Dose and Oxide Thickness Determination by XPS of Plasma-Implanted P in Si

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Specialists in Materials Characterization

INTRODUCTION

Future Node Implant Issues:

- What are the difficulties in measuring dopants?
  - ITRS roadmap has junction depth (X_j) of <10nm at 45nm node
  - Lateral abruptness, channel length, resistivity, and other ITRS targets are pushing dopant levels to >E+20/cm^3
  - Dopant doses required are > mid-E+14 atoms/cm^2.
- Two often cited methods for ULE/USJ implant to provide high dose at shallow controlled depths: [1]
  - (Low Energy) plasma implant using gas phase species, e.g. PH_3, BF_3, B_2H_6 etc.
  - 'Standard' implantation at low energy with poly-atomic species, e.g. $B_{10}H_{18}$, $B_{18}H_{22}$, P_xH_{3x} etc.
- Activation of implant still required – methods under investigation include:
  - 'spike' anneals (RTA, laser, etc.)
  - solid phase epitaxial re-growth

[1]W. J. Taylor et.al., Materials Challenges for CMOS Junctions, Mat. Res. Soc. Symp. Proc. Vol. 810, 2004

Some Fundamental Problems Measuring ULE/USJ Implant Dopants

- **At X_j <15nm and Dose > E+20 atoms/cm^3**

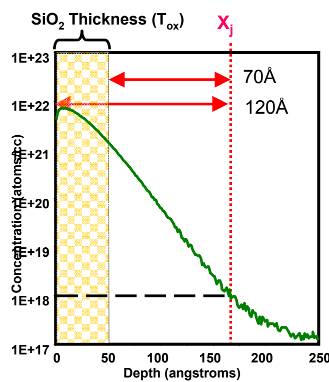
⇒ Concentration is on the order of a few at%

∴ This is ideally suited to measurement by XPS

- Regardless of technique used to implant dopant, some amount of surface oxide will be present on the Si.
  - X% of dopant dose will be implanted into the Si substrate.
  - Y% of dopant dose will be implanted in SiO_2 layer.
  - Z% of dopant dose may be lost or unaccounted for in implant process.
- Anneal/Activation may re-distribute dose in oxide, dose in substrate, and/or cause additional loss of implant dose.

BACKGROUND

Focus on the Oxide Layer Problem

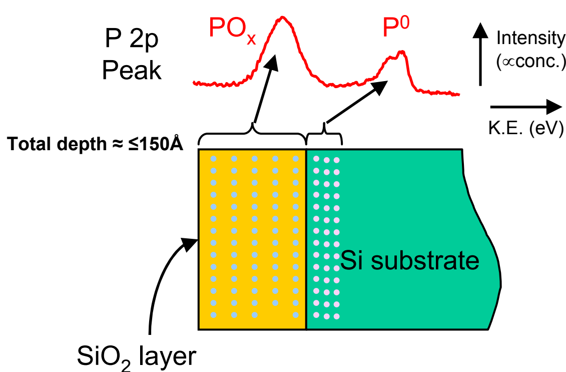


Junction Depth, X_j:

If we define X_j as the depth at which the implant attains a concentration of 1X10^{+18} atoms/cm^3, ***Then***, inclusion or exclusion of the oxide layer can change X_j by >70% in this case!

This also implies that the dose in the oxide must be known separately and independently from the dose in the Si substrate.

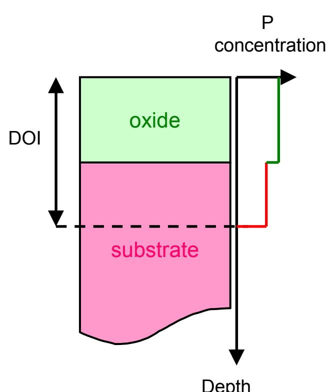
XPS Perspective of Plasma Doped P in Si



No PO_x atoms are in substrate and no P^0 atoms are in oxide.

