UNIVERSITÉ DE NANTES

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

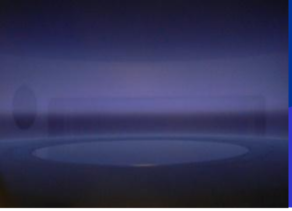
INSTITUT des MATÉRIAUX JEAN ROUXEL
IMN
Physique Chimie et Génie des Matériaux

Development of pulsed plasma doping system for semiconductor processing: characterization of the plasma and its interaction with the materials

Ludovic Godet

Thesis Advisors: C. Cardinaud (IMN, France)
G. Cartry (IMN, France)
J. Scheuer (VSEA, USA)
S. Radovanov (VSEA, USA)

varian semiconductor equipment

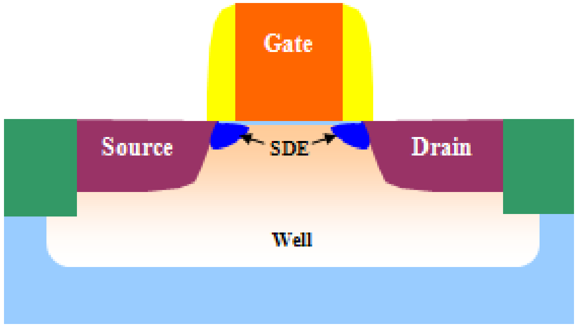


Outline

- **Introduction**
  - Plasma Doping Principle
  - Motivation for Plasma Diagnostic
- **Experimental Setup**
- **Prediction of the Dopant Depth Profile**
- **Plasma Characterization**
- **Dopant Depth Profile Engineering**
- **Conclusion**

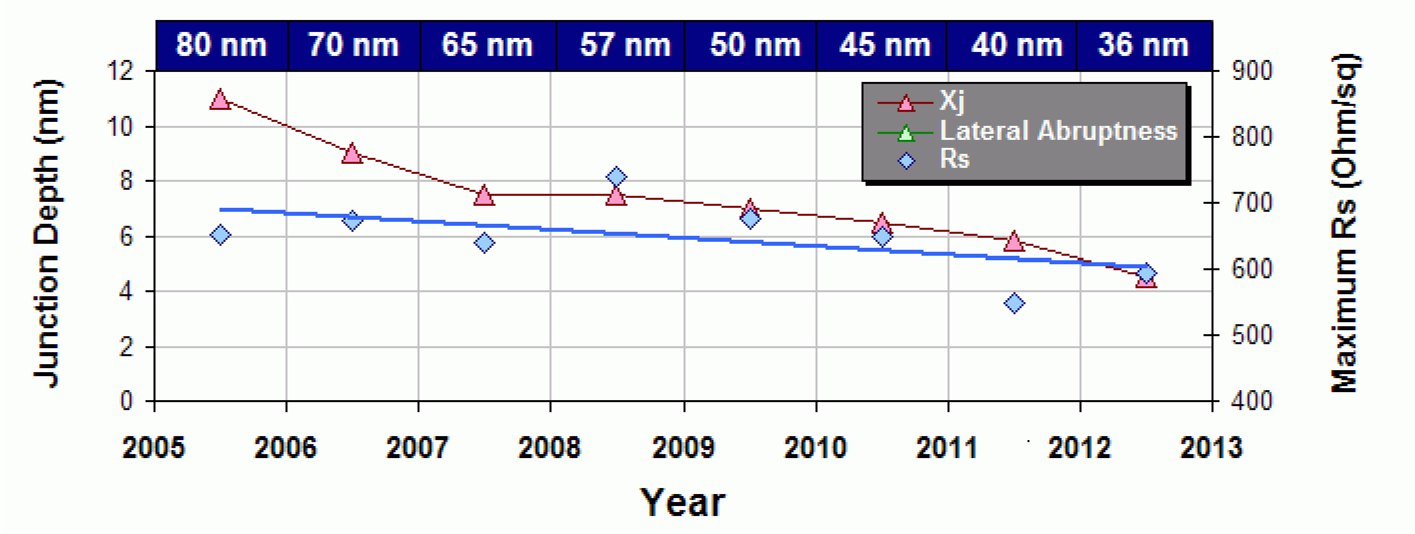
Introduction

Implantation in Semiconductor Technology Doping Requirements

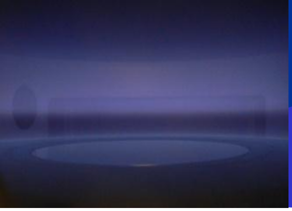


- ❑ Main ion implantation areas
  - ▪ Well doping
  - ▪ Gate doping
  - ▪ Source drain extension doping
  - ▪ Source and drain doping

- ❑ Source drain extension doping requirements for the 45 nm node:



- ➢ **Decrease the implantation energy**
- ➢ **Increase the dopant concentration**



Introduction

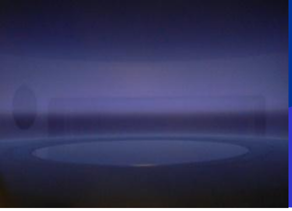
Traditional Ion Implantation

- **Single ion specie at a defined energy**
- **At low energies** (ε < 1keV): Space charge in traditional ion implanters limits the beam transport
    - Low implantation current
    - Degradation of the process throughput & uniformity

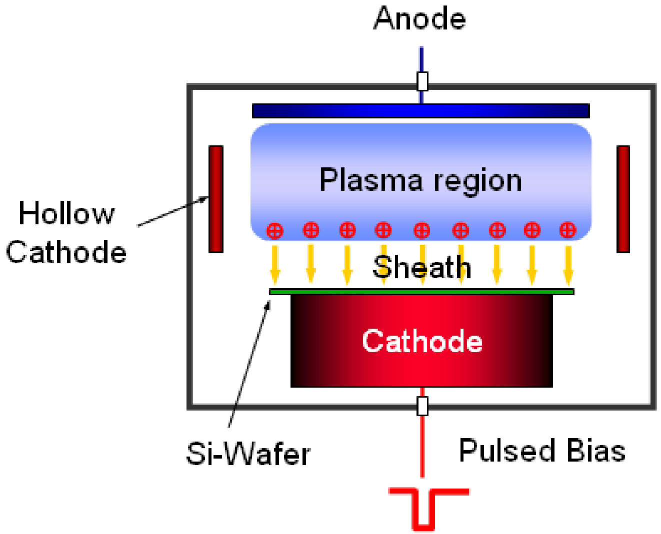
- **Solution**: Decelerate the beam just before the wafer (**U**ltra **L**ow **E**nergy implanters: ULE)

Limitation: Energy contamination by neutral atoms or molecules

↳ Alternative: PLAD (PLAsma Doping)



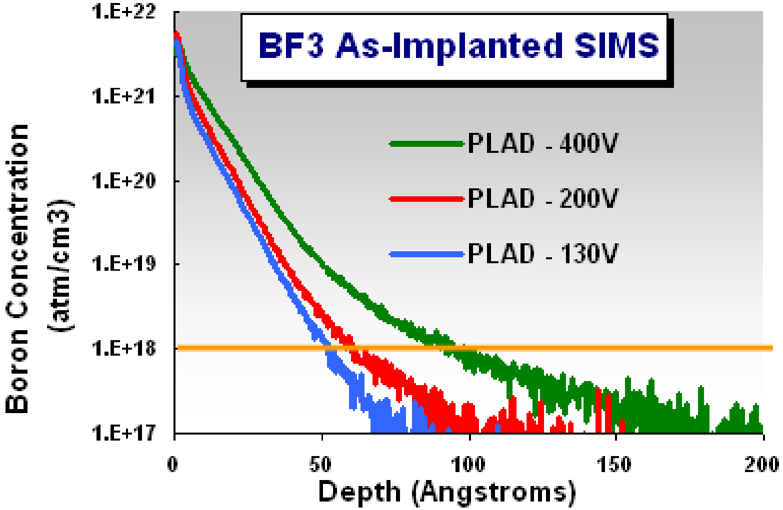
PLAD Principle



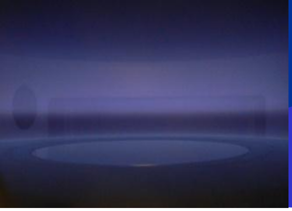
- Negative pulsed voltage is applied to a wafer immersed in a plasma of dopant ions
- **PLAD** ignites the plasma with each pulse
- Multi-ion species at various energies
- A pulsed hollow cathode is used to ignite and maintain plasma at very low energy $\varepsilon < 1$ keV

Advantages:

- Simple & reliable
- High throughput at low energy
- Better energy control (E.C. free)
- Minimal plasma exposure



Dopant depth distribution simulation: Need incident ion energy and mass distribution



Motivation for Plasma Diagnostic

Goals:

- Measure ion energy distribution to predict the dopant depth profile in a plasma based implantation system (PLAD)
- Understand BF_3 plasma and sheath collision processes to optimize plasma based ion implantation

Requirements

- Ions bombarding the wafer and their proportion in the total ion flux sampled from the wafer side
- Time resolved measurements of the Ion Energy Distribution (IED)
- Development of a dopant depth profile simulation protocol

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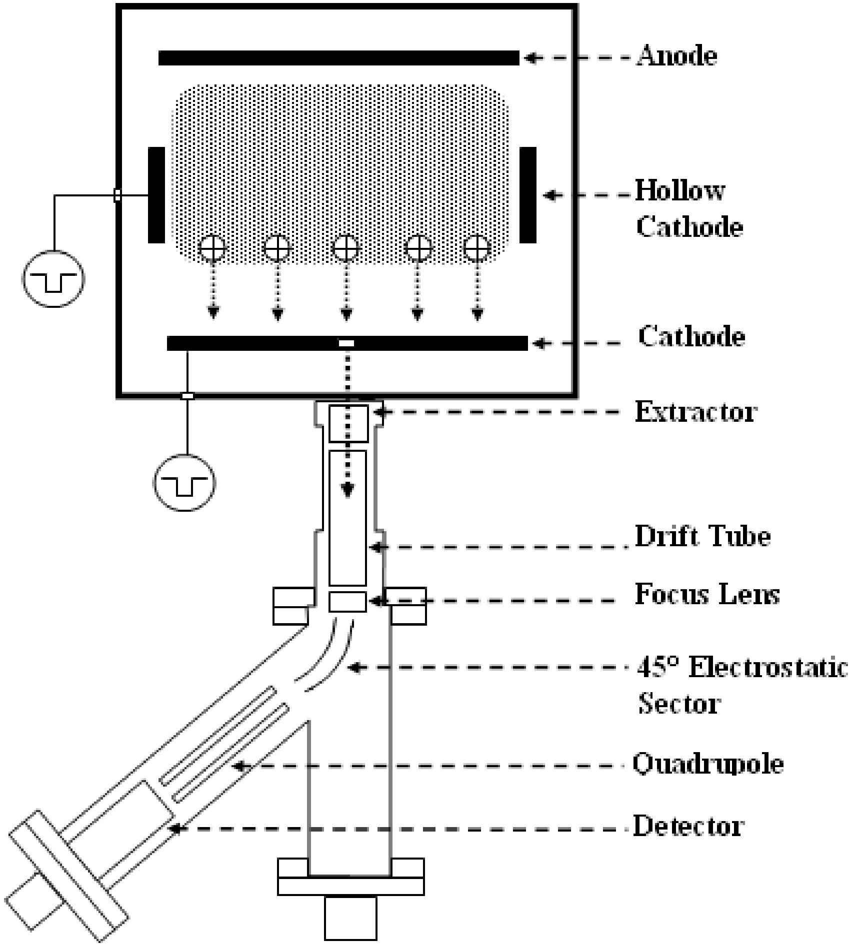
Experimental Setup

