Consequences of Implanting and Surface Mixing During Si and SiO_2 Plasma Etching*

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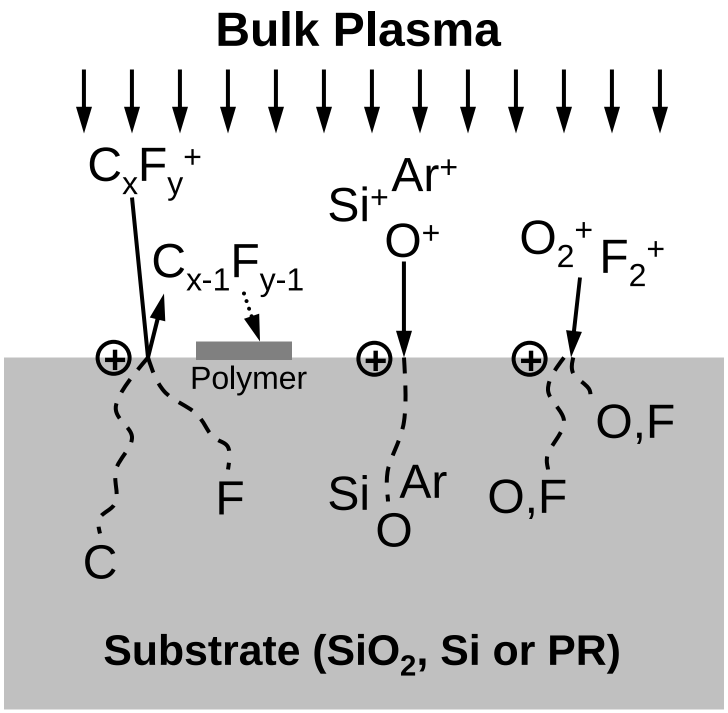
36th ICOPS, June 2009, San Diego, CA

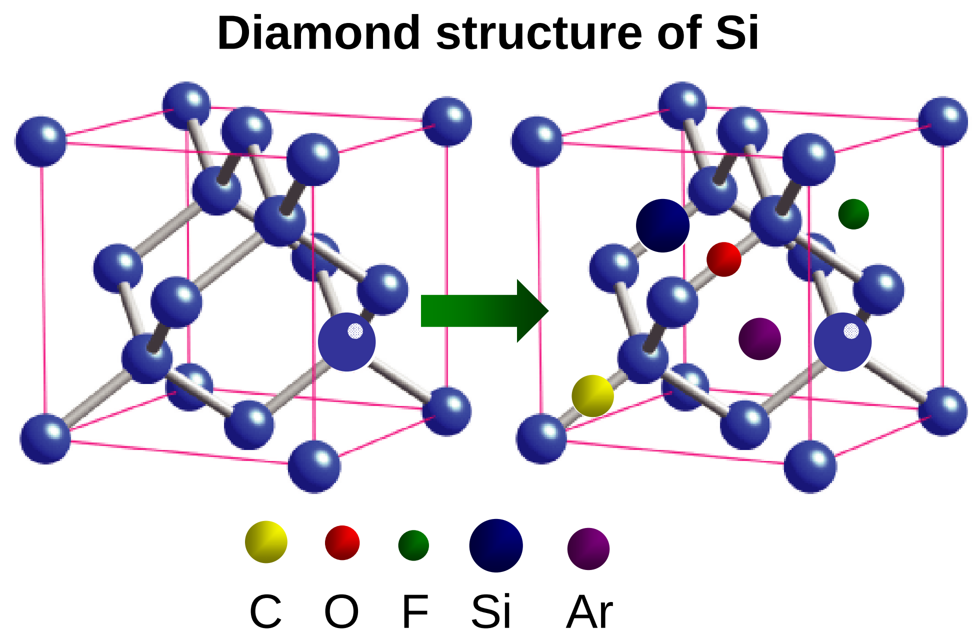
*Work supported by Tokyo Electron Ltd. Micron Inc. and the SRC.

AGENDA

- Implanting, mixing and photoresist (PR) erosion
- Processes
    - Molecular ion dissociation on surfaces
    - Small ion penetration and mixing
    - PR cross-linking
- Description of Model
- Scaling of Mixing and Implantation
- Concluding Remarks

IMPLANTATION AND MIXING DURING PLASMA ETCHING





- **Small ions accelerated by the sheath implant into the wafer surface forming weakly bonded or interstitially trapped species.**
- **Implanting causes surface mixing which produces damage during plasma etching.**

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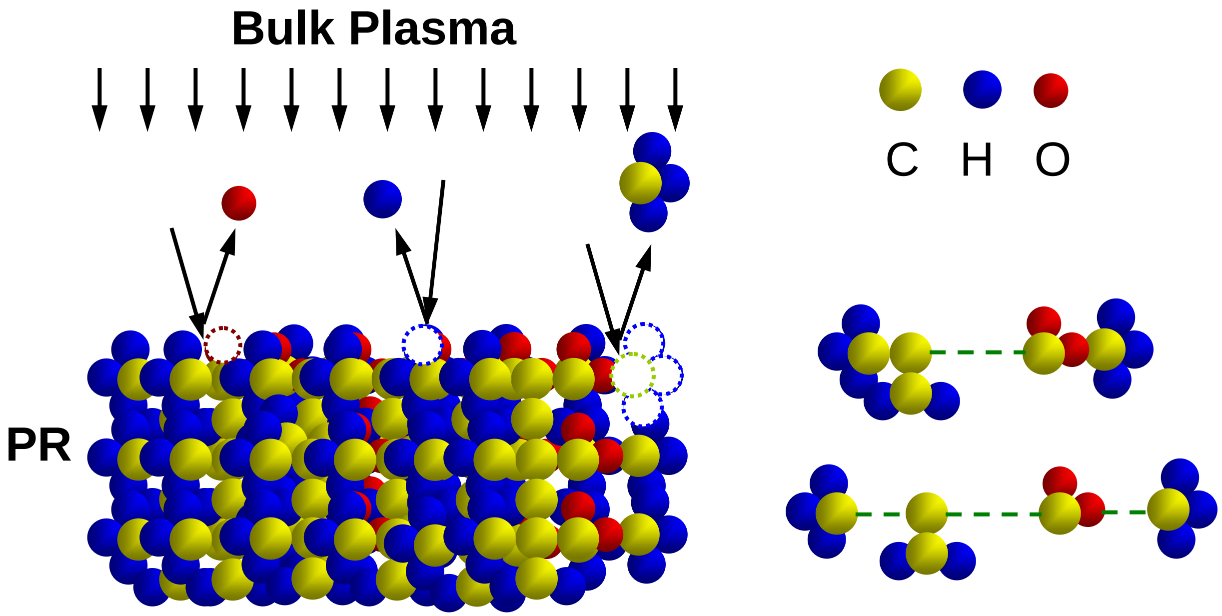
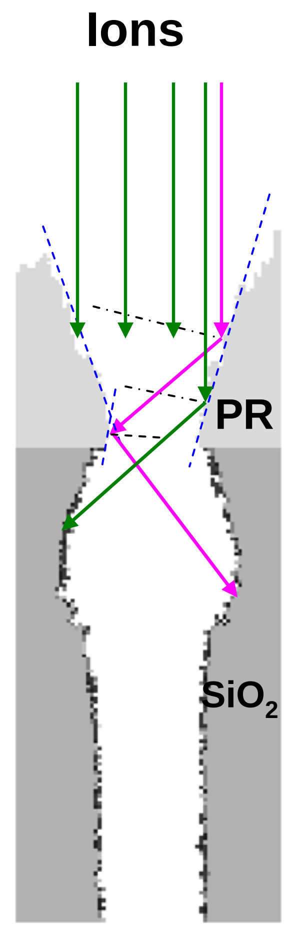
PHOTORESIST (PR) EROSION





- **Photoresist defines the features to be etched – usually a hydrocarbon polymer.**
- **PR is sputtered by energetic ions. Fragmented PR segments are more easily eroded.**
- **Profile of high aspect ratio (HAR) features can be modified due to PR erosion.**

