Alumina and Silicon Oxide Sidewall Passivation for P- and N-Type Sensors

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Outline

• Slim Edges – Motivation and Approach

• Type of Sidewall Passivation and Edge Damage

• Results for P-Type Sensors
  - Alumina for P-Type Silicon Passivation
  - IV Curves for P-Type Diodes with Alumina Passivation
  - Charge Collection Measurements

• Results for N-Type Sensors
  - PECVD Oxide and Nitride Passivations
  - IV Curves for N-Type Sensors
  - Large Area Sensors

• Conclusions and Outlook
Motivation – Slim Edges

If you obtain
1. minimal damage at edge and
2. “right” sidewall surface charge
one can make slim edges with post processing.

Slim edges offer:
• better tiling of sensors
• reduced inactive area
Type of Sidewall Passivation – N-Type Si

A passivated trench with a \textit{thermally} grown oxide (\textit{positive} charge density $10^{11}$ cm$^{-2}$) trench will lead to [idea from J. D. Segal and C. J. Kenney, IEEE NSS 2010]:

- control potential drop toward the cut edge,
- protection from saw cut edge.
Alumina passivation, *negative* interface charge $\sim -10^{13}$ cm$^{-2}$, leads to:

- high electric field strip edge,
- partially controlled potential drop towards the cut edge.
Fabrication Sequence

Laser-cutting or XeF$_2$-scribing and cleaving (see detailed slides)

Al$_2$O$_3$ ALD at 300 °C

annealing at 400 °C

RIE with hard mask

The process sequence is analogous for n-type Si but the ALD deposition is replaced by SiO$_2$ and Si$_3$N$_4$ PECVD (plasma enhanced chemical vapor deposition).

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Al$_2$O$_3$ and SiO$_2$ sidewall passivation for p- and n-type sensors
Edge Scribing and Cleaving

- used finished dies (post-processing)
- laser scribing **only at edge** → **no laser damage near active area**
- most separation is done by pure cleaving → no sidewall damage

Cleaving is still done by hand using tweezers, but can be done automatically.
P-Type Diodes

- **Device A**
  - 14 μm
  - diode edge
  - cleaved edge

- **Device B**
  - Si diode
  - guard ring
  - SiO₂

- **Graphs**
  - Current vs. Bias
  - Leakage Current vs. Bias Voltage
  - Notations:
    - Slim edge
    - No guard ring
    - Die level processing
  - Images:
    - Processed device with alumina layer
    - Un-processed reference
Charge Collection – P-Type Strip Sensor

- Consistent beam profiles taken at different positions is an indication of high efficiency at the edge.
- By scanning the thresholds we can derive the collected charge on each strip.
- We observe the same collected charge at all locations to a few percent.

*Graphs and data plots are not transcribed.*

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Al₂O₃ and SiO₂ sidewall passivation for p- and n-type sensors
GLAST Sensors

GLAST Test Structures
- “Baby”, 32 strips, 3.5cm
- Mos Structures
- Bonding Test Structure
- Photo Diodes
- “Skinny”, 8 strips, full length,

GLAST2000 SSD
8.95cm x 8.95cm

Al₂O₃ and SiO₂ sidewall passivation for p- and n-type sensors
Applying the same method to n-type using a *positive* sidewall passivation:
• PECVD (plasma enhanced chemical vapor deposition),
• variation in deposition temperature and material (next slide).
Silicon nitride side wall passivations shows lowest leakage currents for n-type sensors.
Un-cut

\[ \text{Vbias}=150\text{V}, \sim 100\text{ nA.} \]

Cut

\[ \text{Vbias}=500\text{V (200 V efficient).} \sim 15\text{ uA} \]

Charge collection tests with Beta particles performed at U. of Florence. Charge collection profile is unchanged.
Large Area Sensors

- CIS strip sensor from PPS submission.
- 8-guard ring design originally from Liverpool.

SEMI standard for flat/crystal alignment: +/- 0.9 degrees
Typical values for FZ material: +/- 0.1 degrees

Cleaving is easier if
- device aligned with <100> direction,
- no mechanical stress from thin films.

**BUT pure cleaving is not practical for large sensors!**
• XeF$_2$ vapor phase etching exhibits nearly infinite selectivity of silicon to photo-resist, polymers, SiO$_2$, Si$_3$N$_4$, and aluminum -- ideal for processing finished sensors.
• Being a vapor phase etchant, XeF$_2$ avoids many of the problems typically associated with wet processes.
• XeF$_2$ etch introduces no mechanical stress or heat effect zone.
“XeF₂-Scribing” and Cleaving

• used finished dies (post-processing)
• laser scribing **only at edge** $\rightarrow$ no laser damage near active area
• cleaving $\rightarrow$ no sidewall damage
• very shallow XeF₂ etch will guide cleavage plane (*details next slides*)

Optical micrograph, top view

SEM micrograph, cross-section

before cleaving

tweezers

after cleaving

Cleaving is still done by hand using tweezers, but can be done automatically.
XeF₂ Etching

SEM micrographs (bird’s-eye view)

cleavage plane

guard ring

laser damage

after cleaving

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Al₂O₃ and SiO₂ sidewall passivation for p- and n-type sensors
Large Area Sensors

- GLAST Baby sensor (1.5 x 3 cm)
- cut distance to guard 50 µm
Large Area Sensors

- GLAST Baby sensor (1.5 x 3 cm)
- XeF₂ scribing through guard
- cut distance to “jog-outs” from bias ring ~ 20 μm

Si₃N₄ sidewall passivation deposition done at 300 °C

Optical micrograph, top view
Conclusions and Future Work

- Cleaved sidewall has no silicon damage.
- **P-type** silicon requires *negative* side wall passivation.
- Alumina/silicon interface has negative charge.
- **N-type** silicon requires *positive* side wall passivation.
- Excellent charge collection for **p-type Si** with alumina sidewall passivation.
- Silicon nitride sidewall passivation shows lowest leakage current for **n-type Si**.
- Large area sensor by cleaving along a shallow XeF$_2$ etched groove.