Mass spectrometer inside the high-voltage cathode: Concept

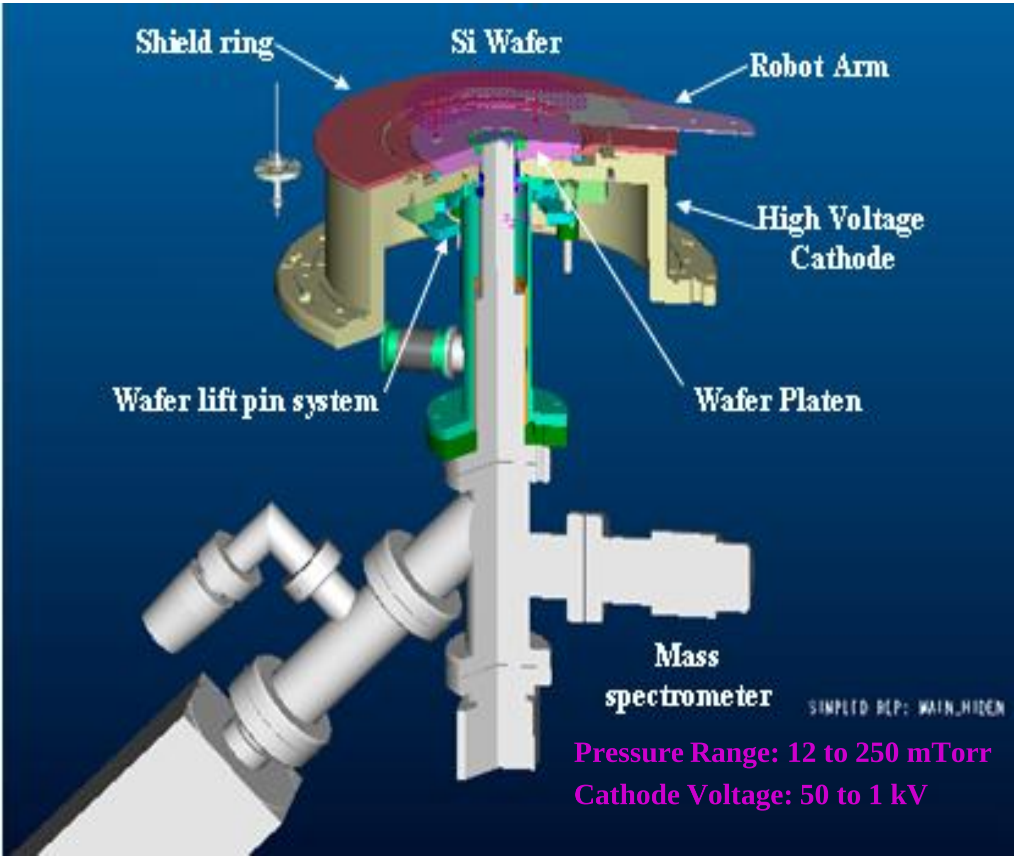


- Commercial ion mass and energy analyzer installed inside the cathode :
  - Can measure ion energy distribution from 0 to 1000 eV
  - Ions extracted through the cathode sheath
  - IED measured in the center of the cathode

Provide: Ion energy and mass distribution

Experimental Setup

Mass spectrometer inside the high-voltage cathode: Design



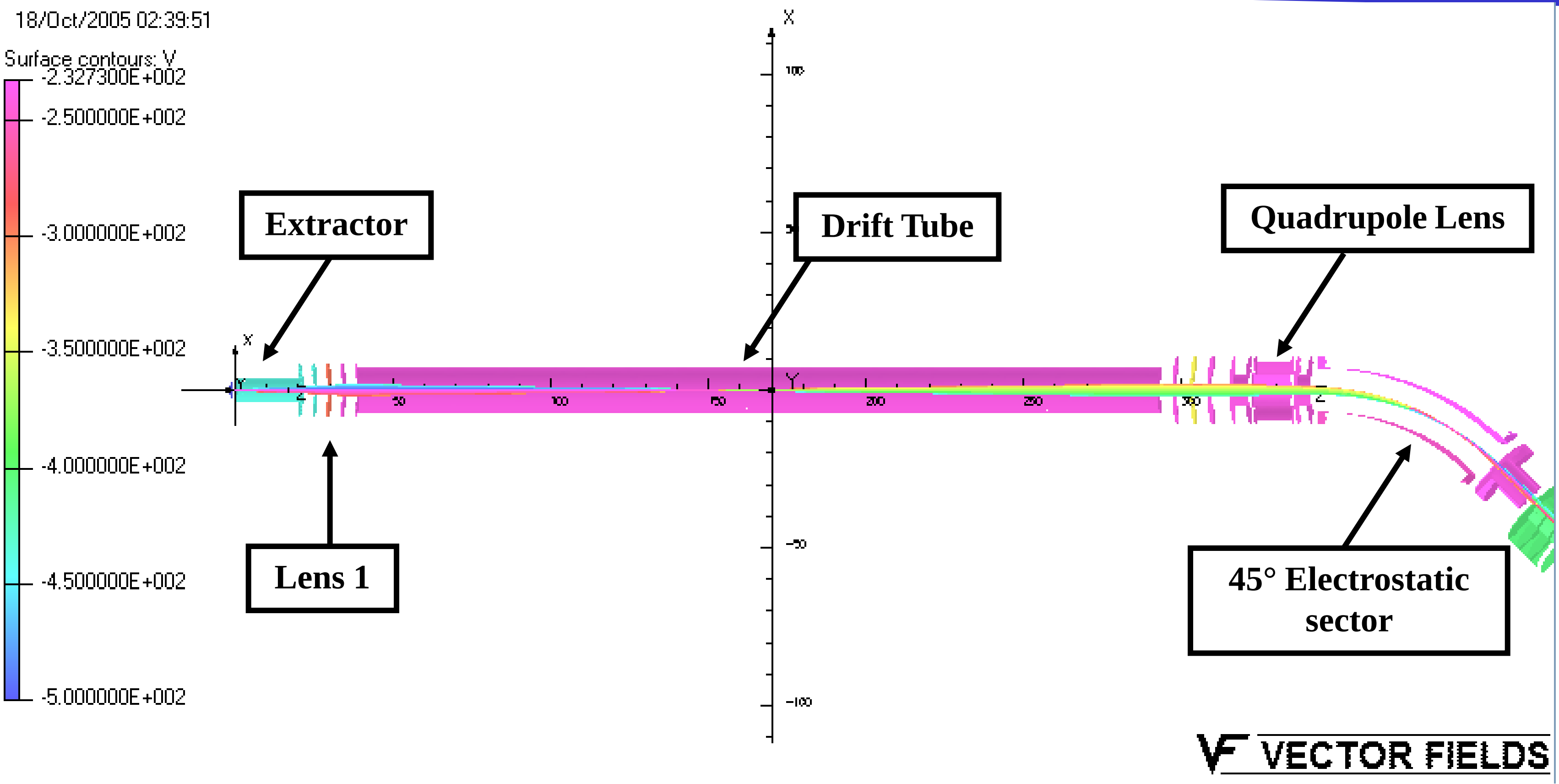
Pressure Range: 12 to 250 mTorr

Cathode Voltage: 50 to 1 kV

- ❑ Mass spectrometer installed inside the high-voltage cathode
- ❑ Ion extracted through 75µm aperture in the center of the cathode
- ❑ Differential pumping minimize the collisions at the entrance of the mass spectrometer (~10^{-7} Torr)
  - ▪ Pressure range inside PLAD chamber: 12 to 250 mTorr
- ❑ Silicon wafer can be replaced using a special modified lift pin system

Experimental Setup

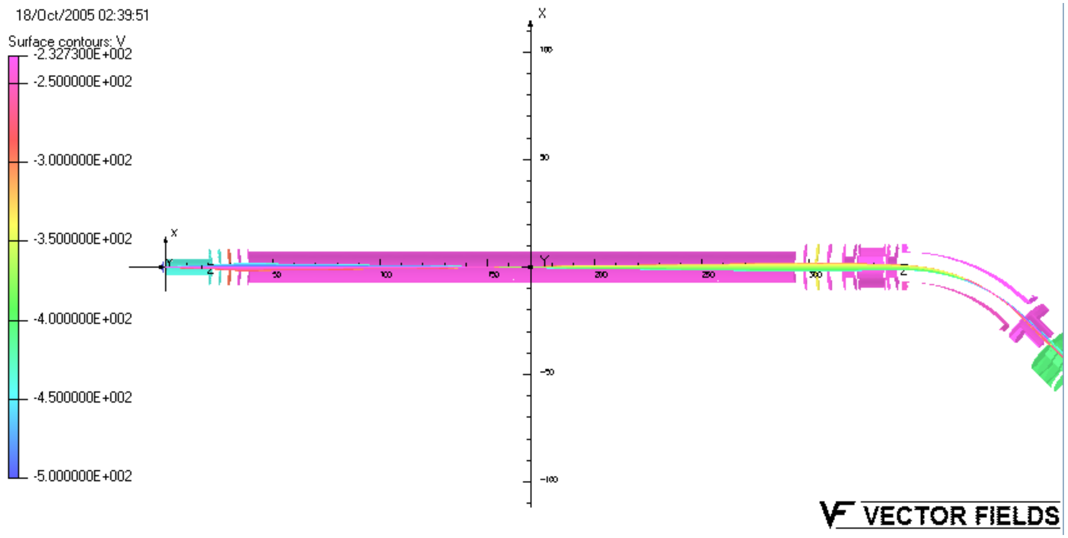
Mass spectrometer inside the high-voltage cathode: 3D simulation

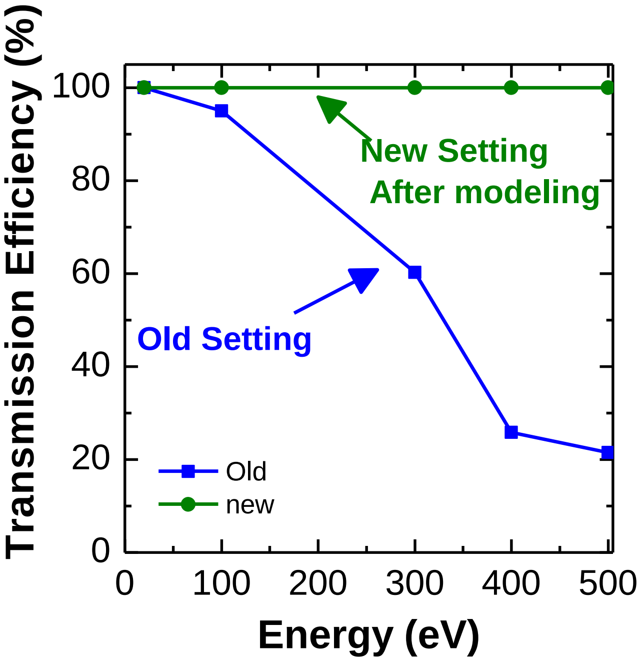


- ❑ Simulation of the ion beam inside the Mass spectrometer

Experimental Setup

Mass spectrometer inside the high-voltage cathode: 3D simulation

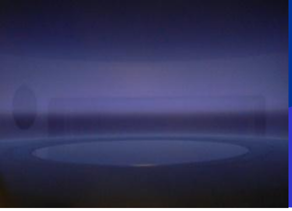




- ❑ Simulation of the ion beam inside the Mass spectrometer

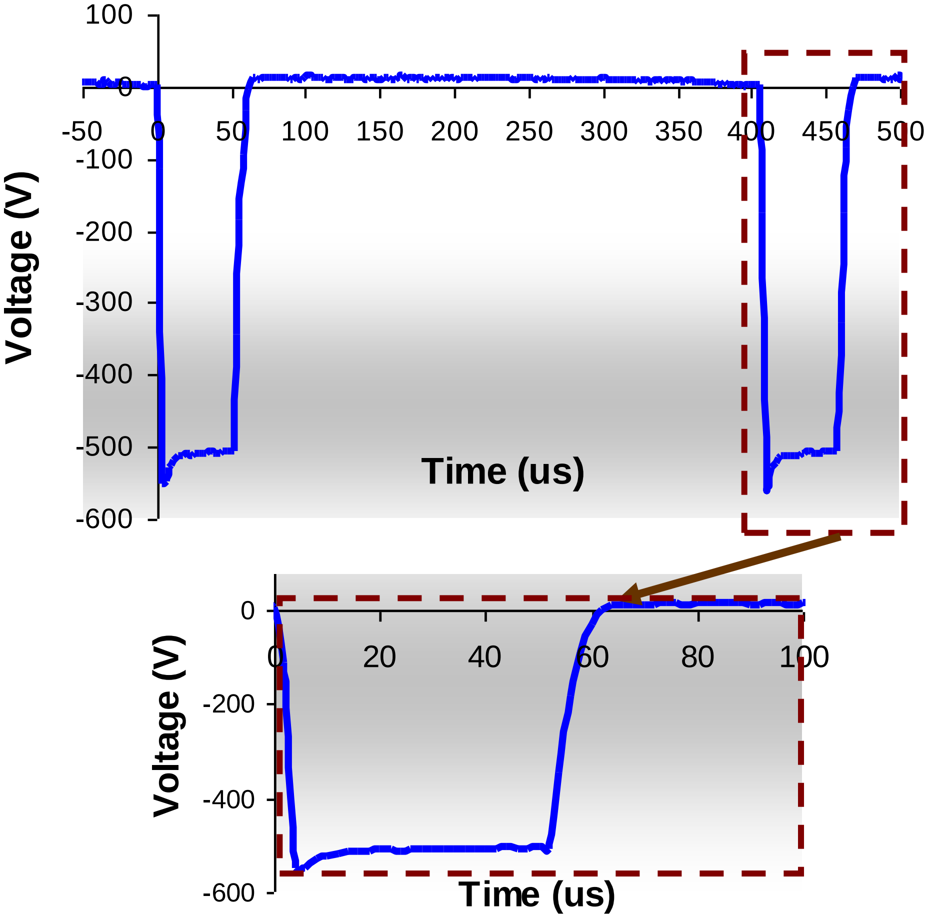
→ modification of optic voltage set-up

Transmission in energy constant (10 to 1000 eV)

