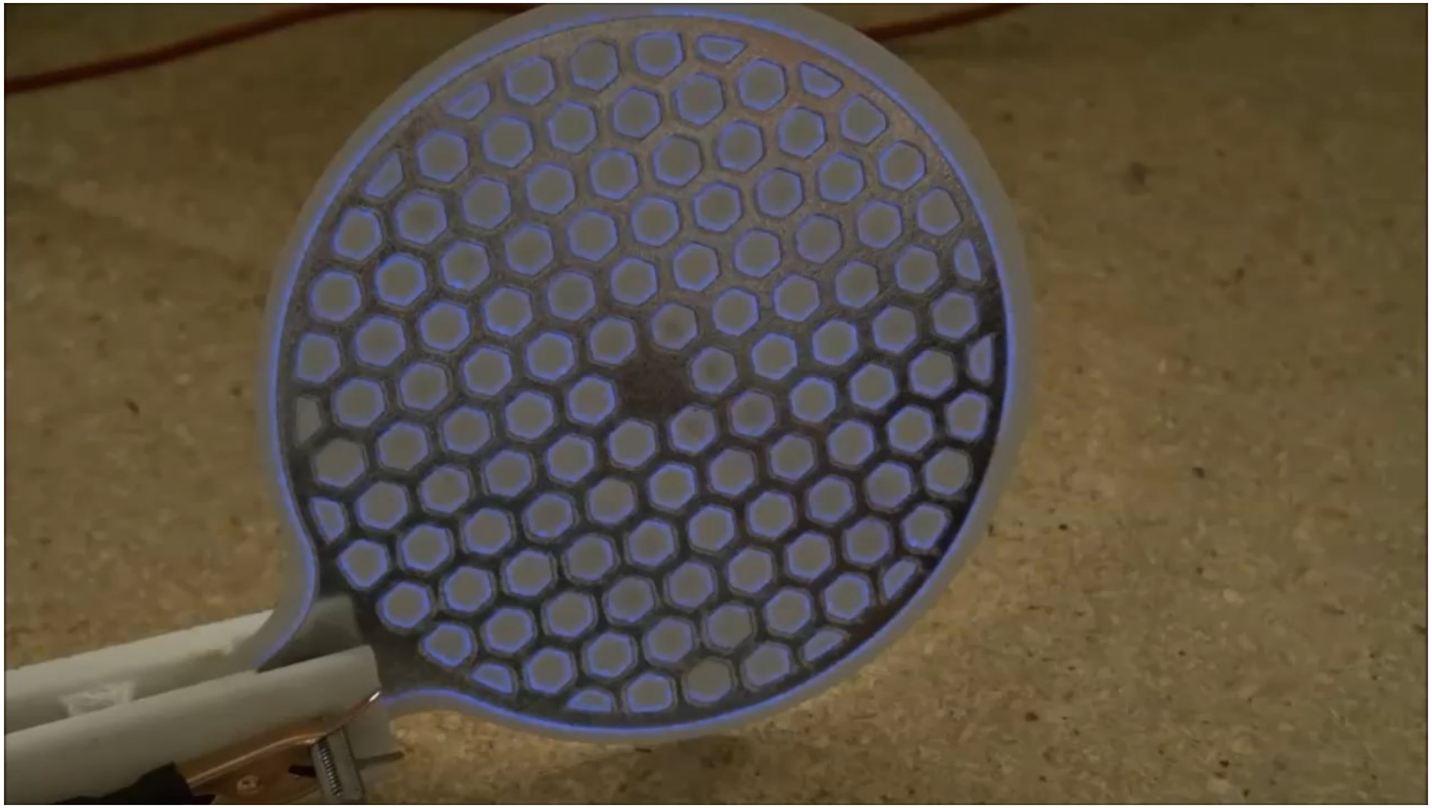
RUTGERS



J. Xie et al., *PNAS*, 2017.

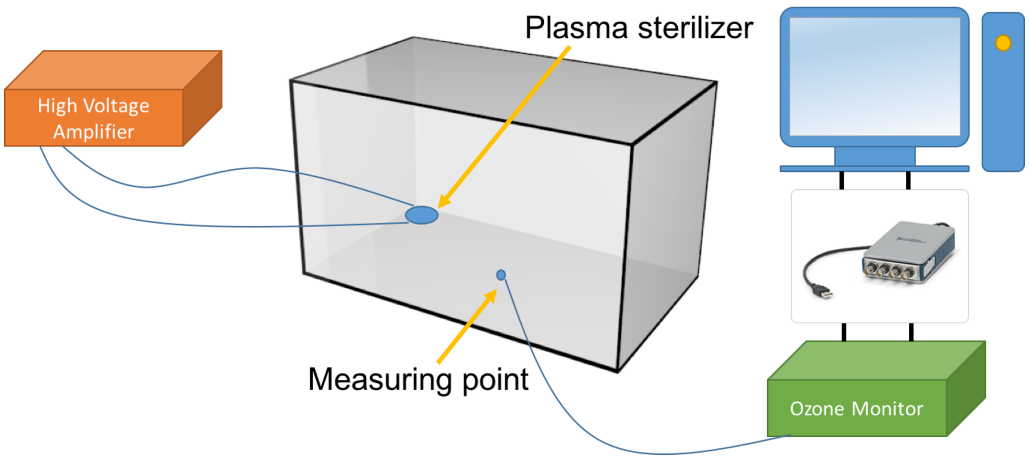
Plasma Generation as a Function of Applied Frequency

