Comprehensive Study of Properties and Characteristics of In-Situ Phosphorous Doped Poly-Silicon Developed in LPCVD Furnace

(USA Patent 7,144,750 & USA Patent 7,160,752)

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Agenda

- ISDP development in custom built cross flow LPCVD furnace
- ISDP properties for different process and anneal conditions
- Flexibility to control stress from highly tensile of as-deposited ISDP film and tuning of stress in a controlled fashion either slightly tensile or slightly compressive
- ISDP thickness considered is 0.3um, 1.5um, 2um and multiple depositions of 1.5um up-to 7.5um for different MEMS device applications
- Comparison of ISDP stress between standard and cross flow LPCVD furnace
- Conclusions

Test Wafer Orientation in Cross-flow LPCVD Furnace

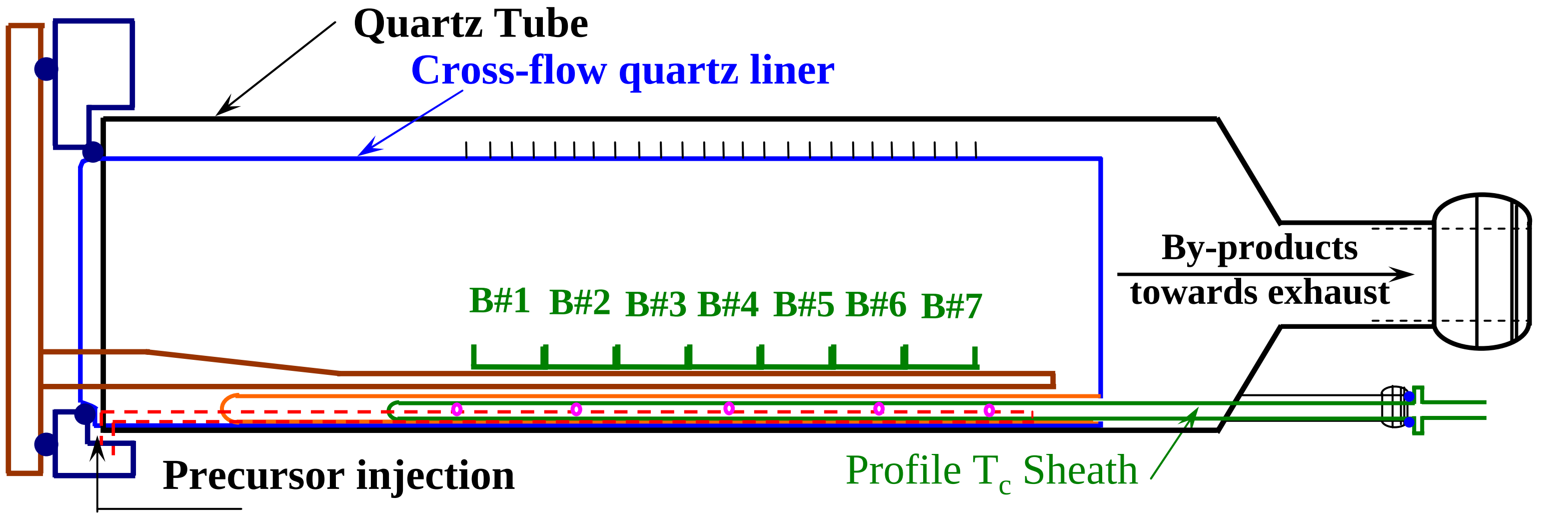


Figure: Schematic diagram of cross flow LPCVD furnace

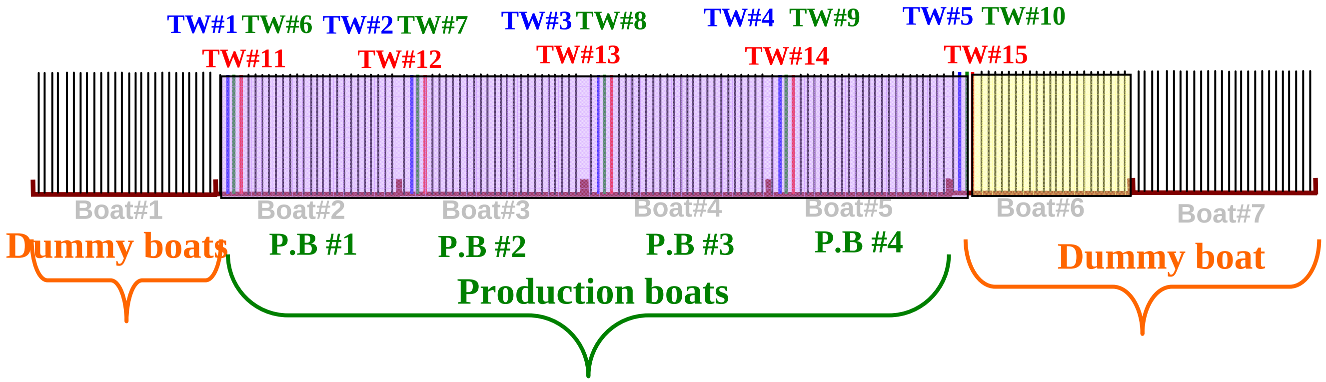


Figure: Test wafer orientation in furnace for ISDP property evaluation

ISDP Thickness and Stress Measurement

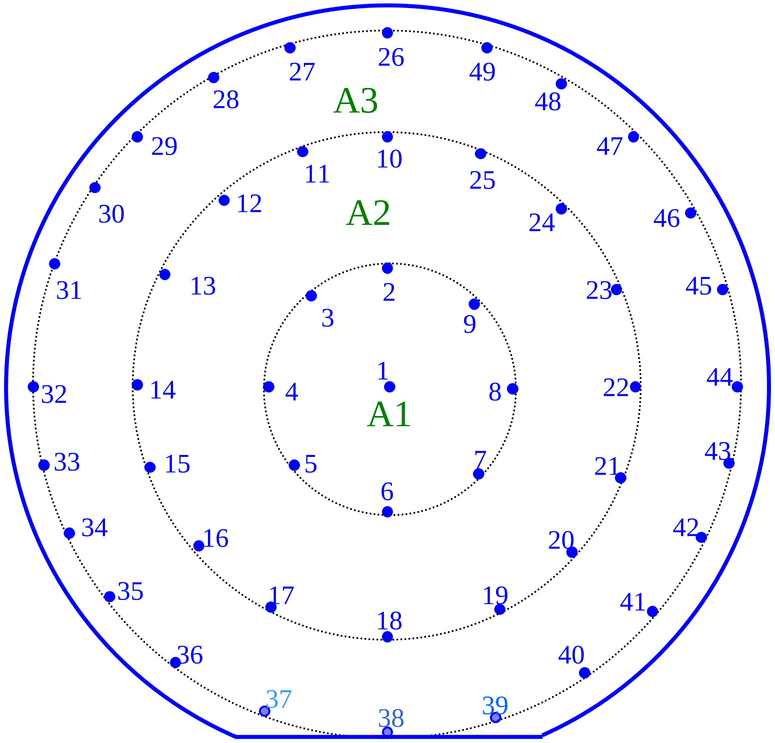


Figure: **46point data per wafer for raw thickness data analyses**

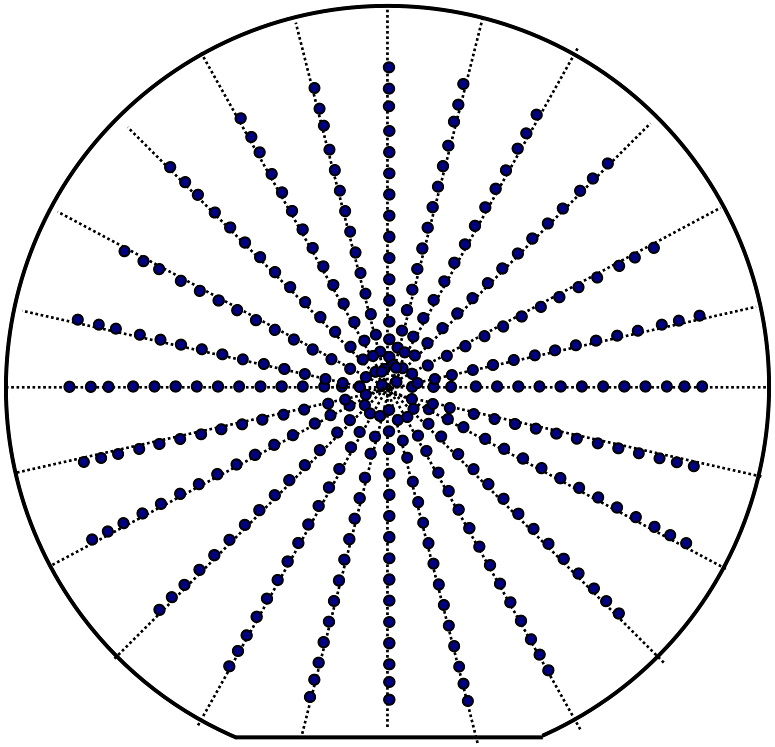
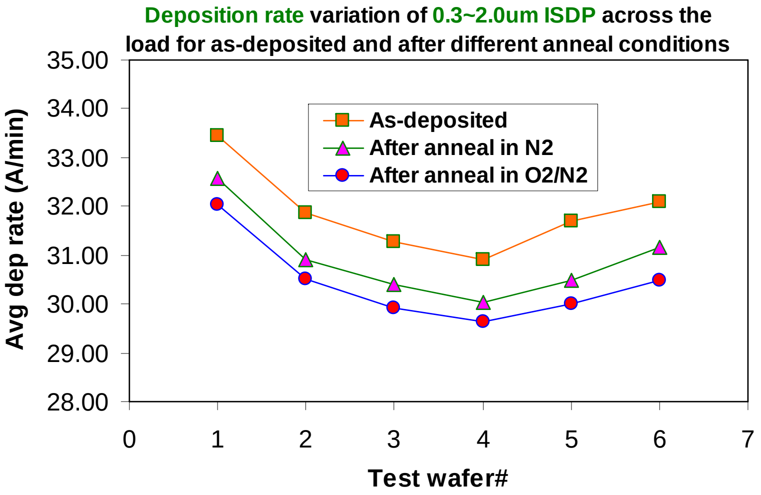
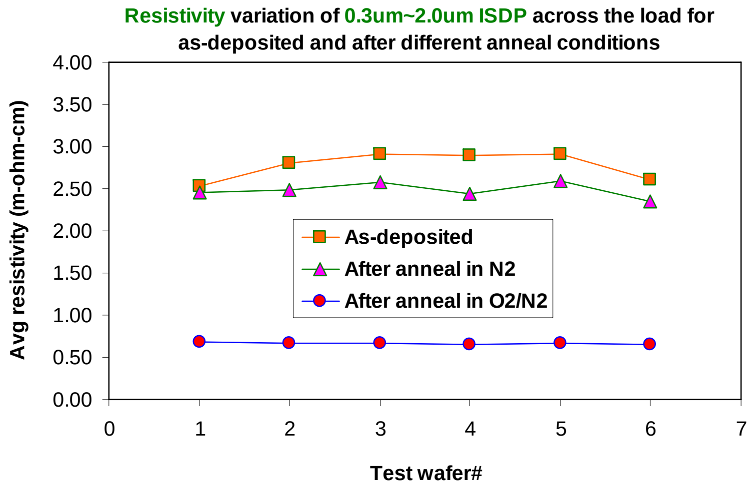