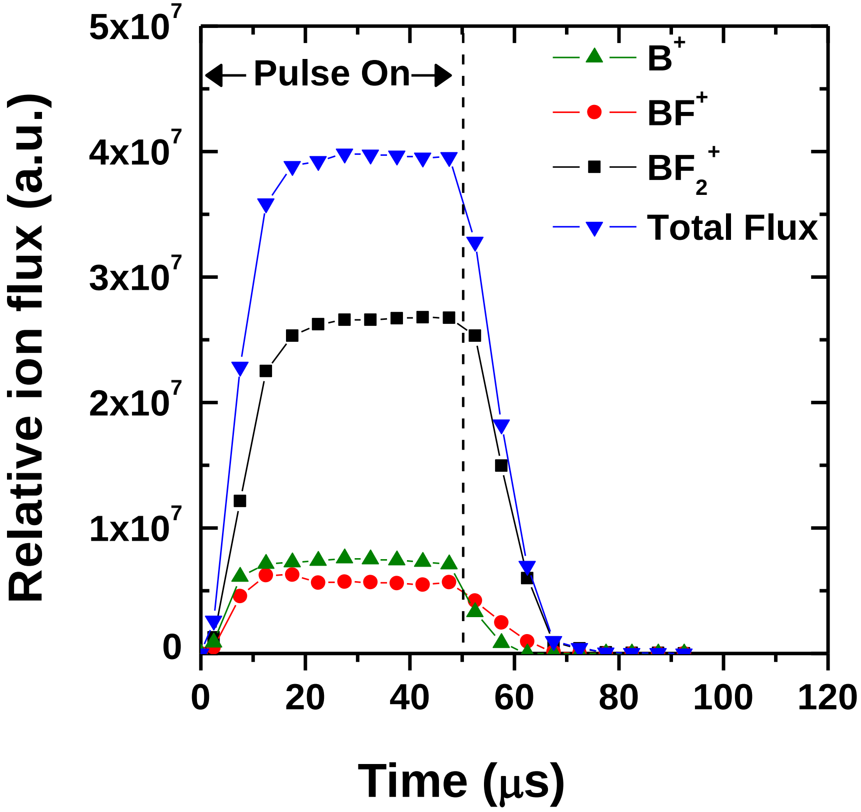


Experimental Setup

Time Resolved Measurements Protocol



- ❑ Rise Time: 5µs
- ❑ Fall Time: 12µs

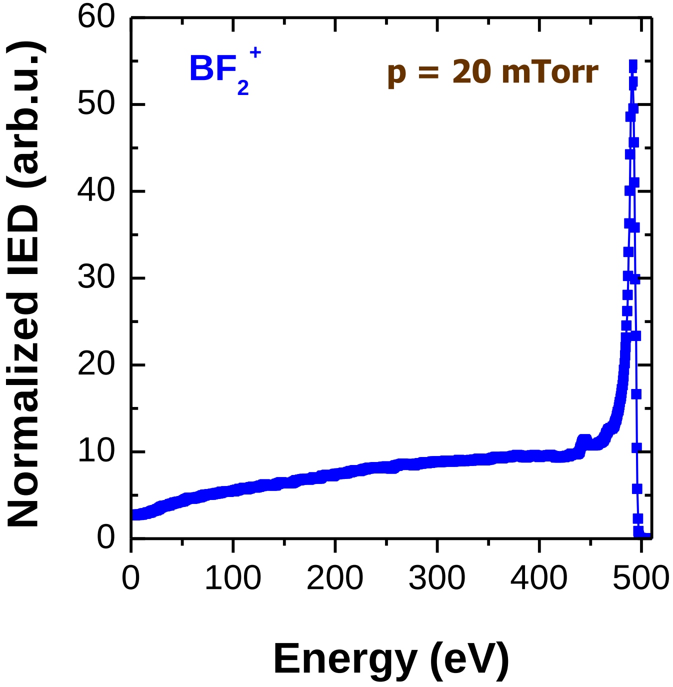


- ❑ Mass Spectrometer data acquisition
  - ▪ Synchronized with the PLAD pulse
  - ▪ When voltage is stabilized

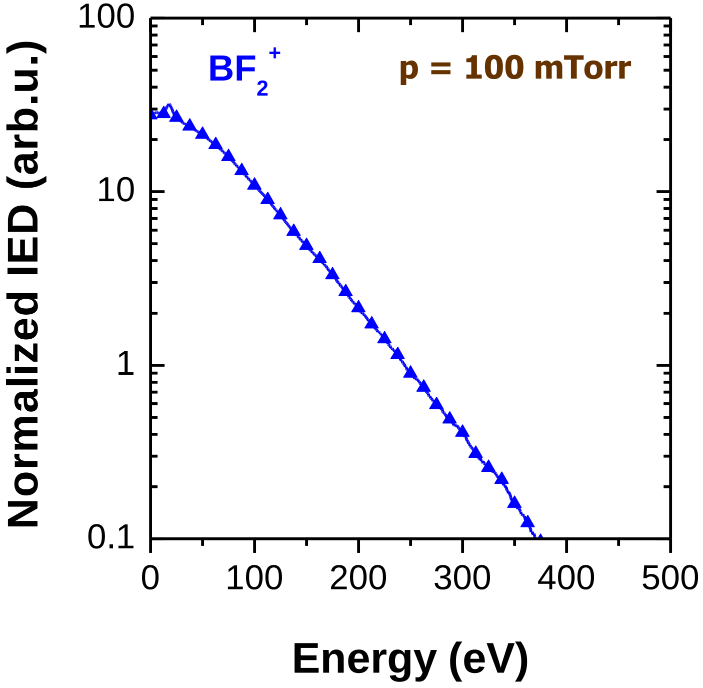
BF_2^+ Ion Energy Distribution BF_3 500V

Ion Reaching the Cathode During Pulse-On period

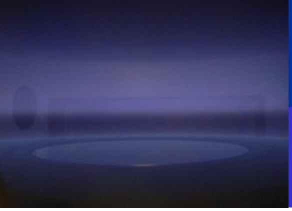
With Hollow cathode



Without Hollow cathode



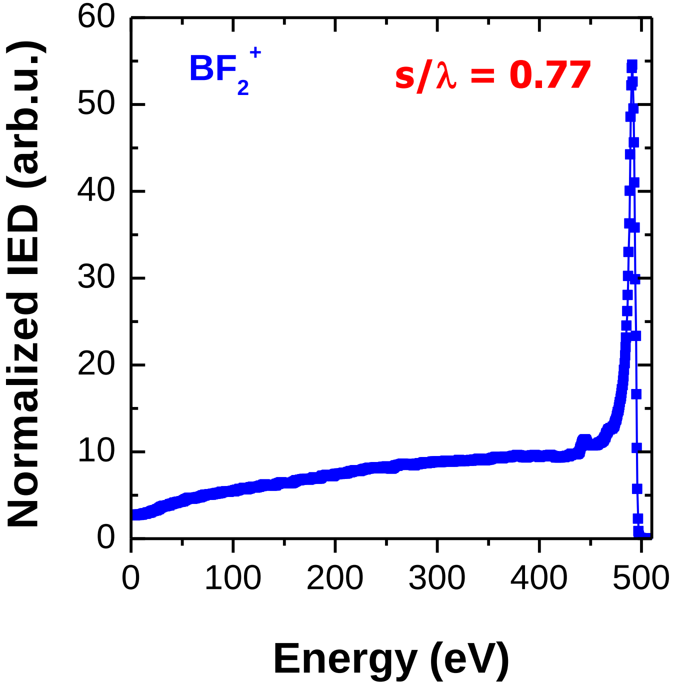
- IED shape strongly varies with experimental conditions
  - Higher fraction of energetic ions in the hollow cathode mode (lower pressure, higher density)
  - Many collisions occur inside the sheath in the no hollow cathode mode (higher pressure, lower density)



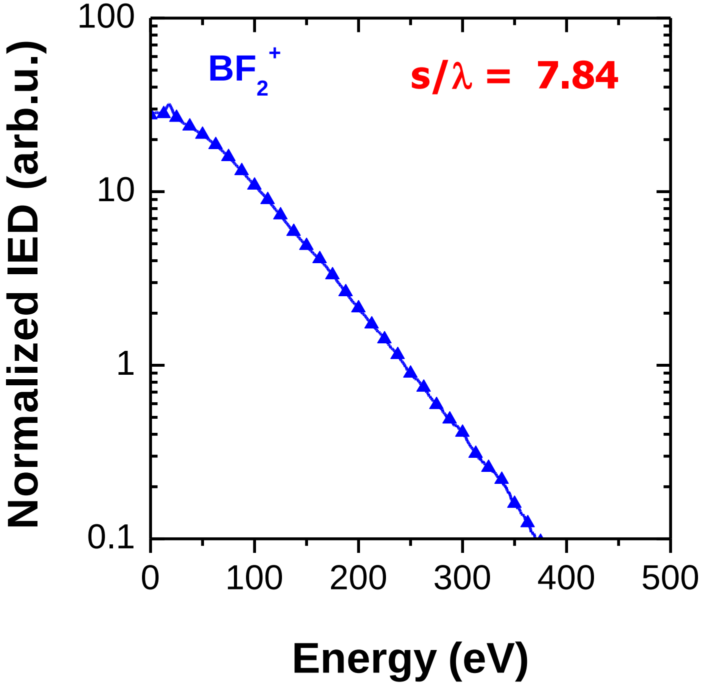
BF_2^+ Ion Energy Distribution BF_3 500V

Ion Reaching the Cathode During Pulse-On period

With Hollow cathode

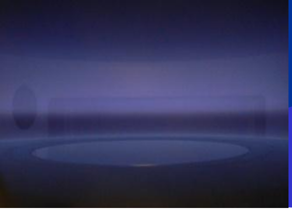


Without Hollow cathode



- IED shape strongly varies with experimental conditions
  - Higher fraction of energetic ions in the hollow cathode mode (lower pressure, higher density)
  - Many collisions occur inside the sheath in the no hollow cathode mode (higher pressure, lower density)

Ion energy distribution at the cathode can be measured



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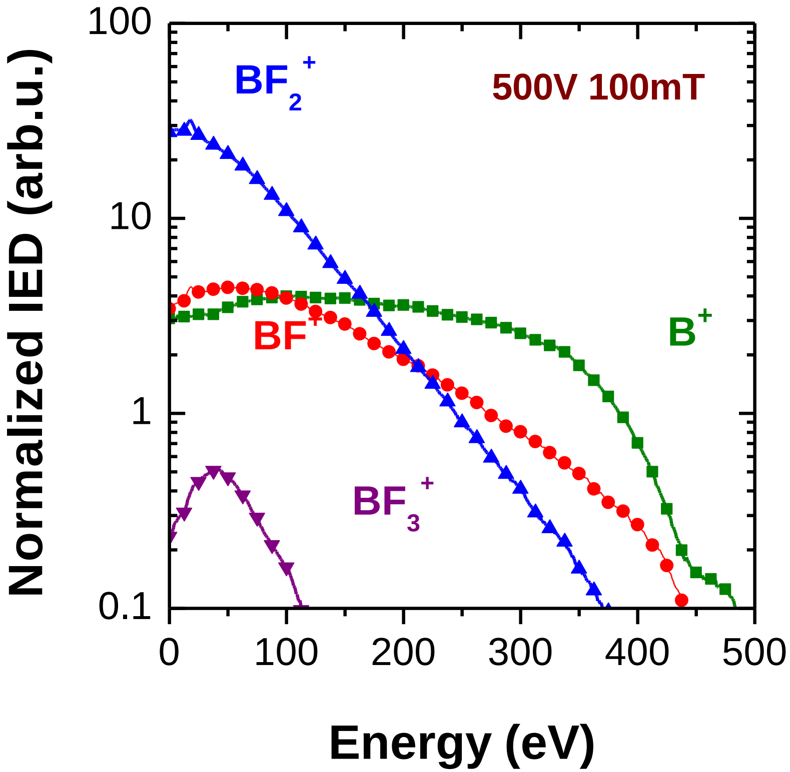
Ion Energy Distribution BF_3 500V

Ions Reaching the Cathode During Pulse-On Period



- Main ions detected:
  - B^+
  - BF^+
  - BF_2^+
  - BF_3^+
- BF_2^+ dominant ion