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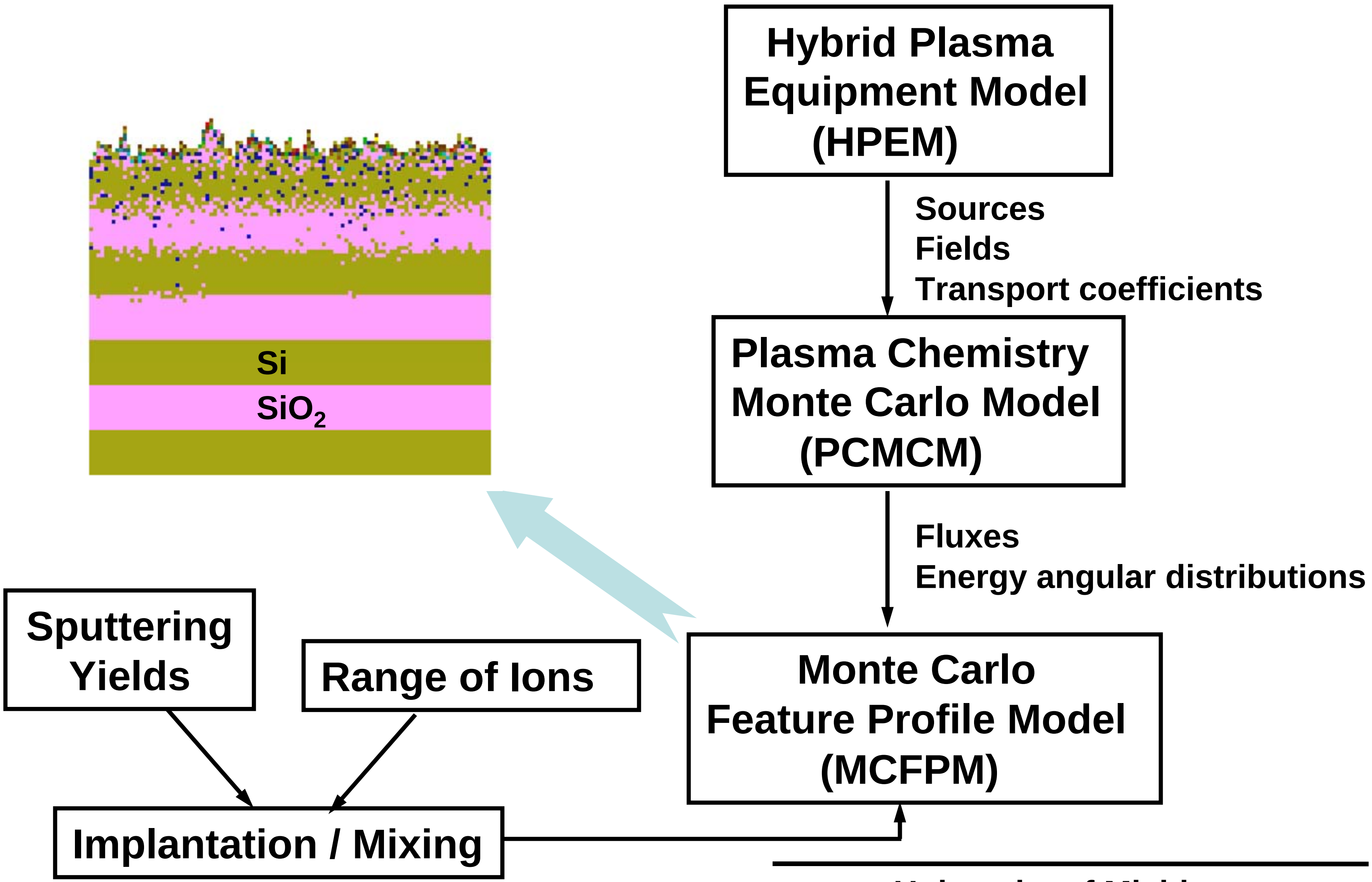
APPROACHES AND GOALS OF INVESTIGATION

- Consequences of implantation and mixing are poorly characterized in modeling of plasma etching.
- Usually only included in compute-intensive molecular dynamics simulations.
- Incorporate implantation, mixing, and sputtering into Monte-Carlo Feature Profile Model coupled to equipment scale plasma models.
- Investigate:
  - Scaling of implantation, mixing, and etching selectivity.
  - Degradation and cross-linking of PR surface due to energetic bombardment.
- Goals
  - Characterize mixing damage during etching.
  - Develop strategies to preserve pattern transferring while minimizing damage.

DESCRIPTION OF MODEL



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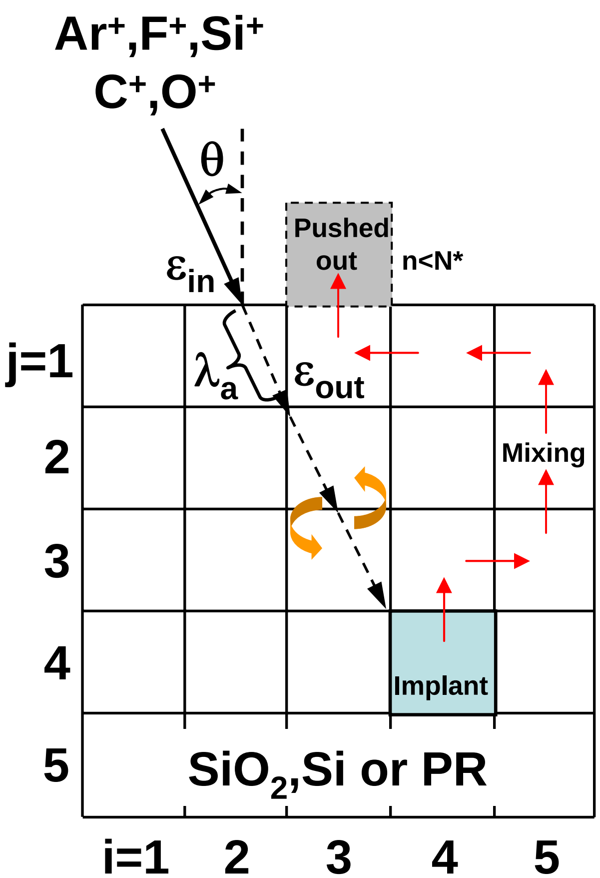
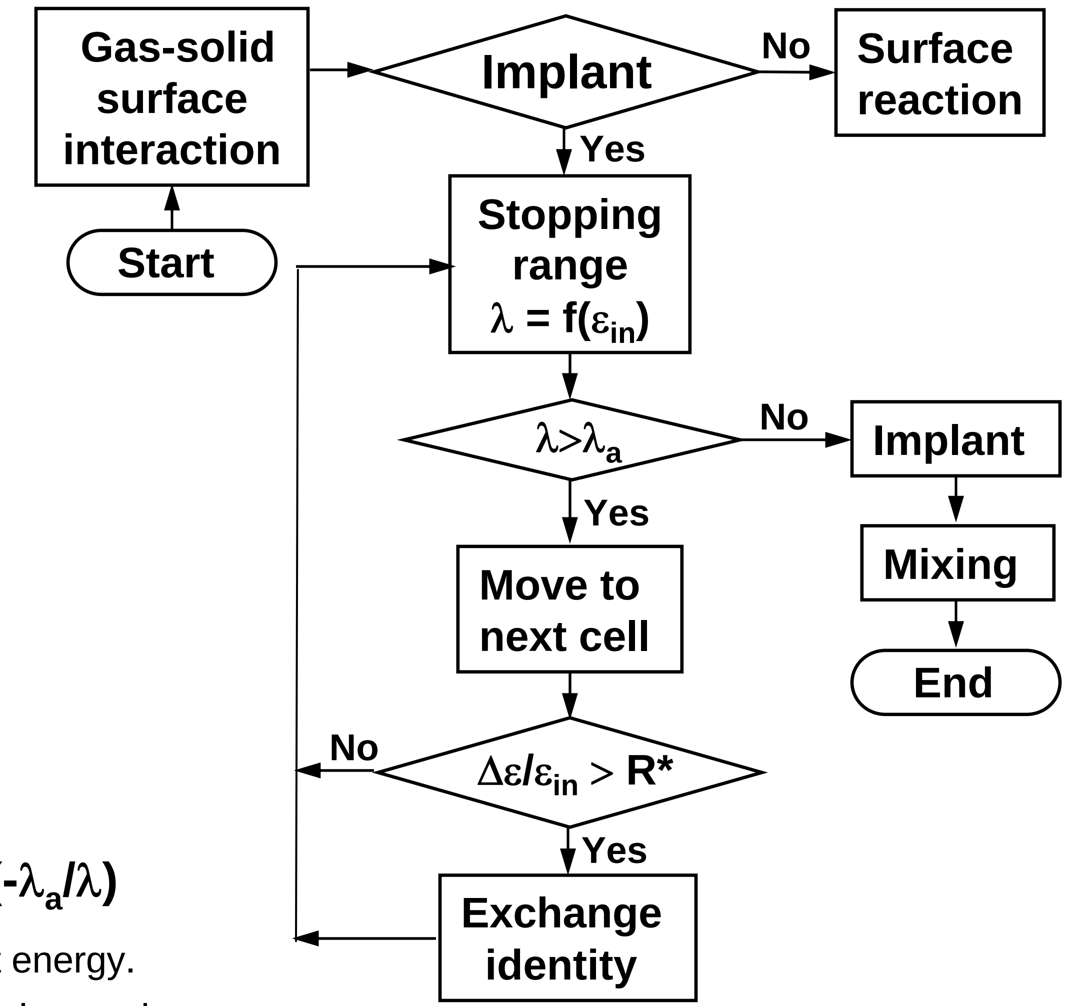
IMPLANTATION MODEL





Within one cell: $\varepsilon_{out} = \varepsilon_{in} \exp(-\lambda_a/\lambda)$

Where ε_{in} = incident energy; ε_{out} = left energy.

λ_a = Actual length that the particle travels.

λ = Calculated stopping range $f(\varepsilon_{in})$.

*n = mixing step; N = allowed maximum mixing step.

*R = Random number

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SURFACE REACTION MECHANISM

- **Etching of SiO_2 is dominantly through a formation of a fluorocarbon complex.**
  - $SiO_2(s) + C_xF_y^+(g) \rightarrow SiO_2^*(s) + C_xF_y(g)$
  - $SiO_2^*(s) + C_xF_y(g) \rightarrow SiO_2C_xF_y(s)$
  - $SiO_2C_xF_y\,(s) + C_xF_y^+(g) \rightarrow SiF_y(g) + CO_2\,(g) + C_xF_y(g)$
  - **Further deposition by $C_xF_y(g)$ produces thicker polymer layers.**
- **Example reaction of surface dissociation.**
  - $M(s) + C_xF_y^+(g) \rightarrow M(s) + C_{x-1}F_{y-1}(g) + C(g) + F(g)$
- **Sputtering of PR and redeposition.**
  - $PR(s) + Ar^+(g) \rightarrow PR2(s) + Ar(g) + H(g) + O(g)$
  - $PR(s) + C_xF_y^+(g) \rightarrow PR(s) + C_xF_y(g)$
  - $PR(g) + SiO_2C_xF_y(s) \rightarrow SiO_2C_xF_y(s) + PR(s)$