Figure: **334point data per wafer for raw stress data analyses**

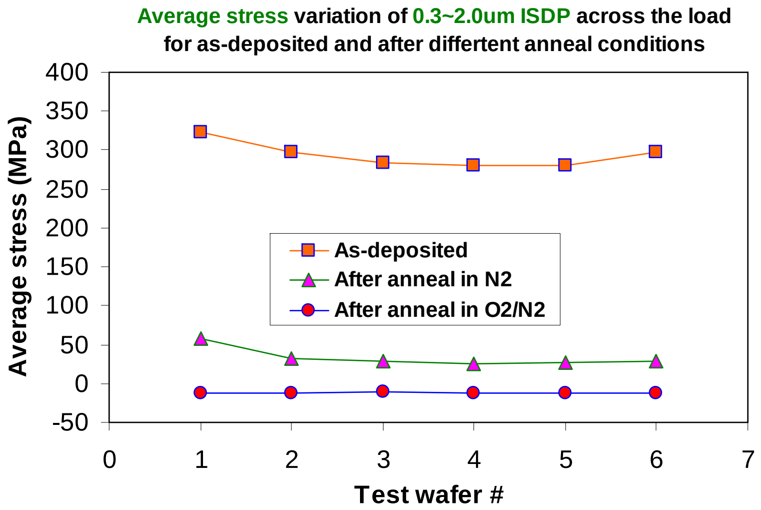
Impact of Anneal on ISDP Properties


Deposition rate variation of 0.3~2.0um ISDP across the load for as-deposited and after different anneal conditions

a) Deposition rate


Resistivity variation of 0.3um~2.0um ISDP across the load for as-deposited and after different anneal conditions

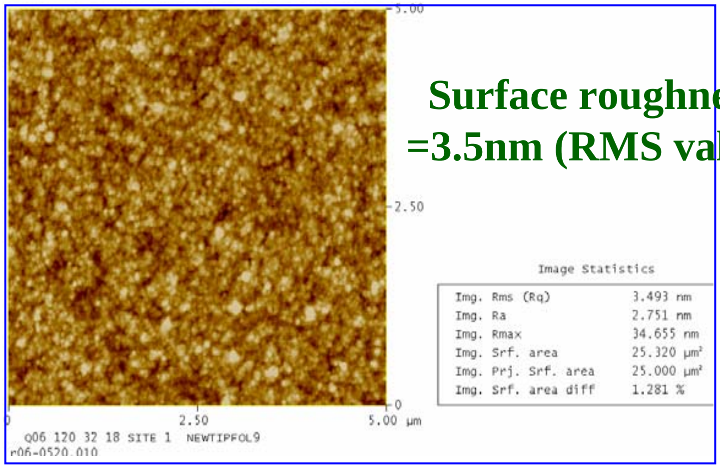
b) Resistivity


Average stress variation of 0.3~2.0um ISDP across the load for as-deposited and after differtent anneal conditions

c) Stress

- ❖ Resistivity of ~0.6m-ohm-cm is achieved after O2/N2 anneal
- ❖ Stress can be controlled from highly tensile to slightly tensile or slightly compressive by different types of anneal

Impact of Anneal on Surface Roughness of ISDP



```
Image Statistics
Img. Rms (Rq)           3.493 nm
Img. Ra                 2.751 nm
Img. Rmax               34.655 nm
Img. Srf. area          25.320 µm²
Img. Prj. Srf. area     25.000 µm²
Img. Srf. area diff     1.281 %
```

Surface roughness =3.5nm (RMS value)

Figure: As-deposited ISDP (1.5um)