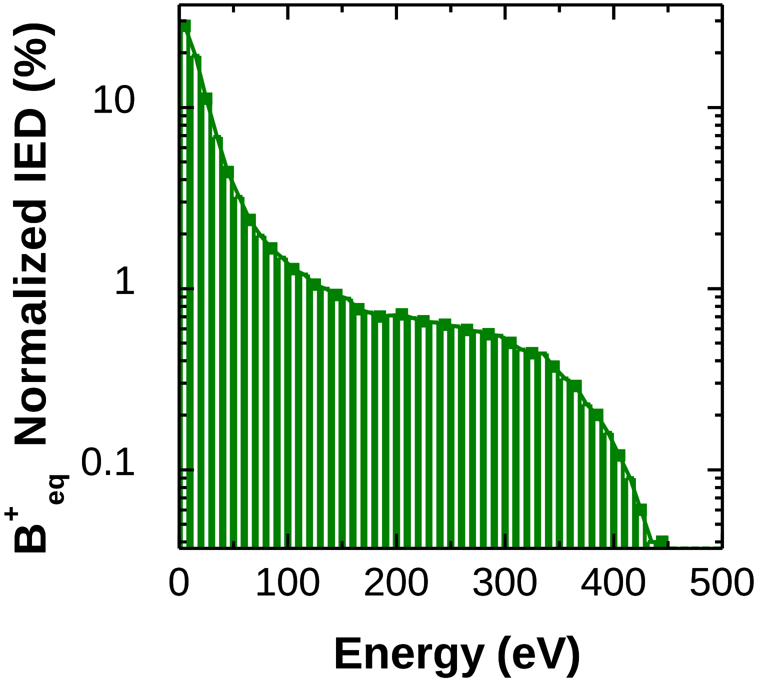
- Implantation of multi-ion species at various energies
- Need to modify the depth profile simulation protocol used with traditional ion implantation

Simulation of Dopant Depth Profile: Protocol

- **Goal:** prediction of the dopant depth profile using SRIM* and experimental ion energy distributions

  - The SRIM code accepts only atomic ions: BF_x^+ ion energy distributions are converted into equivalent boron, B^+_{eq} ion energy distribution

$$E(B^+_{eq}) = \sum_x E(BF_x^+) \times \frac{m(B^+)}{m(BF_x^+)}$$

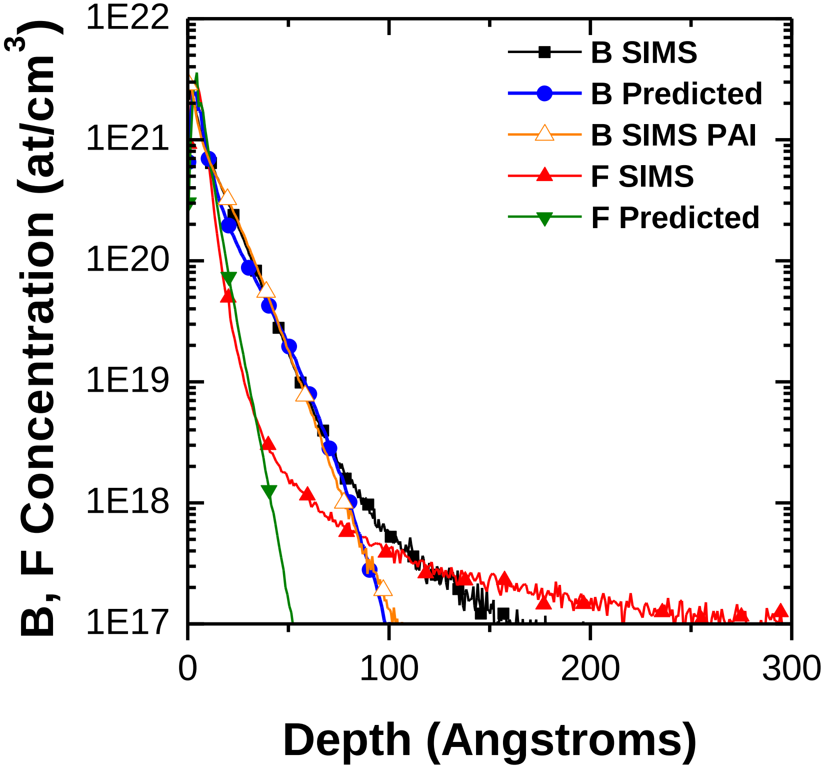


  - Boron Equivalent IED is divided in 10eV increments and input into the SRIM software
  - The simulation output is normalized to the SIMS measured dose

* J. F. Ziegler, J. P. Biersack and U. Littmark, Pergamon Press, New York, 1985

Simulation of Dopant Depth Profile: Predicted dopant profiles and comparison with measured SIMS profiles

500V 100mTorr BF_3 plasma

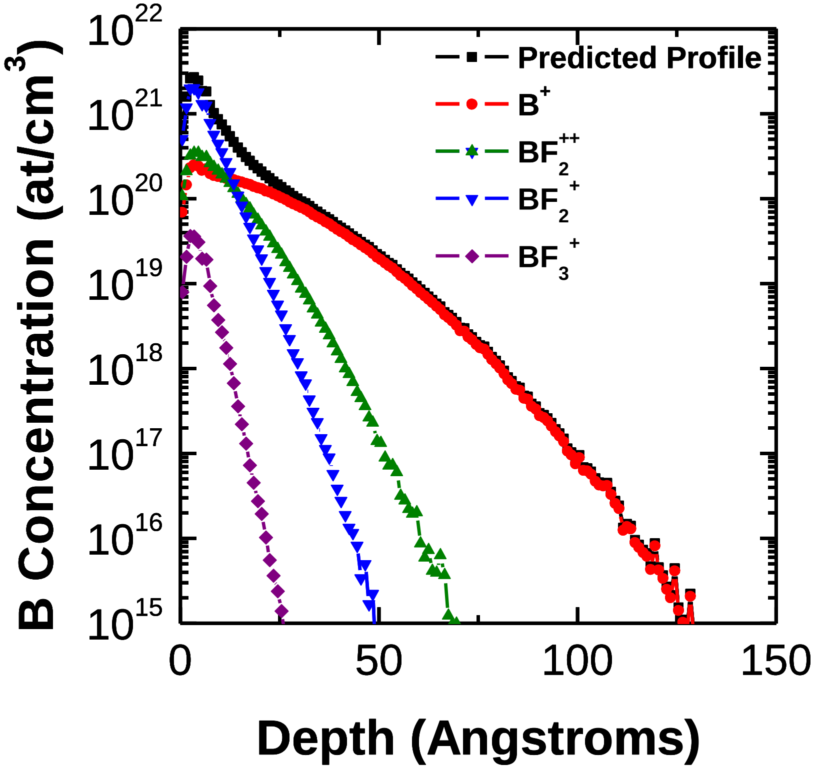


- Channeling inside the silicon → low implantation angle
- Good correlation between SIMS and predicted profiles

The simulation can be used for dopant profile prediction

PLAD Dopant Depth Profile Analysis

- Simulation allows for dopant depth profile analysis

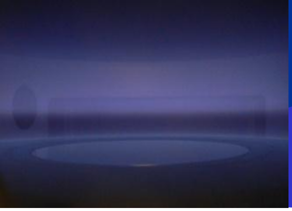


- B^+ defines the depth part of the dopant profile
- BF_2^+ defines the surface concentration and dose
- BF_3^+ plays a minor role in the dopant profile

- To obtain shallower junction with PLAD

→Need to understand how B^+ is created
  - Bulk plasma characterization
  - Cathode sheath characterization

→Control the B^+ ion flux and energy



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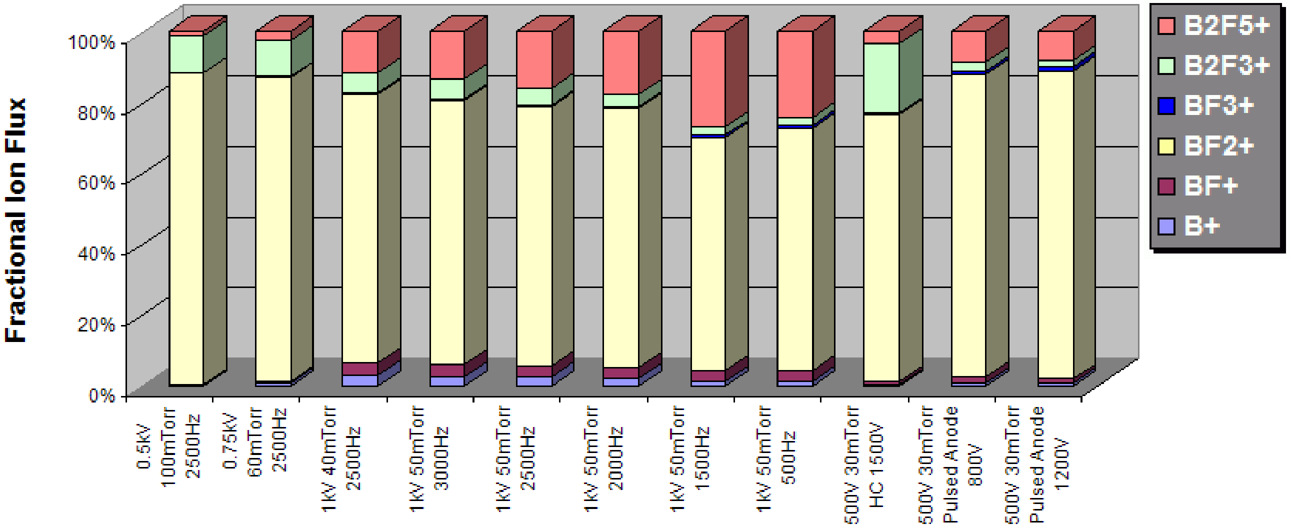
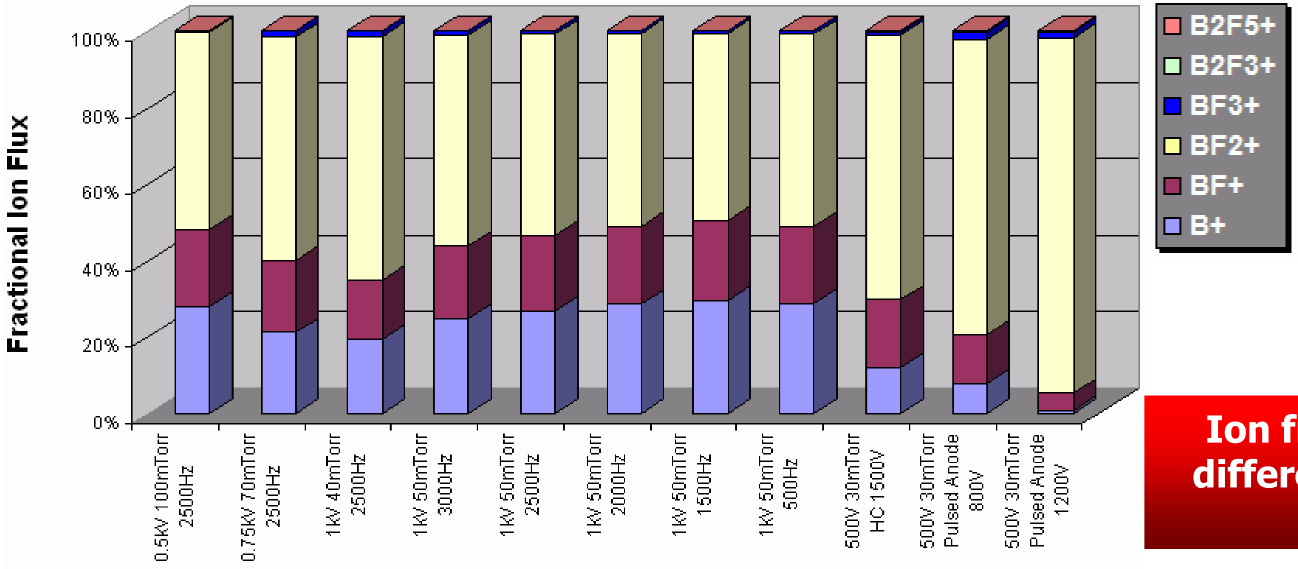
Plasma Characterization

Ion fractions



Bulk plasma

- BF_2^+ is the dominant ion
- Small fraction of B^+ and BF^+ (<2% of the total ion flux under all different conditions)
- Heavy ion detected ($B_2F_3^+$, $B_2F_5^+$)

