Anodic Aluminium Oxide for Passivation in Silicon Solar Cells

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Never Stand Still
Faculty of Engineering
School of Photovoltaic & Renewable Energy Engineering

Zhong Lu

Supervisor: Alison Lennon

Co-supervisor: Stuart Wenham

May. 2015

Outline

- Introduction to the Research Topic
  - *Objective and research area*
- Manipulation of stored charge in AAO
  - *Self-patterned localized metal contacts for silicon solar (motivation)*
  - *Manipulation of stored charge in AAO dielectric stacks*
  - *Investigation of stored charge distribution and stability*
  - *Impact of annealing*
- Passivation from AAO
  - *Passivation of AAO dielectric stacks on p^+ and n^+ surfaces*
  - *Improving the Passivation on p+ Surfaces by Charge Management*
  - *Demonstration of Bulk Passivation by Annealing AAO Stacks*
- Summary

Introduction

- Objective of the Project:

  To integrate the anodic aluminium oxide (AAO) into cells designs to achieve localized rear contact, enhanced passivation.

- Research Areas:

  - Localized contact using AAO as self-patterning template
  - Manipulation of the stored charge in AAO
  - Investigation on the mechanism about charge manipulation
  - Using AAO to passivate silicon surface with different doping

Outline

- Introduction to the Research Topic
  - *Objective and research area*
- Manipulation of stored charge in AAO
  - *Self-patterned localized metal contacts for silicon solar (motivation)*
  - *Manipulation of stored charge in AAO dielectric stacks*
  - *Investigation of stored charge distribution and stability*
  - *Impact of annealing*
- Passivation from AAO
  - *Passivation of AAO dielectric stacks on p^+ and n^+ surfaces*
  - *Improving the Passivation on p+ Surfaces by Charge Management*
  - *Demonstration of Bulk Passivation by Annealing AAO Stacks*
- Summary

Manipulation of Stored charge in AAO

- Motivations
- There are two important aspects about surface passivation:

(1) chemical passivation; and (2) field effect passivation.

- Chemical Passivation is to deactivate surface defects
- Field-effect passivation mainly affected by Q_{eff}.

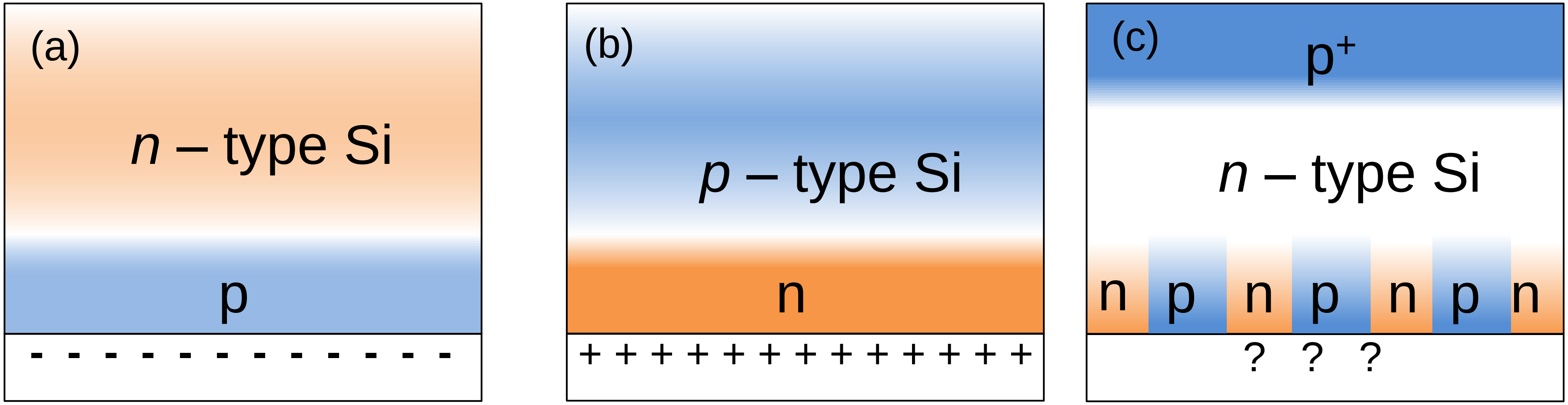
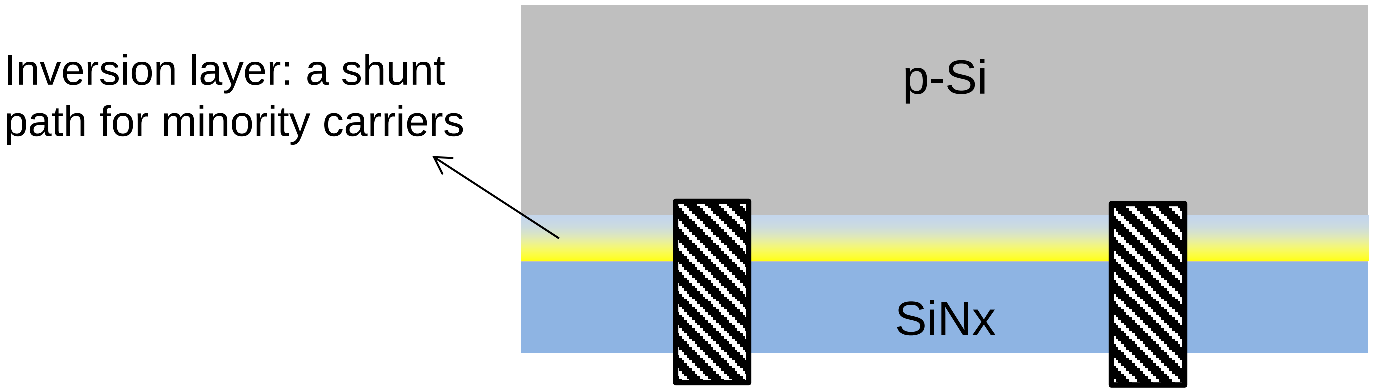