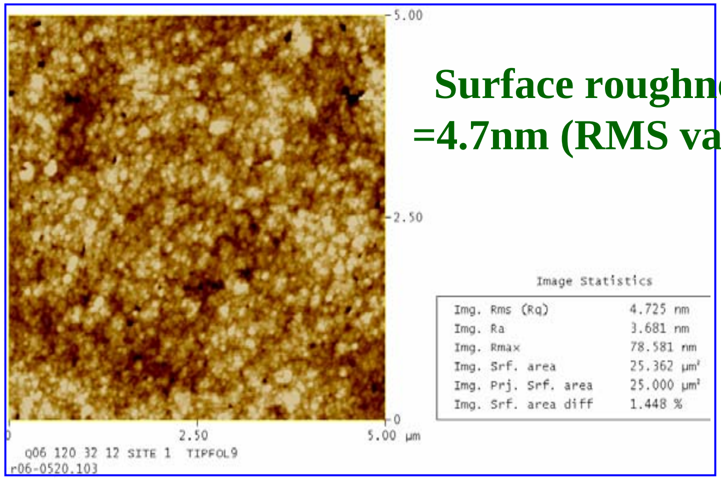


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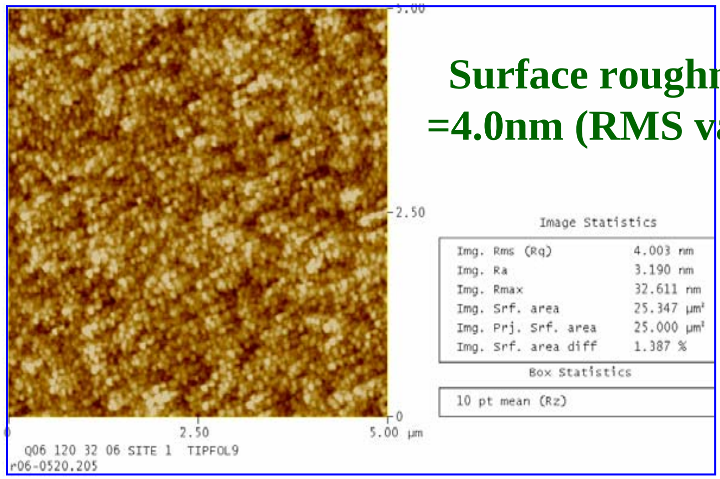
Image Statistics
Img. Rms (Rq)           4.725 nm
Img. Ra                 3.681 nm
Img. Rmax               78.581 nm
Img. Srf. area          25.362 µm²
Img. Prj. Srf. area     25.000 µm²
Img. Srf. area diff     1.448 %
```

Surface roughness =4.7nm (RMS value)

Figure: ISDP after N2 anneal (1.5um)



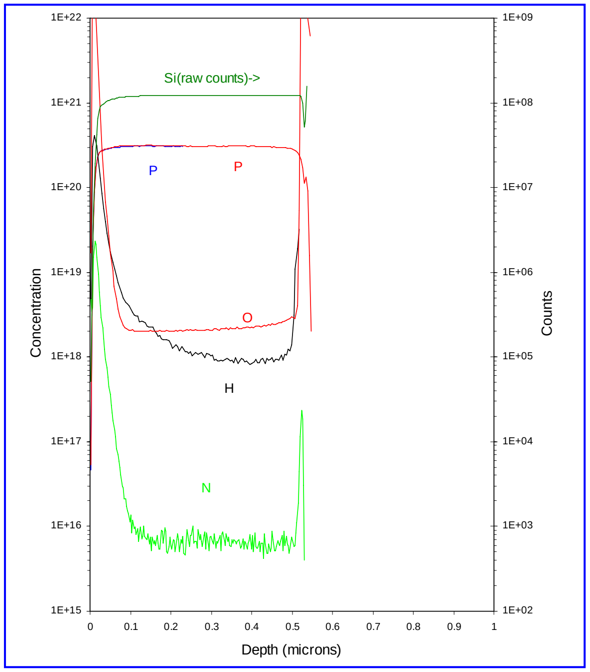
```
Image Statistics
Img. Rms (Rq)           4.003 nm
Img. Ra                 3.190 nm
Img. Rmax               32.611 nm
Img. Srf. area          25.347 µm²
Img. Prj. Srf. area     25.000 µm²
Img. Srf. area diff     1.387 %
Box Statistics
10 pt mean (Rz)
```