- A demonstration of a two-layer configuration:

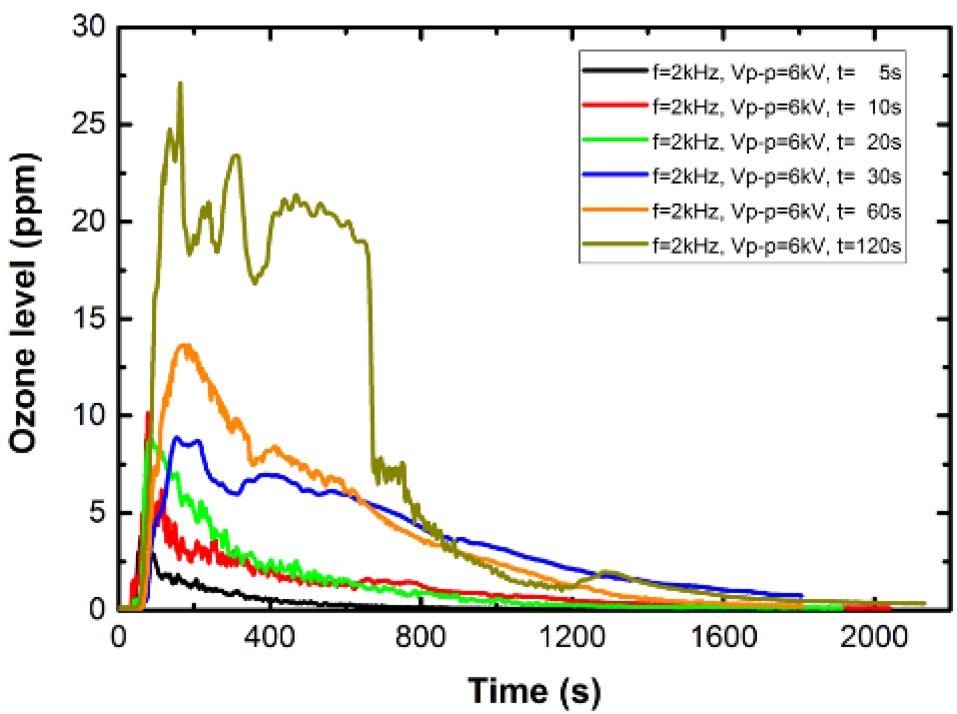


Frequency: 2kHz -10 kHz

Characterization of Ozone Generated

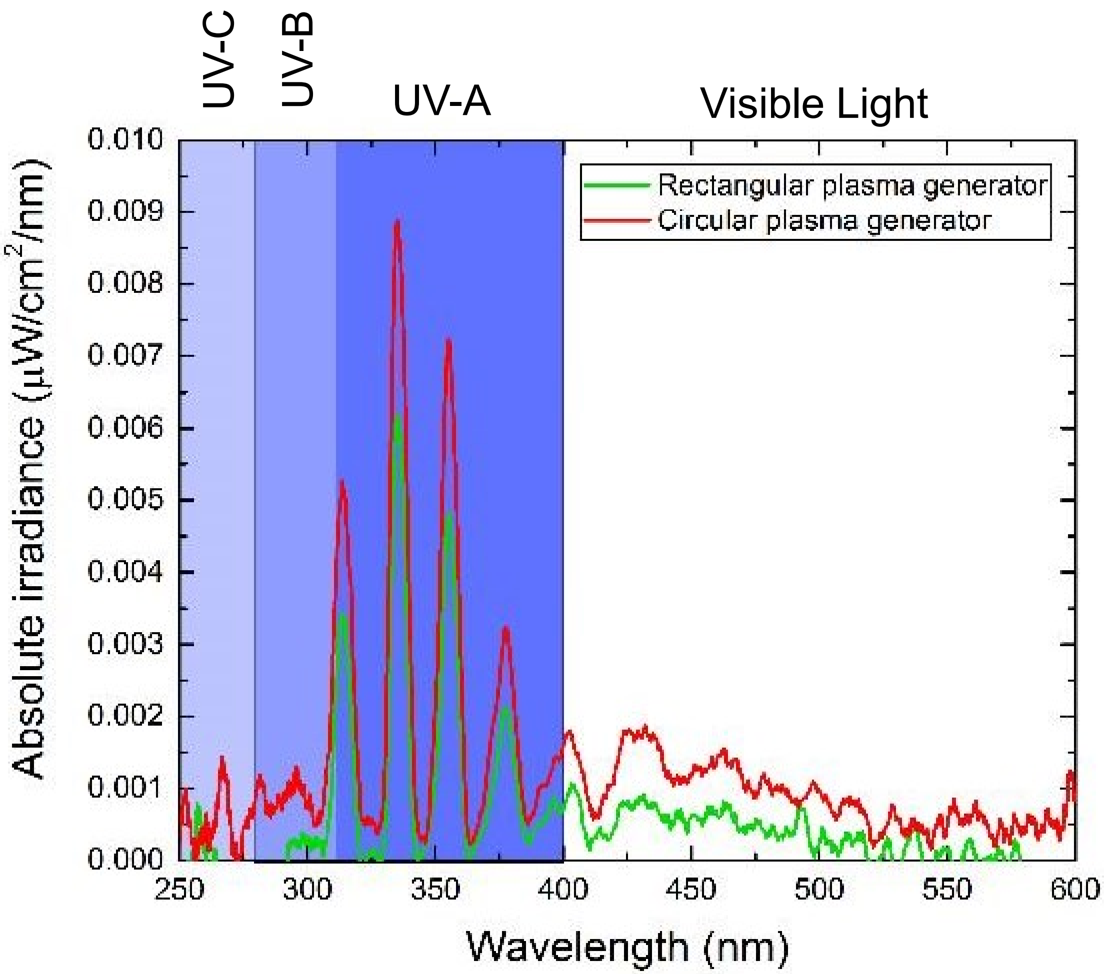


Time-of-activation [s]	Peak ozone level [ppm]
5	5.6
10	7.2
20	9.8
30	9.0
60	13.5
120	27.3