Fig. 2. Preferable dielectric stored charge polarity for (a) p^+ surface; (b) n^+ surface and (c) interdigitated n-p surface

[2] S. Dauwe, L. Mittelstädt, A. Metz, and R. Hezel, P.I.P., **10**, pp. 271-278, (2002)

Manipulation of stored charge in AAO

- Motivation

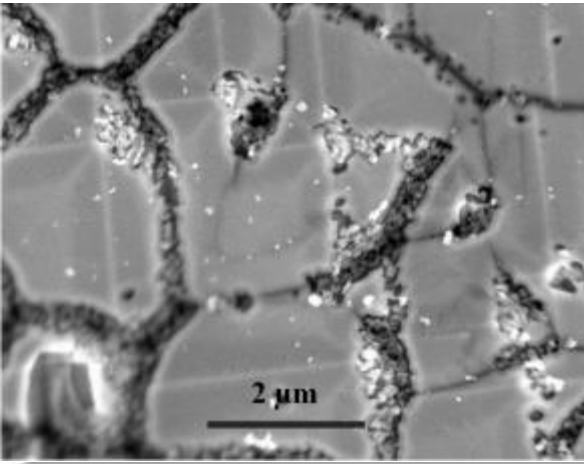


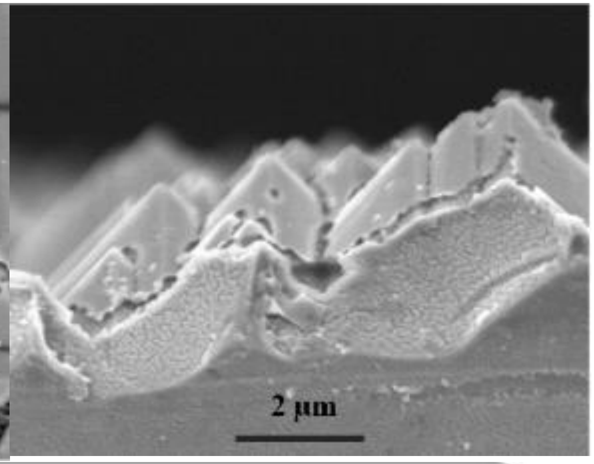
Manipulate the stored charge polarity and density to avoid inversion layer that causes parasitic shunting [2].

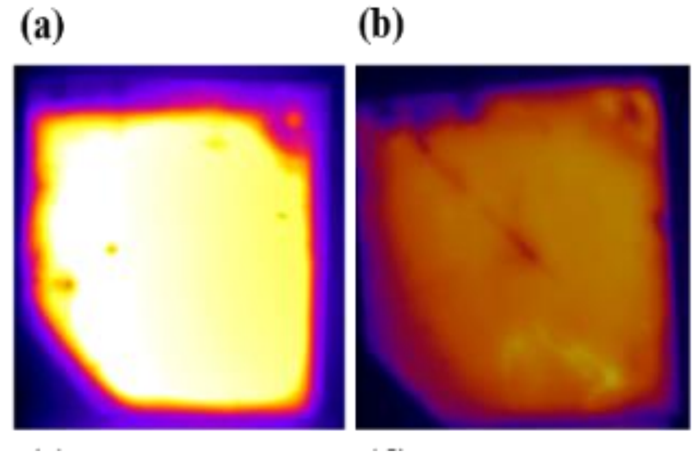
[2] G. D. Wilk, R. M. Wallace, and J. M. Anthony, *J. of Applied Physics,* **89**, 5243-5275, (2001)

