A MICRODISCHARGE BASED PRESURE SENSOR*

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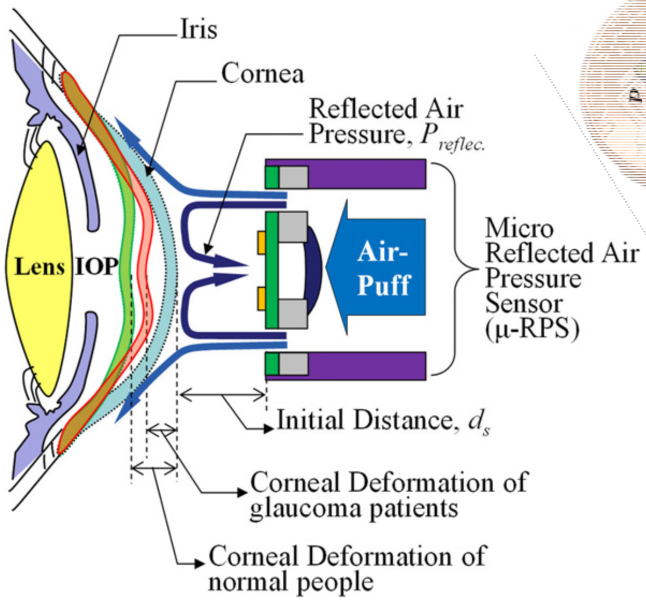
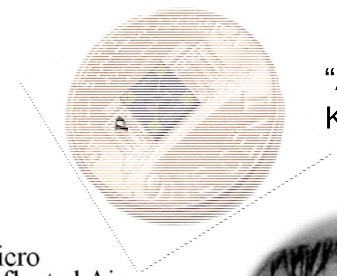
AGENDA

- Introduction to pressure sensors
    - Conventional pressure sensors and challenges in harsh environments
    - Discharge-based pressure sensors
- Description of model
- Microplasmas in pressure sensors
    - Microplasma sustained in Ar
    - Current vs. membrane deflection (external pressure)
    - Differential current vs. membrane deflection
- Concluding Remarks

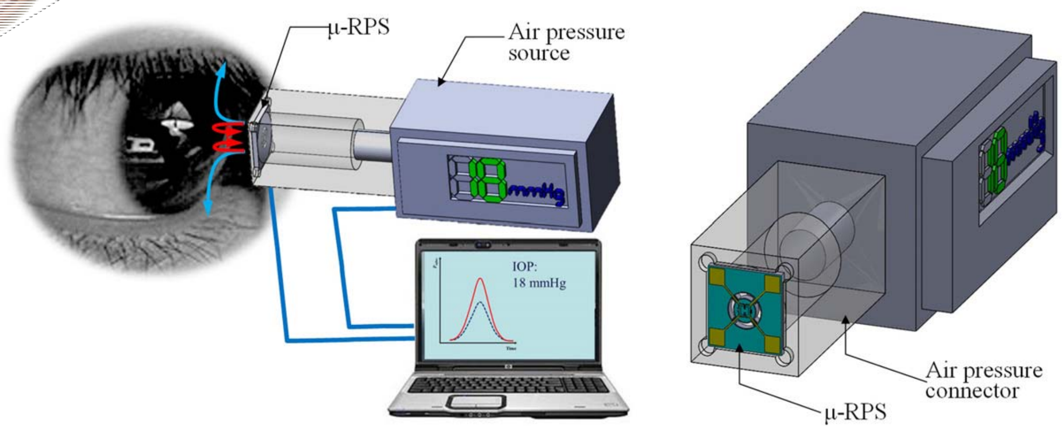
MICROMACHINED PRESSURE SENSORS

- **"Micromachined pressure sensors" are used for automotive, biomedical and industrial applications.**
  - **Automotive: fuel lines, exhaust gases, tires…**
  - **Biomedical: ocular, cranial or bowel pressure.**
  - **Industrial: etching, deposition are sensitive to operating pressure.**





"**A noncontact intraocular pressure measurement device.....**", K. H. Kim et al, J. Micromech. Microeng., 22, 2012.

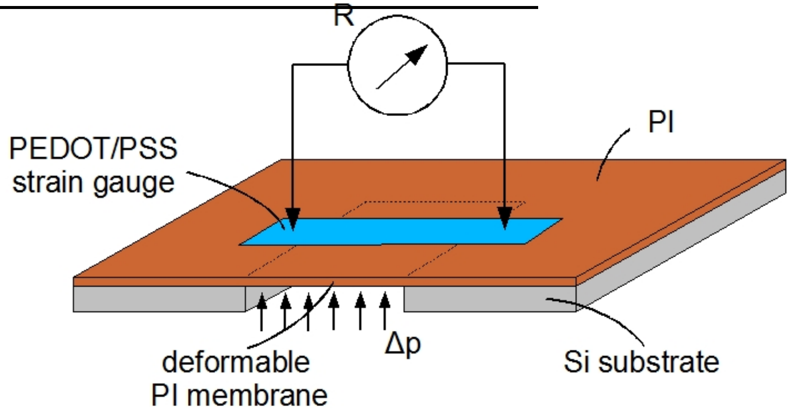


Ref:

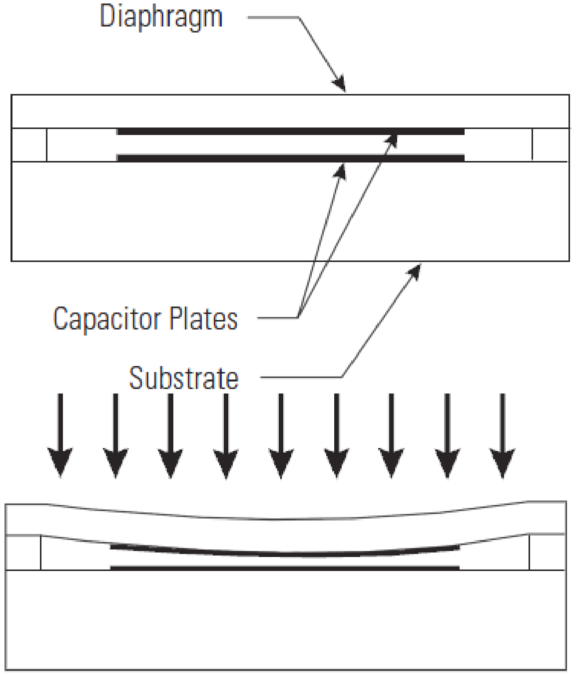
- **"Micromachined Pressure Sensors: Device, Interface Circuits, and Performance Limits", by Y. B. Gainchandani et al.**

MICROMACHINED PRESSURE SENSOR

Piezoresistive method



Capacitive method

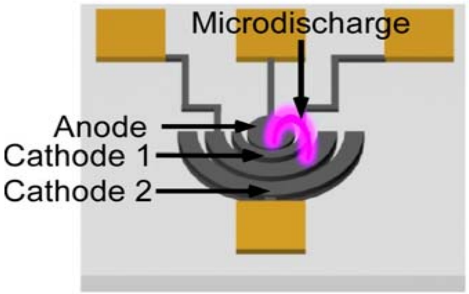


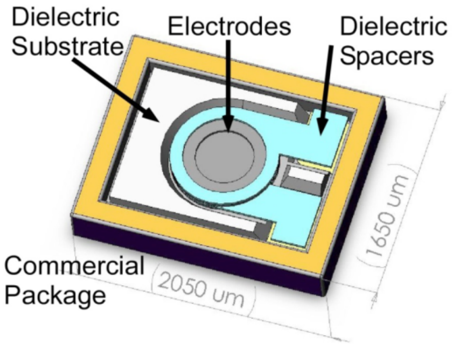
- Microscale pressure sensors (100's µm) are based on deflection of a membrane.
  - Piezoresistive materials (membrane) change resistance as deformed by pressure.
  - Capacitance between electrodes changes as the membrane is deflected by pressure.
- Harsh environments (eg., oil borehole) are challenging:
  - High temperature (> 100 ºC).
  - high pressure (50-100 Mpa, 1 Mpa ≈ 9.87 atm.).
  - Tight constraints for device volume.