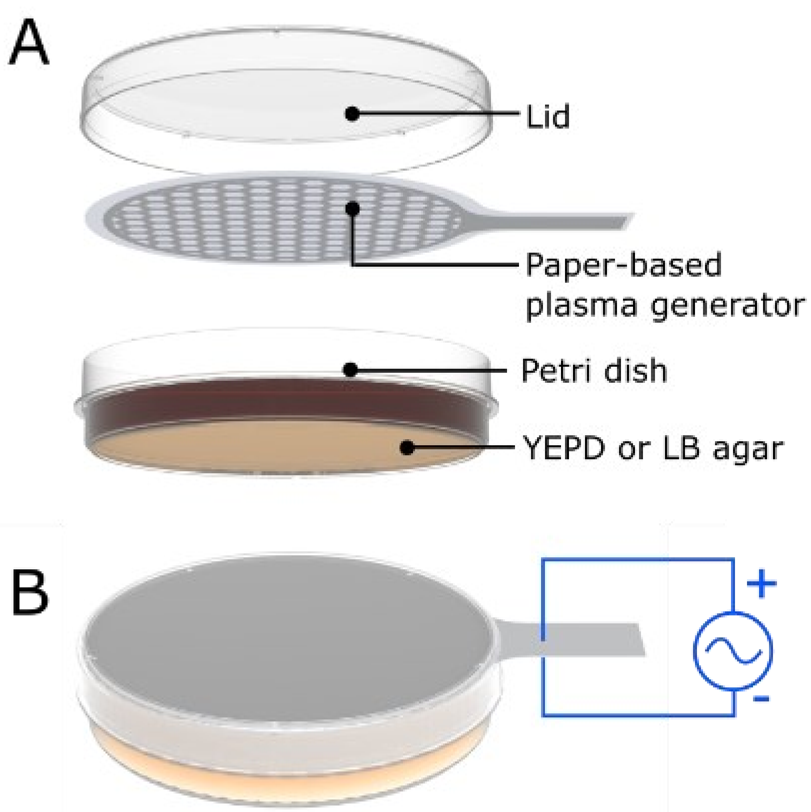


Characterization of Generated UV Radiation

- UV Radiation Generated from Plasma Generators
- Visible Spectrum
  - 400 nm to 700 nm
- UV-A
  - 315 nm to 400 nm
- UV-B
  - 280 nm to 315 nm
- UV-C
  - 100 nm to 280 nm
  - Shown to be of relevance for disinfection