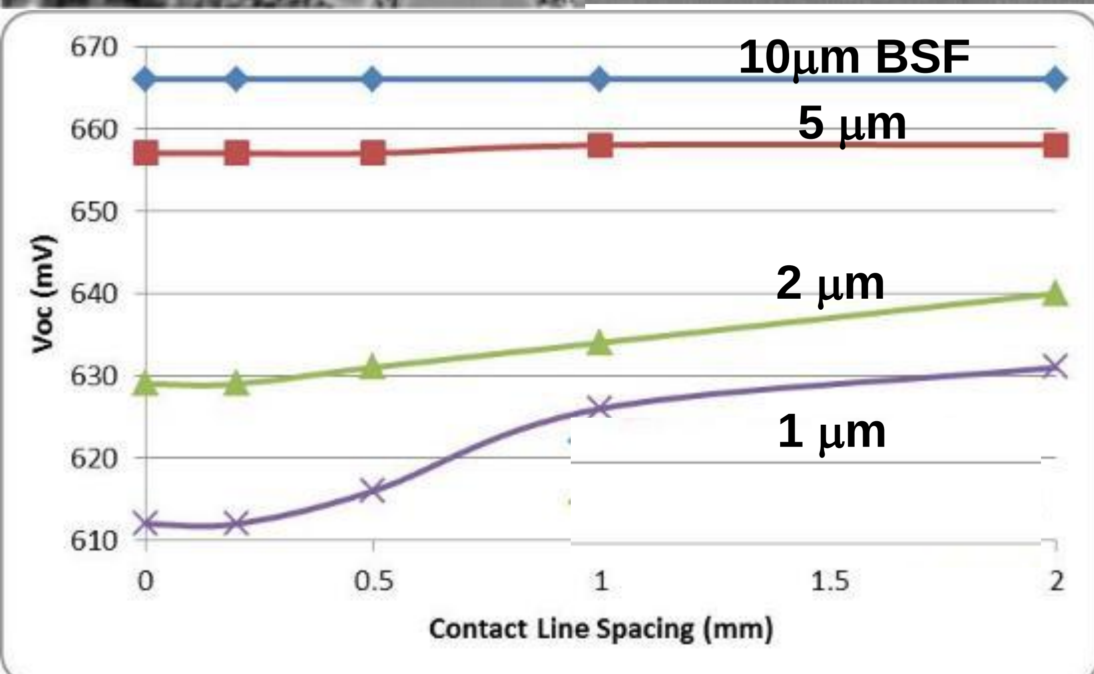
Manipulation of stored charge in AAO

- Motivation







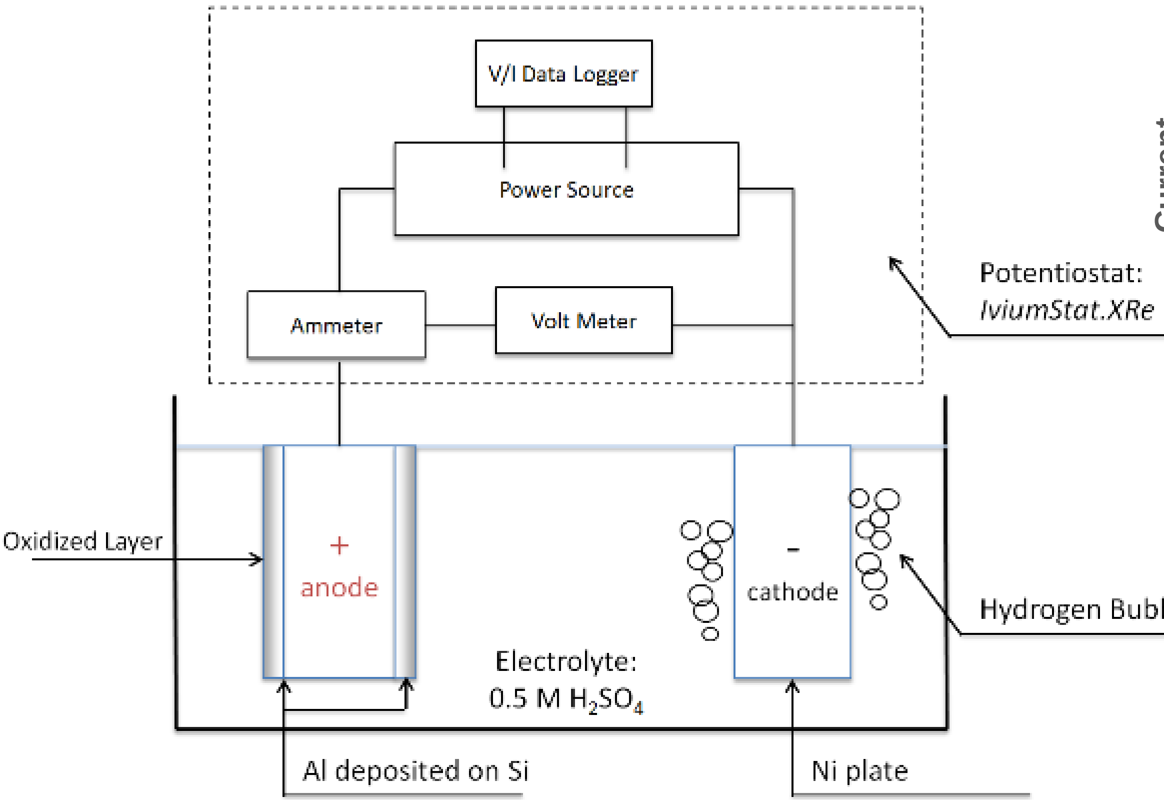


Simulated Voc for localized contact. Different curves correspond to different LBSF thickness

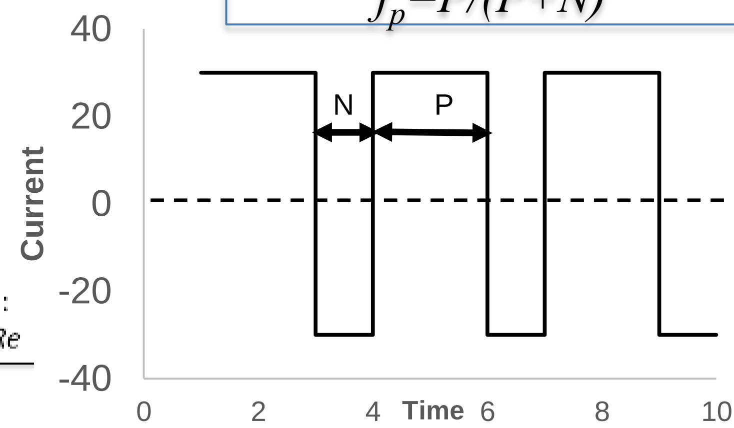
Manipulation of stored charge in AAO

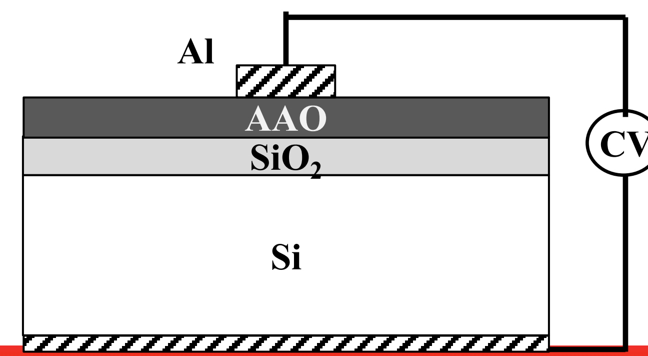
- Methods

Use pulse anodization where the metal experiences both positive and negative cycles. The stored charge is manipulated by tunning f_p