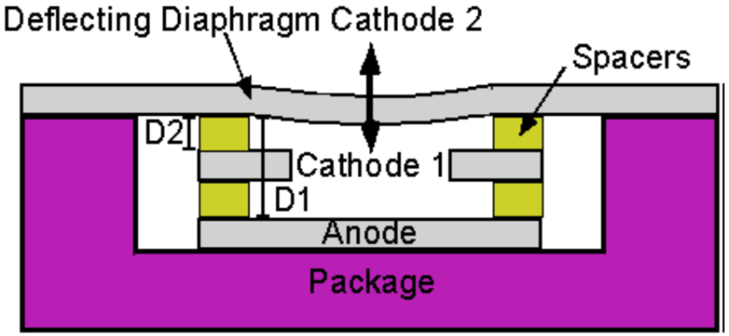
Ref:

- **www.zfm.ethz.ch/alumni/lang/page21.htm**
- **www.sensata.com/download/ipt_tech-note_1.pdf**

MICROPLASMA SENSOR



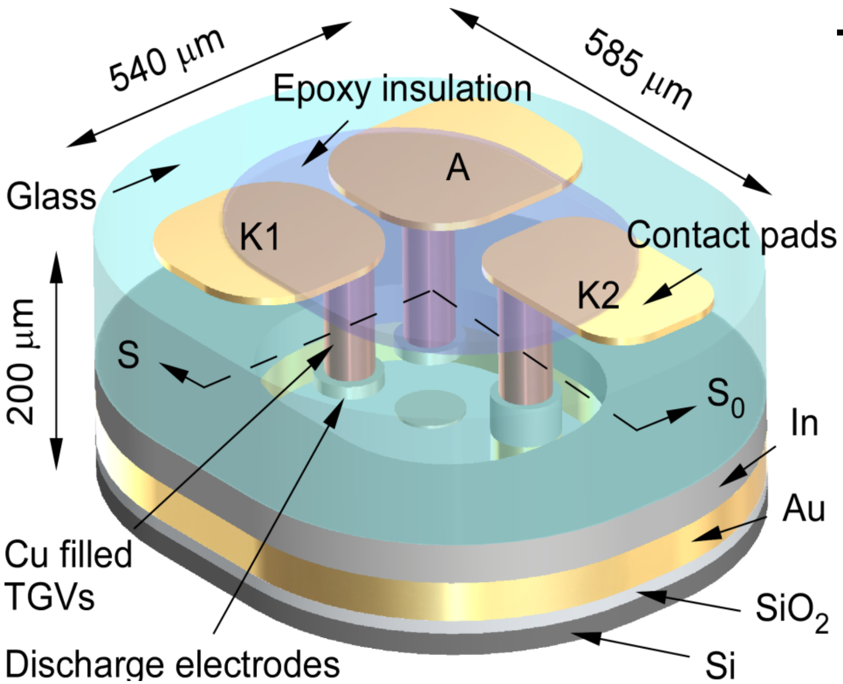


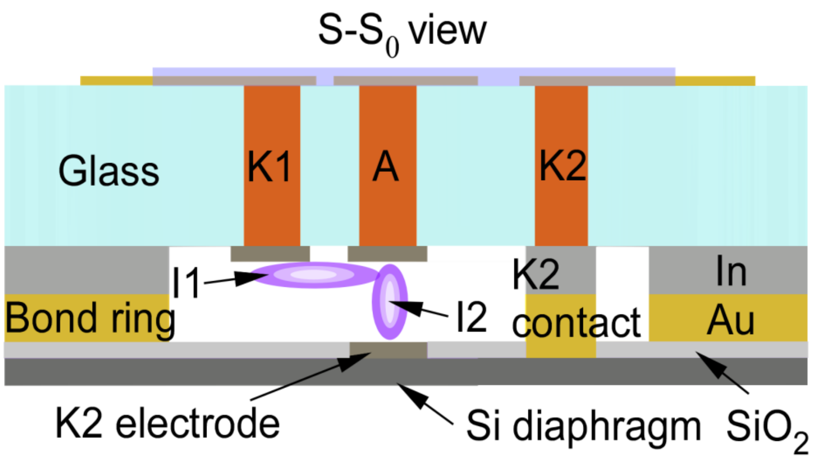


- **Microplasma-based pressure sensors are structurally simple.**
- **External pressure deflects the diaphragm and changes the inter-electrode spacing, which redistributes the current to each of the cathodes.**
- **λ_{mfp}, E/N can be controlled to optimize the current distribution.**
- **Potential advantages in harsh environments:**
    - **Immune to high external temperature.**
    - **Large inherent signal (relatively simple interface circuits).**
    - **Small size (10's μm).**

Ref: S. Wright and Y.B. Gianchandani, "Discharge-Based Pressure Sensors for High Temperature Applications Using Three-Dimensional and Planar Microstructures," *Journal of Microelectromechanical Systems*, 18(3), pp. 736-743, June 2009

MICROPLASMA SENSOR





- **Two cathode microdischarge-based pressure sensor:**
  - **Cathode 1 (K_1) adjacent to anode (A).**
  - **Cathode 2 (K_2) below anode (A).**
  - **Microplasma initiated between A and two competing cathodes (K_1, K_2).**
  - **A diaphragm attached to one electrode is deflected by external pressure.**
  - **The changing inter-electrode spacing redistributes current to two competing cathodes.**
- **Modeling will improve fundamental understanding and provide design rules.**

Ref:
- **"A Microdischarge-Based Monolothic Pressure Sensor" by Y. B. Gainchandani et al.**

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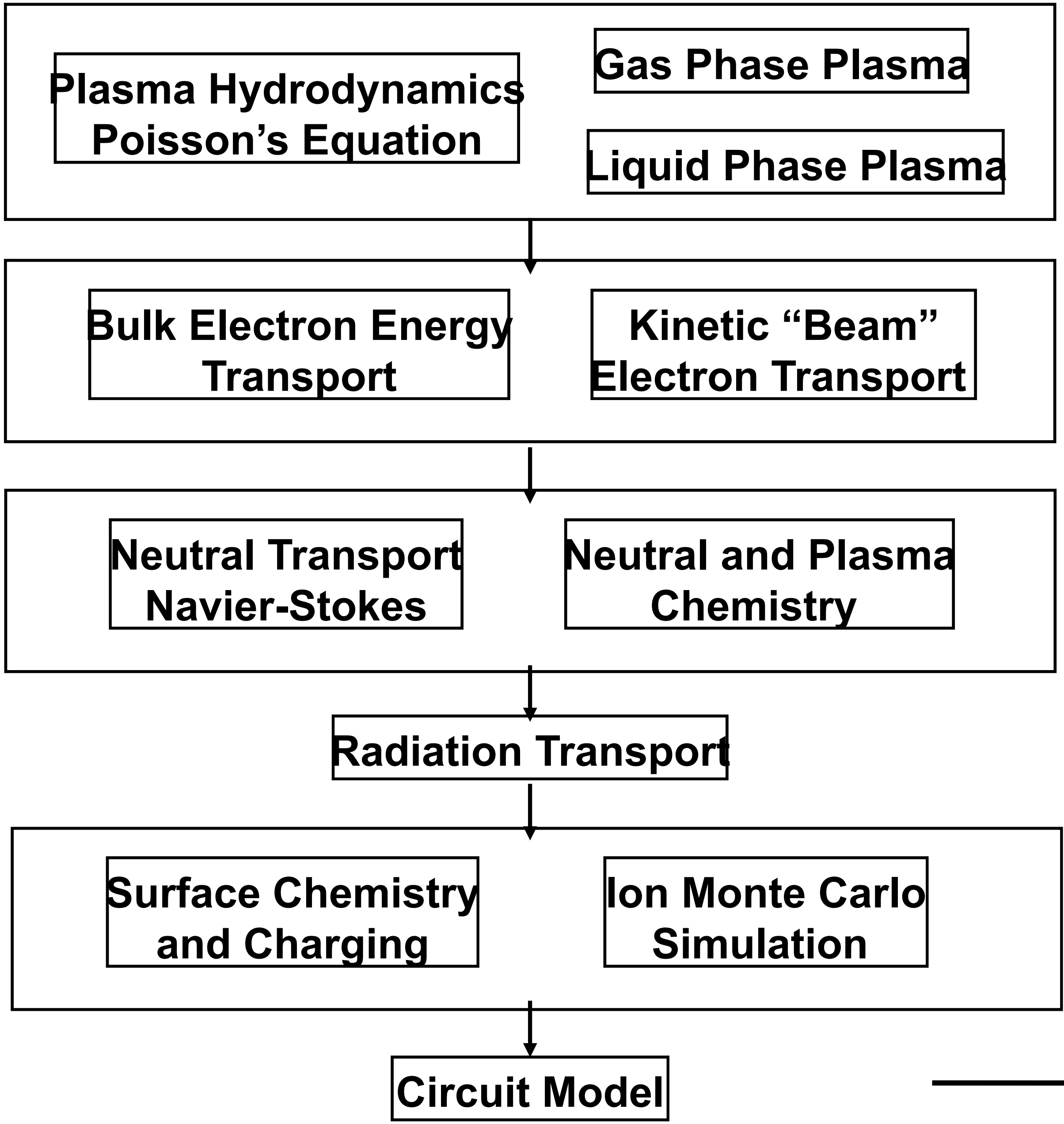
MODEL: *nonPDPSIM*