Find alternative to manual cleaving using tweezers (*ongoing*).
Determine exact alumina/silicon interface charge (*CV plots*).
Alumina surface charge region sensitive to radiation/dose (*ongoing*)?
Laser-Scribing and Cleaving

- used finished dies (post-processing)
- laser scribing → less laser damage → lower leakage currents
- cleaving → no damage

Laser-scribing done at U.S. Naval Research Laboratory using an Oxford Laser Instruments E-Series tool. Cleaving done by hand using tweezers, but can be done automatically.
SiO$_2$ – Si Interface Charges

“Origin” of excellent passivation for n-type Si:
- Thermally grown oxides typically have from ~ $10^{10}$ to $1-2\times10^{11}$ positive charges per cm$^2$.
- Surface recombination rate: FZ n-type Si (10 Ωcm): ~ 60 cm/s.

Properties of sidewall passivation for HEP sensors:
- Low recombination rate for sidewall passivation → high carrier life time, low trap density at interface
- Fixed interface charge (positive for n-type Si)
- Low temperature process for processing finished dies.
Analysis of GLAST Skinny sensor: cut/un-cut

Un-cut

Distribution: $\sigma=4.7$ ADCs
$V_{bias}=150\text{V}$.  

Cut

Distribution: $\sigma=4.7$ ADCs.
$V_{bias}=500\text{V}$. 

No noise increase due to laser cutting.
Aside – Alumina as an Effective P-Stop

- Inter-strip shortening due to electron accumulation is a problem for any segmented p-type and double-sided n-type detectors.
- **ALD deposited alumina acts as an effective p-stop for n- and p-type Si substrates** (U.S. patent pending).
- We successfully fabricated a double-sided strip detector (DSSD) on n-type Si with alumina as an effective p-stop for n-on-n strips.
- DSSD was tested under gamma-ray irradiation (~ 6 keV FWHM energy resolution at 122 keV).

Details given in 2011 IEEE NSS presentation by M. Christophersen
Industrial Applications of Laser-Scribing & Cleaving

- Laser-scribing and cleaving common in LED industry
- Automated tools for scribing and breaking of devices on wafer-scale

Al₂O₃ and SiO₂ sidewall passivation for p- and n-type sensors
Introduction - ALD

- Similar in chemistry to CVD (chemical vapor deposition), except that the ALD (atomic layer deposition) reaction breaks the CVD reaction into two half-reactions, keeping the precursor materials separate during the reaction.

- ALD film growth is self-limited and based on surface reactions, which makes achieving atomic scale deposition control possible.

- Perfect 3-D conformality, 100% step coverage: uniform coatings on flat, inside porous and around particle samples.

- Origin of negative interface charge: Functional surface groups on the silicon wafer are not optimal for an adsorption of the TMA (trimethylaluminium) precursor molecules, which leads to an incomplete reaction of the TMA and, consequently, an increased relative oxygen concentration at the interface (F. Werner et al., 25th European Photovoltaic Solar Energy Conference, Valencia, Spain, 6-10 September 2010).
Equilibrium Electron-Concentrations for SiO$_2$ and Al$_2$O$_3$

- **Positive charge (+1E11 cm$^{-2}$), no bias (V=0)**
  - silicon oxide: electrons path from n-strip to sidewall
  - alumina: electrons “pushed away” from sidewall

- **Negative charge (-1E11 cm$^{-2}$), no bias (V=0)**

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Al$_2$O$_3$ and SiO$_2$ sidewall passivation for p- and n-type sensors
Goal of our research:
- slim edges with finished devices on die level
- slim edges on p- and n-type devices
Negative Surface Charge for P-Type Passivation

Surface recombination rate for FZ p-type Si (2 Ωcm), Al₂O₃ passivation

- Low recombination rate after Al₂O₃ passivation → high carrier life time
- Detector material kΩcm → higher life times
- Fixed negative interface charge
- Low temperature process (< 400 °C)
- Standard process in solar cell industry

Values for surface recombination rate and charge density for Al₂O₃/p-type Si are comparable to SiO₂/n-type Si.

Data from G. Dingemans, et al., 35th IEEE PVSC 2010.

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Type of Sidewall Passivation and Edge Damage

Data taken from 6th Trento Workshop presentation, March 2011

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If you obtain
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2. “right” sidewall surface charge
one can make slim edges with post processing.

• slim edge
• no guard ring
• die level processing
• p-type diode

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Al₂O₃ and SiO₂ sidewall passivation for p- and n-type sensors
Oxidized Trench for P-Type Si

An oxidized trench leads to:
• high electric field at trench edge,
• no control potential drop toward the cut edge,
• no protection from saw cut edge.
XeF$_2$ Etching

- XeF$_2$ etch generates very shallow trench.
- Trench “guides” cleavage plane.
- No mechanical stress or localized heating.
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