$$f_p = P/(P+N)$$





Manipulation of stored charge in AAO

- Effects of positive pulse percentage on Q_{eff}

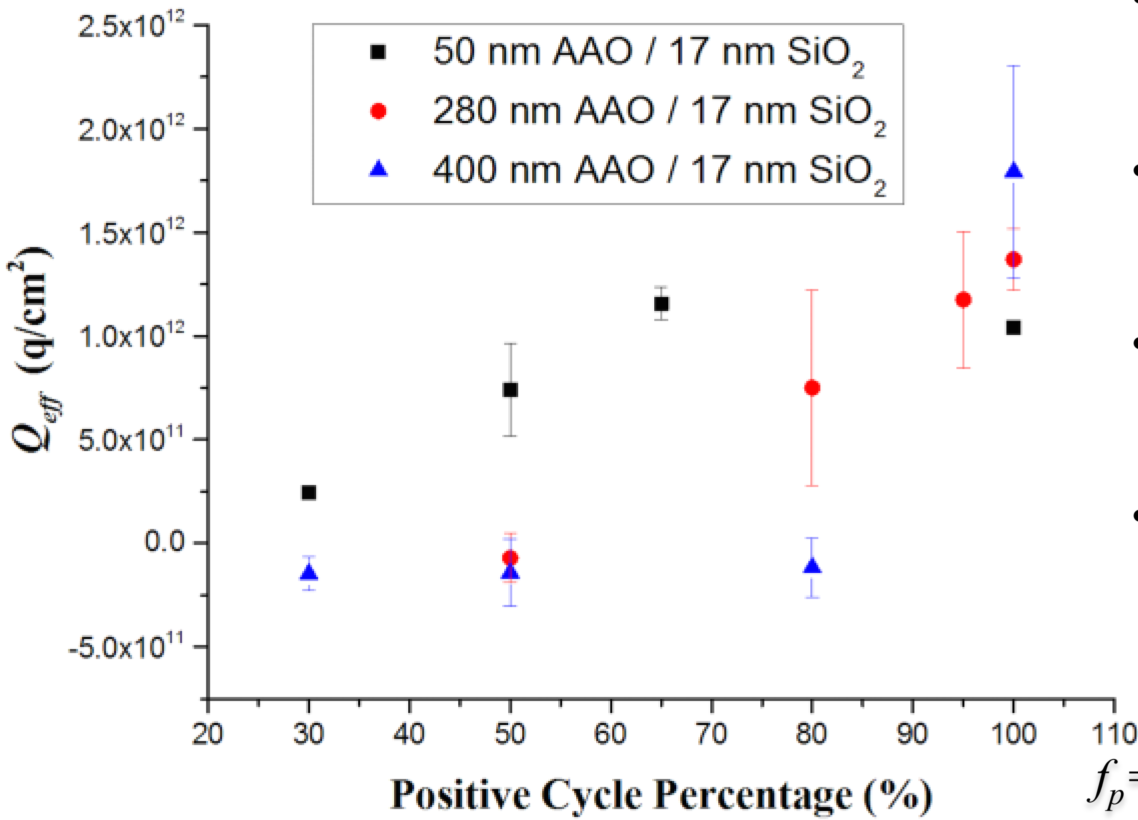
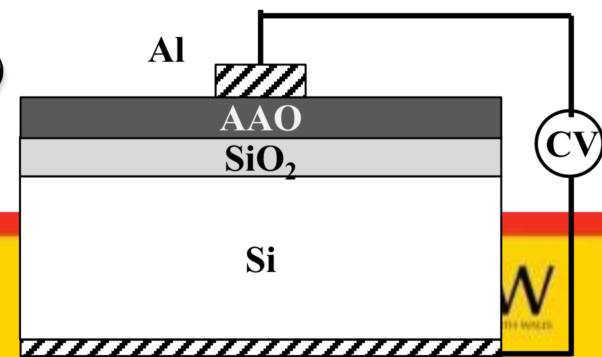


Fig. 3 Q_{eff} as a function of positive cycle percentage with AAO thickness of 1) 50 nm, 2) 280 nm and 3)400 nm

- With decreasing positive cycle percentage, Q_{eff} reduces.
- Larger variation range for thicker layers (from 2×10^{12} to – 2×10^{11})
- Similar negative values for all experiments
- More negative Q_{eff} are achieved if the SiO_2 thickness is reduced

$f_p=P/(P+N)$

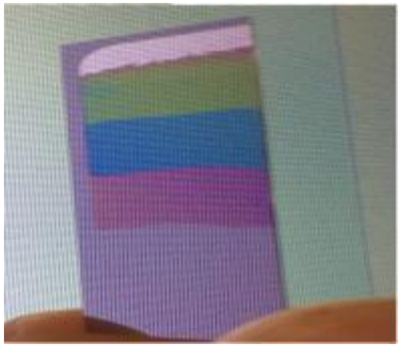


[4] **Z. Lu,** Z. Ouyang, Y. Wan, N. Grant, A.Lennon. "Manipulation of stored charge density and polarity in AAOfor silicon solar cell passivation," the 5th silicon PV, Konstanz, 2015