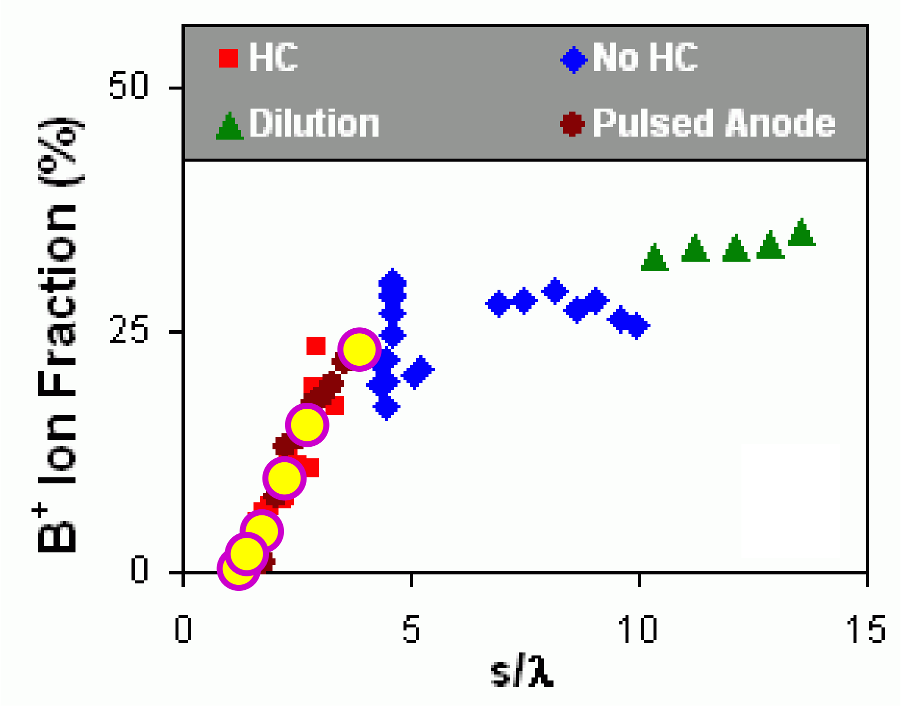


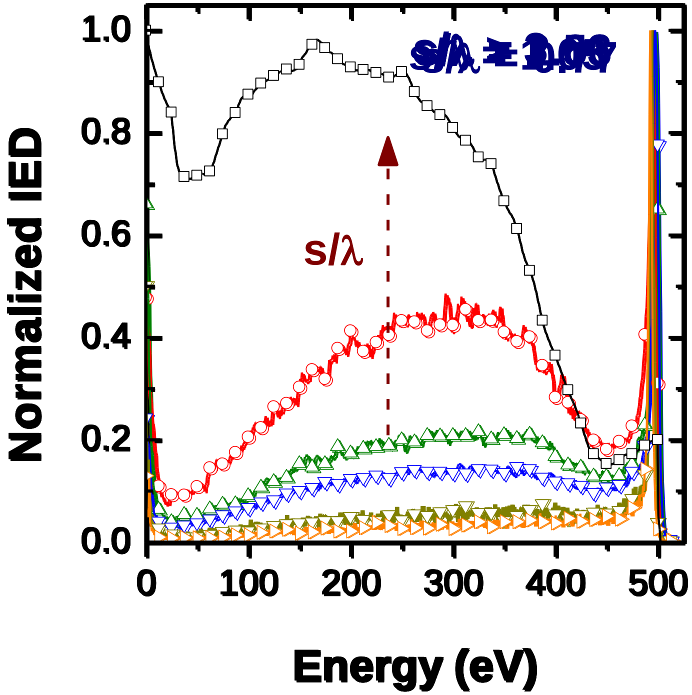
Ion across the sheath

- Heavy ion fraction strongly reduced
- Lighter ion fraction significantly increased inside the sheath
- B^+ and BF^+ most probably created inside the sheath

Ion fraction from the bulk plasma different than the one measured at the cathode

B^+ ion fraction as a function of the number of collisions inside the sheath





- ❑ B^+ ion fraction strongly increases when the number of collision inside the sheath increases
- ❑ B^+ fraction at the cathode similar to its fraction from the bulk in case of collision-less sheath
- ❑ Confirm that B^+ is created inside the sheath
- ❑ **Two different hypothesis:**

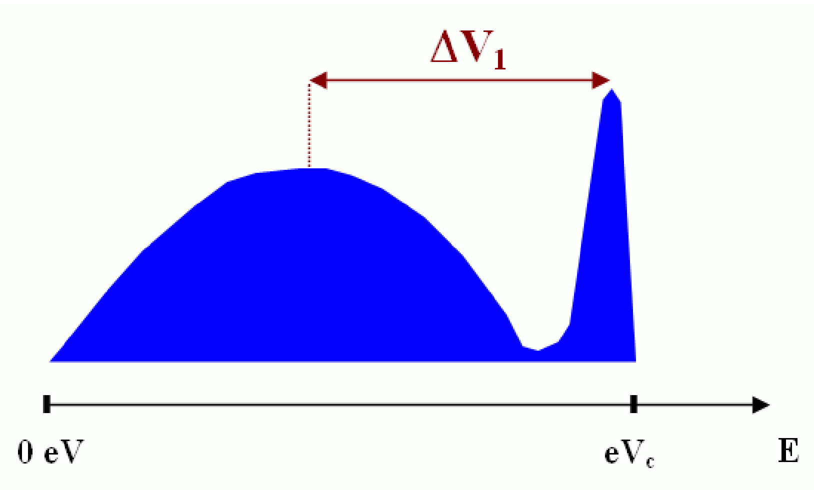
Ionization inside the sheath (not likely)

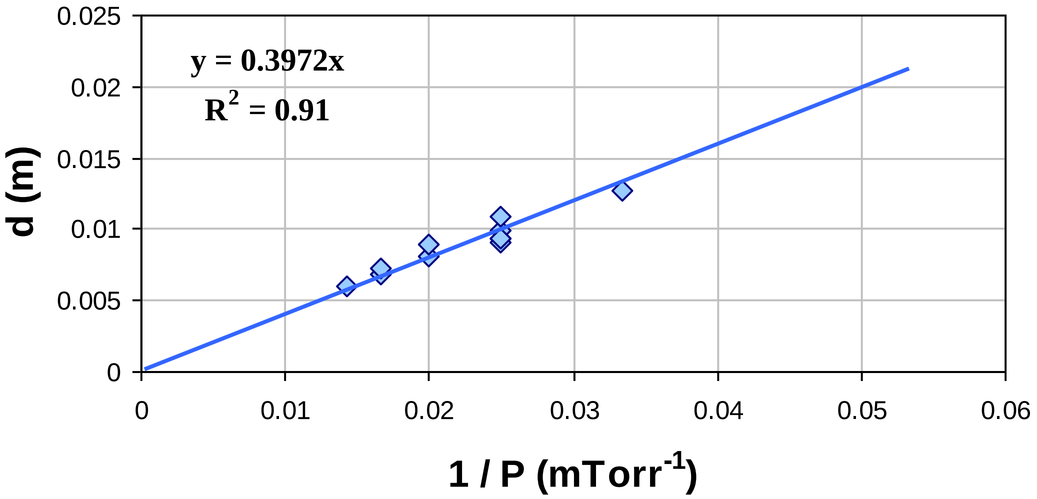
Dissociation of heavier ions by collisions with neutrals

Heavy ion dissociation into B^+ inside the sheath

Validation of the hypothesis

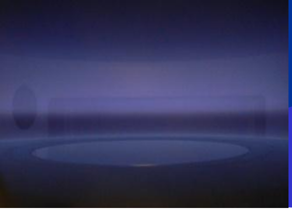
$$B_xF_y^{\,+} + M \longrightarrow B^{+} + \text{Neutral\_fragments} + M$$





- Child Langmuir Law allows for the conversion of ΔV1 into a distance d traveled inside the sheath
- If the heavy ions dissociate inside the sheath to produce B^+, the distance d is equal to the heavy ion dissociation mean free path and is inversely proportional to the pressure

B^+ is created by dissociation of heavy molecular ions inside the sheath



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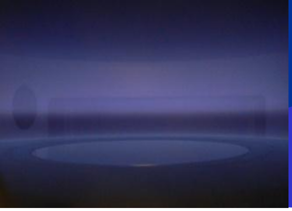


Shallower Dopant Profile:

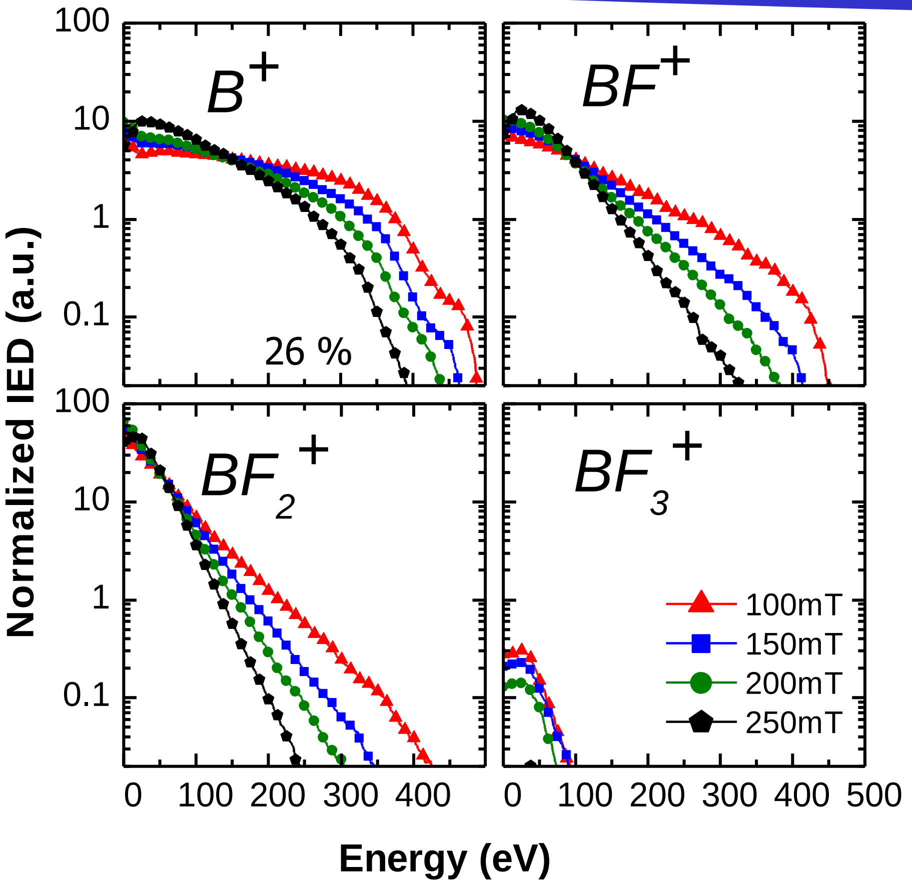
Two Different Approaches:

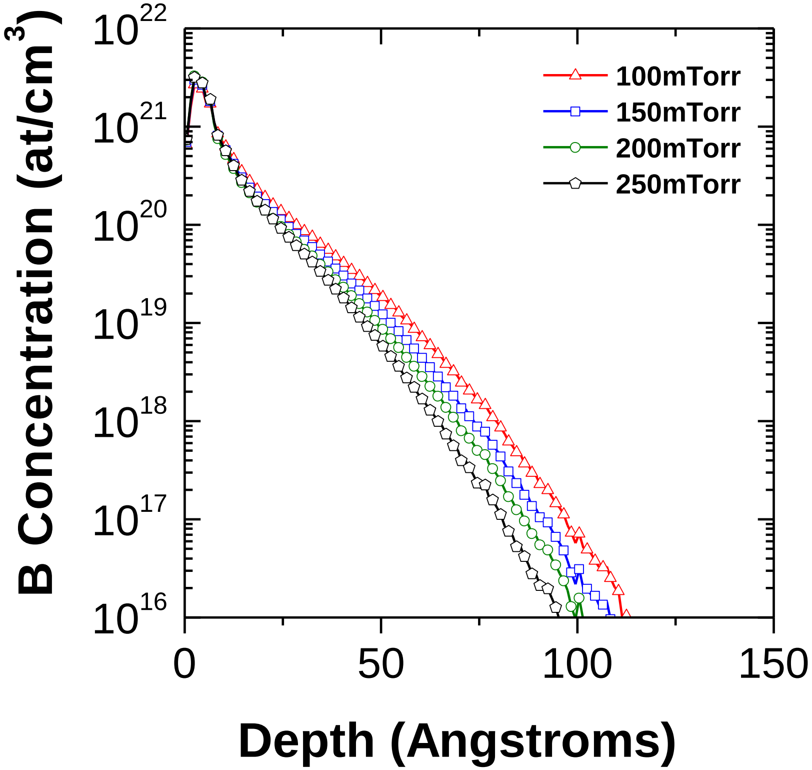
- Highly collisional sheath
  - High B^+ fraction but low mean energy
- Collision-less sheath
  - Low B^+ fraction but high mean energy