*PR2 = cross-linked PR

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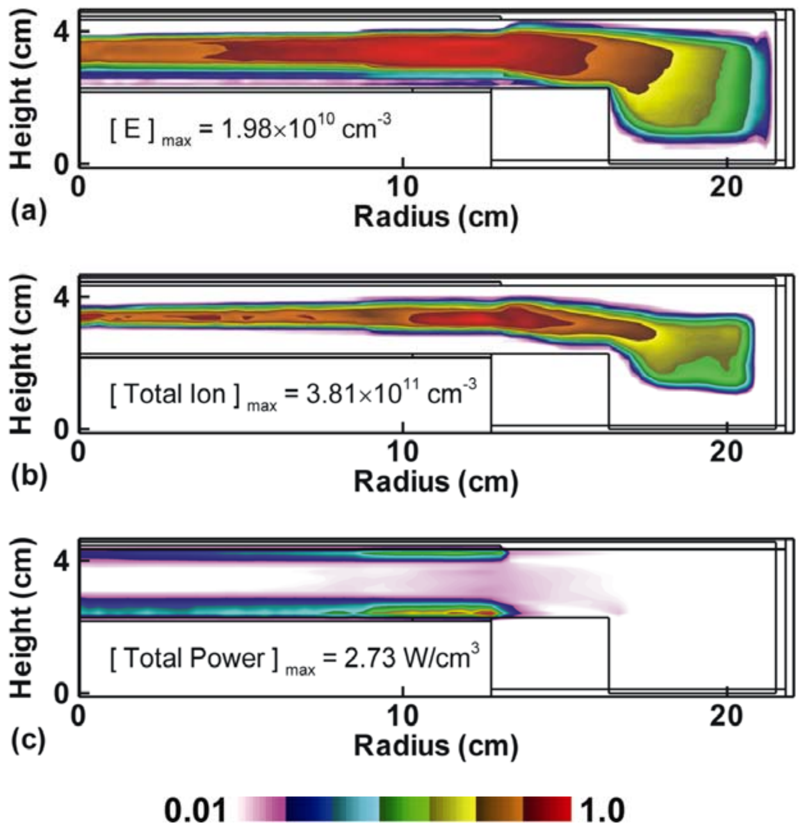
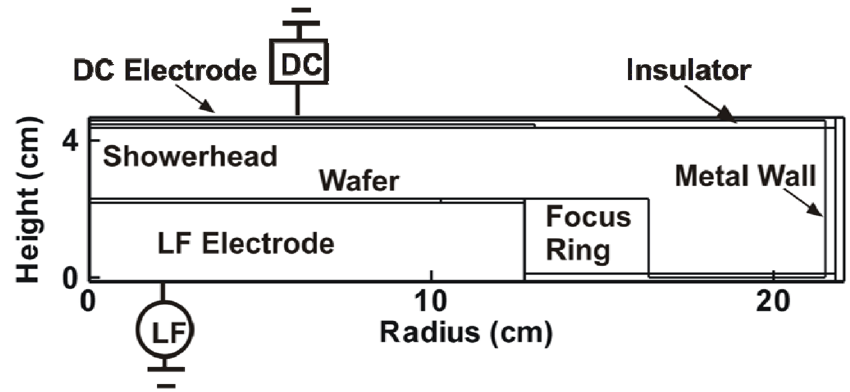
FLUOROCARBON ETCHING OF SiO_2

- DC augmented single frequency capacitively coupled plasma (CCP) reactor.
- DC: Top electrode   RF: Substrate





- Plasma tends to be edge peaked due to electric field enhancement.
- Plasma densities in excess of 10^{11} cm^{-3}.
- $Ar/C_4F_8/O_2$ = 80/15/5, 300 sccm, 40 mTorr, RF 1 kW at 10 MHz, DC 200 W/-250 V.

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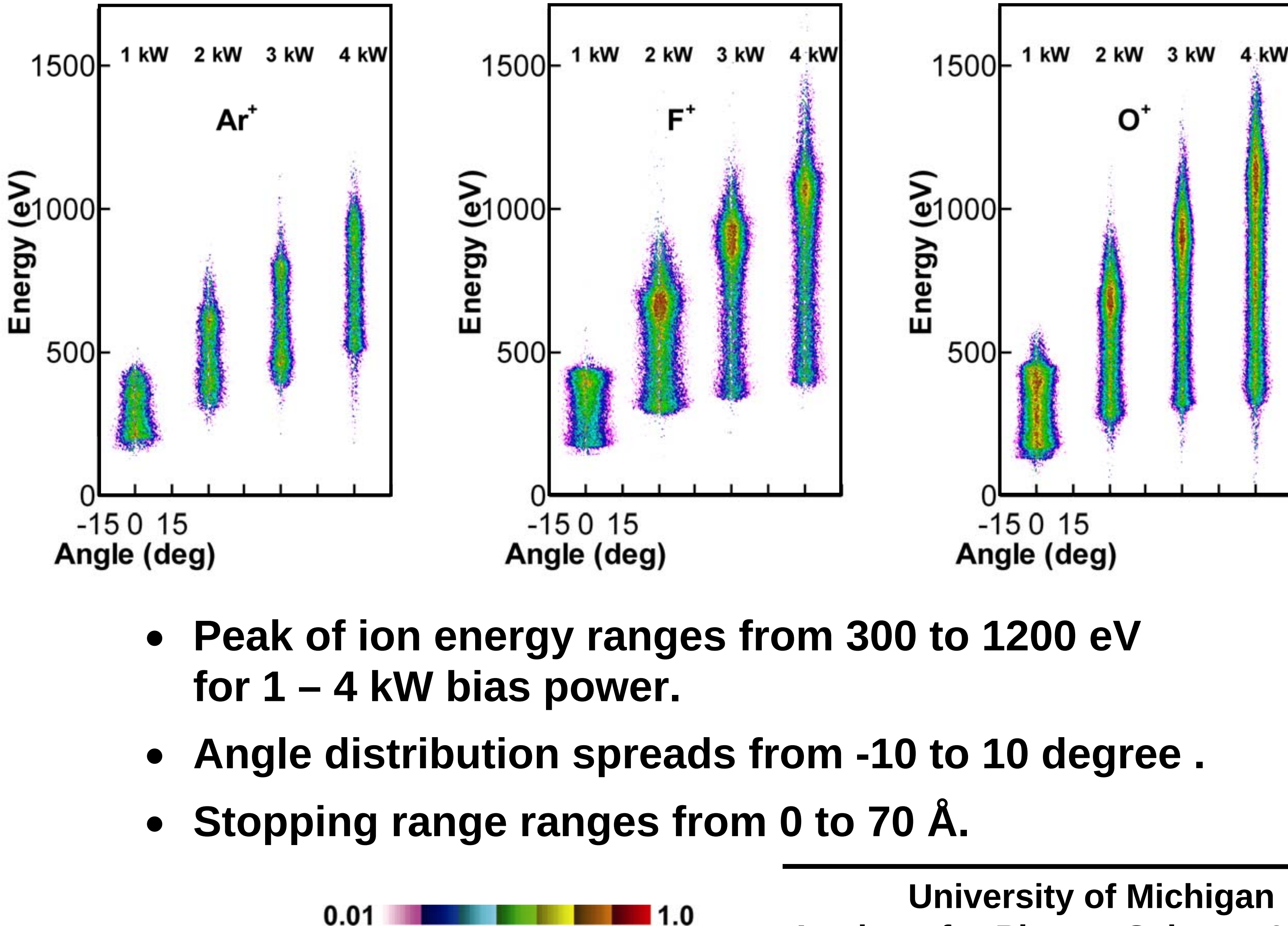
ION ENERGY ANGULAR DISTRIBUTIONS (IEADs)



- **Peak of ion energy ranges from 300 to 1200 eV for 1 – 4 kW bias power.**
- **Angle distribution spreads from -10 to 10 degree .**
- **Stopping range ranges from 0 to 70 Å.**

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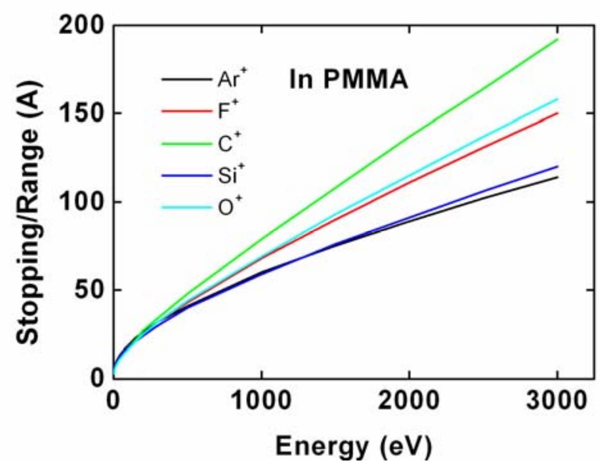
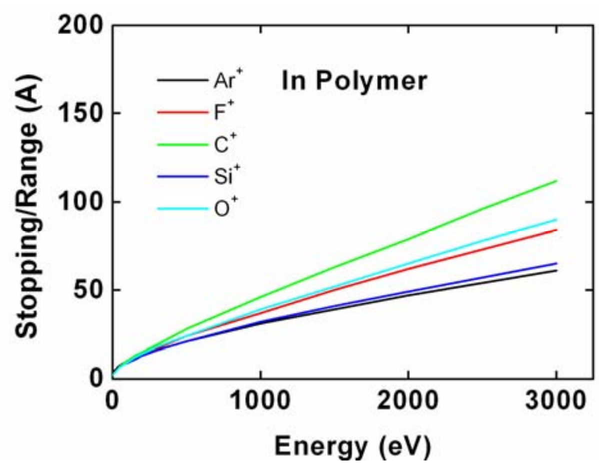
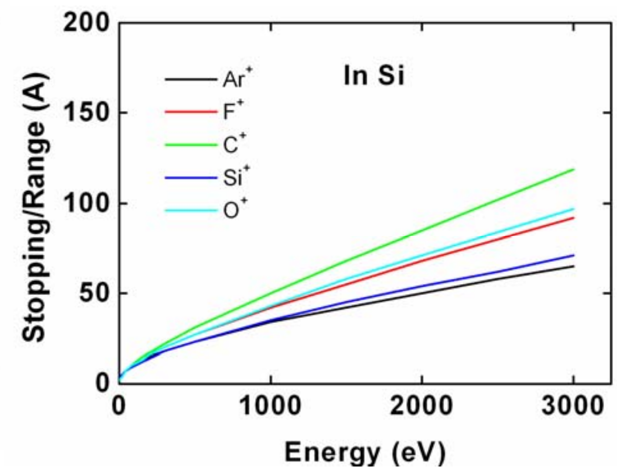
STOPPING RANGE IN PR, POLYMER, Si, AND SiO_2