Manipulation of The Stored Charge

- Distribution of Q_{eff} in the SiO_2/AAO stack

- Etching-off methods

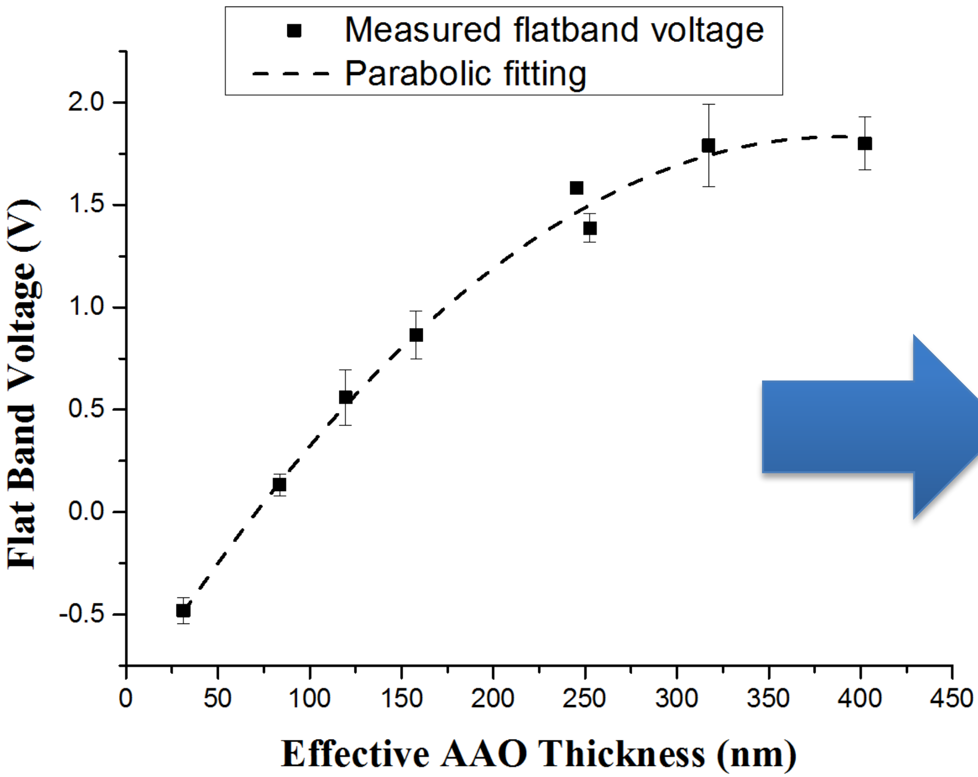


- Deposit a step profile

$$V_{FB} = \phi_{MS} - \frac{1}{C_{tot}}\left(Q_{SiO2} + Q_{AAO}\frac{t_{eff\,AAO}}{t_{eff}} + \int_0^{t_{eff\,AAO}} \frac{\rho(x)\cdot x}{t_{eff}}\,dx\right);$$

Manipulation of The Stored Charge

- Distribution of Q_{eff} in the SiO_2/AAO stack

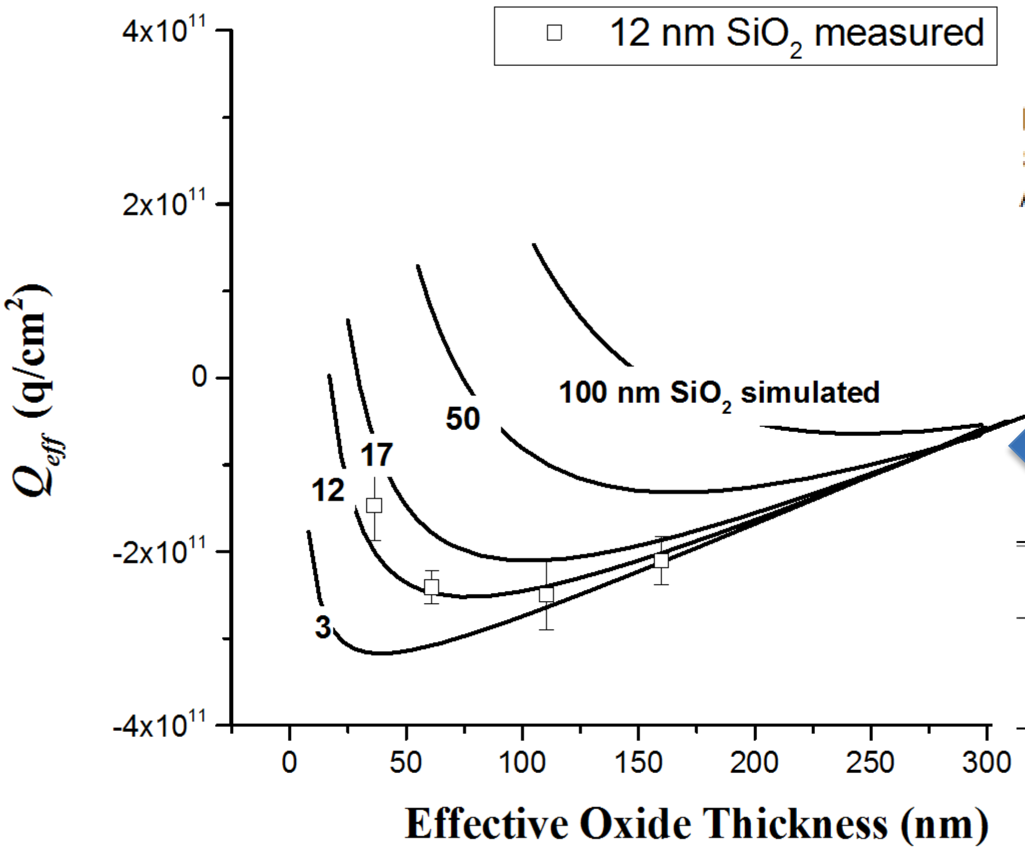


Q_{AAO} (q/cm^2)	Q_{SiO2} (q/cm^2)	ρ (q/cm^3)
$-5.81 \pm 0.16\times10^{11}$	$1.79 \pm 0.10\times10^{11}$	$2.30 \pm 0.13\times10^{16}$

$$V_{FB} = \phi_{MS} - \frac{1}{\varepsilon_{Si}}\left(Q_{SiO2} \cdot t_{eff} + Q_{AAO} \cdot t_{eff_{AAO}} + \frac{\rho \cdot t_{eff_{AAO}}^2}{2}\right)$$

