Low-Temperature Oxidation/Nitridation Processes enabling Advanced Junctions

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NCCAVS Junction Technology Group
Semicon West 2013 Meeting
San Francisco, July 11th 2013
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Motivation

- Geometrical Scaling in 2D: (More Moore, comes to a physical end)
  - Thermal budget reduction for smaller feature size and for deactivation reduction: RTP and ms-annealing (MSA)
  - Plasma-assisted technologies for process temperature reduction

- Transition planar to 3D Gate Structures: (technology challenges occurring)
  - Extreme conformity required
  - Excellent dopant activation
Oxidation Enhanced Diffusion during Flash Annealing, pMOS

- For (D) less dissolution of immobile peak compared to (B).
  In case of 100 ppm O₂ ~20 % reduced retained dose.
- Ideal case: 10% O₂ during Flash and 100 ppm O₂ during Spike to avoid outdiffusion (dopant loss).

Advanced Activation Trends for Boron and Arsenic by Combinations of Single, Multiple Flash Anneals and Spike Rapid Thermal Annealing
Dose Protection during “Oxidizing” Flash Annealing, nMOS

- Dopant loss reduced by 30%, similar mobility values of 40 cm²V⁻¹s⁻¹.
- In case of (B) the activation is 44 % and 30 % for (C).
- No impact on profile due to use of oxidizing ambient except reduced outdiffusion (reduction of dopant loss).

Dopant Activation by Annealing Strategies, nMOS

- Spike + Flash optimum strategy regarding Xj and Rs
- Annealing ambient of paramount importance or a low-T oxide capping layer to avoid As evaporation

For arsenic implants in c-Si the defect density after flash and spike + flash is below TEM-WBDF detection limit.

The difficulty for the activation and annealing process is that plasma doping profiles of either B and As reside directly under the surface and it is of paramount importance to deposit a capping layer at low-temperature to avoid massive dopant out-diffusion during the suitable annealing condition for controlled dopant redistribution and activation.
Deactivation a Driver for Low-Temperature Oxidation

**R_s-Evolution (t / T) for highly activated 500 eV Boron, 1 keV Arsenic Profiles**

- Deactivation / “reactivation” process for t / T regime
- Time dependent increase in R_s followed by marked drop
- Max. R_s decrease with T suggesting a thermally activated process
- Probably SiAs clusters and As-V cluster formation cause R_s increase within 3 s


Interim Conclusions

- Outdiffusion needs to be controlled in shallow junctions
  - Use of higher oxygen concentration during anneal
  - Use a low temperature cap layer
- Post anneal process temperatures must be limited to prevent deactivation
HEAT: A Blunt Instrument for Device Fabrication?

- Historically HEAT enabled:
  - Reaction
  - Phase change
  - Bond rearrangement
  - Atomic diffusion

- Sometimes we want these changes, sometimes not

- But HEAT alone is not the only possible driver

- Kinetics & reaction path must be optimized by design of thermal cycle and ambient conditions

- Non-thermal energy (photons, PLASMA, particle beams) provide desirable alternative reaction paths
Plasma Apparatus Schematic

Concept of a plasma chamber with microwave plasma generation and possible wafer preheating by lamps
Advantages of Microwave Plasma Generation

A ~100x higher frequency than RF results in a ~$10^4$ times higher degree of dissociation.

High electron concentration around the plasma source.

Shielding of microwave radiation by this high electron concentration.

Plasma damage is greatly reduced, even near the plasma sticks.

Less heating of the wafer.

Neutral atoms/molecules and radicals are not shown, number of particles are adjusted for the sketch and do not represent real situation!
Growth Curves

oxide thickness = f (time)

Oxide growth up to 4 nm with wafer temperature below 200 °C
(wafer heated up by plasma, no preheat by lamps)

Oxide growth up to 30 nm with elevated wafer temperature up to 800 °C
(wafer preheated by lower lamp field, gaseous ambient O₂ and H₂)

Si-SiO₂ interface roughness on atomic scale. Equivalent to high-T furnace
No plasma- /microwave-damage observed!

Temperature < 400 °C
Time: 80 s in O₂
t₀ₓ = 5.1 nm

TEM Oxide Growth Characterization

O$_2$ Plasma

- t: 80 sec
- p: 260 mTorr

STI structure (AR 3.2:1) with CAP nitride

Conformal oxide growth on the sidewall for both oxidation of silicon and reoxidation of nitride
Conclusions

- CMOS device scaling will require extremely low-temperature processing (close to room temperature) or very high temperature/very short time processing as an enabling technology.

- Interface engineering, gaseous ambient control, dopant outdiffusion control, topography control and reduction of parasitic resistances will become increasingly important as new device structures, especially 3D, and new materials are integrated.

- Non-thermal energy sources and new reactive species provide enabling capabilities like the low-T plasma oxidation apparatus:
  - Excellent corner rounding
  - Atomically flat interface
  - Nearly orientation independent oxidation
  - Low thermal budget processing
  - Excellent electrical isolation characteristic

- More-Moore, More-than-Moore and especially 3D devices will be enabled by low thermal budget processing.
Acknowledgments

Our personal thanks to …

…. our colleagues in centrotherm for their patience while preparing for talks

…. Zsolt Nenyei for continuous inspiring and helpful discussions

…. Fred Roozeboom for providing the sophisticated extremely deep trench samples

…. CEMES-CNRS laboratory especially F. Cristiano for his great TEM pictures
Thank you very much for your attention!

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