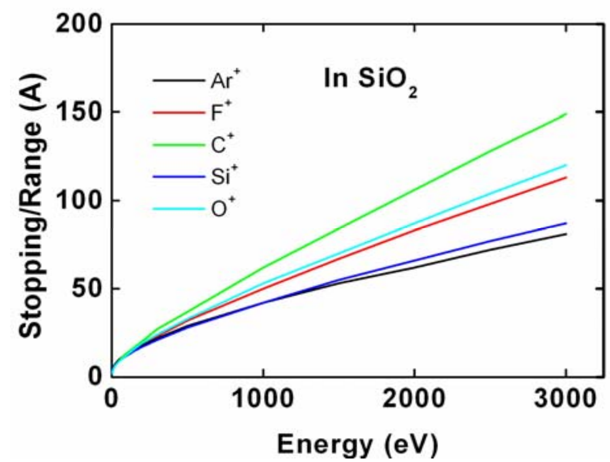
- **Stopping range increases with increasing energy.**
- **At specific energy, implanting depth:**

  PR(PMMA*) > SiO_2 > Si $\geq$ Polymer

  *PMMA = Polymethylmethacrylate

- **Data from SRIM (the Stopping and Range of Ion in Matter)**

  Stopping range $\lambda = f(\varepsilon_{incident})$



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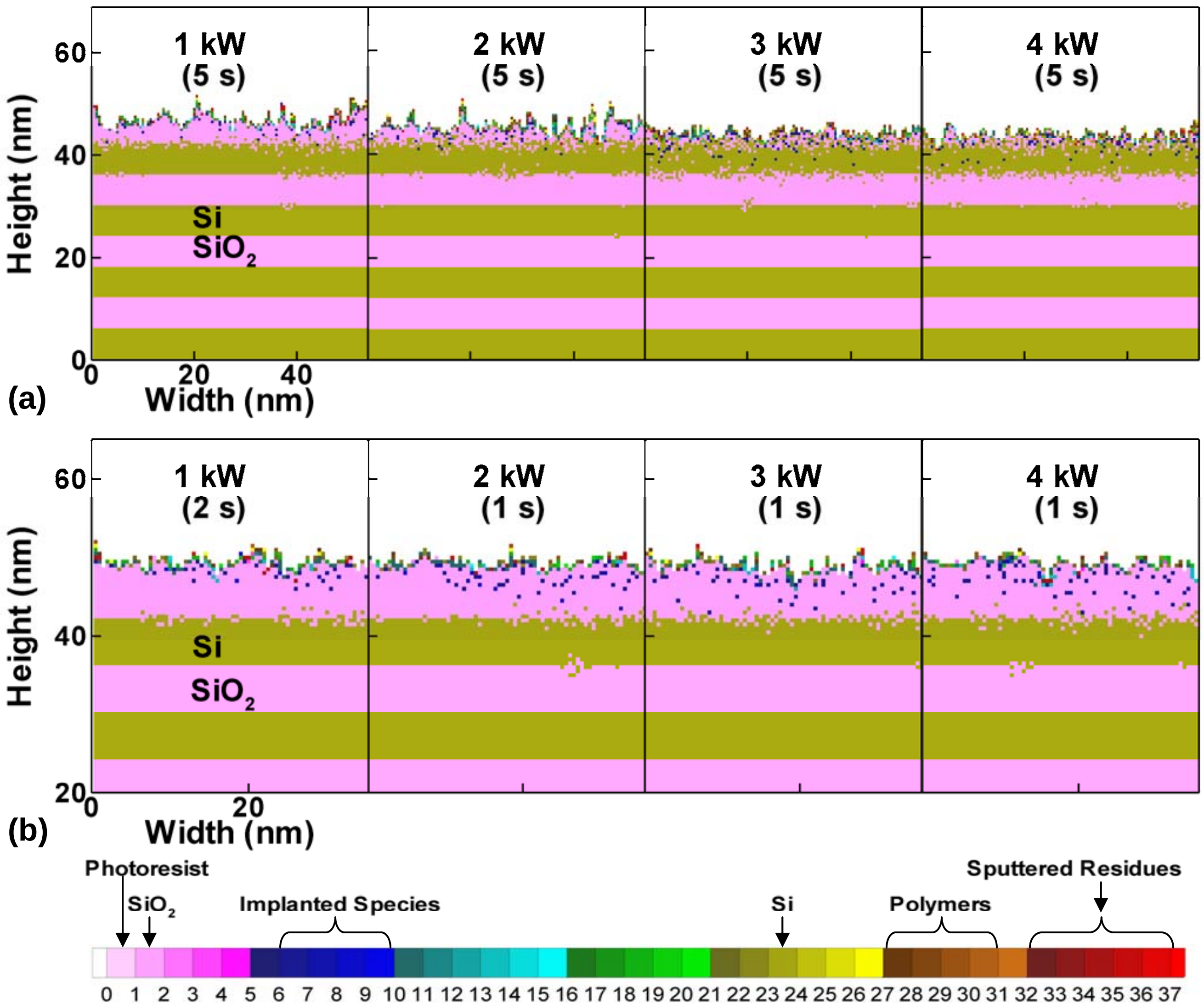
IMPLANTING AND MIXING DEPTH vs BIAS POWER



- **After 5 s**
- **Etch rates, degree of mixing and depth of implantation increase with bias power.**
- **After same etch level**

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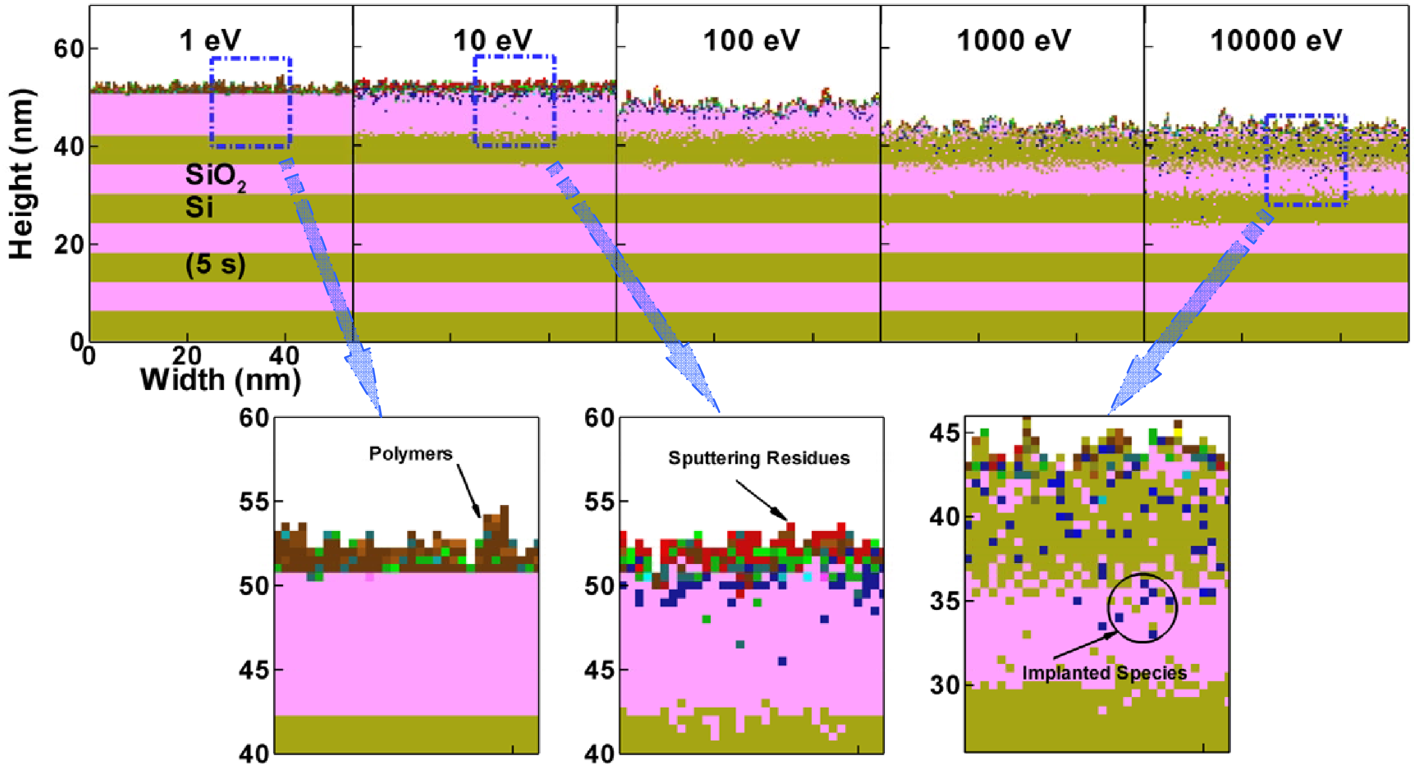
IMPLANTING AND MIXING DEPTH vs ENERGY



- **Only polymer deposition occurs at 1 eV.**
- **Sputtering, implanting and deposition coexist at 10 eV.**
- **Depth of implantation and mixing increases with increasing ion energy (100 eV~10 keV).**