Manipulation of The Stored Charge

- Distribution of Q_{eff} in the SiO_2/AAO stack



Q_{AAO} (q/cm²)	Q_{SiO2} (q/cm²)	ρ (q/cm³)
$-5.81 \pm 0.16 \times 10^{11}$	$1.79 \pm 0.10 \times 10^{11}$	$2.30 \pm 0.13 \times 10^{16}$

$$Q_{eff} = Q_{SiO2} + Q_{AAO} \cdot \frac{t_{eff\,AAO}}{t_{eff}} + \frac{\rho \cdot t_{eff\,AAO}^2}{t_{eff}}.$$

Manipulation of The Stored Charge

- Stability of Q_{eff} in the SiO_2/AAO stack

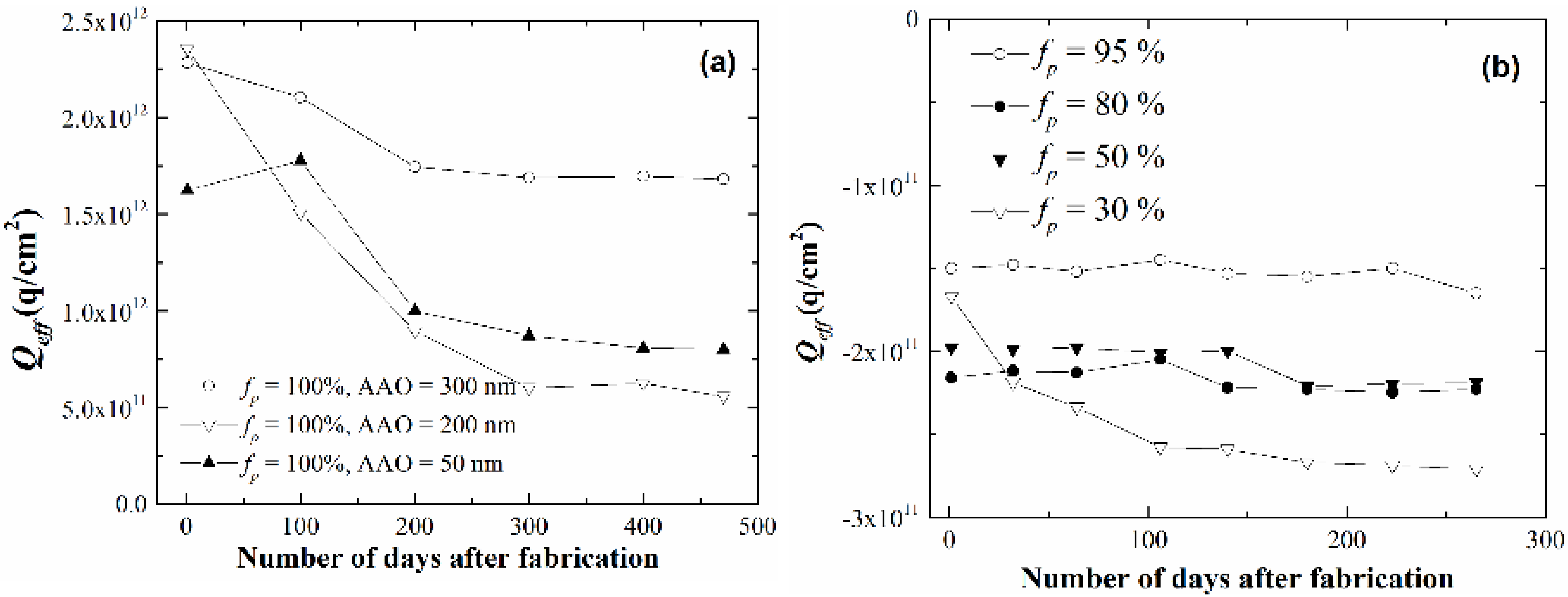


Fig. 4 (a) stability of the negative Q_{eff} over time for test structures fabricated at different f_p; (b) stability of the positive Q_{eff} over time for test structures (all at f_p = 100%) with different AAO thicknesses

[4] **Z. Lu,** Z. Ouyang, Y. Wan, N. Grant, D.Yan, A.Lennon. "Manipulation of stored charge density and polarity in anoidc oxides for silicon solar cell passivation," the 5th silicon PV, Konstanz, 2015

Manipulation of The Stored Charge

- Impact of annealing

- Two groups: annealed with or without aluminium capping:
- Annealing at 400 ^{0}C for 30 min in:

Positive Charge **Negative Charge**

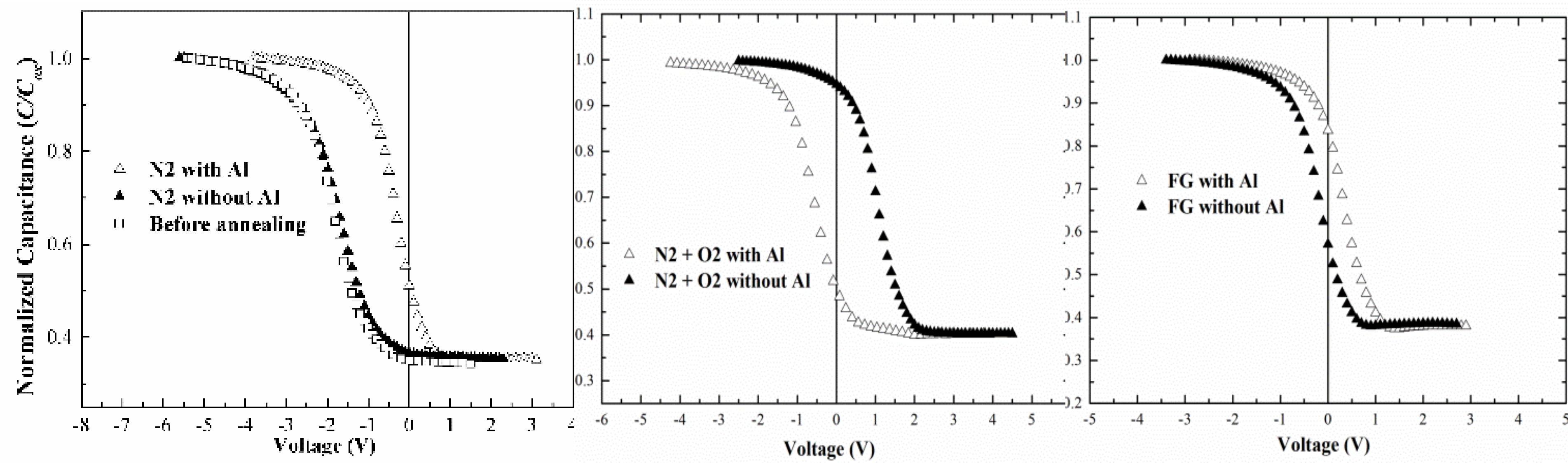
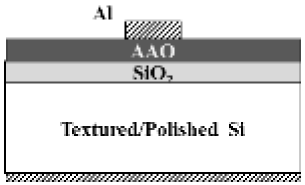


Fig 5. C-V curves of SiO_2/AAO annealed in three different gases with and without the Al capping on AAO

[5] **Z. Lu,** Z. Ouyang, Y. Wan, N. Grant, D. Yan and A. Lennon. "Manipulation of stored charge in AAO/SiO_2 dielectric stacks by the use of pulse anodization", *Applied Surface Science*, 2015 (under review)

Manipulation of The Stored Charge



- Impact of annealing
- Two groups: annealed with or without aluminium capping:

- Annealing at 400 ^{0}C for 30 min in:

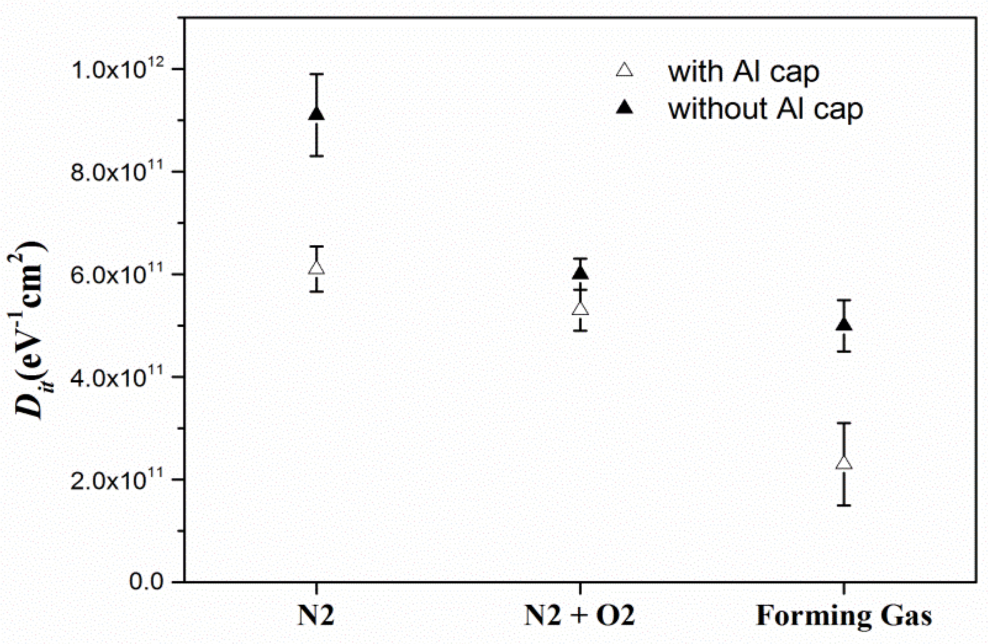


Fig 5. Midgap Dit of SiO_2/AAO annealed in three different gases with and without the Al capping on AAO

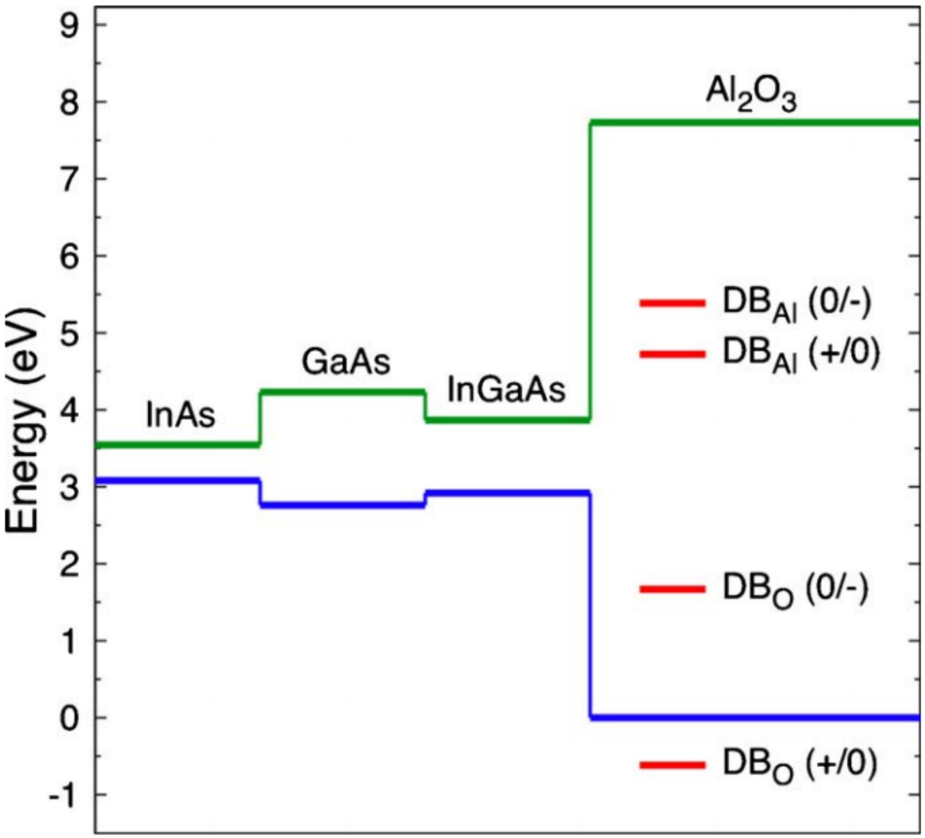
[5] **Z. Lu,** Z. Ouyang, Y. Wan, N. Grant, D. Yan and A. Lennon. "Manipulation of stored charge in AAO/SiO_2 dielectric stacks by the use of pulse anodization", *Applied Surface Science*, 2015 (under review)