Surface roughness =4.0nm (RMS value)

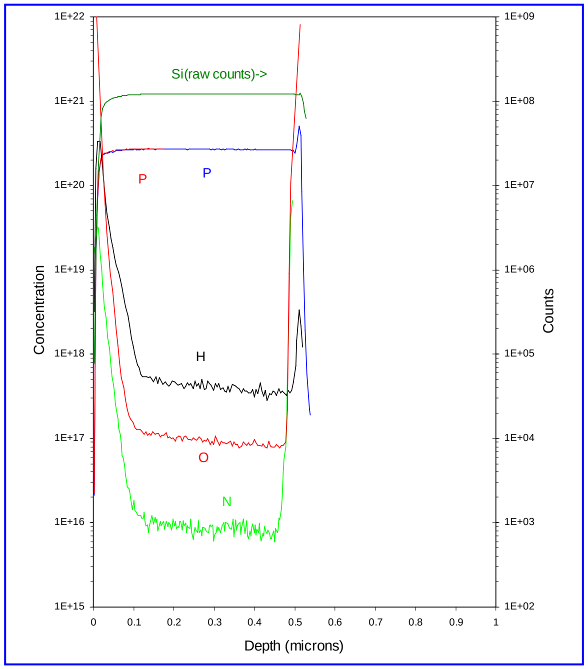
Figure: ISDP after O2/N2 anneal (1.5um)

- Anneal either in N_2 or in O_2/N_2 environment has almost no impact on surface roughness
- No CMP operation is required for subsequent processing steps after ISDP depositions because of very low surface roughness

SIMS Analyses of 0.5um ISDP



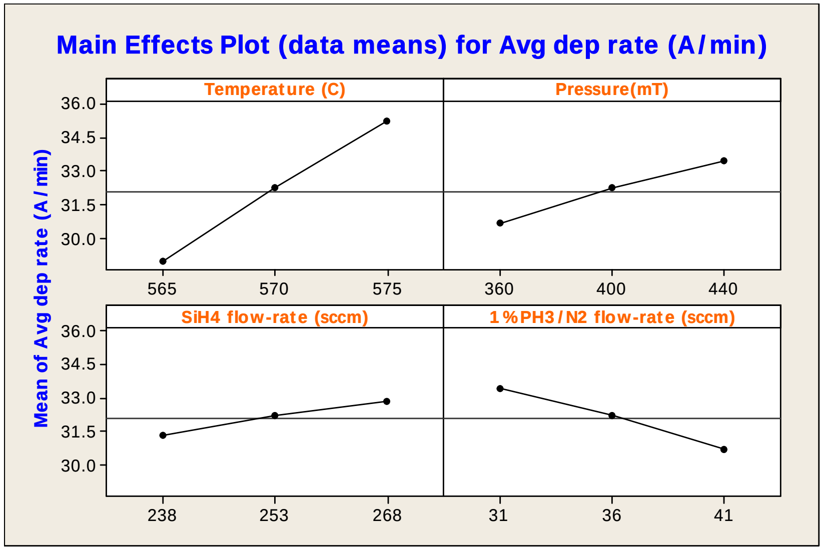
a) As-deposited ISDP

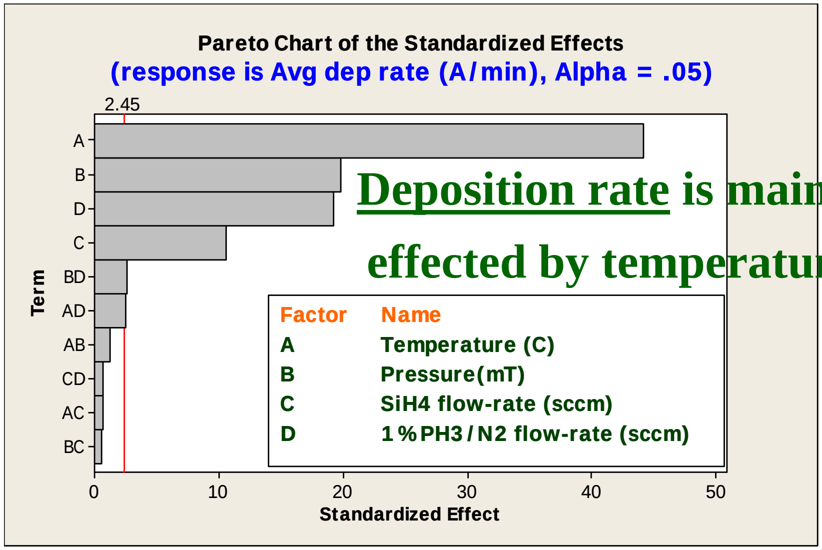


b) ISDP after O_2/N_2 anneal

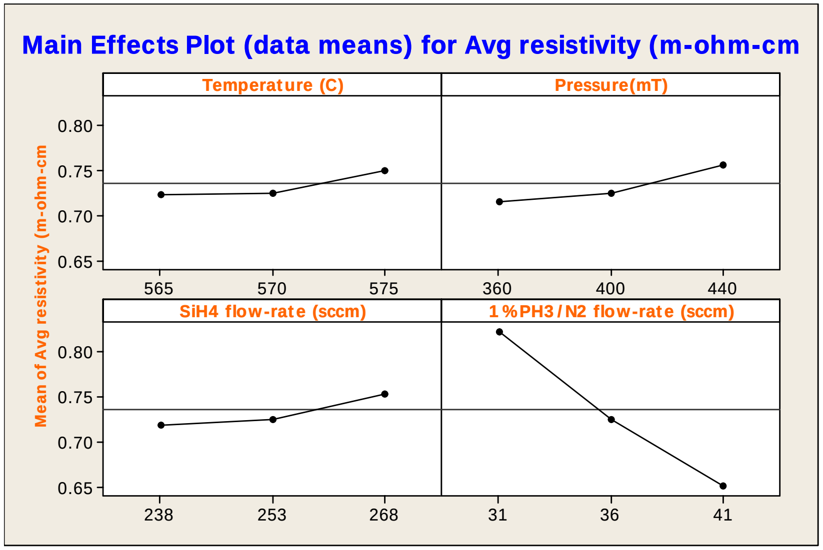
Elements	Concentration (%) As-deposited ISDP	Concentrations (%) ISDP after O2/N2 anneal
P	0.6%	0.6%
O	0.004 - 0.006%	0.0002%
H	0.01 - 0.002%	0.001%
N	0.00002%	0.00002%
O and H contents significantly drops after anneal		