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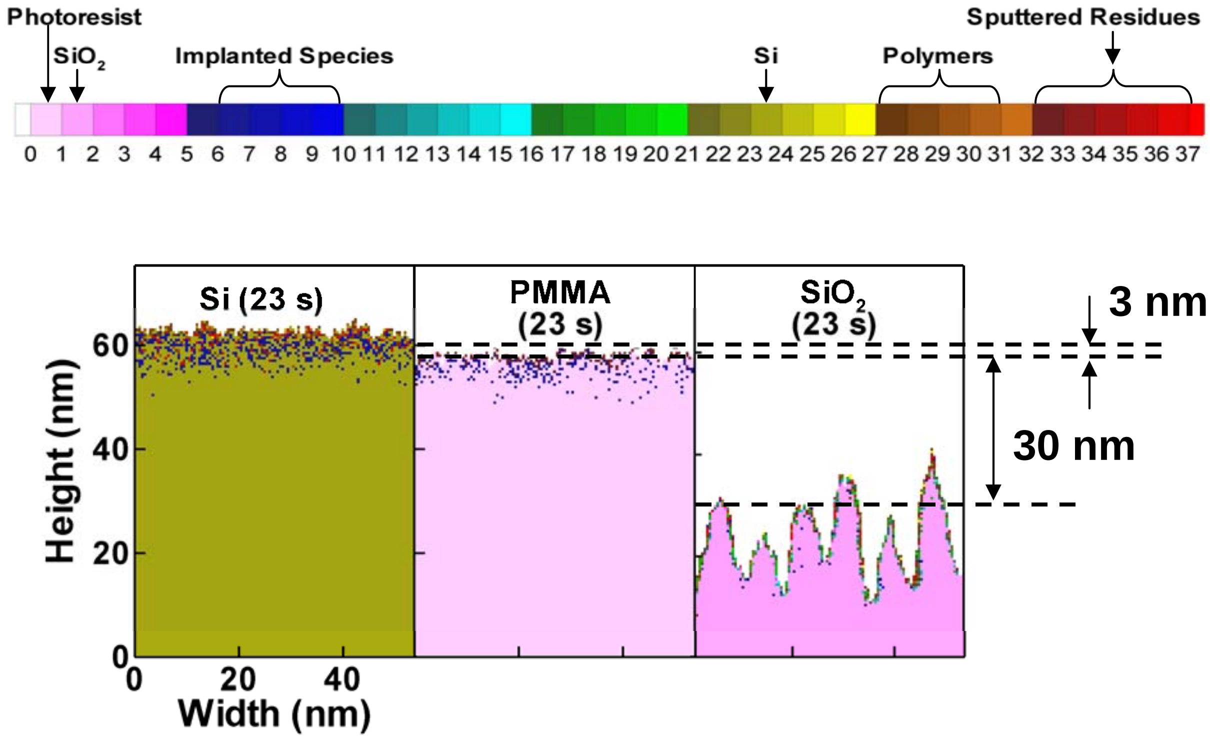
ETCHING SELECTIVITY

- Etch stop occurs at Si surface due to low reaction rate with CF_x.
- Etching selectivity for SiO_2/PR(PMMA) is around 10.
- The roughness of SiO_2 surface is due to non-uniform polymer deposition.



Micro-masking ⟶ Micro-trenching

- $Ar/C_4F_8/O_2$ = 80/15/5, 4 kW, 300sccm, 40mTorr, DC 200W/-250V.

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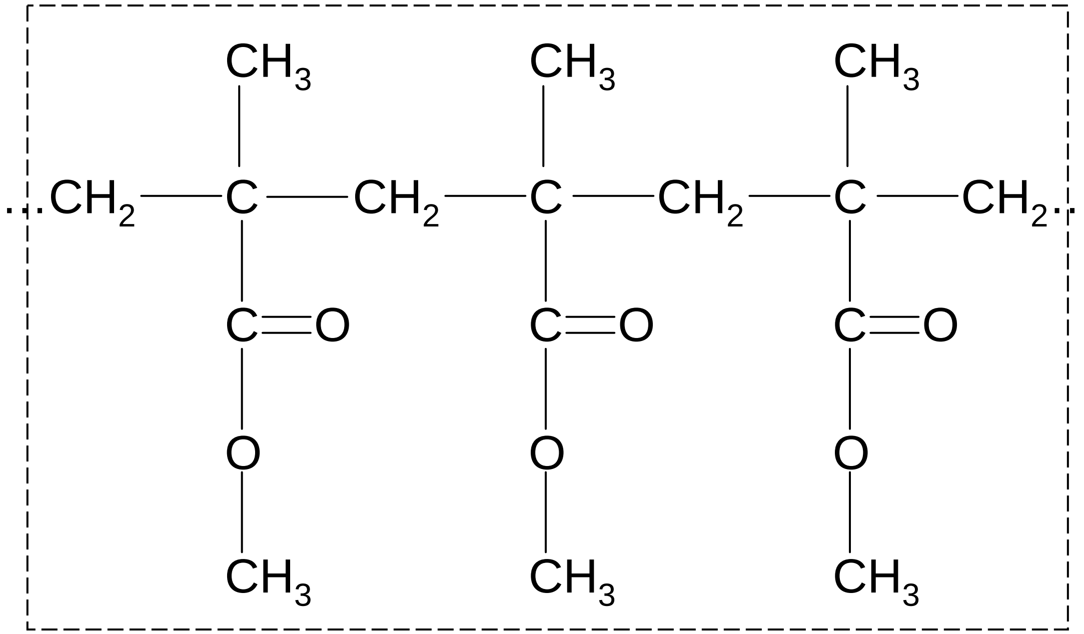
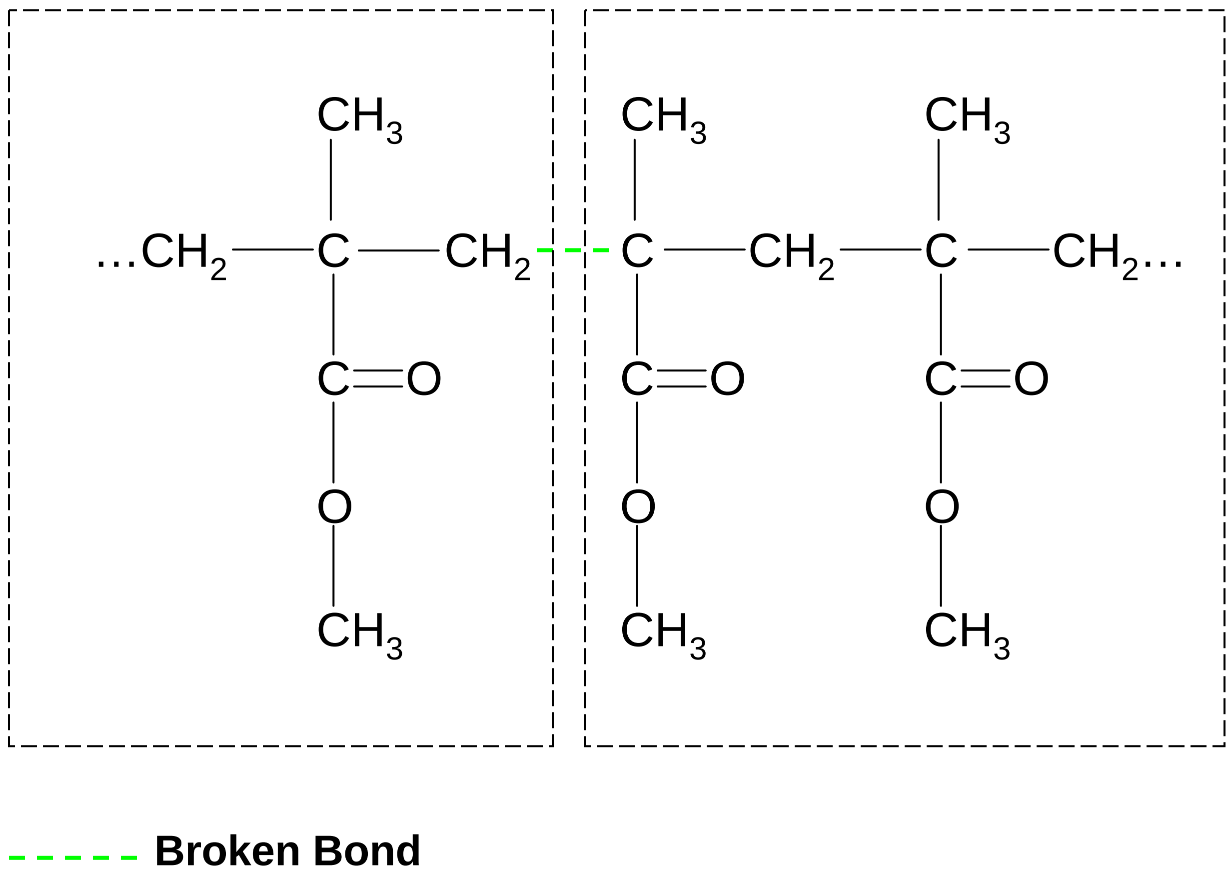
MECHANISM FOR DEGRADATION AND CROSS-LINKING OF PR

Structure of PR(PMMA)



- **PR molecule is degraded due to energetic ion sputtering.**
- **Degraded PR segments are more easily eroded.**
- **Newly formed dangling bonds are recombined (cross-linking), and cross-linked PR forms a "hard crust".**
- Sputtering yield is calculated using SRIM.