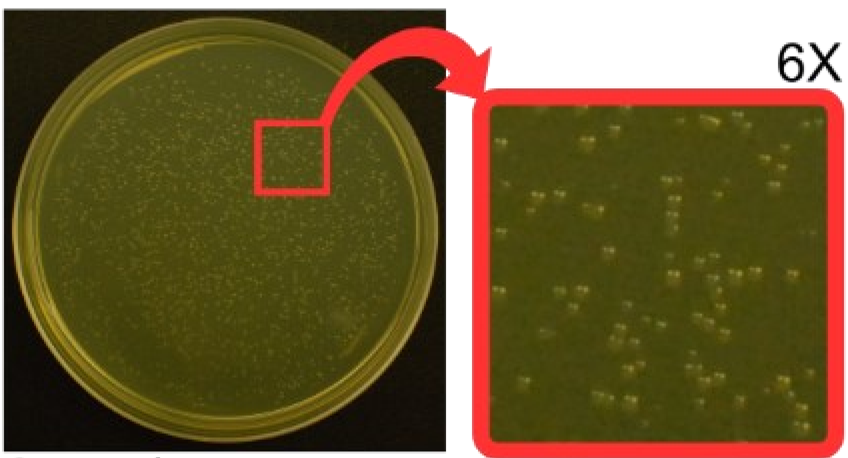


Non-contact Experiment

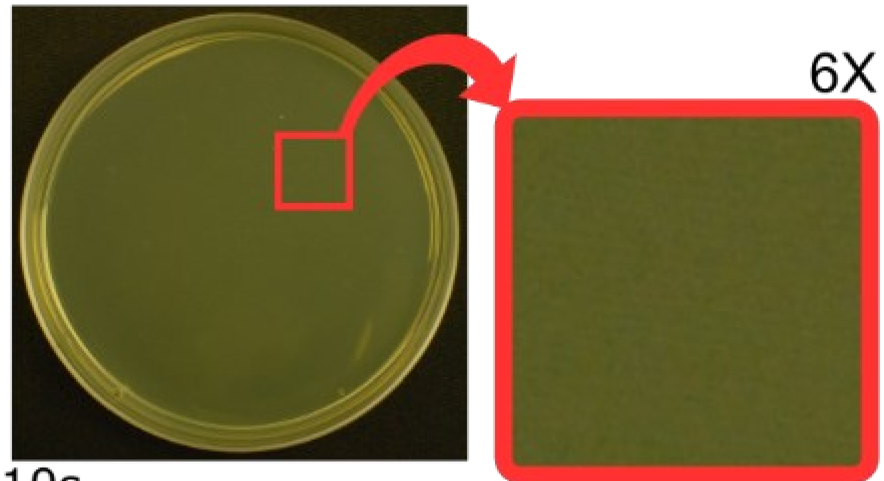


- Test target:
  - *Saccharomyces cerevisiae (Yeast) (3.6×10^4 unit/mL)*
  - *Escherichia coli (E.coli) (3.5×10^4 unit/mL)*
- Medium
  - Yeast extract peptone dextrose (YEPD)
  - Lysogeny broth (LB)
- Power supply:
  - Frequency: 2 kHz
  - Voltage: Vpp = 6.3 kV