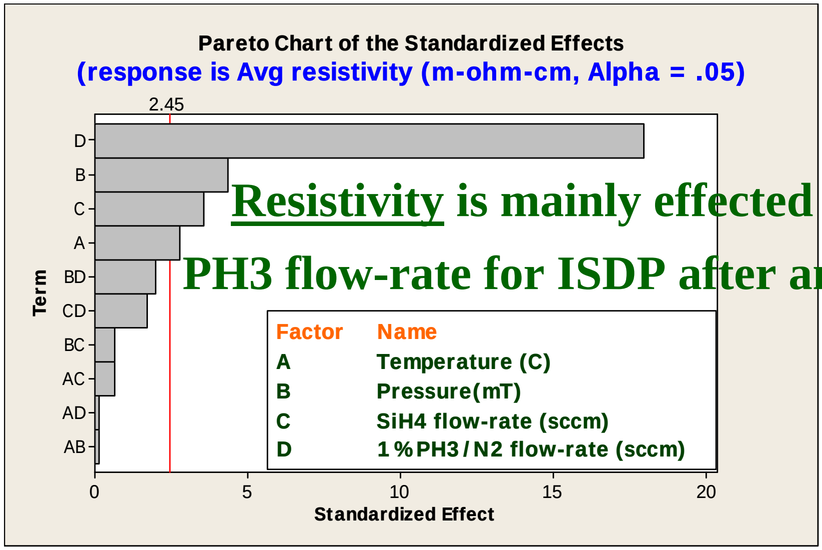
Impact of Process Conditions on ISDP Characteristics





Deposition rate is mainly effected by temperature





Resistivity is mainly effected by PH3 flow-rate for ISDP after anneal

Impact of Process Conditions on ISDP Characteristics

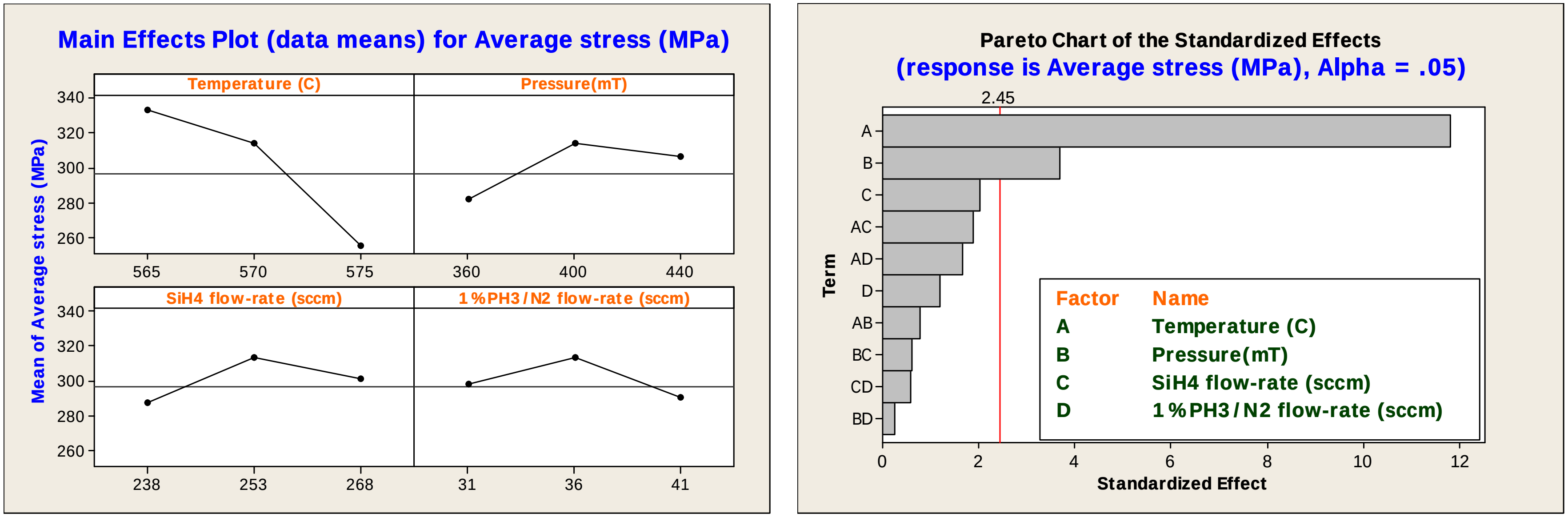
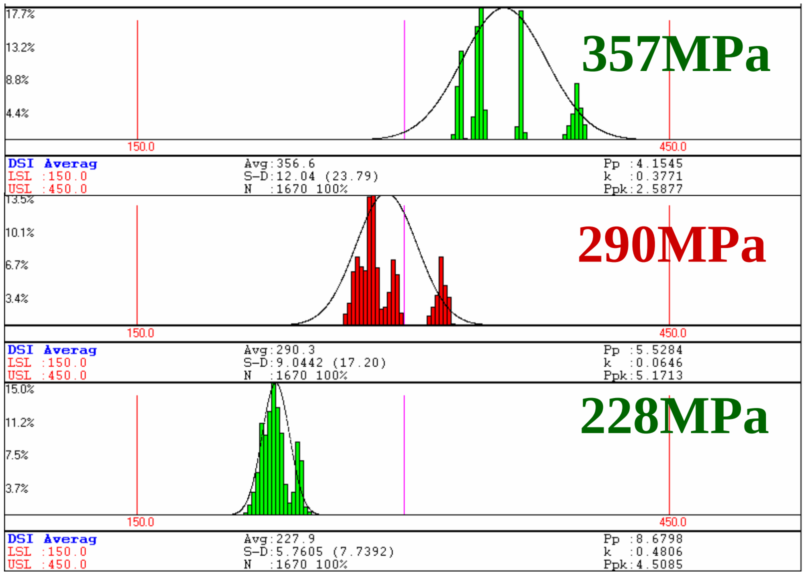


Figure: Impact of process conditions on as-deposited ISDP (1.5um)

- Temperature is the main factor of the Pareto to control stress of as-deposited ISDP and ISDP after N2 anneal
- **Stress** of ISDP after O2/N2 anneal is effected not only by temperature but also by PH3 flow-rate

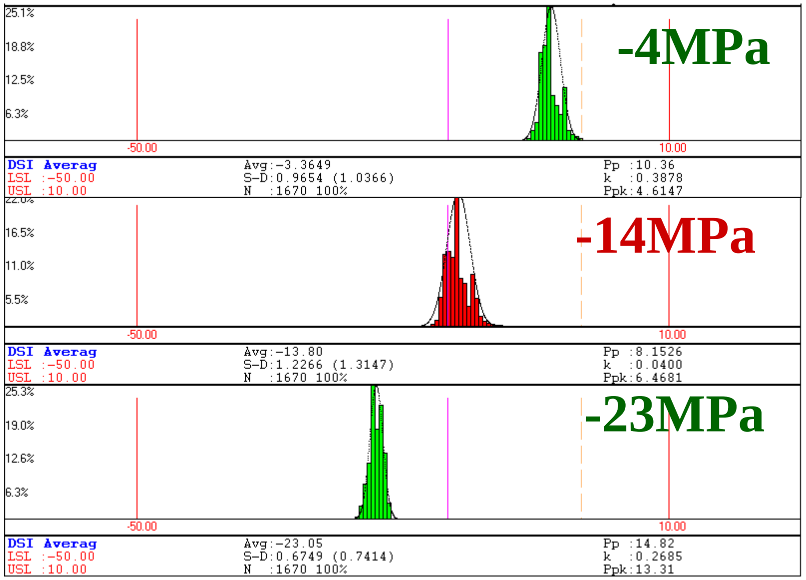
Flexibility to Control Stress