DEGRADATION OF PR (SPUTTERING)



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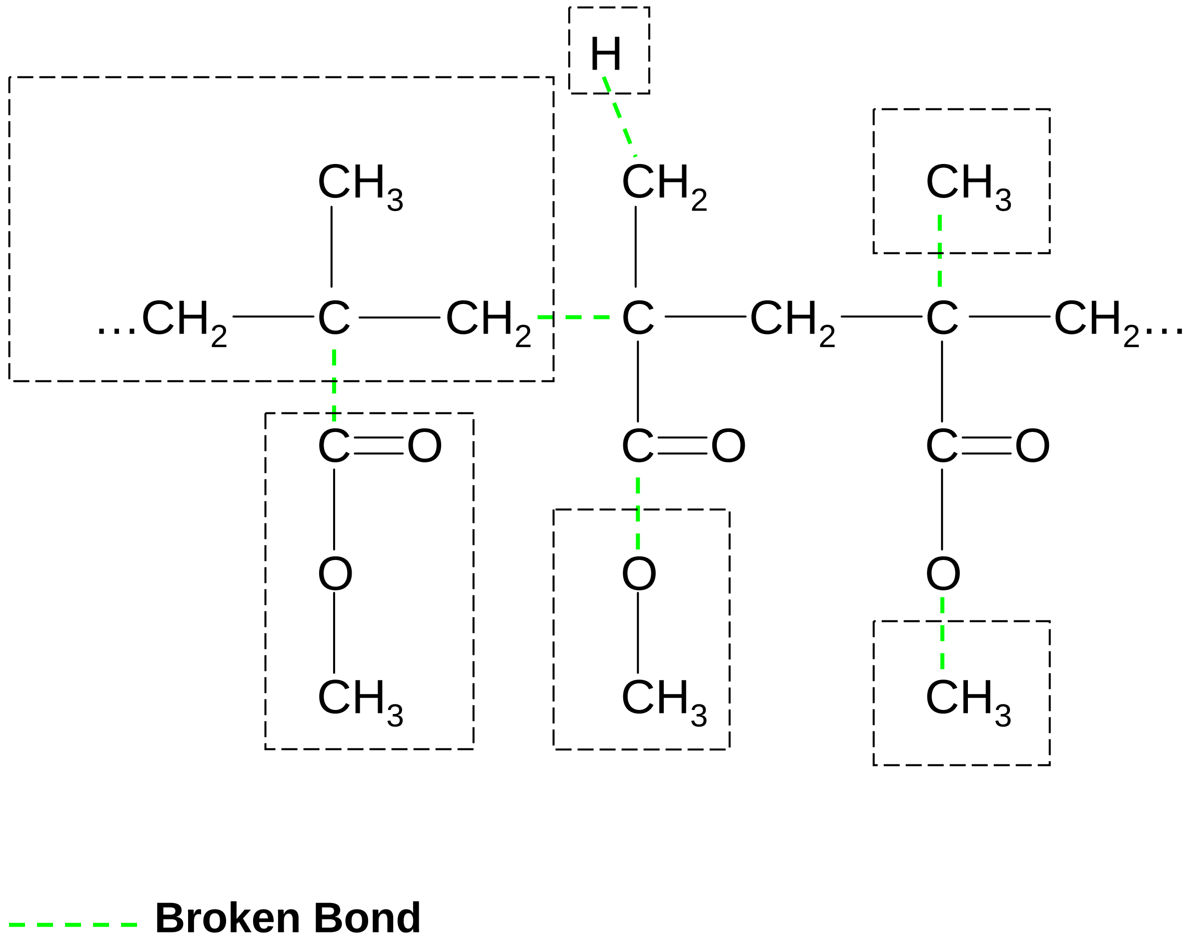
DEGRADATION OF PR (SPUTTERING)



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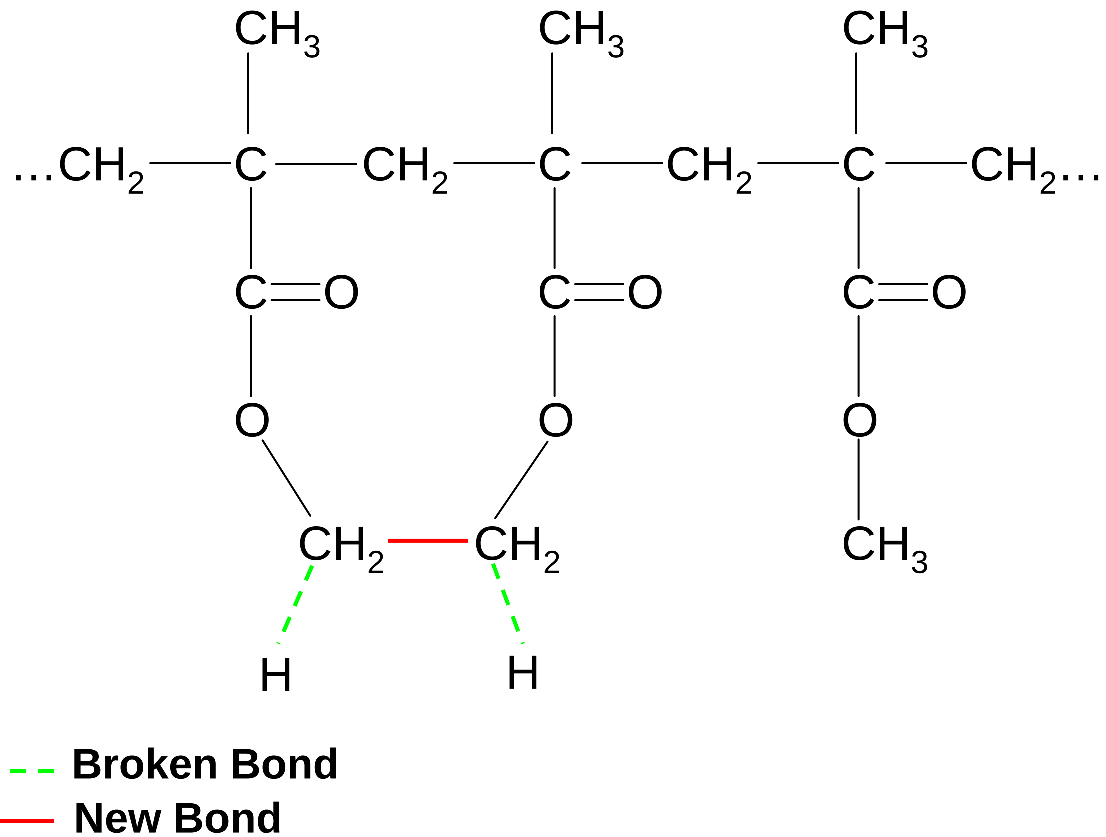
INTER-MOLECULE CROSS-LINKING



Broken Bond

New Bond

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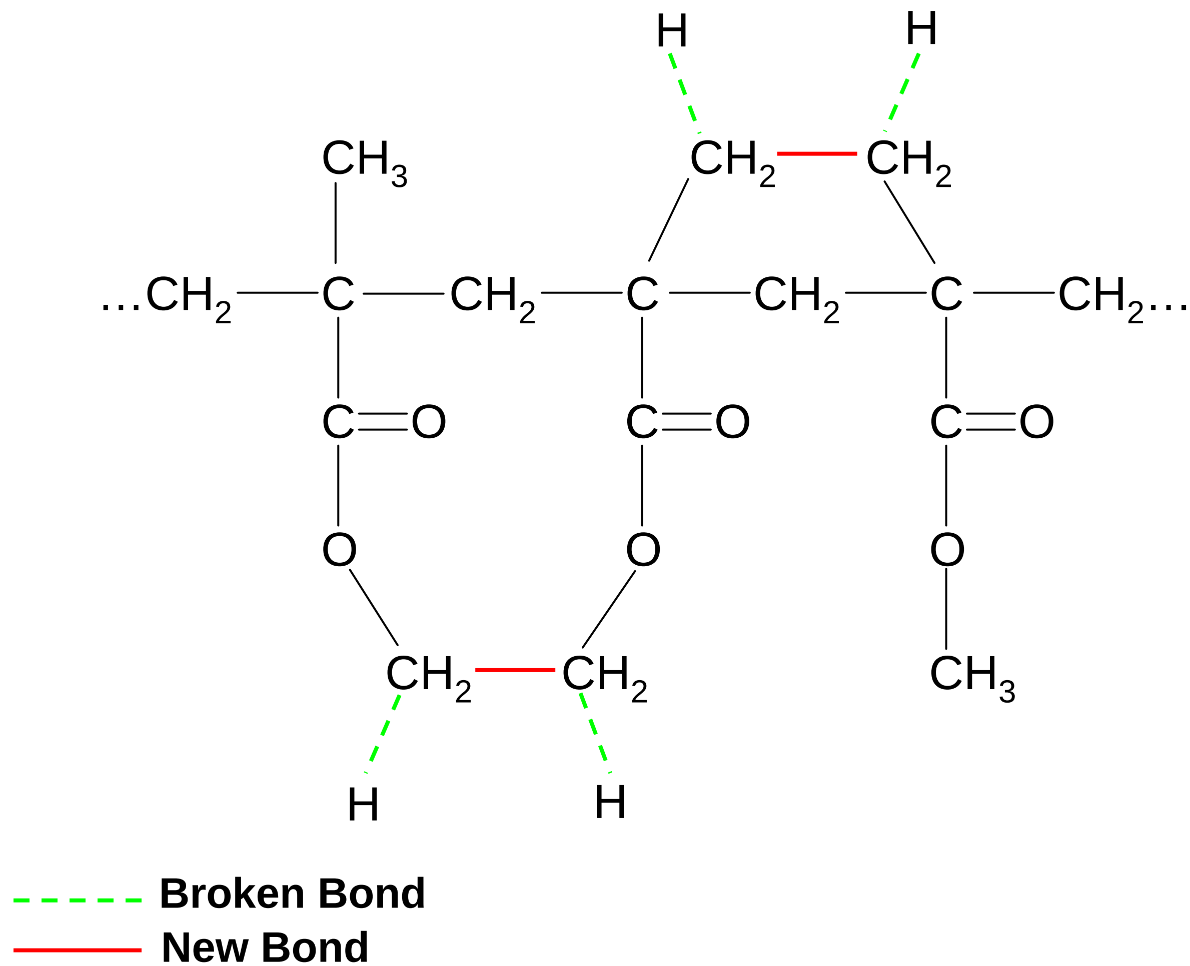
INTER-MOLECULE CROSS-LINKING