- **2-unstructured mesh with spatial dynamic range of 10^4.**
- **Fully implicit plasma transport.**
- **Time slicing algorithms between plasma and fluid timescales.**

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MODELING PLATFORM: *nonPDPSIM*

- **Poisson's equation:** $$\nabla \cdot (\varepsilon \nabla \Phi) = -(\sum_j q_j N_j + \rho_s)$$
- **Transport of charged and neutral species:** $$\frac{\partial N_j}{\partial t} = -\nabla \cdot \vec{\Gamma}_j + S_j$$
- **Surface Charge:** $$\frac{\partial \rho_s}{\partial t} = \left[\sum_j q_j \left(-\nabla \cdot \vec{\Gamma}_j + S_j \right) - \nabla \cdot \left(\sigma \left(-\nabla \Phi \right) \right) \right]_{material}$$
- **Electron Temperature (transport coefficient obtained from Boltzmann's equation)**

$$\frac{\partial (n_e \varepsilon)}{\partial t} = \vec{j} \cdot \vec{E} - n_e \sum_i \Delta \varepsilon_i K_i N_i - \nabla \cdot \left(\frac{5}{2} \vec{\phi}_e \varepsilon - \overline{\overline{\kappa}}(T_e) \cdot \nabla T_e \right)$$

- **Radiation transport and photoionization:**

$$S_m(\vec{r}_i) = N_m(\vec{r}_i) \cdot \sum_k \sigma_{mk} A_k \int N_k(\vec{r}_j\,') G_k(\vec{r}_j\,', \vec{r}_i) d^3 \vec{r}_j\,'$$

$$G(\vec{r}_j\,', \vec{r}_i) = \frac{\exp\left(-\sum_l \int_{\vec{r}_j\,'}^{\vec{r}_i} \sigma_{lk} N_l(\vec{r}_j\,') d\vec{r}_j\,' \right)}{4\pi \left| \vec{r}_j\,' - \vec{r}_i \right|^2}$$

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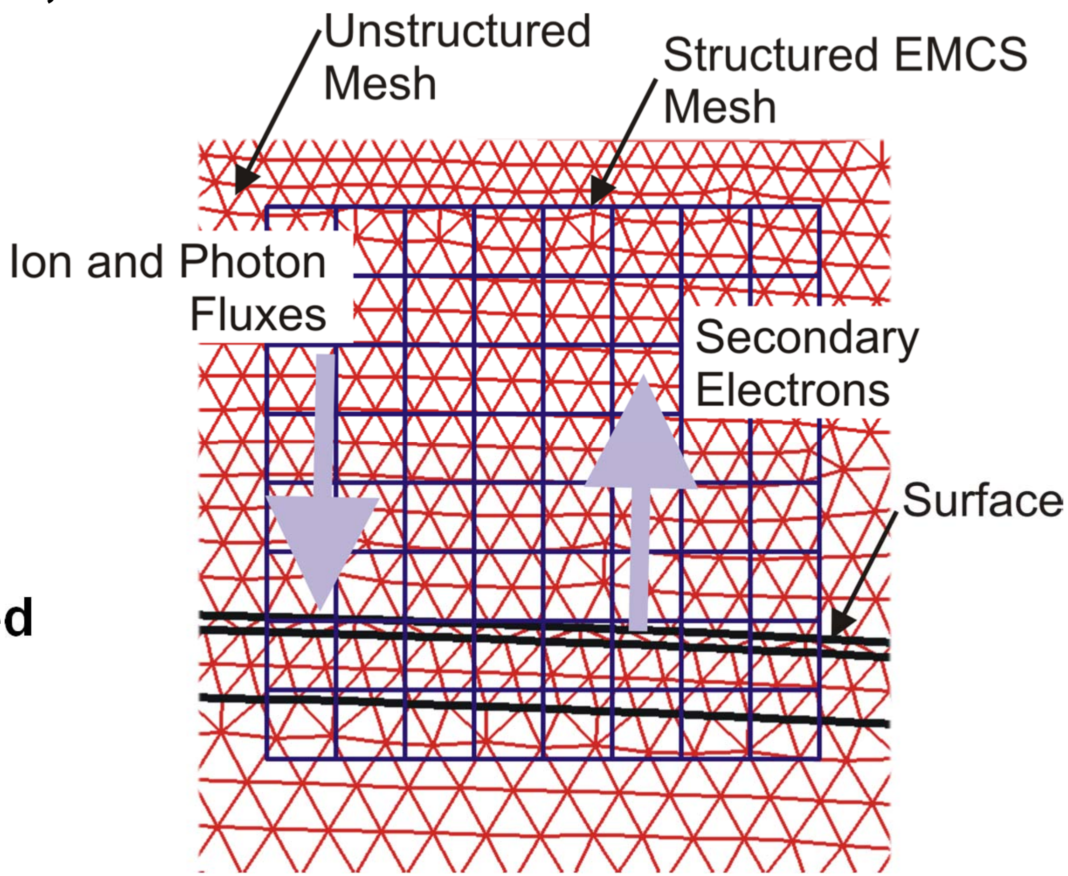
SECONDARY ELECTRONS FROM SURFACES

- Using a beam-bulk formulation, an electron Monte Carlo Simulation is used to follow trajectories of secondary electrons from surfaces.
- Structured EMCS mesh overlyed onto unstructured fluid mesh – E-fields interpolated onto mesh.
- Pseudo-particles are launched from sites on surfaces for emission produced by
  - Ion bombardment
  - Photon fluxes
  - Electric field enhanced thermionic emission.



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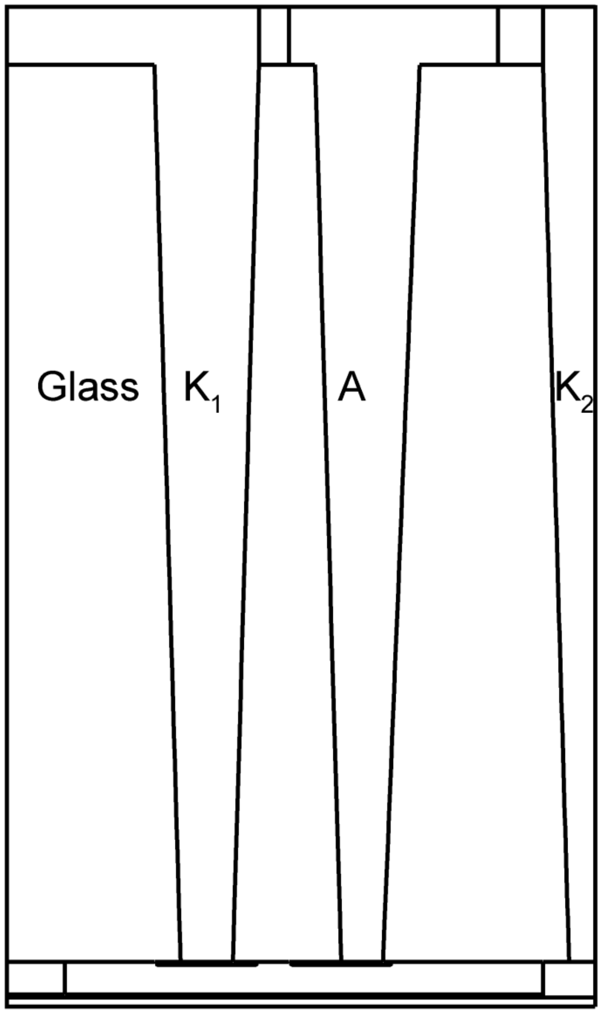

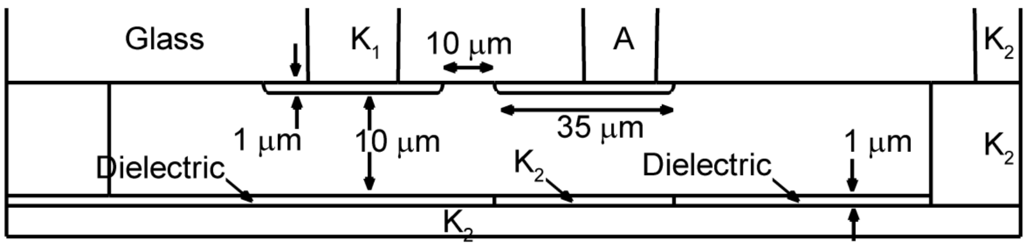

MODEL GEOMETRY

- **Three electrodes (two cathode) structure:**
  - **Inter-electrode spacing: A-K_2, A-K_1 = 10 μm.**
  - **K_1, K_2: grounded, A: 400 V.**
  - **Ballast resistor: 100 Ω (K_1, K_2) and 500 Ω (A).**
  - **Discharge initiated with emission current of 10^{-2} A-cm^{-2} for 10 ns at cathode corner.**
  - **1 atm Ar (Ar, Ar(4s,4p), Ar^+, Ar_2^+, Ar_2^* and electrons).**