Collisional Sheath

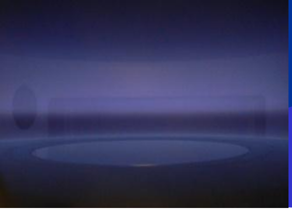
BF_3 500V, High pressure

Ion Energy Distribution



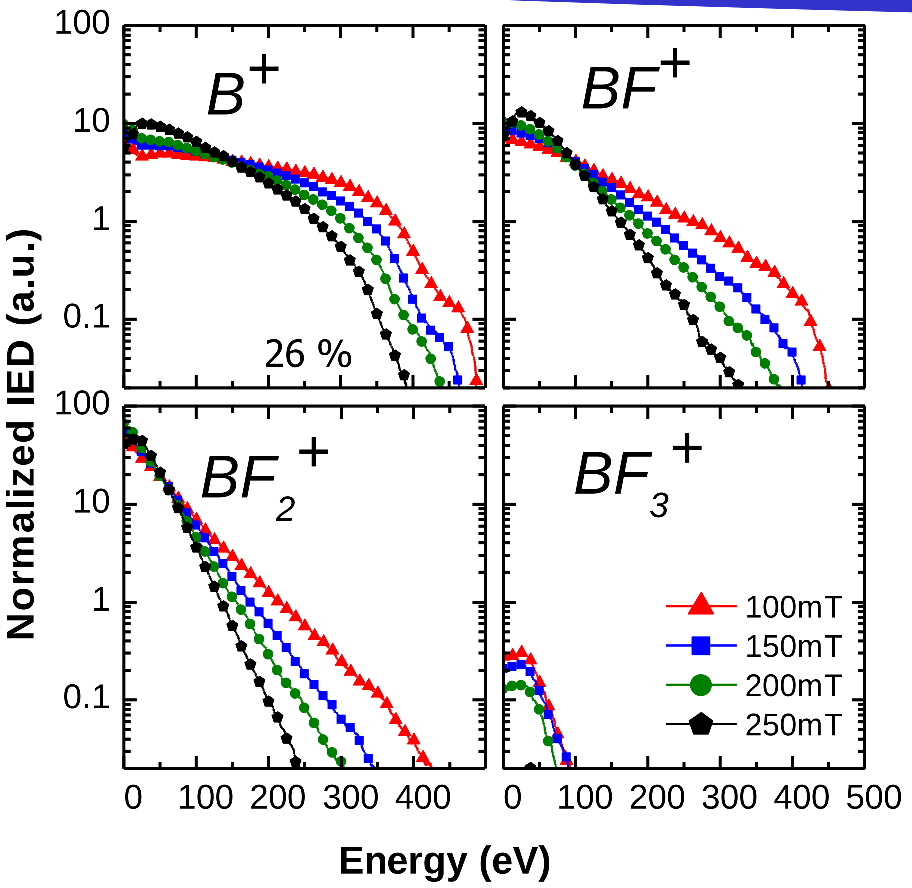


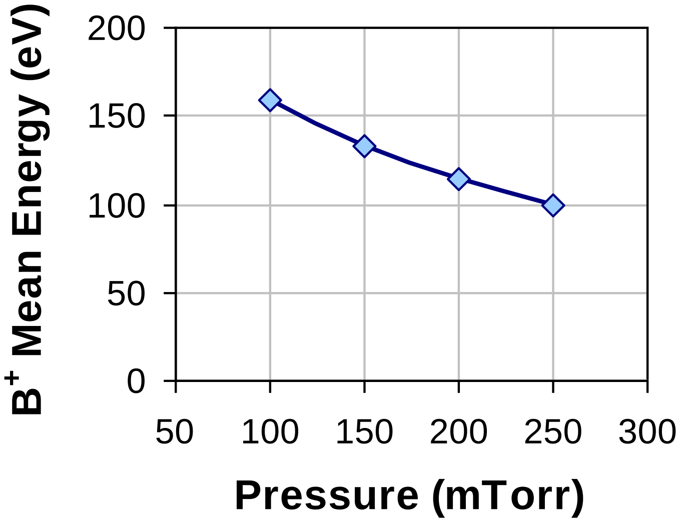
- B^+ mean energy is reduced
- Higher pressure, provides shallower dopant depth profile
- Paschen's curve limitation



BF_3 500V, High pressure

Ion Energy Distribution





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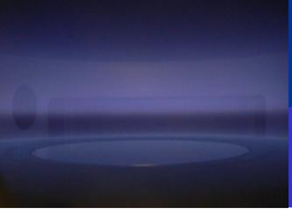


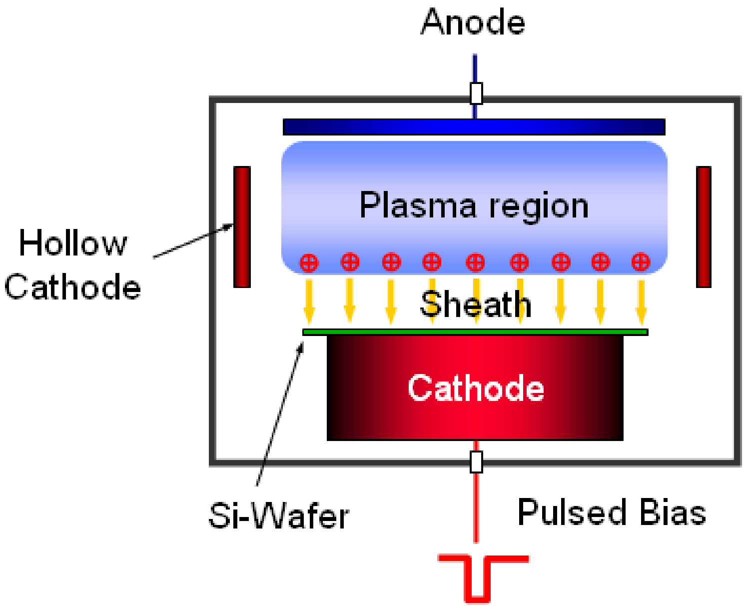
Collision-less sheath

Hollow cathode plasma

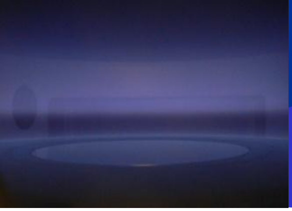
Control of the Plasma Density

Hollow Cathode Function

- Self sustained discharge for low energy implantation (V_b<600V)
  - Secondary Electron production
    - Mirror electric field for electrons
    - Confinement
  - Higher plasma density
  - Lower discharge pressure

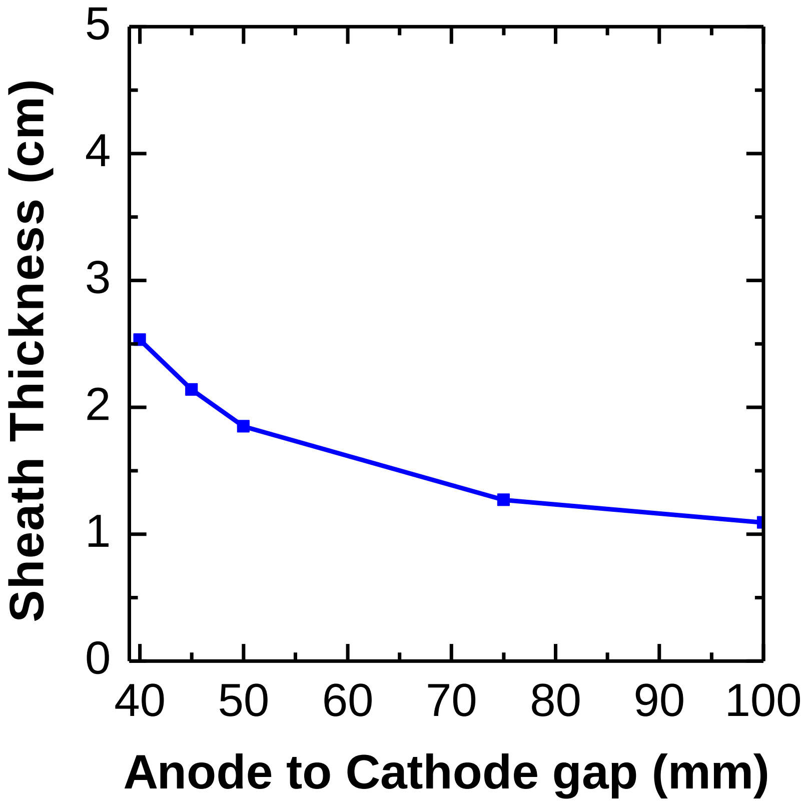


- New operating parameter: anode to cathode spacing
  - Electric field strength and E/N variations due to a change of the effective anode to cathode gap



Sheath Thickness with different Anode-to-Cathode Spacing

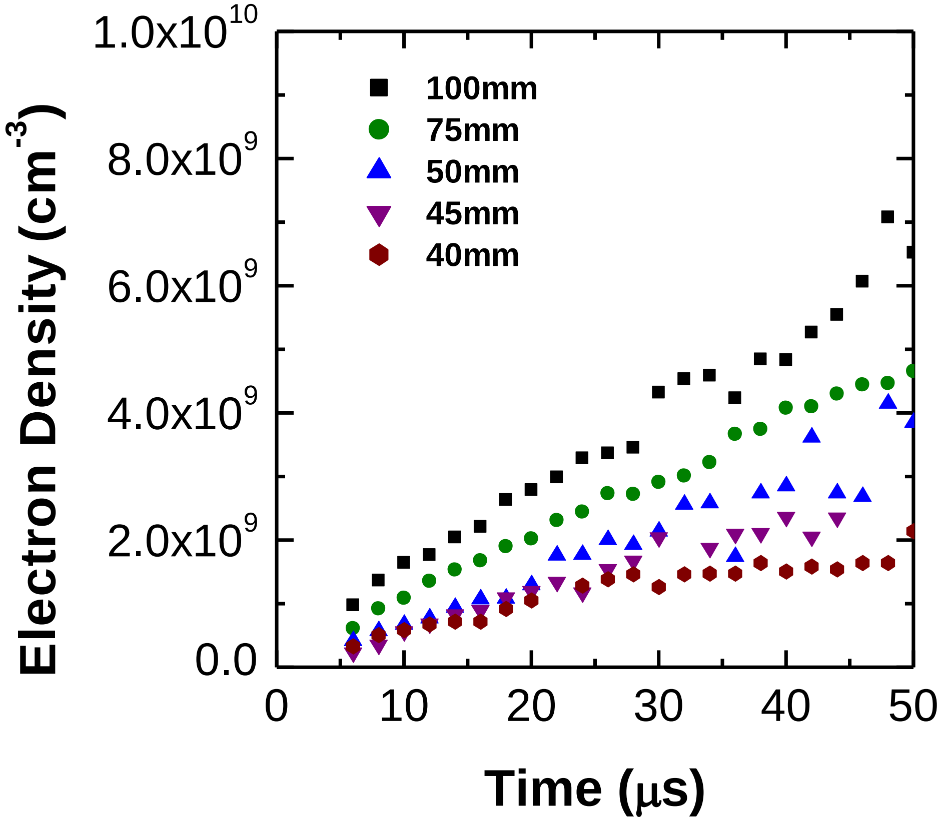
500V 30mT 50μs BF$_3$ discharge – Hollow cathode: 1400 V



- ❑ Effective hollow cathode surface is increased by increasing the anode to cathode spacing
- → Plasma density increases
- → Sheath thickness decreases