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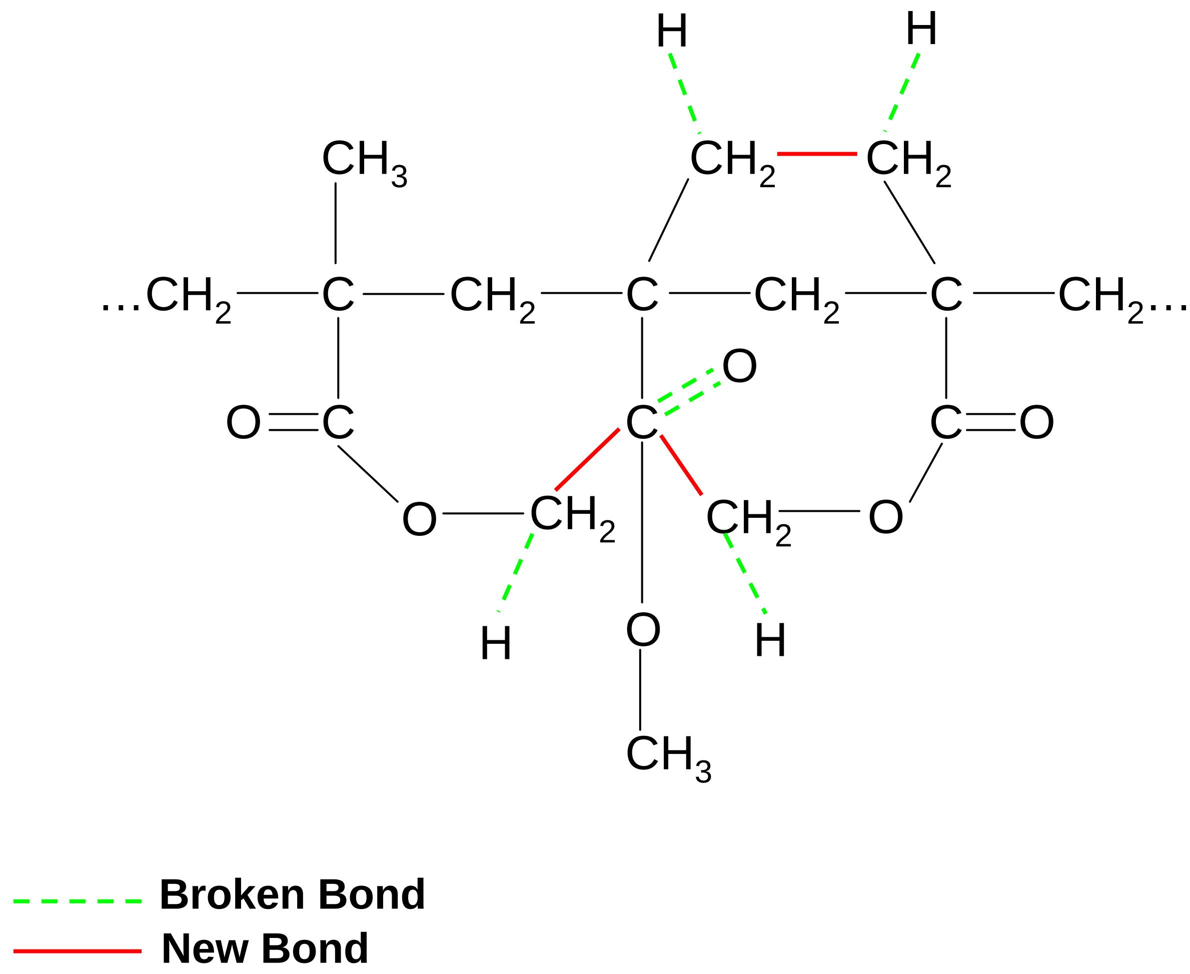
INTER-MOLECULE CROSS-LINKING



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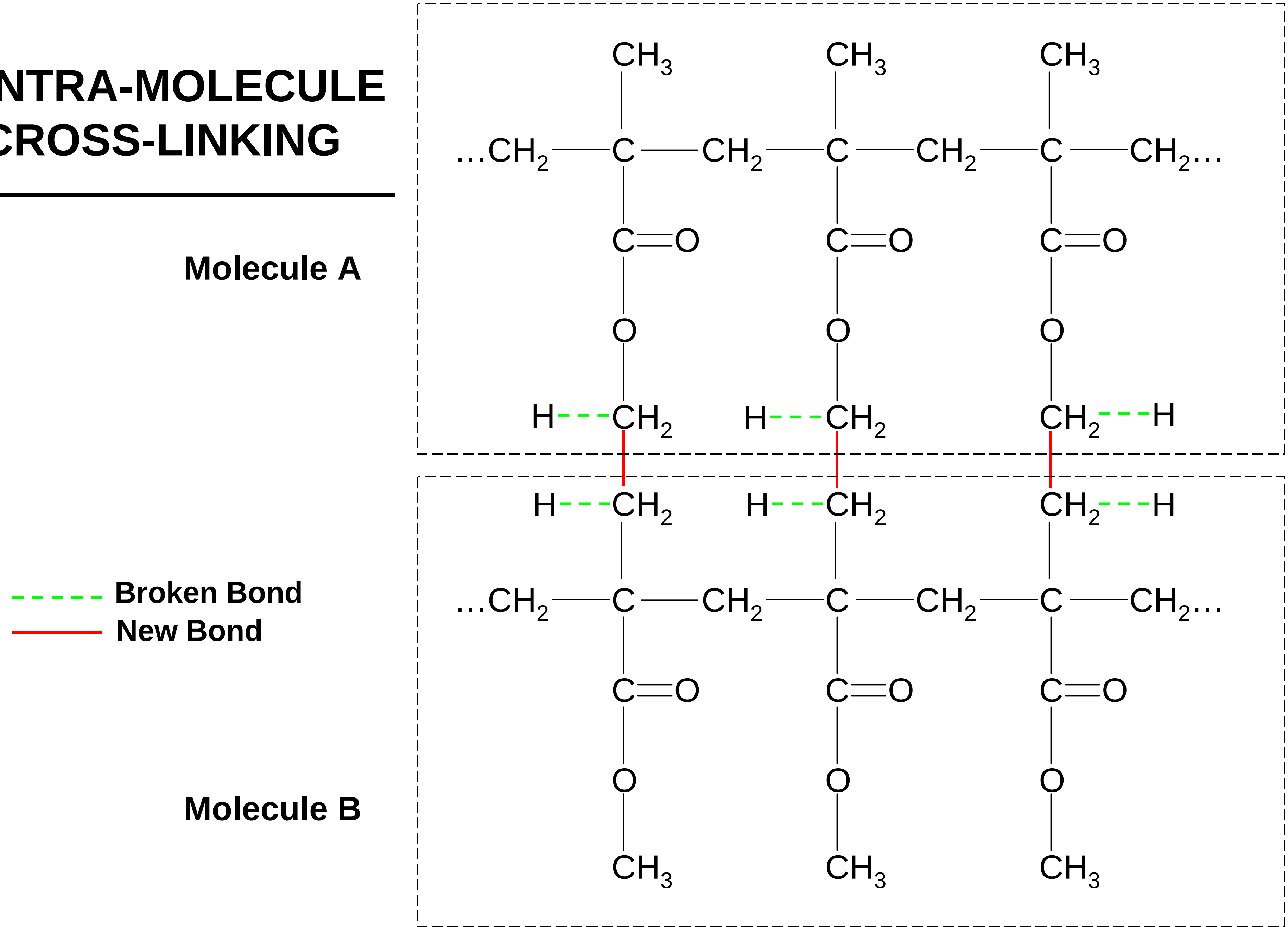
INTRA-MOLECULE CROSS-LINKING



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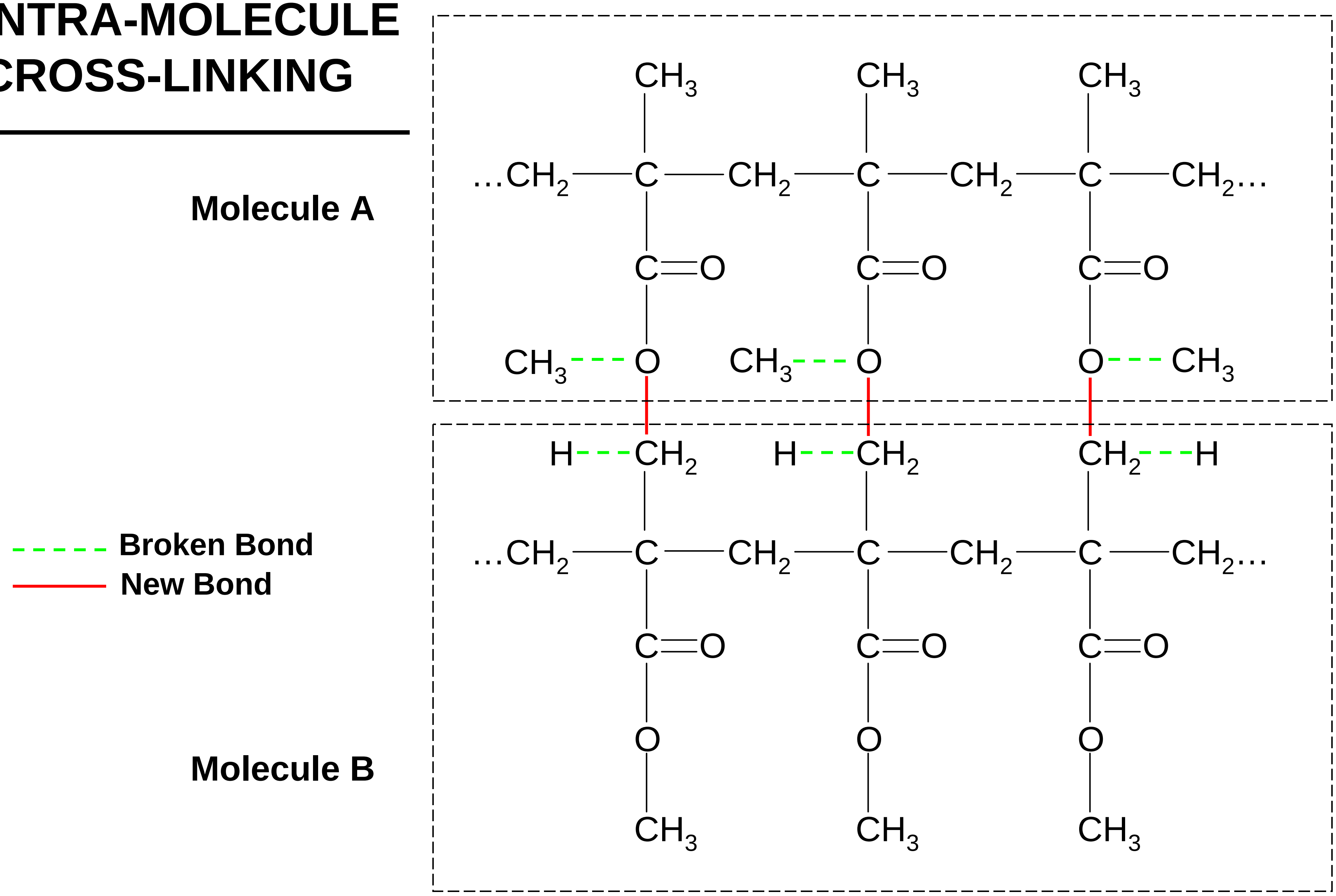
INTRA-MOLECULE CROSS-LINKING