- **X/Y=0.5**

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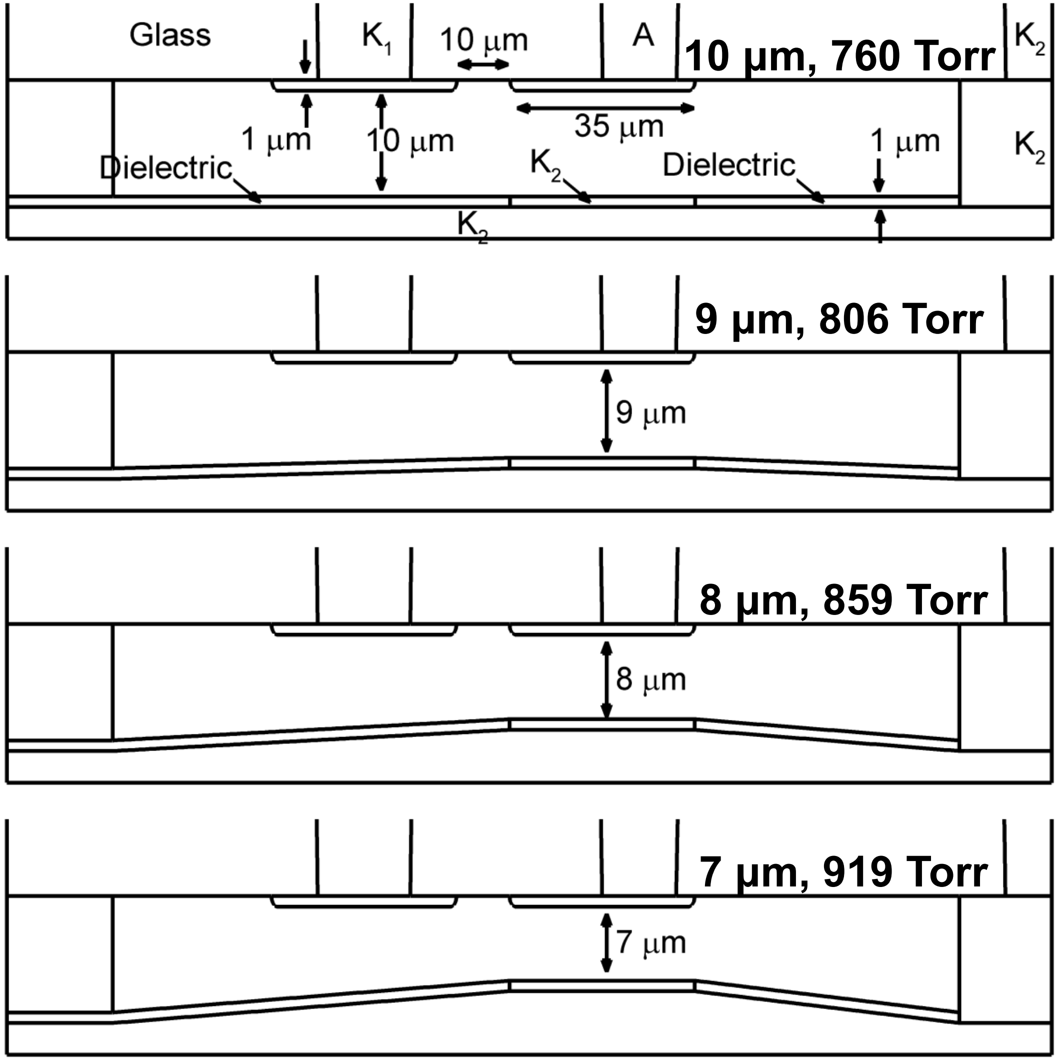
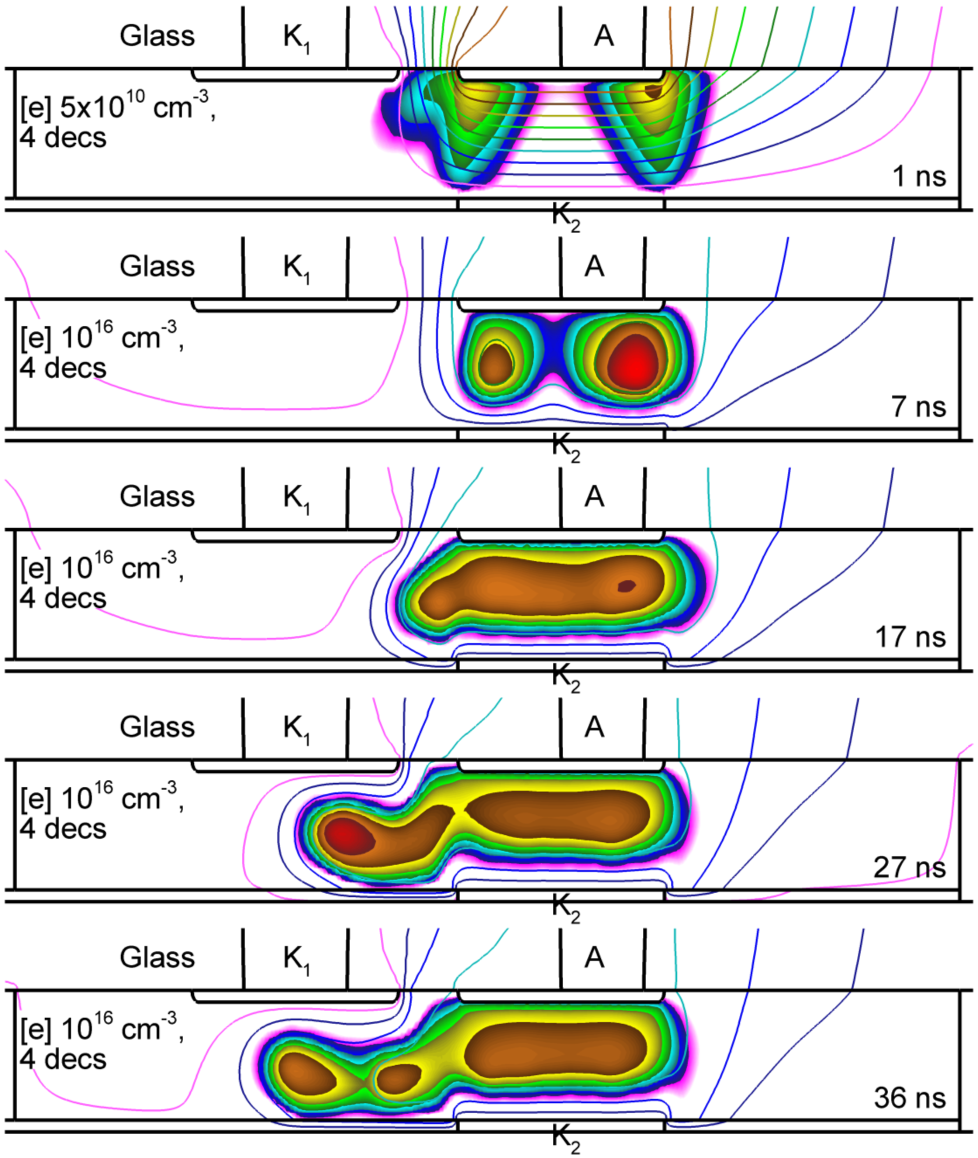
MODEL GEOMETRY



- Three electrodes (two cathodes) pressure sensor structure:
  - A-K_1 = 10 µm.
  - Gap spacing (A-K_2) reduced by external pressure.
  - A-K_2: 10 – 7 µm. (0 – 25 MPa external pressure)
  - Chamber Pressure: 760 – 919 Torr Ar.