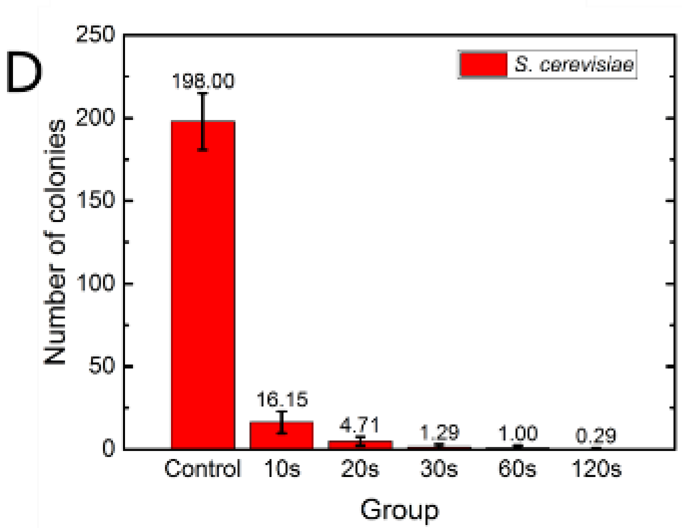
Non-contact Experiments

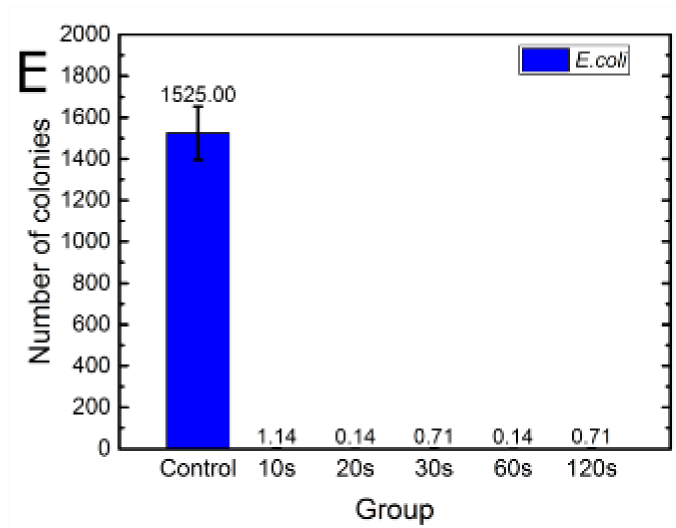


Control



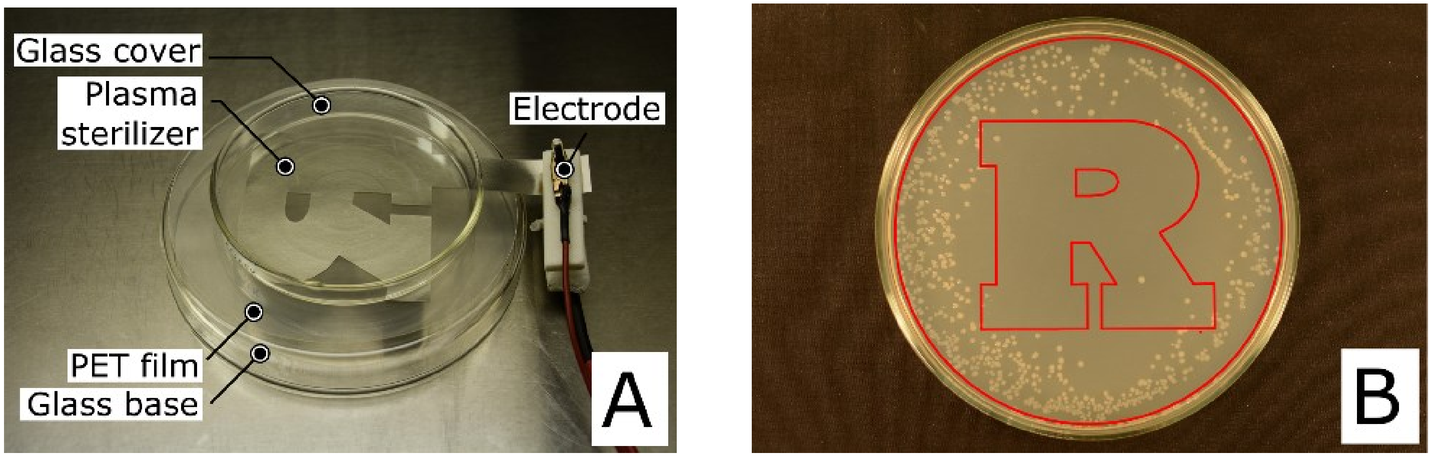
10s





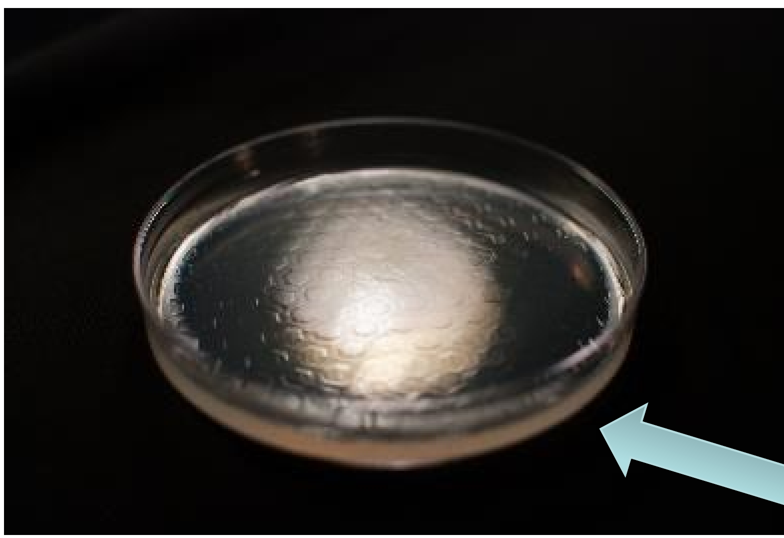
- 99% of *Saccharomyces cerevisiae* were deactivated after 30s.

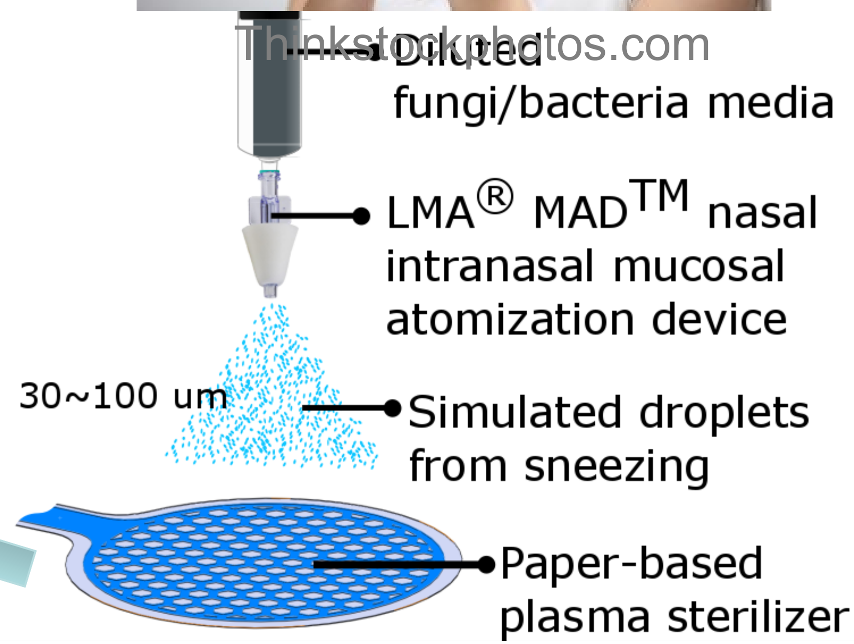
Patterning Plasma?