Sheath Thickness with different Anode-to-Cathode Spacing

500V 30mT 50μs BF_3 discharge – Hollow cathode: 1400 V



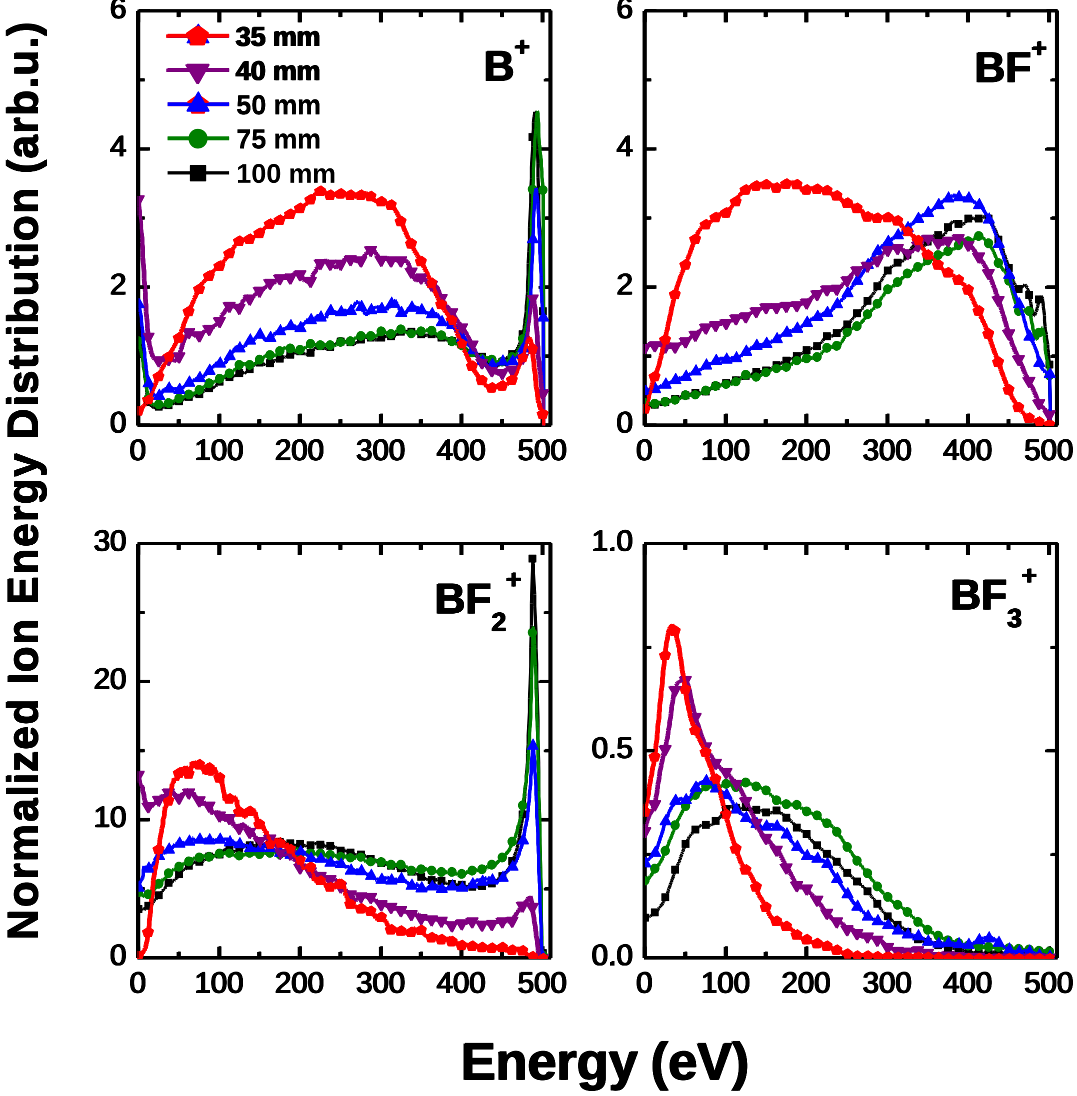
- ❑ Effective hollow cathode surface is increased by increasing the anode to cathode spacing
- → Plasma density increases
- → Sheath thickness decreases
- ❑ Pressure is constant, mean free path stays the same

→Less collisions occur inside the sheath

Increasing anode to cathode gap → affects the IED of the ions reaching the wafer

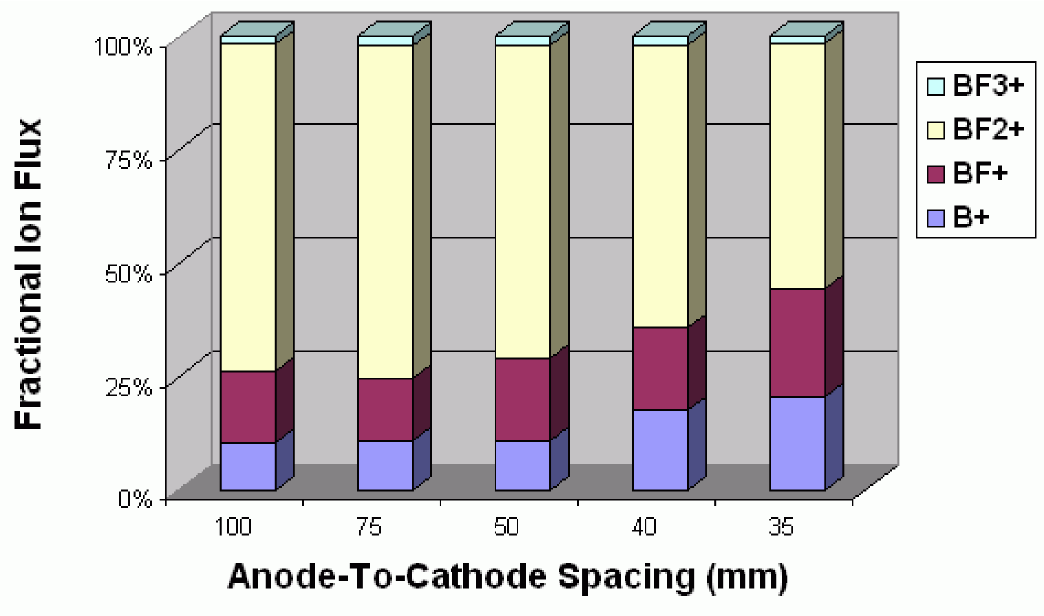
Anode Spacing Effect on the Ion Energy Distribution

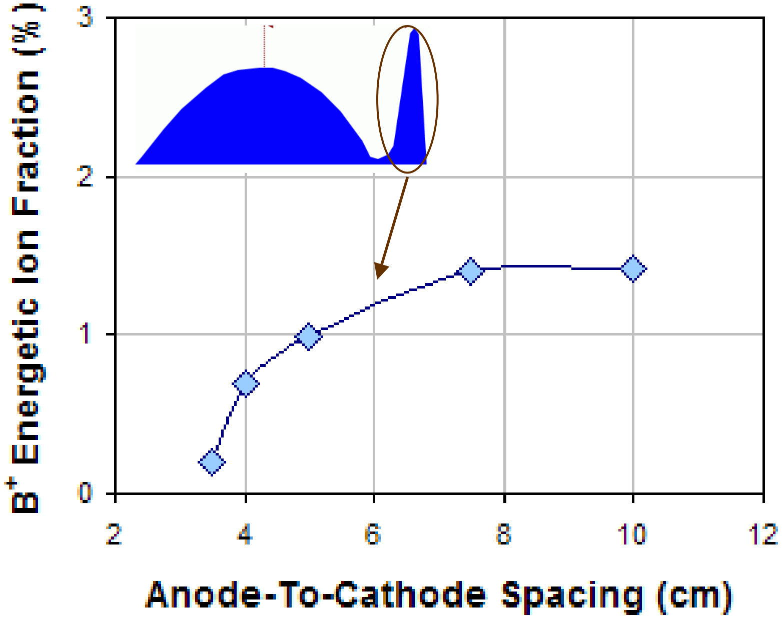
500V, 30mT, 2500Hz, 5sccm, Dose 1e15, Hollow cathode: 1400V



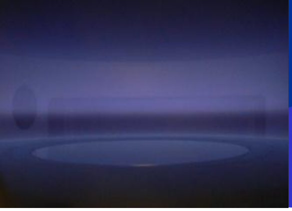
Anode Spacing Effect on the Boron Molecular Ion Fractionation and Fraction of B^+ Energetic

500V, 30mT, 2500Hz, 5sccm, Dose 1e15, Hollow cathode: 1400V



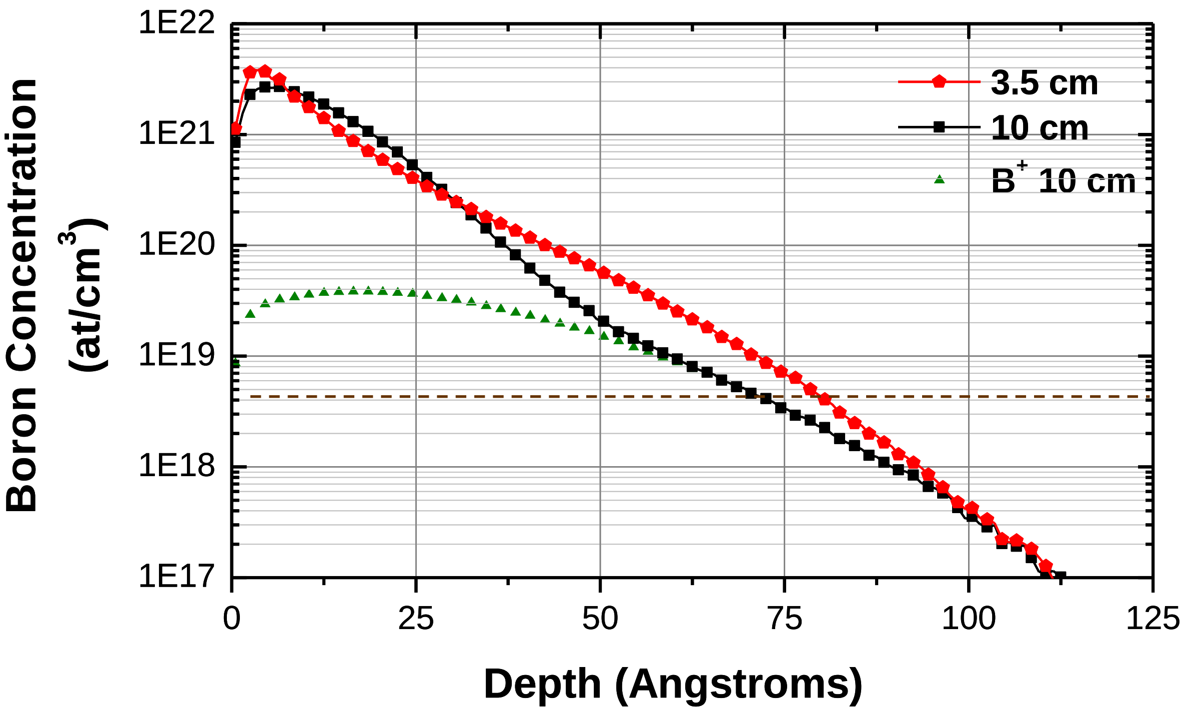


By increasing anode to cathode spacing, the collisions in the sheath decrease and production of light ions decreases



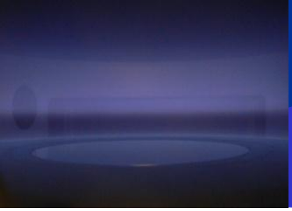
Predicted dopant profile based on IED

500V 30 mTorr BF_3 discharge at different anode-to-cathode spacing



- ❑ **Shallower junction for larger gap**
  - ▪ Lower B^+ ion flux
  - ▪ Higher fraction of B^+ energetic
- ❑ **Optimum dopant profile not reached**