- X/Y=0.5

MICROPLASMA DYNAMICS: [e]



- **Inter-electrode spacing: A-K_2, A-K_1=10 μm.**
- **A: 400 V, K: 0 V , ΔV = 40 V (Contours).**
- **760 Torr Ar.**

MIPSE_2013 **MIN** **MAX**

- **Avalanche between edges of cathodes and anode produces a conductive plasma within 10 ns.**
- **After avalanche, plasma shields out E-field and reduces E/N, T_e, S_e.**
- **Conductive plasma transfers anode potential to cathodes. T_e and intense ionization peak at K_2 and A-K_1.**
- **I_{K2} produced by plasma between A-K_2 sustained by K_2.**
- **Increasing [e] at A-K_2 reduces E/N, T_e and S_e, which reduces [e].**
- **E/N, T_e and S_e then rebound to produce high density [e]. A self-pulsing I_{K2} is then produced.**

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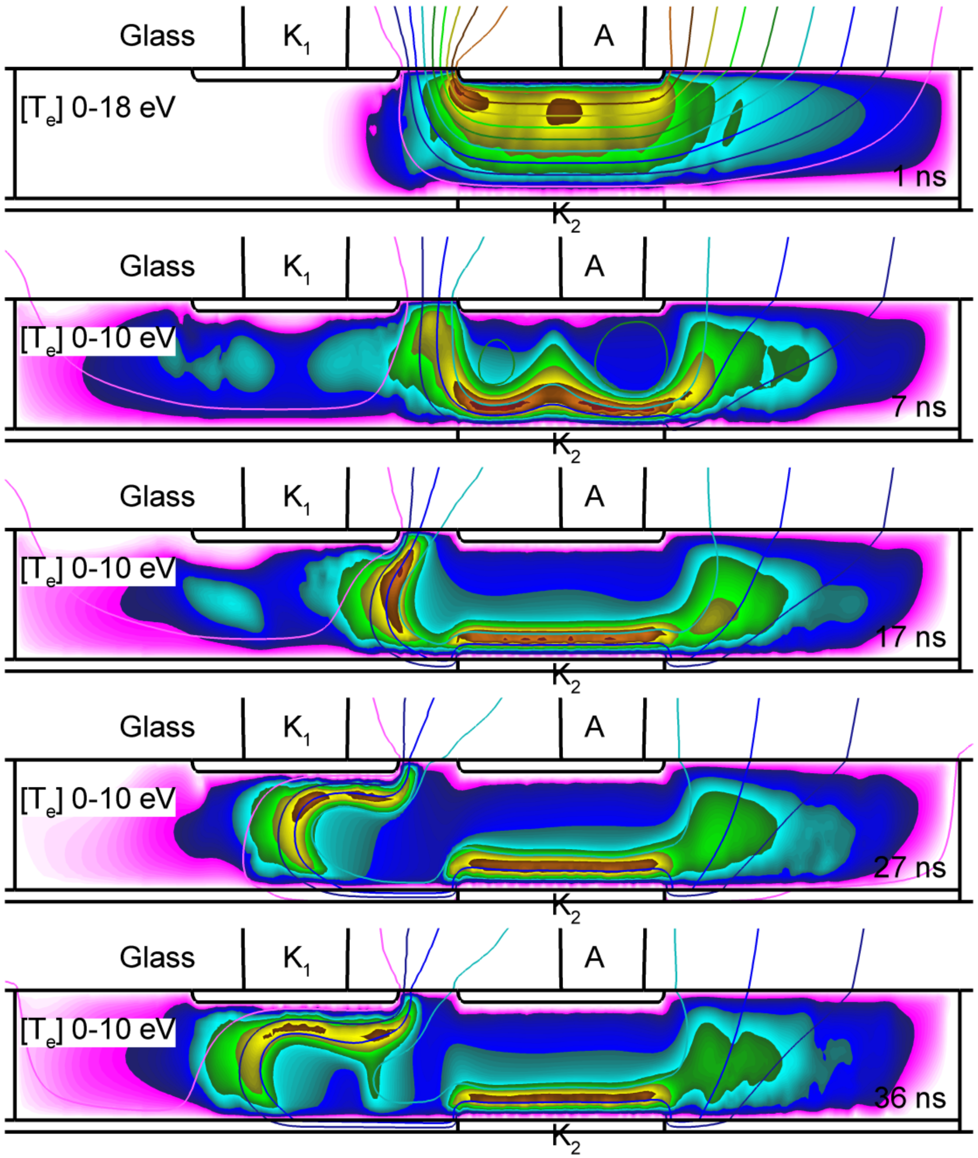
MICROPLASMA DYNAMICS: $[T_e]$



- Due to charge separation, high voltage drop at A-K_1 trigger a bullet-like ionization wave (IW).
- IW propagates along K_1 producing current pulses (I_{K1}).
- A striation from A to K_1 is due to the repetitive bullet-like IW.
- Ionization source S_{sec} at cathode sheaths is comparable with S_e from bulk plasma.

- Inter-electrode spacing: A-K_2, A-K_1=10 μm.
- A: 400 V, K: 0 V , ΔV = 40 V (Contours).
- 760 Torr Ar.

MIN MAX

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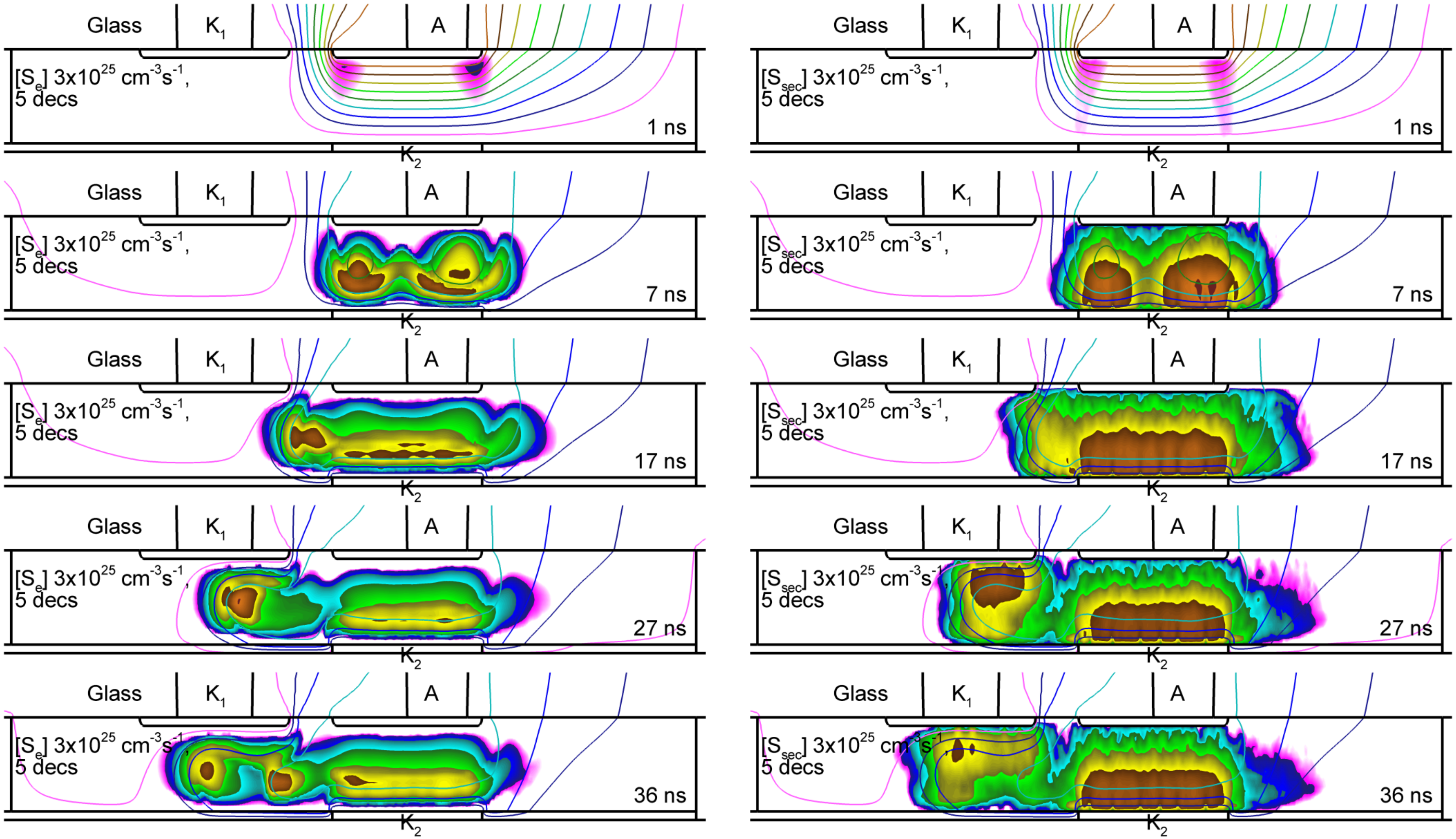
MICROPLASMA DYNAMICS: [S_e], [S_{sec}]



- **Inter-electrode spacing: A-K_2, A-K_1=10 μm.**
- **A: 400 V, K: 0 V , ΔV = 40 V (Contours).**
- **760 Torr Ar.**