Direct-contact Experiment

- One sneeze:
  - droplets of saliva
  - secretions from respiratory tract
  - microorganisms
  - infectious diseases
  - 95% of the droplets <100 μm[1]





[1] Duguid JP. The size and the duration of air-carriage of respiratory droplets and droplet-nuclei. The Journal of Hygiene. 1946;44(6):471-479.

Direct-contact Experiment – Characteristic Results

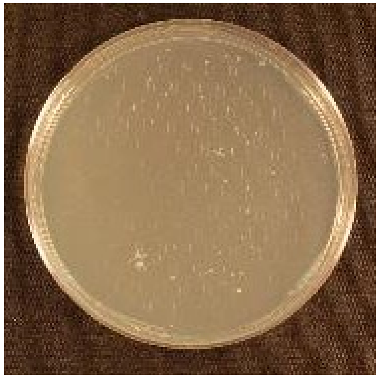
- Yeast (*3.5 X 10^8 unit/mL*)

Control

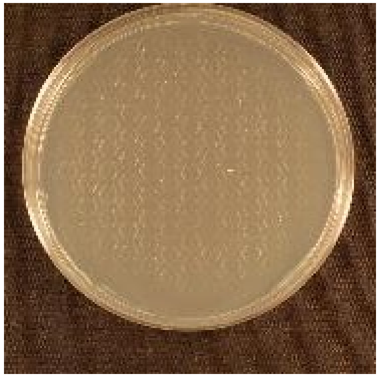
5s

10s

20s

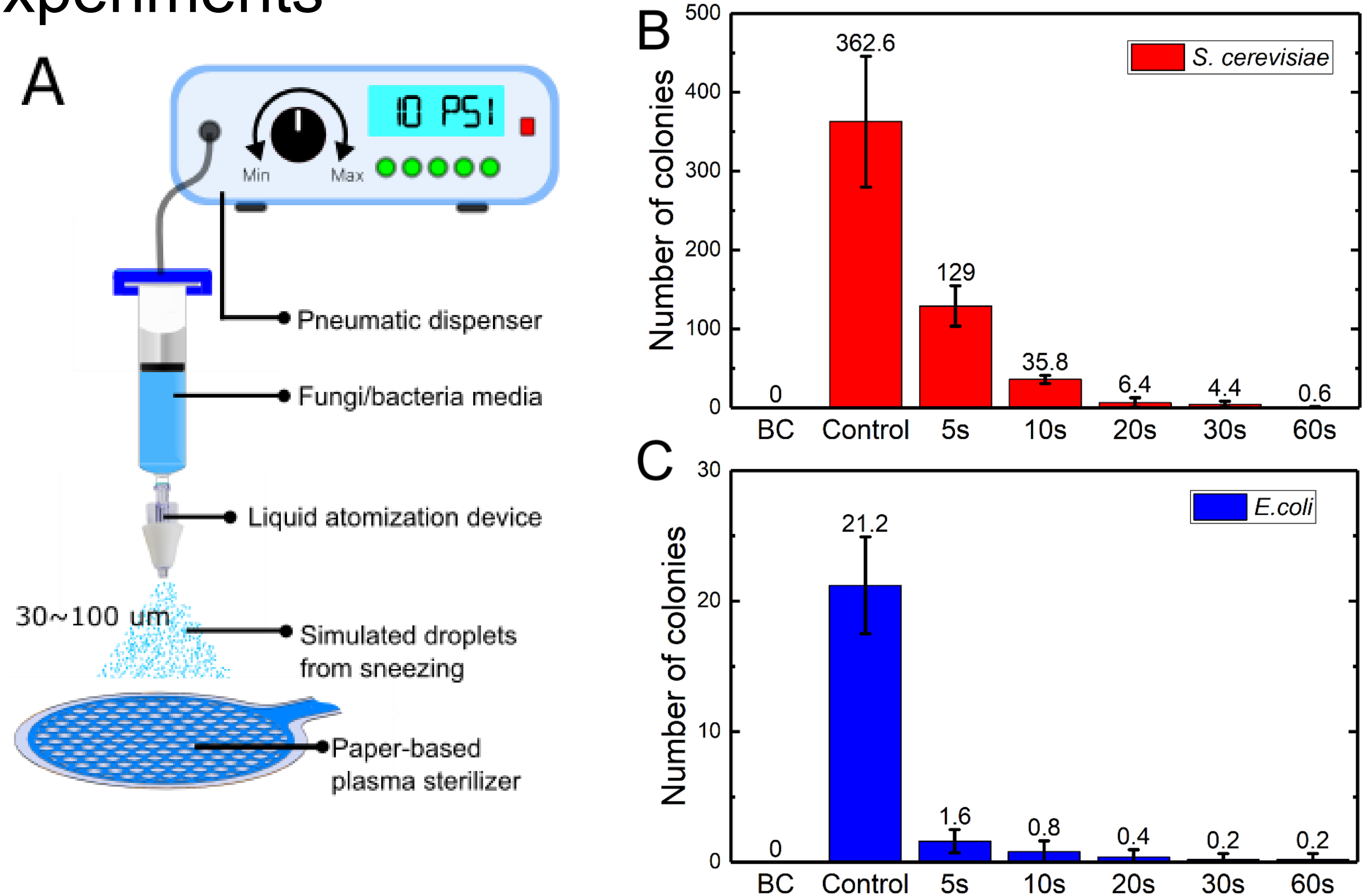


30s

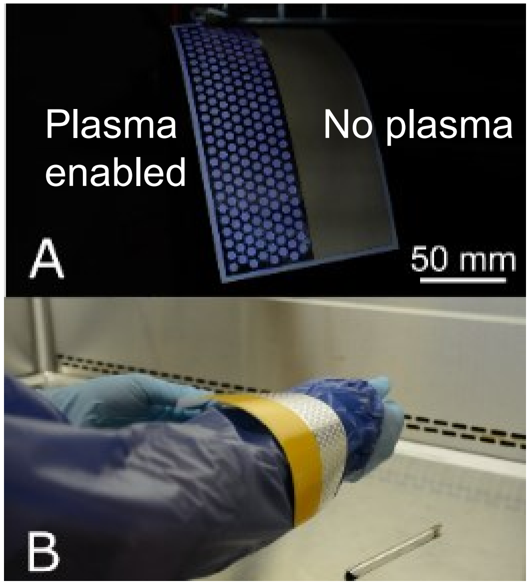


60s

Summarized Results for Direct-contact Experiments



Protective garment

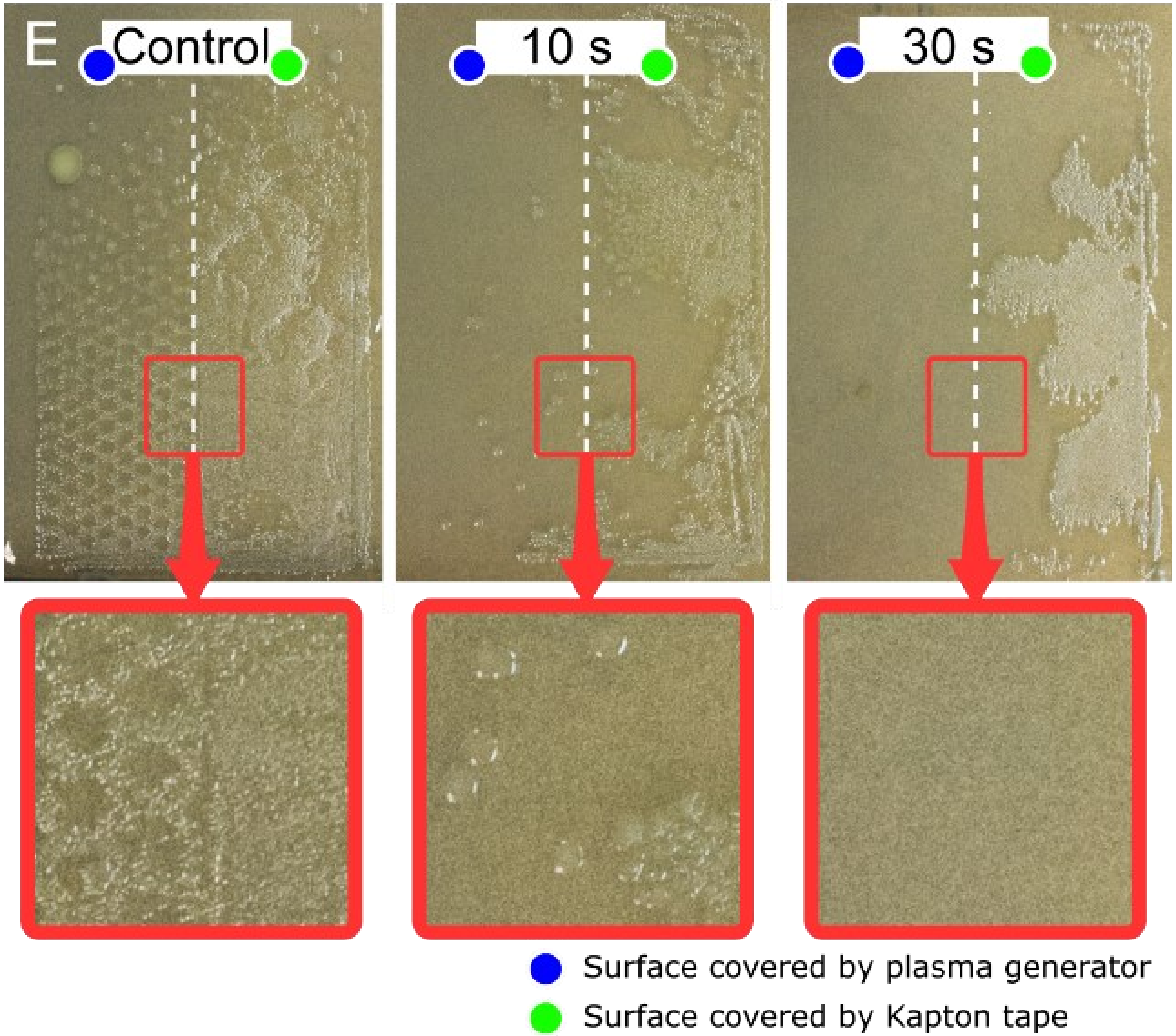


Plasma enabled:
- Honeycomb

No plasma:
- Ablated by laser
- Covered with Kapton film (waterproof, avoid absorption of bacteria)