→ **Need to further minimize the number of collisions inside the sheath**

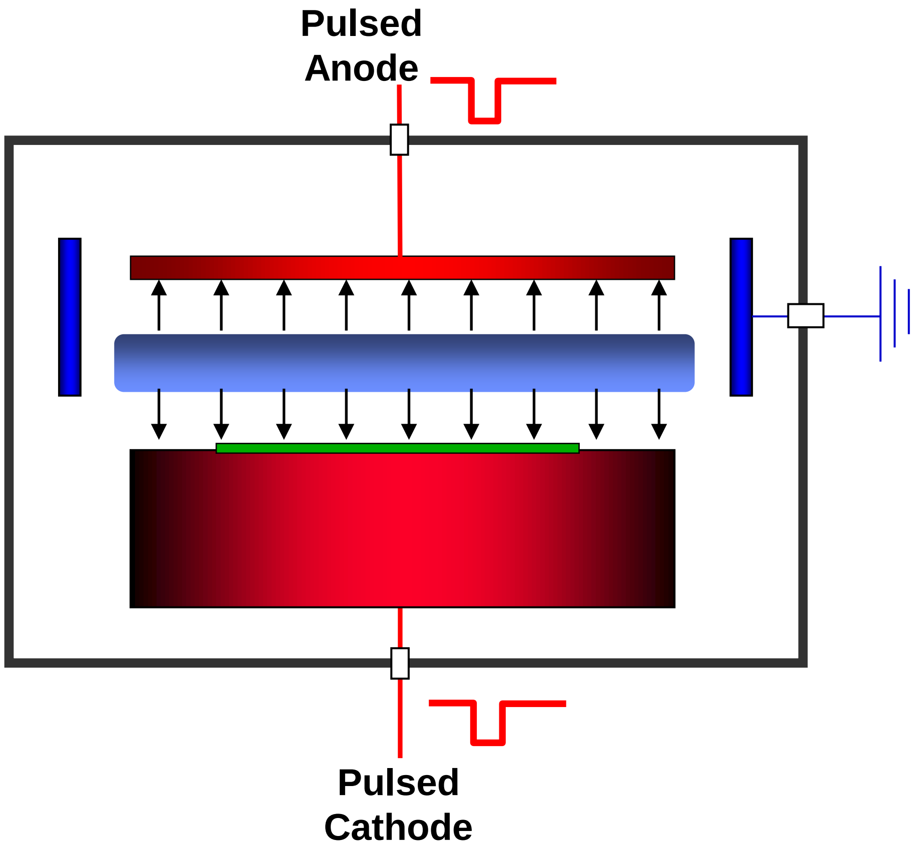


Collision-less sheath

Pulsed Anode Plasma

Pulse Anode Mode

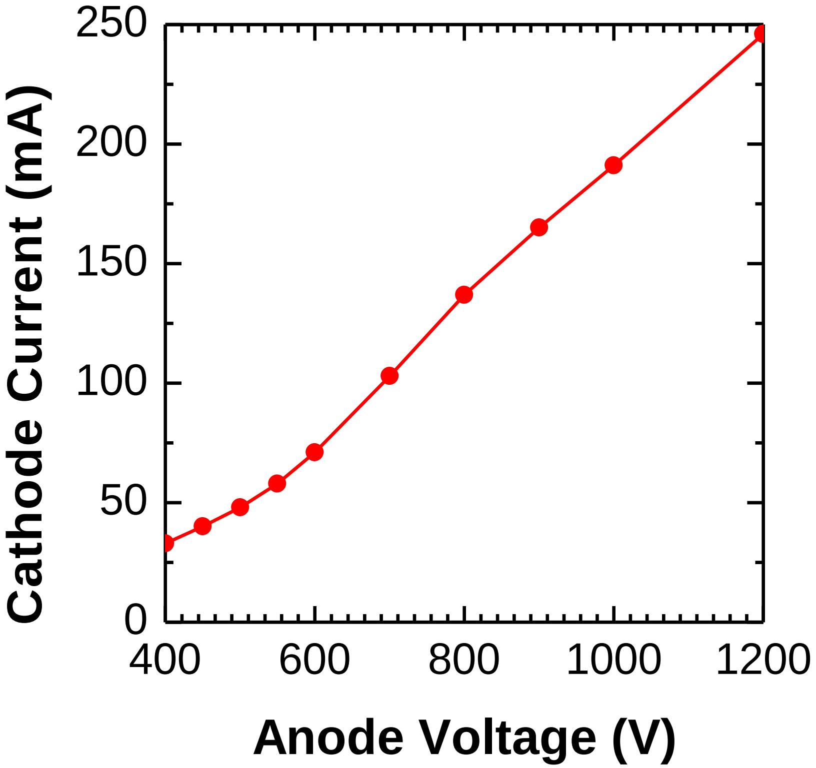
- **Pulsed anode mode (V_a>400V)**
  - Electron confinement between the two pulsed electrodes
  - Higher plasma density
  - Lower discharge pressure

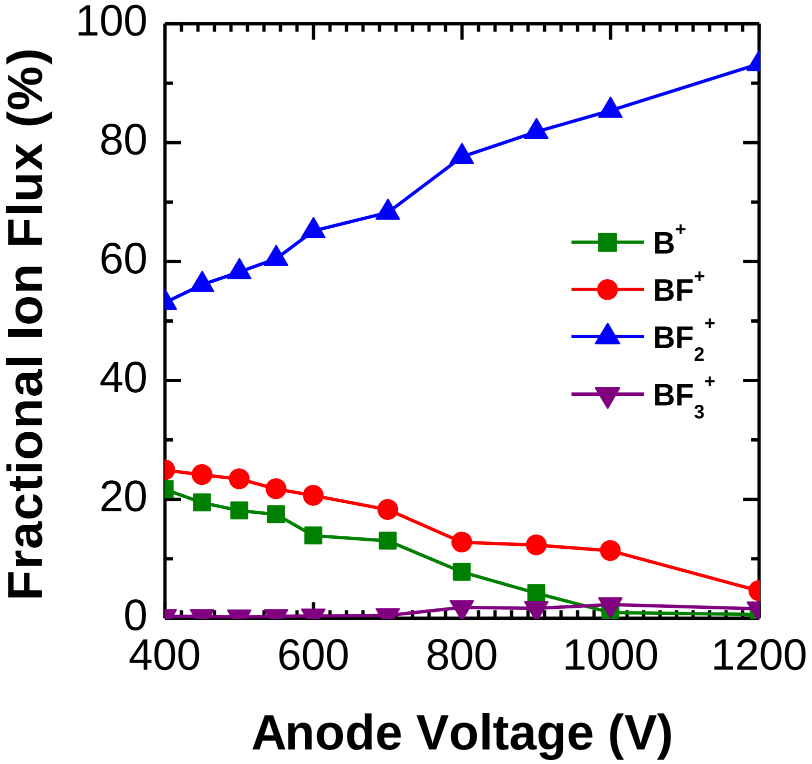


- **Anode voltage: New operating parameter**

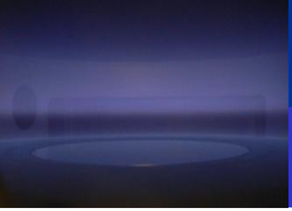
Pulsed Anode Voltage Effect on the Boron Ion Flux Content

500V, 30mT, 50μs, 2500Hz, 5.5cm



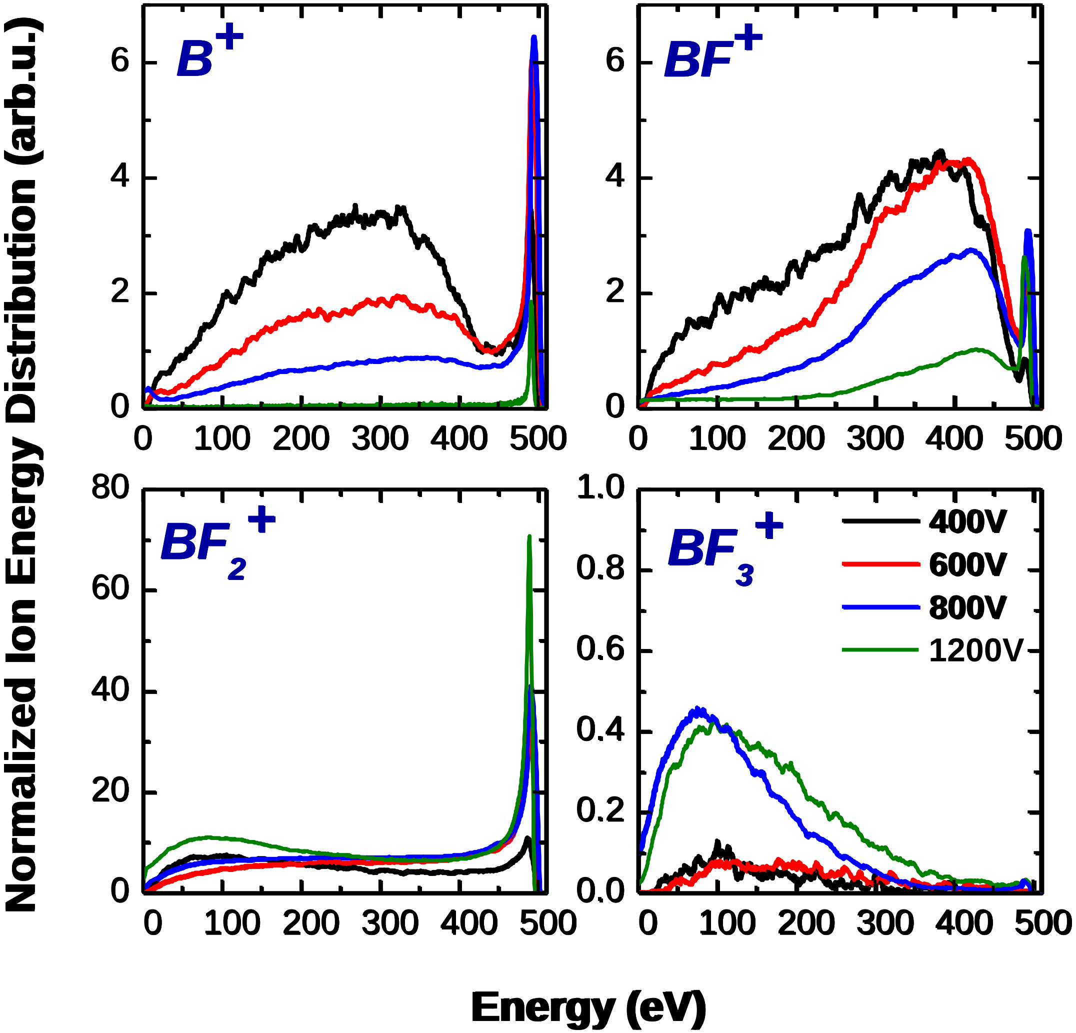


By Increasing the plasma density, number of collisions in the sheath decrease and production of light ions decreases



Ion Energy Distribution for different Pulsed Anode Voltage

500V 30mT 50μs BF$_3$ discharge



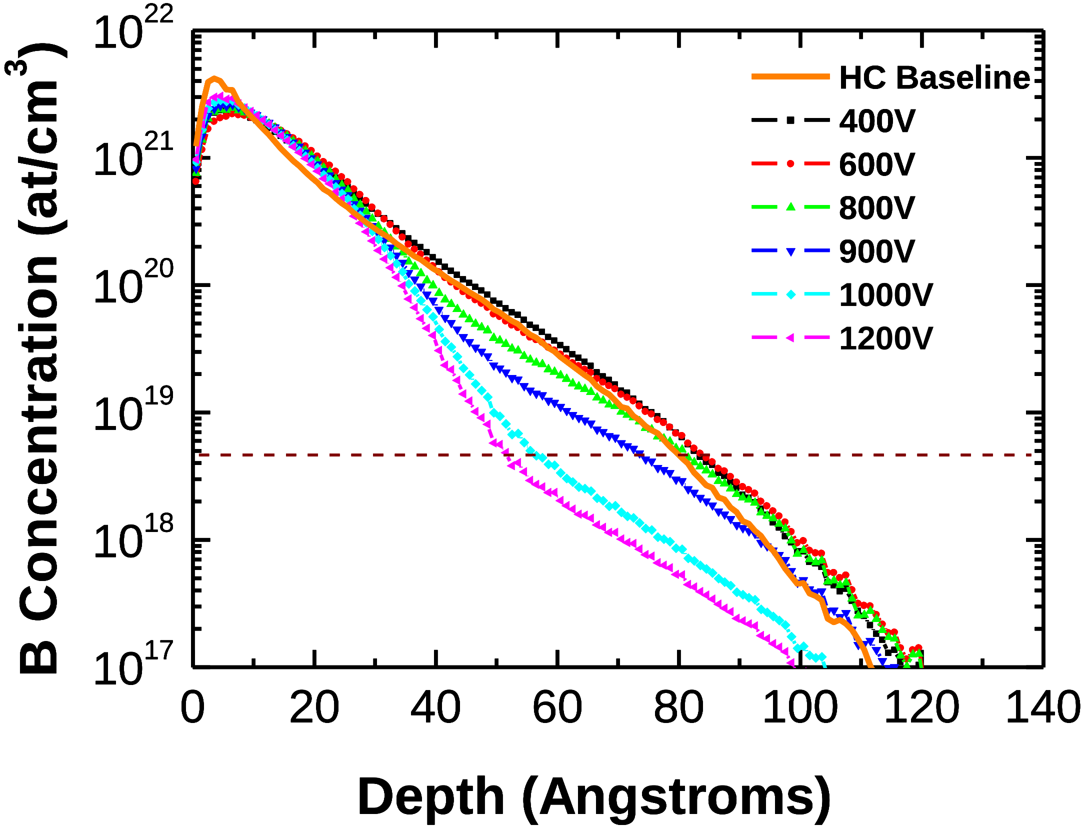
- No more B$^+$ creation in the sheath for high anode voltage

  → Minimization of the B$^+$ fraction

- B$^+$ energetic fraction does not increase

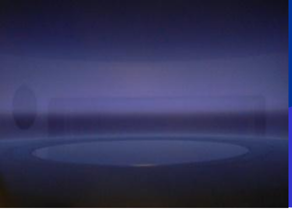
Pulsed Anode versus Hollow Cathode Baseline

500V, 30 mTorr, 50 μs, 2500 Hz



- Shallower Junction depth with higher anode voltage

Control of dopant depth profile

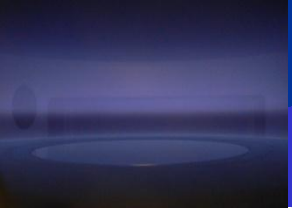


Summary and Conclusion

- ❑ Bulk plasma mass spectrometry measurement not sufficient to predict dopant depth profile into silicon
- ❑ Measurement of the ions reaching the cathode during pulse-on period provide the necessary information to predict the dopant depth profile

- ❑ A fraction of B^+ and BF^+ measured at the cathode are created by dissociation of heavier ions inside the sheath

Characterization of bulk plasma and cathode sheath are needed to optimized the dopant depth profile and obtain shallower junction



Perspective

- Scientific
  - Heavy ions characterization
  - Negative ions (role in the discharge)

- Industrial
  - Study new chemistry (B_2H_6, AsH_3, PH_3…)
  - Profile engineering
  - Global model for process simulation