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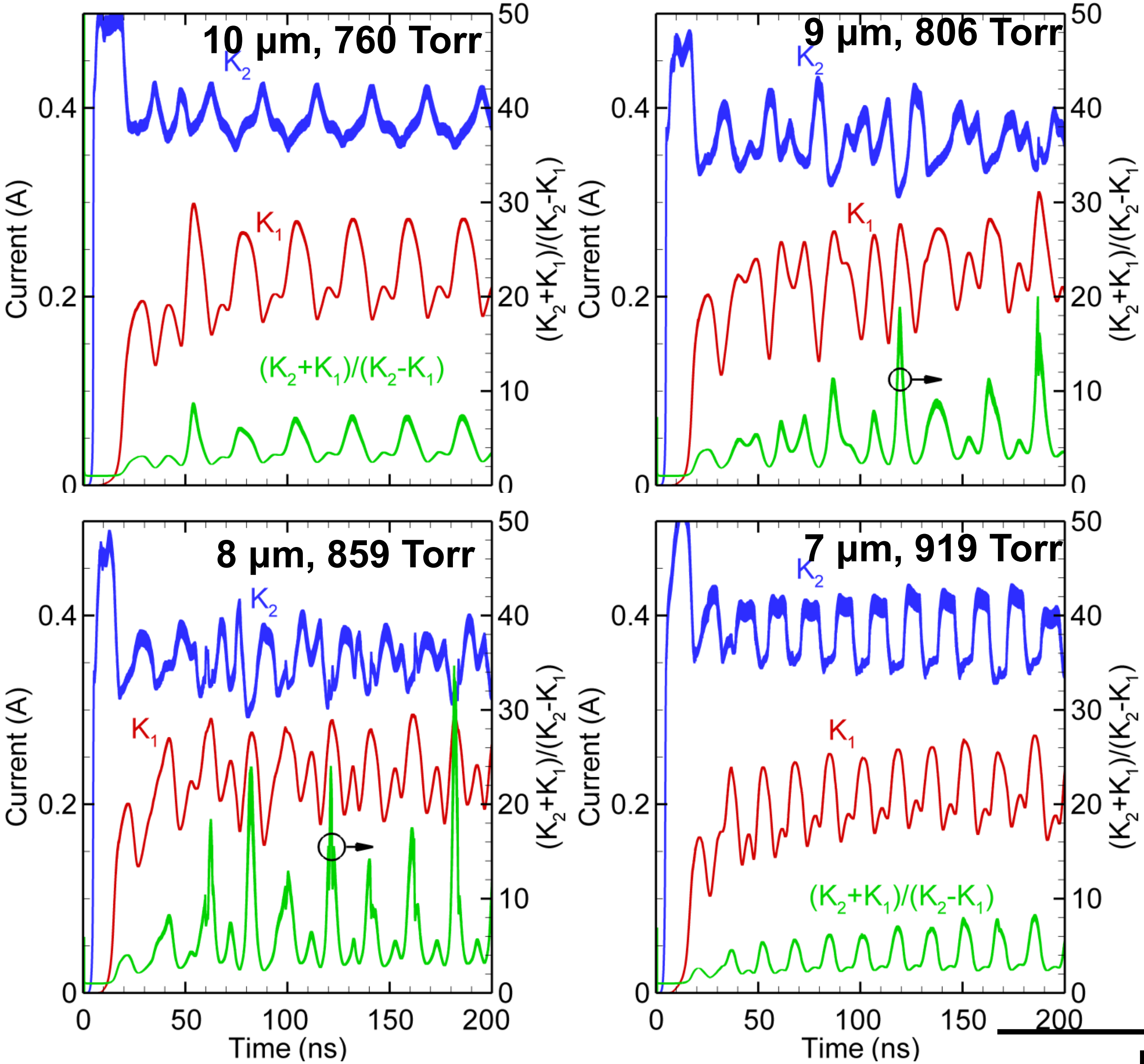
MICROPLASMA CURRENT ON CATHODES



- Gap (A-K_2) spacing: 10-7 µm.
- A: 400 V, K: 0 V.
- 760-919 Torr Ar.
- Self-pulsing results in high frequency oscillation in I_{K1} and I_{K2}.
- Averaged $I_{K2}+I_{K1} \approx$ constant.
- Averaged $I_{K2}-I_{K1}$ decreases with deflection (from 10 – 8 µm).

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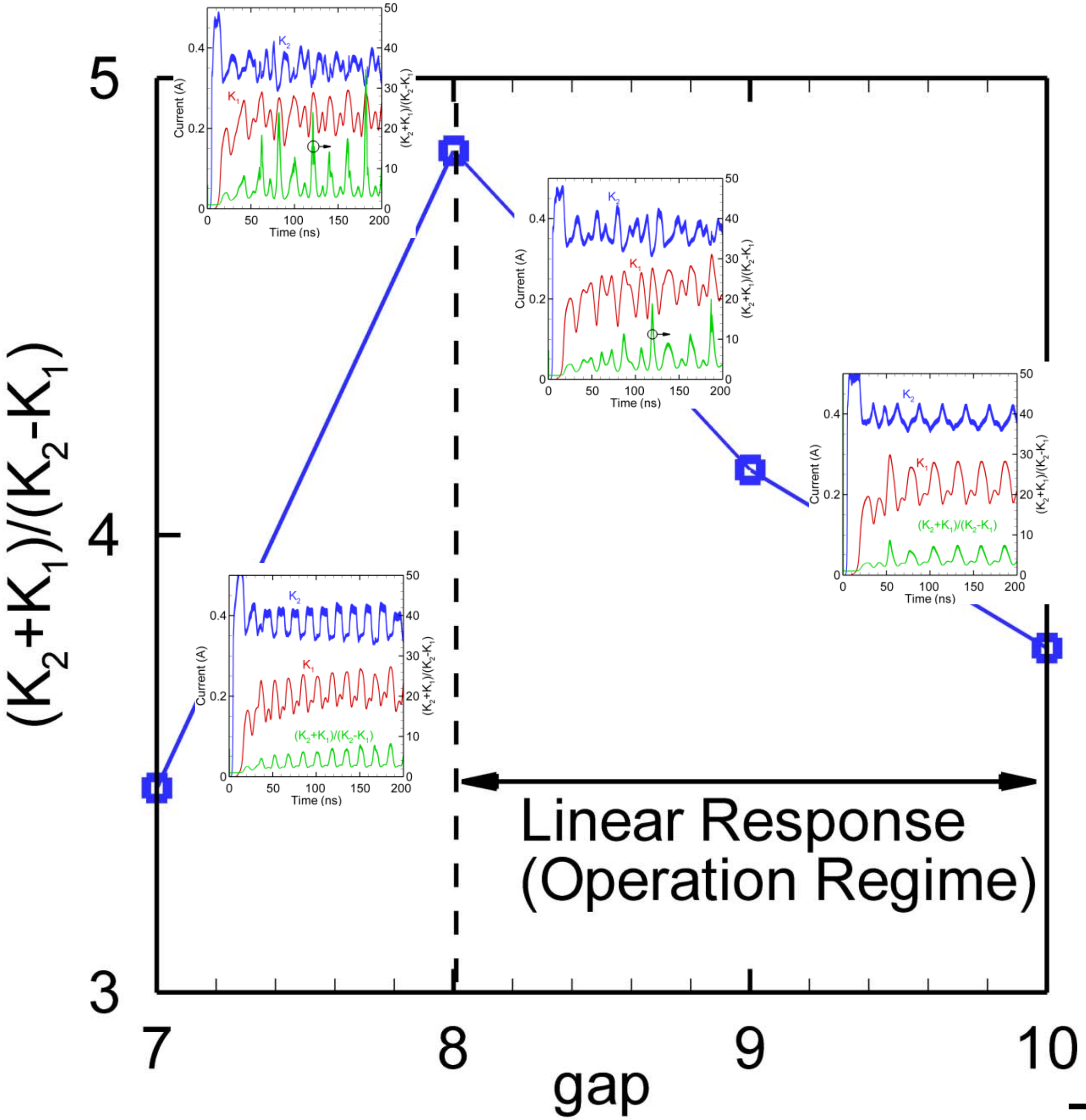
MICROPLASMA DIFFERENTIAL CURRENT



- Gap (A-K_2) spacing: 10-7 µm.
- A: 400 V, K: 0 V.
- 760-919 Torr Ar.
- Averaged $I_{K2}+I_{K1} \approx$ const.
- 8 – 10 µm
  - Averaged $I_{K2}-I_{K1}$ decreases with deflection.
  - Differential current $(K_2+K_1)/(K_2–K_1)$ linearly increases with deflection (external pressure).
- Operating regime (8-10 µm deflection or 0-20 Mpa)