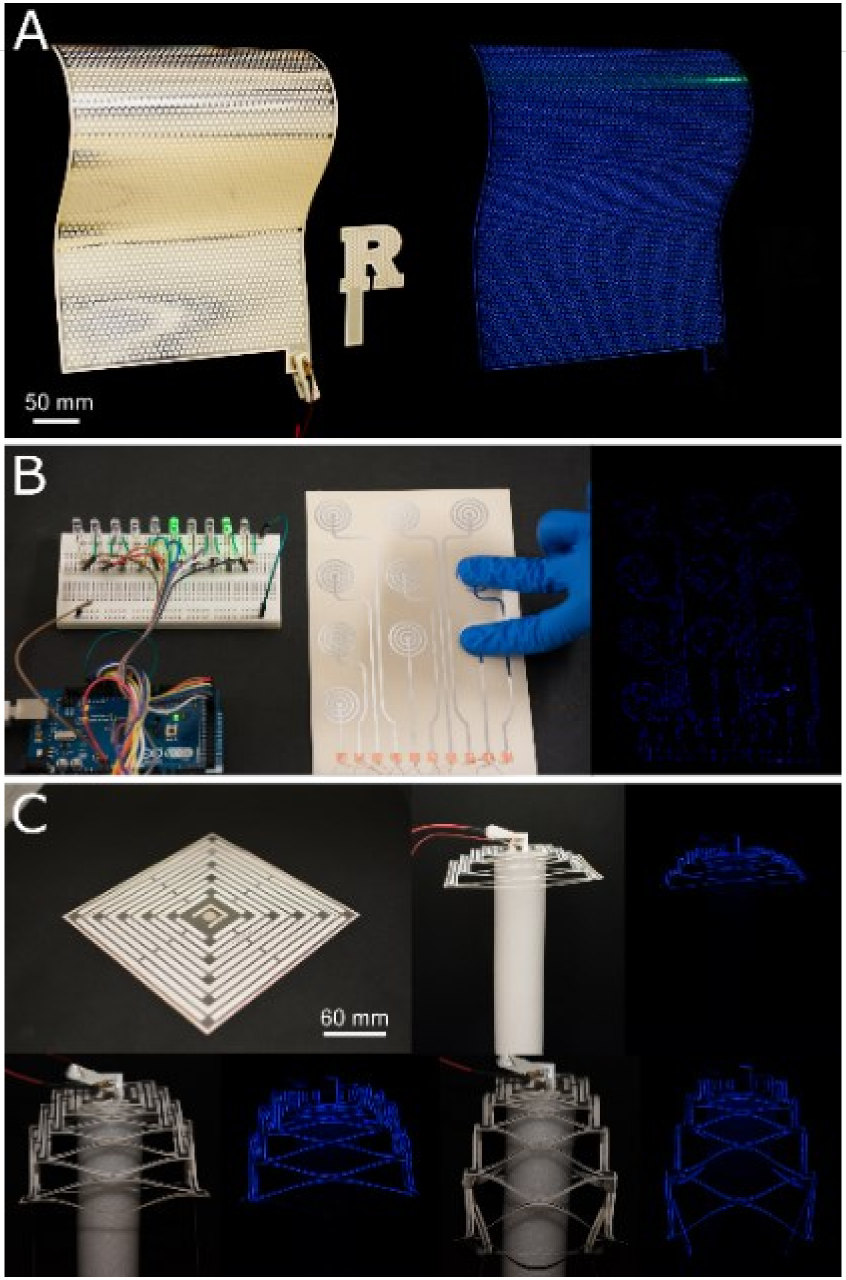
Bacteria: *E.coli*

Contact Deactivation of Microbes



Multi-functionality

- Stackable
- Scalable
- Safe???
- Sterile???



Takeaways for Paper-based Sanitizers

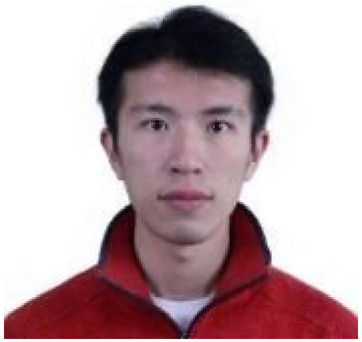
- ❑ Sanitization of electronic devices, surfaces, or user interfaces exposed to infectious diseases in hospital environments that may cause nosocomial infections.
- ❑ Developing areas which need low-cost, eco-friendly method for sanitization
- ❑ Electronic devices can also carry bacteria and virus
- ❑ Biomedical applications including wound treatment
- ❑ Food processing

What is Next for Flexible Plasma Generators?

- Active Directions (research/proposals)

- Potential Future Directions

Acknowledgements



Rutgers University

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University of Florida

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