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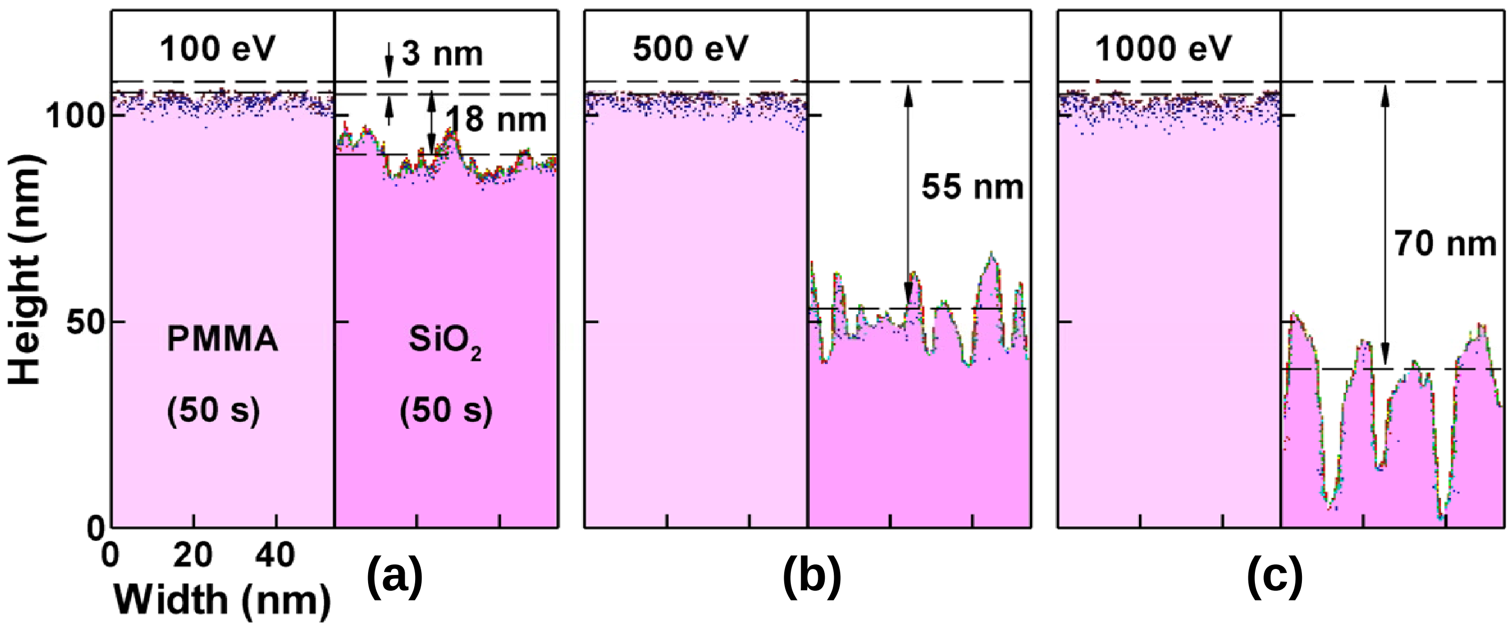
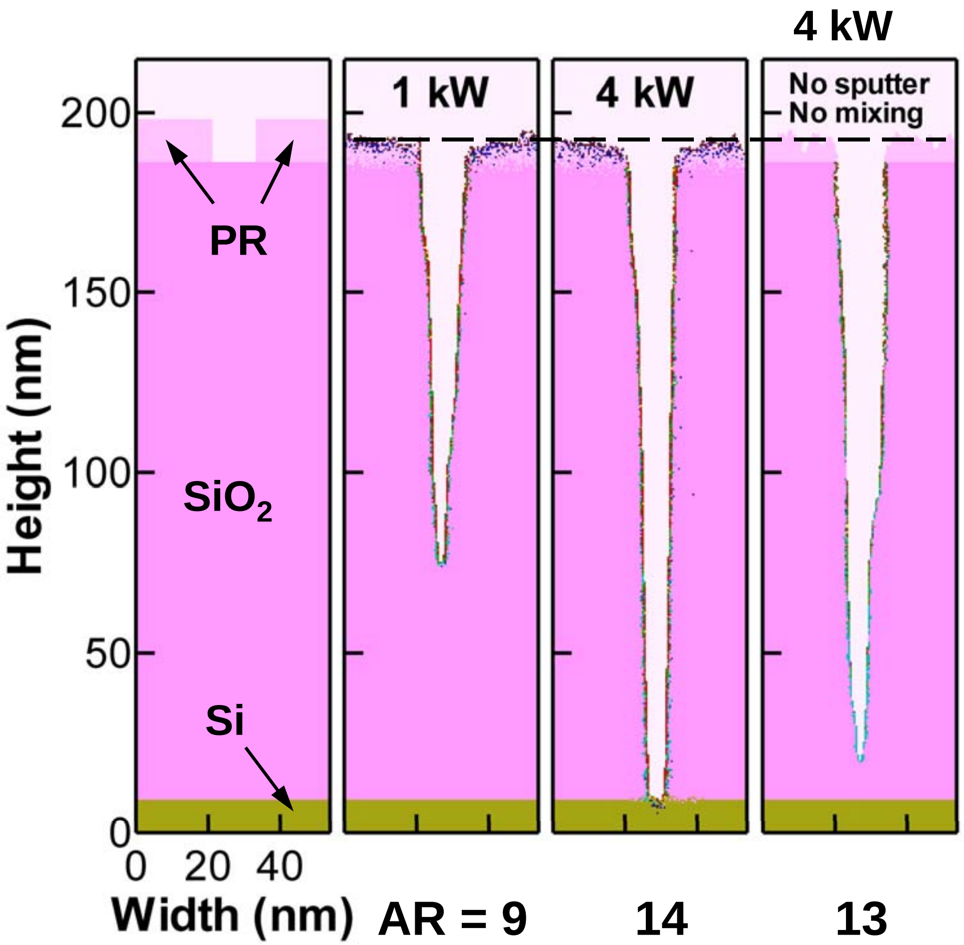
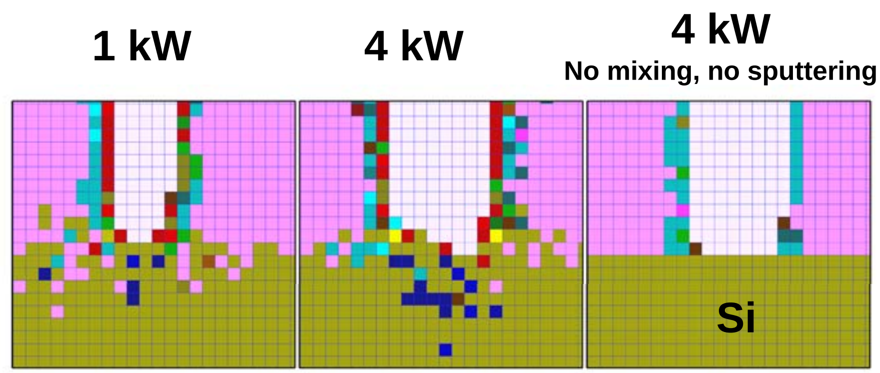
ETCHING SELECTIVITY vs ENERGY



- Etching rate for SiO_2 increases with increasing ion energy.
- Balance between sputtering and cross-linking (more resistive to etching) on PR(PMMA) surface results in similar etching rate for all energies.
- Surface roughness of SiO_2 increases as etching proceeds due to micro-masking.
- Etching selectivity (SiO_2/PR): 100 eV, 6; 500 eV, 18; 1000 eV, 23.

ETCHING SELECTIVITY vs RF BIAS POWER





- At similar etching level of PR, aspect ratio (AR) of the trench increases with bias power.
- Etching selectivity increases when PR is cross-linked.
- Si is damaged during over-etch by implantation and mixing.

- $Ar/C_4F_8/O_2$ = 80/15/5, 300 sccm, 40 mTorr, 10 MHz, DC 200 W/-250 V.

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CONCLUDING REMARKS

- Algorithms have been incorporated into the MCFPM to predict implanting and mixing.
  - Depth of implanting and mixing increases with increasing bias power and ion energy.
  - More damage is obtained at higher etching rate.
- PR surface is cross-linked due to sputtering.
  - At higher bias power and ion energy, etching selectivity for SiO_2/PR is better.
- Strategies to be developed for high power processing:
  - Protect pattern transferring at higher etching rate.
  - Reduce damage during over-etch.

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