```
DSI Averag          Avg:356.6                 Pp :4.1545
LSL :150.0          S-D:12.04 (23.79)         k  :0.3771
USL :450.0          N  :1670 100%             Ppk:2.5877

DSI Averag          Avg:290.3                 Pp :5.5284
LSL :150.0          S-D:9.0442 (17.20)        k  :0.0646
USL :450.0          N  :1670 100%             Ppk:5.1713

DSI Averag          Avg:227.9                 Pp :8.6798
LSL :150.0          S-D:5.7605 (7.7392)       k  :0.4806
USL :450.0          N  :1670 100%             Ppk:4.5085
```

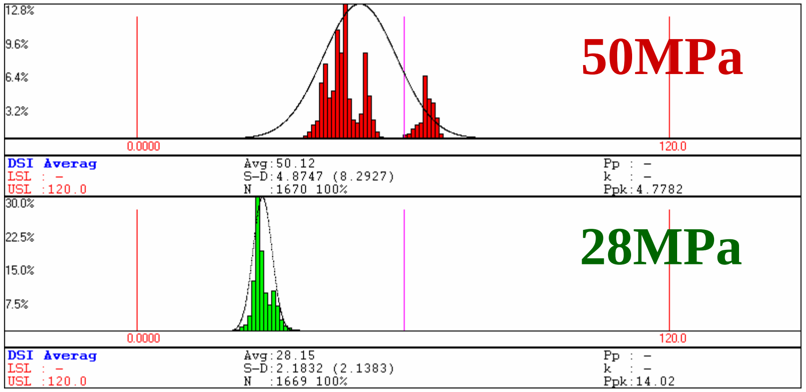


```
DSI Averag          Avg:-3.3649               Pp :10.36
LSL :-50.00         S-D:0.9654 (1.0366)       k  :0.3878
USL :10.00          N  :1670 100%             Ppk:4.6147

DSI Averag          Avg:-13.80                Pp :8.1526
LSL :-50.00         S-D:1.2266 (1.3147)       k  :0.0400
USL :10.00          N  :1670 100%             Ppk:6.4681

DSI Averag          Avg:-23.05                Pp :14.82
LSL :-50.00         S-D:0.6749 (0.7414)       k  :0.2685
USL :10.00          N  :1670 100%             Ppk:13.31
```

As-deposited ISDP→ Different process conditions → ISDP after O2/N2 anneal



```
DSI Averag          Avg:50.12                 Pp : -
LSL : -             S-D:4.8747 (8.2927)       k  : -
USL :120.0          N  :1670 100%             Ppk:4.7782

DSI Averag          Avg:28.15                 Pp : -
LSL : -             S-D:2.1832 (2.1383)       k  : -
USL :120.0          N  :1669 100%             Ppk:14.02
```

ISDP after N2 anneal → Different process conditions

Highly flexible process to tune stress in a controlled fashion from highly tensile to slightly tensile or slightly compressive

Raw stress data analyses

Comparison of Stress of ISDP after O2/N2 Anneal between Standard and Cross-flow LPCVD furnace

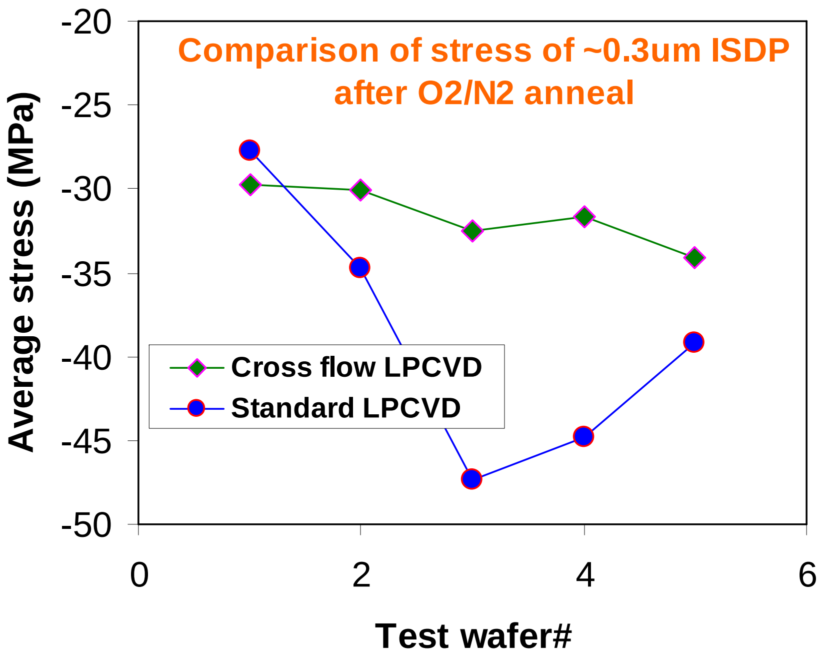
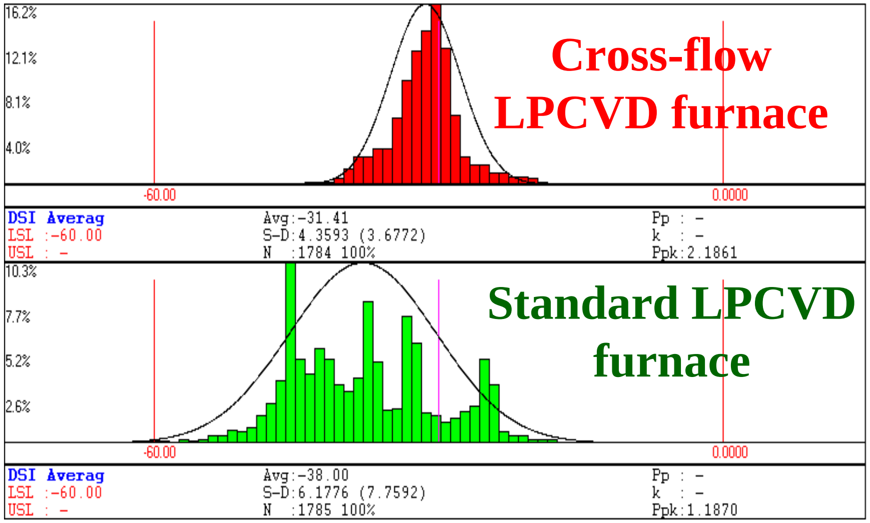


Figure: Comparison of average stress variation across the load