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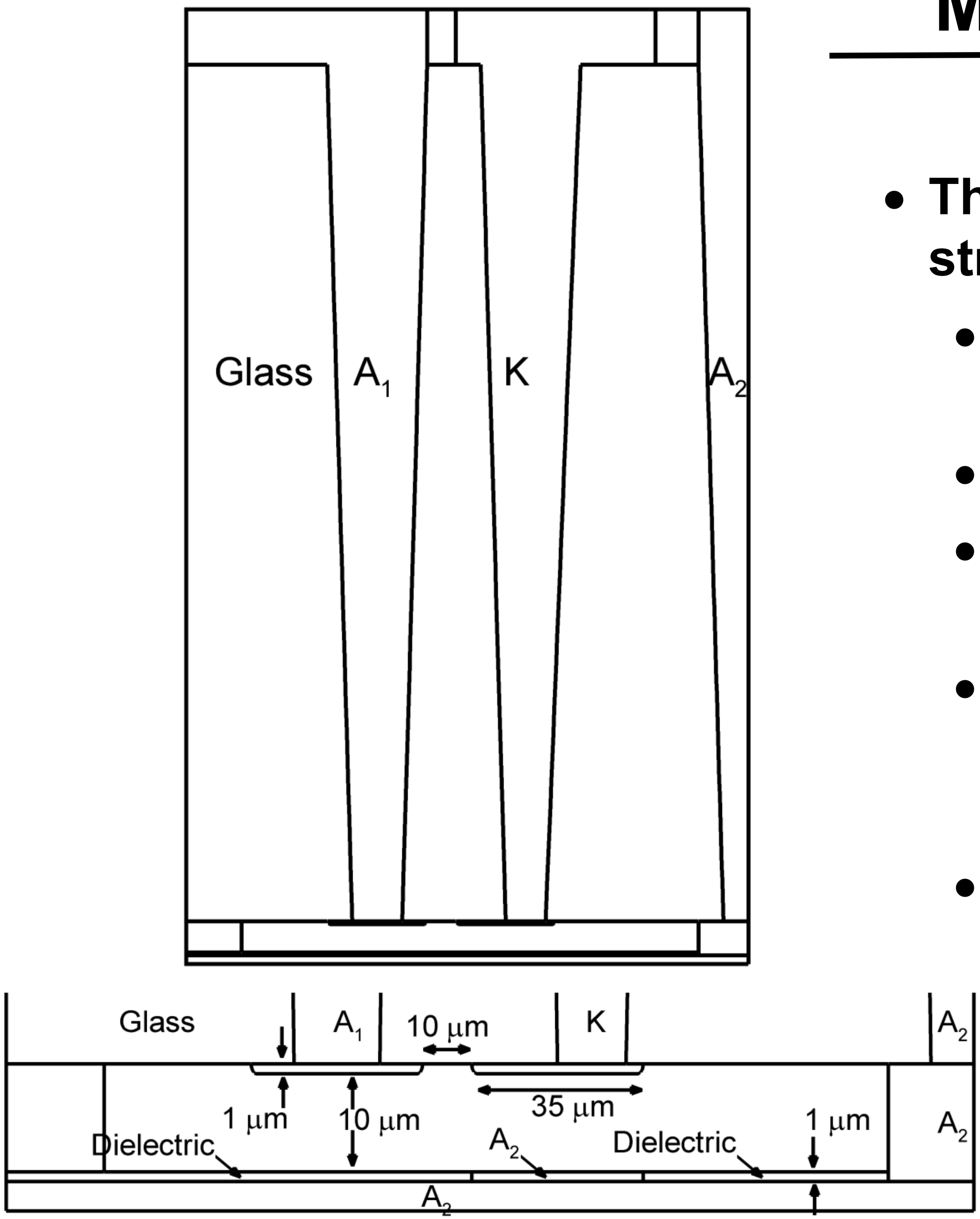
MODEL GEOMETRY II



- Three electrodes (two anode) structure:
  - Inter-electrode spacing: K-A_1, K-A_2=10 μm.
  - A_1, A_2: grounded, K: -400 V.
  - Ballast resistor: 100 Ω (A_1, A_2) and 500 Ω (K).
  - Discharge initiated with emission current of 10^{-2} A-cm^{-2} for 10 ns at cathode corner.
  - 1 atm Ar.
- X/Y=0.5

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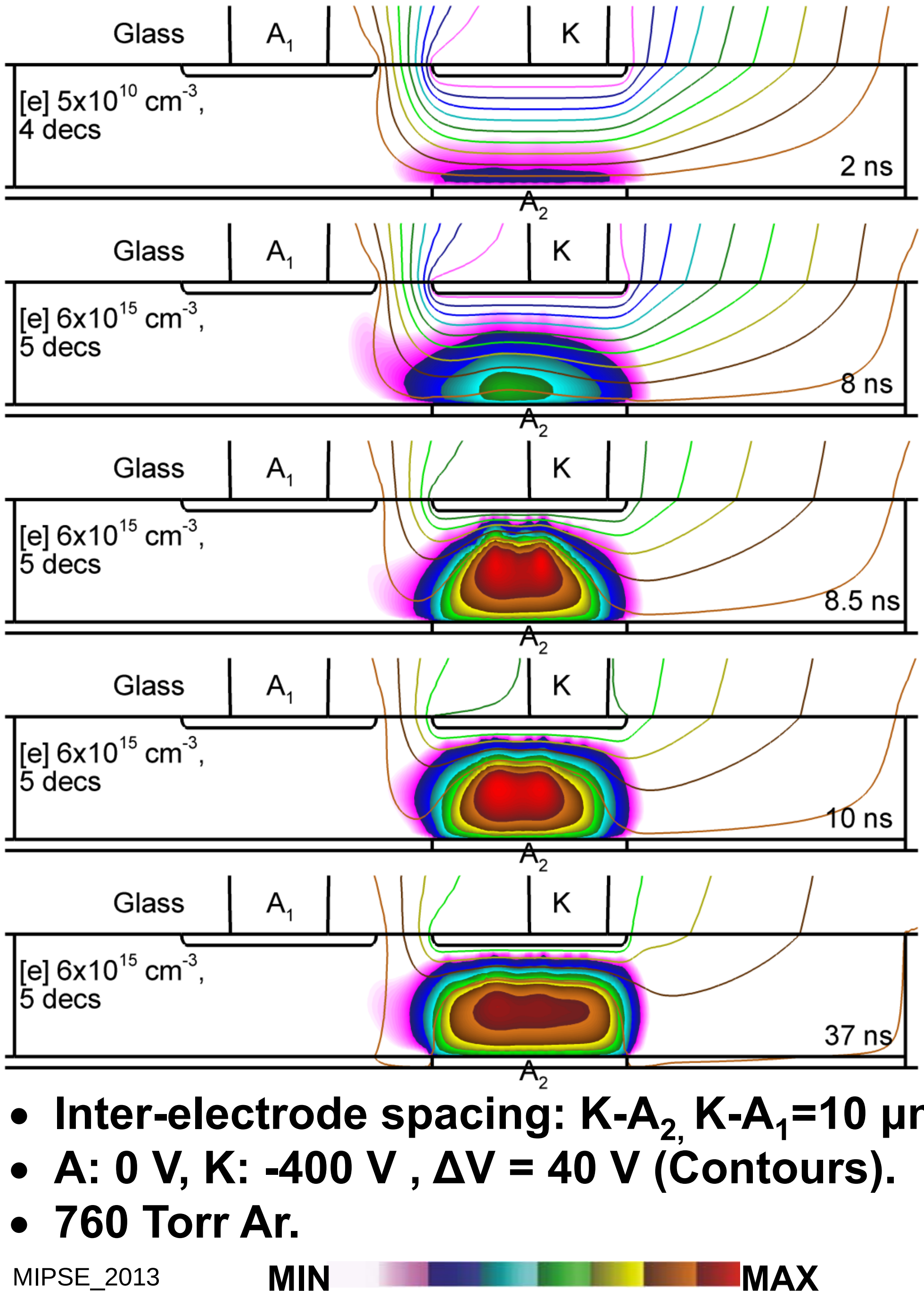
MICROPLASMA DYNAMICS: [e]



- Avalanche between edges of cathode and anodes produces a conductive microplasma at K-A_2 within 10 ns.
- After avalanche, plasma shields out E-field and reduces E/N, T_e, S_e.
- Conductive plasma transfers A_2 potential to cathode. T_e and intense ionization peak at K.

- Inter-electrode spacing: K-A_2, K-A_1=10 μm.
- A: 0 V, K: -400 V , ΔV = 40 V (Contours).
- 760 Torr Ar.

