Plasma Doping of Silicon Fin Structures

S. Felch, C. Hobbs¹, J. Barnett², H. Etienne, J. Duchaine, M. Rodgers³, S. Bennett⁴, F. Torregrosa, Y. Spiegel, and L. Roux

IBS, Peynier, France
¹SEMATECH, Albany, NY, USA
²SEMATECH, Austin, TX, USA
³CNSE, Albany, NY, USA
Outline

- Introduction to plasma doping and 3D doping challenges
- Experimental details
  - PULSION hardware features
  - Si fin test structures
- Results
  - SIMS profiles for BF$_3$ and AsH$_3$ plasma implants into bare wafers
  - Amorphous layer produced by BF$_3$ plasma implant
  - XSEM images of fins chemically stained to highlight B dopant
  - Top-down SIMS profiles through unannealed and annealed fins doped by BF$_3$ and AsH$_3$ plasmas
  - XTEM image of annealed BF$_3$ plasma doped fin
- Summary
Introduction

- Plasma doping in R&D for over 2 decades
  - Ultra-shallow junctions
  - Conformal doping of trenches and fins
- Two very high dose, DRAM applications in production today
  - Polysilicon gate counter-doping
  - Contact doping
- Multiple gate and FinFET devices now in development to enable continued scaling
  - Candidate replacements for conventional planar CMOS devices
    - Excellent short channel effect immunity
  - Conventional, directional beam-line implant processes not well-suited
  - Plasma doping is an attractive implant alternative
    - Uniform junctions in 3-dimensional structures
    - Damage-free after anneal
3D Doping Challenges

- 3D implant is a combination of:
  - Direct implant
  - Sputtering effect
  - Deposition

- 3D doping performance targets:
  - Good conformity
  - No fin erosion

- Fine process parameter tuning is needed to achieve optimal 3D performance.

- Key Factors of Success:
  - Large number of process parameters
  - Wide process window for each parameter
  - Independent tuning of process parameters
PULSION® Hardware Features for 3D Plasma Doping

- Wide process range due to remote plasma source
  - Independent tuning of plasma density and chamber pressure
  - Adjustable pressure differential between source and chamber: up to 2 orders of magnitude
  - Multiple independent knobs to find optimal process conditions and chemistries
  - Ability to balance implant versus deposition to get best conformal doping

- Use of low implant energies
  - No fin corner rounding and height erosion
  - Thin amorphous layers
  - Minimal damage after implant and anneal
Silicon Fin Test Structures

- Fins wider than 16nm node device, but useful to evaluate lateral implant depth and diffusion of dopants
- Fabricated on bulk-Si wafers
- Plasma doping using BF$_3$ or AsH$_3$ gas
- Anneal splits to simulate source/drain junction anneals
- Sample analysis
  - Top-down SIMS after additional amorphous Si deposition and CMP
  - XSEM after delineation etch
  - XTEM to compare vertical and horizontal fin damage
**BF₃ SIMS Profiles for Four Wafer Voltages**

- Implant depth proportional to wafer voltage
- Low energies desired to form ultra-shallow junctions and to minimize sputtering, fin erosion, and implant damage

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**SIMS vs HV**

**Xj vs HV**

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**C [at/cm²]**

**Depth [nm]**

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**Xj [Å]**

**X [Å]**

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**HV [kV]**

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**HP BF3 5kV 1E15**

**HP BF3 1kV 1E15**

**HP BF3 0,5kV 1E15**

**HP BF3 0,2kV 1E15**

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SIMS Profile for BF$_3$, 0.5 kV, 1E15 cm$^{-2}$

- 11B depth at 1E18 cm$^{-3}$ = 7.69 nm
- Total SIMS dose (11B + 10B) = 4.35E14 cm$^{-2}$
- Both B isotopes detected, since this gas was not isotopically enriched
Amorphous Layer Thickness for USJ Implant

- **HRTEM** image of BF$_3$, 0.5 kV, 1E15 cm$^{-2}$ implant
- **Thickness of amorphous Si layer** ~2 nm
  - Thin enough to leave crystalline Si region in interior of 16nm node fin and enable complete regrowth of fin Si
Conformal doping of as-implanted sample
  - White regions on top of fins, along sidewalls, and between fins are B-doped, not B deposition on surfaces of fins (see next slide)
  - Equal thicknesses of all regions

Entire fin is light-colored after PMOS source/drain anneal
  - Anneal caused B to diffuse toward center of fin
Unchanged Dimensions of Plasma Doped Fins

- White layer is inside fin Si, since no change in fin dimensions and bright, white layer disappears in annealed sample
  - White layer is thicker than expected amorphous layer
  - Expected junction depth is close to thickness of white layer
- No evidence of corner rounding or fin erosion
SIMS Depth Profiles through BF$_3$ Plasma Doped Fins

- Anneal improved top-to-bottom uniformity of fin doping
  - Sputtering from fin bottoms may be dominant mechanism
- Significant B outdiffusion caused by anneal
  - Annealed B concentration ~ B solid solubility limit and maximum electrical activation level for typical spike anneal
- $^{10}$B isotope much lower than $^{11}$B due to use of isotopically enriched BF$_3$ gas
XTEM Images of Annealed BF$_3$ Plasma Doped Fins

- No visible damage along tops or sidewalls of fins
- Regrown Si shows good crystalline quality throughout fin
- Thin (~2nm) native oxide present around fin
SIMS Depth Profiles for AsH₃ Implants

- For 1 kV implant, As depth at 1E18 cm⁻³ is 12 nm
- As studied as n-type dopant due to its high electrical activation and low diffusivity
SIMS Profile of Arsenic USJ with Flash Anneal

- AsH₃, 0.3 kV, 2E14 cm⁻²
- 1200°C flash anneal
- As depth at 1E18 cm⁻³ is 7 nm
SIMS Depth Profiles through AsH₃ Plasma Doped Fins

- Top-to-bottom doping uniformity along sidewalls is quite good for both samples
- As sidewall concentration decreased by half order of magnitude due to NFET source/drain anneal
  - Much less than that for BF₃ implanted fins
  - Concentration at fin tops and bottoms decreased by ~ order of magnitude
  - Due to combination of diffusion into fin and substrate and outdiffusion
- As tail extending to right of fin bottom is due to As diffusion into substrate
Summary

- Plasma doping has good conformality around fin structures for source/drain doping applications
- Subsequent annealing diffuses dopant toward center of fin
- Top-down SIMS through fins indicated that subsequent anneal caused significant Boron out-diffusion for BF$_3$ plasma implant, whereas As out-diffusion for AsH$_3$ plasma implant was smaller
- TEM analysis of annealed samples found no significant damage along top or sidewall of BF$_3$ plasma implanted fin