```
DSI Averag          Avg:-31.41                Pp : -
LSL :-60.00         S-D:4.3593 (3.6772)       k  : -
USL : -             N  :1784 100%             Ppk:2.1861
```

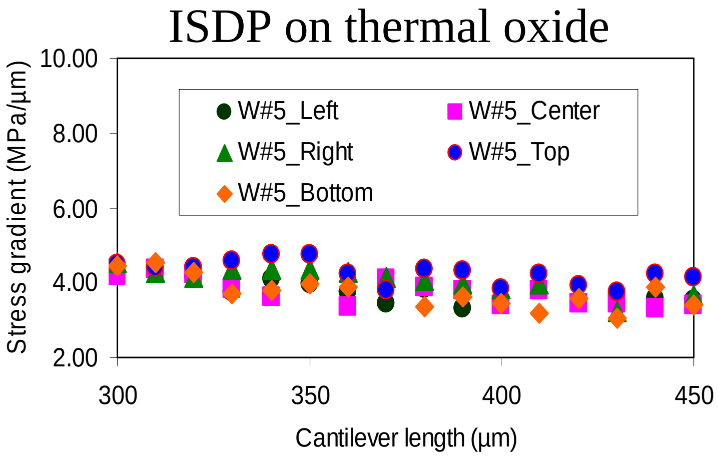
```
DSI Averag          Avg:-38.00                Pp : -
LSL :-60.00         S-D:6.1776 (7.7592)       k  : -
USL : -             N  :1785 100%             Ppk:1.1870
```

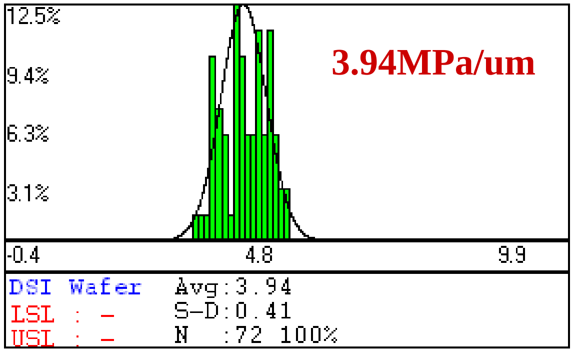
Figure: Comparison of raw stress data variation across the load

Cross flow LPCVD furnace shows better stress control of ISDP across the load and run-to-run as well for as-deposited ISDP and ISDP after different conditions of anneal for thickness of 0.3um ~2.0um

Evaluation of ISDP Properties

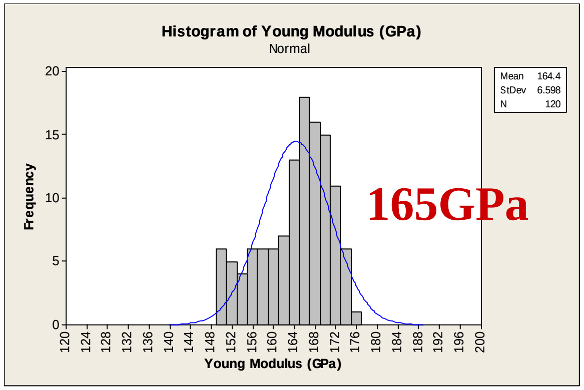
Stress Gradient of 2.0um ISDP after N2 anneal



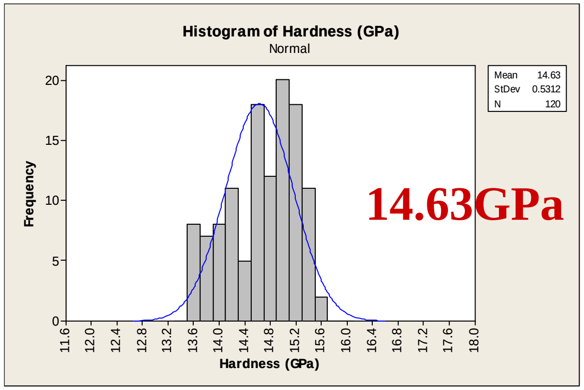


```
DSI Wafer    Avg:3.94
LSL  :  –    S-D:0.41
USL  :  –    N  :72  100%
```

Young’s modulus of 2.5um ISDP



Hardness of 2.5um ISDP



2.5um as-deposited ISDP properties	Average (GPa)	STDEV (GPa)
Reduced Young's modulus (Er) of 2.5um ISDP By Nanoindentation	165	4.6
Young's modulus of 2.5um ISDP E = Er (1-$\gamma^{2)}$	157.8	4.4
Hardness by nanoindentation	14.63	0.53

Conclusions

- Very low resistivity of as-deposited ISDP of ~2.5m-ohm-cm is achieved. Resistivity of ISDP is further reduced to 0.6m-ohm-cm after O2/N2 anneal. Resistivity can be tuned mainly by PH3 flow-rate.
- Very low surface roughness of 3.5nm for as-deposited ISDP, slightly increased by anneal to 4.7nm enables to pursue subsequent processing steps for MEMS application without CMP operations
- Highly flexible developed ISDP process enables to tune stress in a controlled fashion from highly tensile in the range of 228~357MPa to slightly tensile in the range of 28~ 50MPa or to slightly compressive in the range of -4 ~ -23MPa
- Flexibility of stress control, low resistivity, and low surface roughness, thereby avoiding CMP operation make DALSA’s developed ISDP process ideal structural material for MEMS applications

Acknowledgment

- Michel Pomerleau for acquisition, installation, and testing of hardware
- Dominic Carrier for the AFM analyses for surface roughness measurements
- Muriel Dardalhon for ISDP properties evaluation by test structures
- Sylvie Champoux, Dave Rioux, David Turcotte, Kathy Feehan for engineering support
- Robert Sirois, Manon Daigle, and Sonia Smith for operation help
- Jonathan Lachance for device performance evaluation
- Francois Bedard for wet etch recipe development to evaluate stress of ISDP
- All diligent DALSA coworkers who helped with the wafers processing and results extraction.