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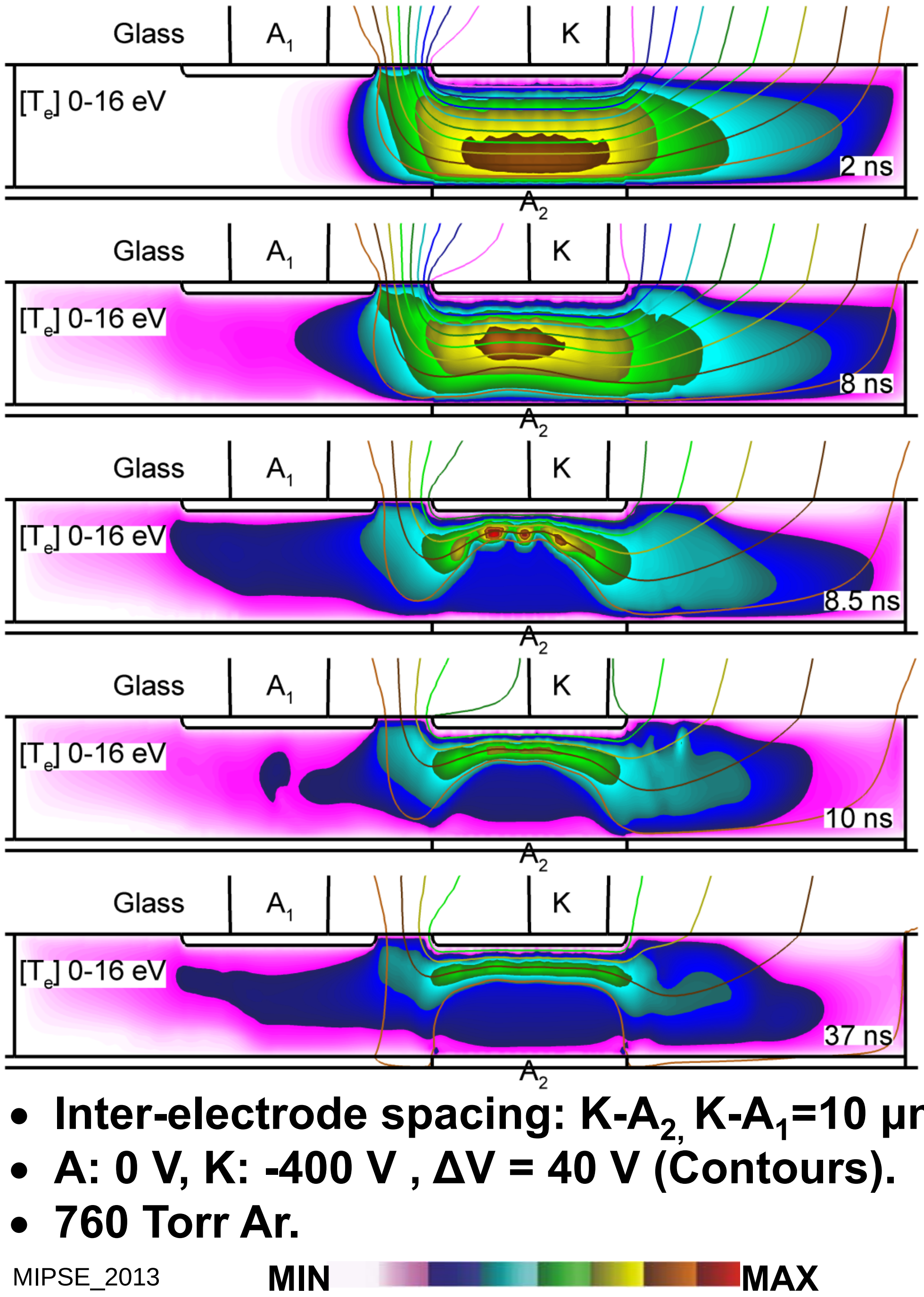
MICROPLASMA DYNAMICS: $[T_e]$



- Inter-electrode spacing: K-A_2, K-A_1=10 μm.
- A: 0 V, K: -400 V , ΔV = 40 V (Contours).
- 760 Torr Ar.

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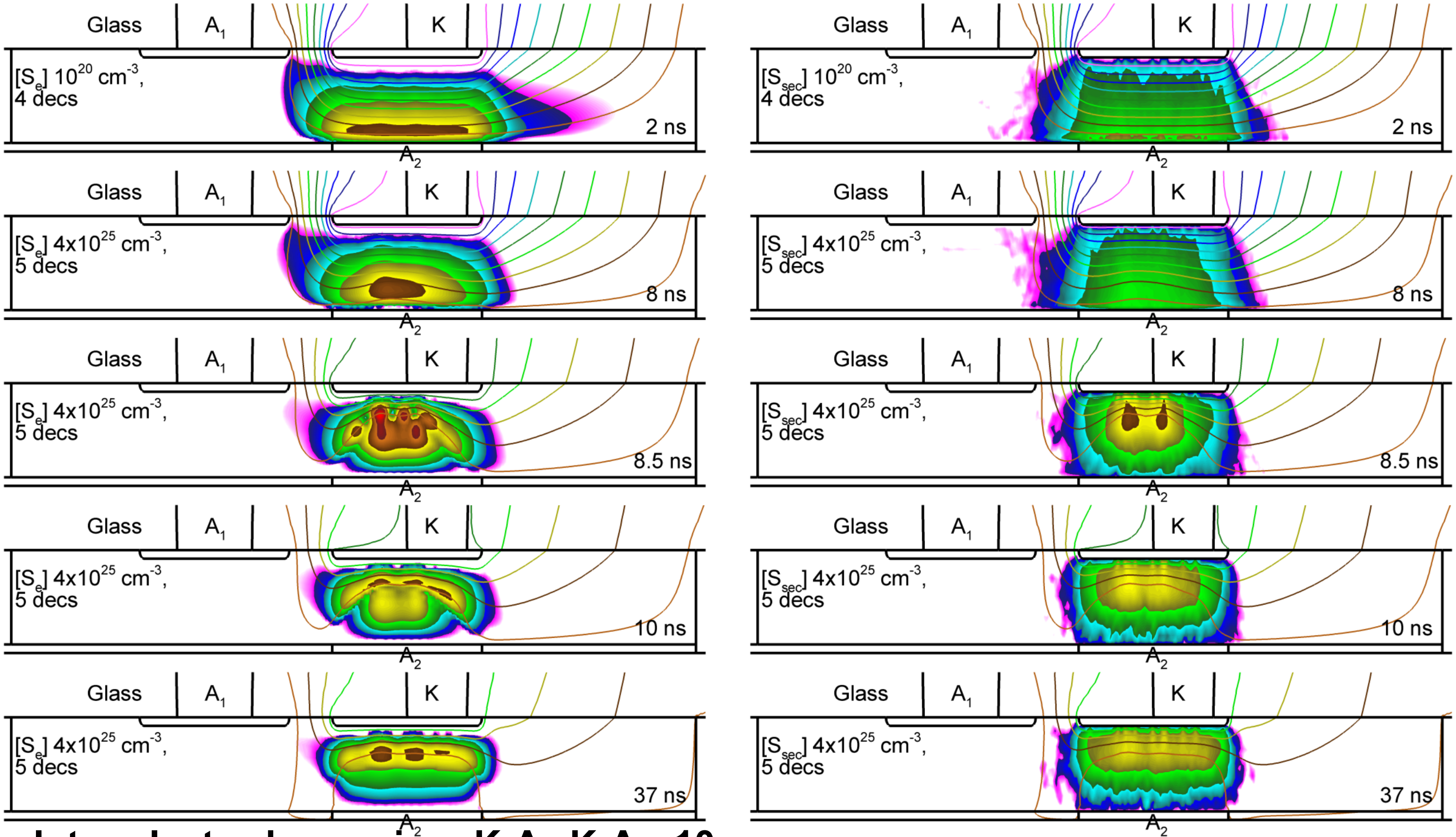
- A large I_{A2} (~0.5 A) produced by plasma between K-A_2 sustained by K.
- A small I_{A1}(~0.5 mA) produced by electron transport from plasma at K-A_2.
- 3 orders of magnitude difference in current collection – differential current method is challenged.
- Ionization source S_{sec} at cathodes sheath is comparable with S_e from bulk plasma.

MICROPLASMA DYNAMICS: [S_e], [S_{sec}]



- **Inter-electrode spacing: K-A_2, K-A_1=10 µm.**
- **A: 0 V, K: -400 V , ΔV = 40 V (Contours).**
- **760 Torr Ar.**

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CONCLUDING REMARKS

- Plasma behavior in a microdischarge based pressure sensor is computationally investigated .
- In two cathode structure, after electron avalanche and microplasma generated at A-K_2, conductive plasma transfers anode voltage to cathodes creating a high voltage drop and intense ionization at K_2 and A-K_1.
- I_{K2} produced by self-pulsing plasma at A-K_2 sustained by K_2.
- A repetitive ionization wave propagating from A to K_1 results in a striation on K_1.
- The striation produces a high frequency current pulses on cathodes.
- Deferential current $(K_2+K_1)/(K_2–K_1)$ linearly increases with deflection in 10-8 µm deflection regime (0 – 20 MPa external pressure).

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