XPS Assumptions & Caveats

- XPS assumes: All the dopant is within the depth of information (DOI). For P in SiO_2/Si, all P must be within ~150Å of surface (oxide layer + Si substrate)
- XPS assumes: All the dopant is uniformly distributed within the oxide layer and the substrate layer.
- If P distribution within a layer (oxide or Si) is peaked toward surface, XPS will overestimate P dose.
- If P distribution within a layer is peaked toward substrate, XPS will underestimate P dose.



SAMPLES

Plasma Doped P in Si Samples

- Samples supplied by a major international research institute
- Plasma method of implantation of P into Si (PH_3 in carrier gas)
- Samples consist of:
  - As-implanted wafers (no post plasma treatment)
  - Annealed wafers at 900C for 10 seconds.
- Portions of 200mm wafers cleaved and analyzed by XPS and SIMS
- P present on as-implanted and annealed samples. Other 'impurities' (probably from plasma implanter) also present.

RESULTS & DISCUSSION

Measured XPS Oxide Thickness (T_{ox}) and Calculated P Dose in Oxide (P_{ox}) and P Dose in Silicon Substrate (P_{sub})

	T_{ox}(Å)	P_{Ox} Dose (at/cm²)	P_{Sub} Dose (at/cm²)	Total P Dose (at/cm²)
P in Si; as-implanted	43.87	4.71E+15	1.92E+15	6.63E+15
P in Si; RTA @900C 10sec	42.96	1.07E+15	1.42E+15	2.48E+15

Intermediate Conclusion:

The following observations can be made:

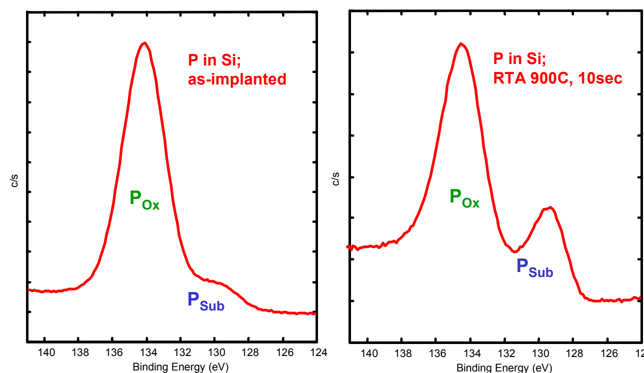
- As-implanted: P dose in oxide > P dose in substrate.
- After RTA 900C-10s: P dose in oxide < P dose in substrate.
- P dose as-implanted in oxide > P dose after RTA anneal in oxide
- P dose as-implanted in substrate ≅ P dose after RTA anneal in substrate

What happened to the P?

-'As-implanted': most of P in oxide w/ small amount in substrate.
-RTA anneal @ 900C for 10s: more P in substrate after anneal.

	Oat%	Siat%	Total P
As-implanted	67.4	24.1	6.63E+15/cm²
RTA @900C 10sec	64.9	31.8	2.48E+15/cm²

Where did the rest of the P (~4.2E+15 atoms/cm²) go after anneal?



'As-implanted' vs. RTA anneal @ 900C-10s change to oxide layer.

Thickness of oxide ~ identical before & after anneal.

	T_{ox} (Å)	P_{Ox} Dose (at/cm²)	P_{Sub} Dose (at/cm²)
As-implanted	43.87	4.71E+15	1.92E+15
RTA @900C/10s	42.96	1.07E+15	1.42E+15
Delta	-0.91 (-2.07%)	-3.64E+15 (-77.28%)	-0.50E+15 (-26.04%)

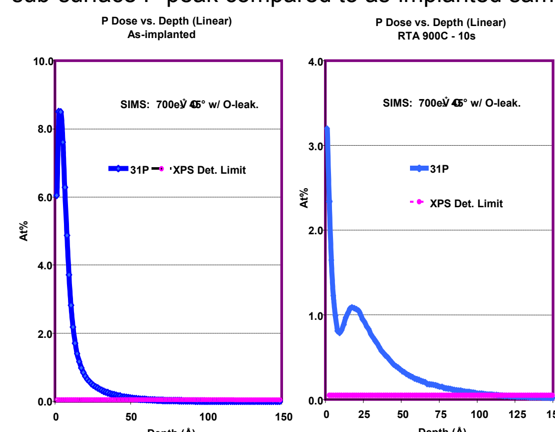
Intermediate Conclusion:

If oxide thickness did not change from as-implanted to annealed;
Then ~60% loss of P is due to:
A. P evaporating during anneal OR
B. P migrating to depth > DOI (XPS)

(DOI = Depth of Information ≅ 160Å @ 75° TOA)

Is XPS measuring all the dopant? From SIMS Profiles:

- XPS 'sees' >99.9% of P! (All of the P is within the XPS depth of information .)
- P concentration peaks just below the surface and then decays steadily.
- Appears highest concentration of P is at surface with deeper sub-surface P peak compared to as-implanted sample.



RESULTS & DISCUSSION

SIMS-XPS Results P Plasma Implant in Si:

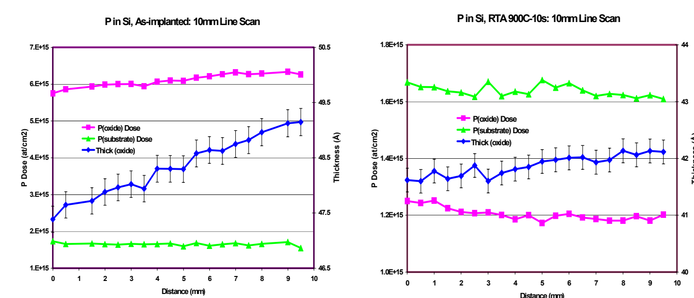
- SIMS shows all the P is detectable by XPS within top 100-150Å!
- Results imply some P is lost to vacuum/air during RTA.
- Shows some P is 'driven' into substrate after anneal.
- XPS cannot accurately determine X_j – requires SIMS profile.

Two-technique measurement gives accurate and precise USJ/ULE dose and X_j values.

XPS Precision and Accuracy for ULE P Dose Measurements in Si

- XPS repeatability (precision) is very high (based on SiON experience)
  - Requirements:
    - Sample stability
    - Stable achromatic/monochromatic source
    - No 'flood' gun/neutralization
    - High signal-to-noise
    - Short measurement time
    - Minimal or no operator intervention
    - Robust algorithm
    - High stability Instrument –stage, electronics, analyzer, vacuum, etc.
    - Long term reproducibility
    - 'Clean' samples
    - Accurate & calibrated – tool matching
  - Achievements of SiON HPM (High Precision Measurement)
    - 4Å ≥ T_{ox} ≥ 150Å
      - (≥90Å with reduced precision)
    - T_{ox} 'static' precision (1σ) <0.05Å
    - Tox typical precision < 0.2Å
    - N Dose (min.) > 1 x 10^{+14} at/cm^2 (lower w/ decreased precision)
    - N Dose: Rel. Std. Dev. <1.0%, typical precision <0.05x10^{+15}/cm^2
  - XPS HPM (High Precision Measurements) are highly specific and require specific instrument configurations and tool matching.
- Absolute accuracy will depend somewhat on P distribution within layer.
- Uniformity of:
  - Dose in substrate
  - Dose in oxide
  - Oxide thickness

  across a wafer will be critical.
- Dose (in oxide or substrate) does not have to correlate to oxide thickness: therefore it is important to measure both independently



CONCLUSIONS

- A single XPS measurement can provide:
  - accurate and precise oxide layer thickness.
  - total P dose and P dose of oxide and substrate regions individually.
- Excellent short term and long term precision of XPS measurement (demonstrated by SiON measurements).
- XPS should have good sensitivity to process changes and conditions.
- XPS can be used for P dose (radial) implant uniformity.

Appendix:

Uniform Constant Concentration Assumption: % Error for Sloped Line +/- Distribution