Manipulation of The Stored Charge

- Impact of annealing

- Annealing in N_2/O_2 mixed atmosphere is most effective in reducing positive charge.
- Why?

- A research about origins of stored charge in AlOx suggest that Al DBs in the bulk AlOx stores positive charge
- Oxygen deficiency contributes to Al DBs. Since Al DBs is above the Fermi level, they are positively charged



[6] B. Shin, J. R. et. Al., "Origin and passivation of fixed charge in atomic layer deposited aluminum oxide gate insulators on chemically treated InGaAs substrates," *APL,* vol. 96. 2010.

Manipulation of The Stored Charge

- Impact of annealing

- Annealing in N_2/O_2 mixed atmosphere is most effective in reducing positive charge.
- Why?

- N_2/O_2 annealing supplies extra oxygen, reducing O deficiencies thus reducing the positive bulk charge

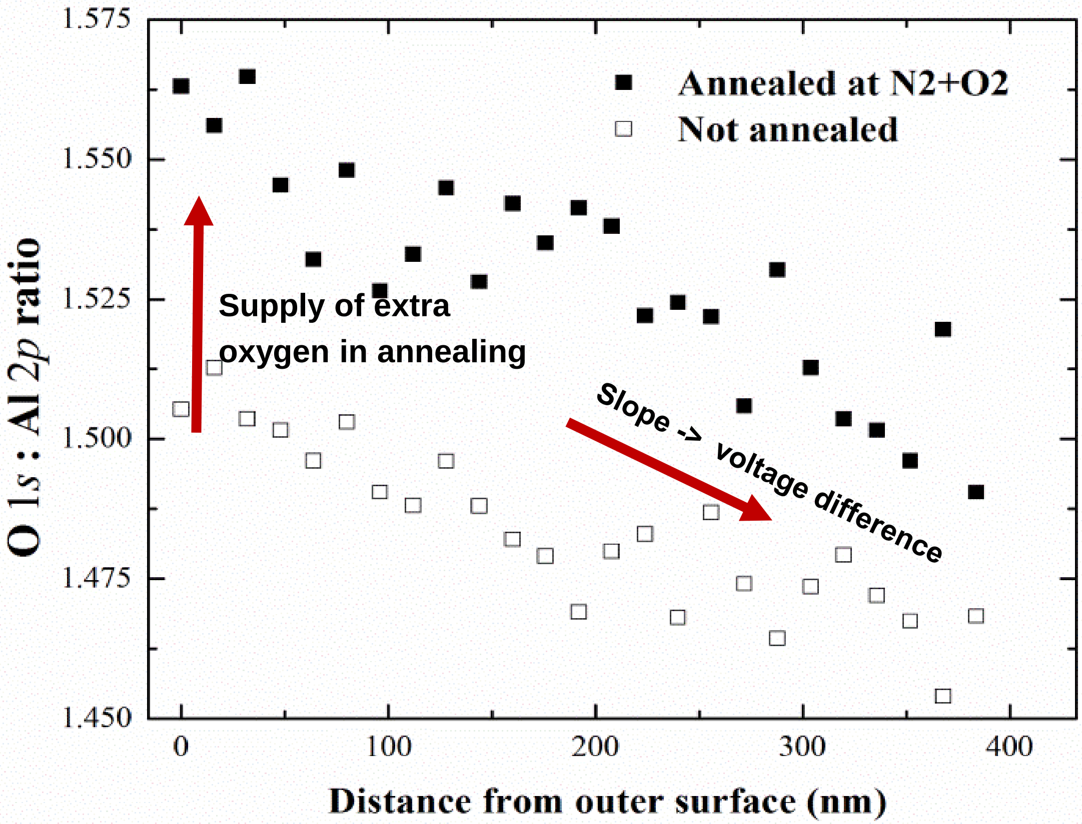
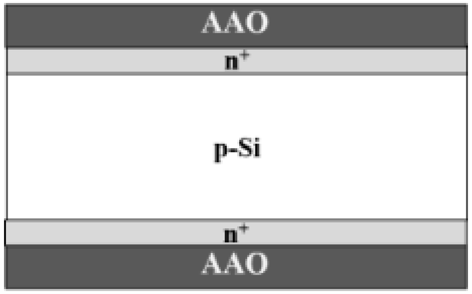


Fig 6. Depth profiles of the ratio of O 1*s* to Al 2*p* measured from XPS for SiO_2/AAO test structures before and after annealing in N_2/O_2

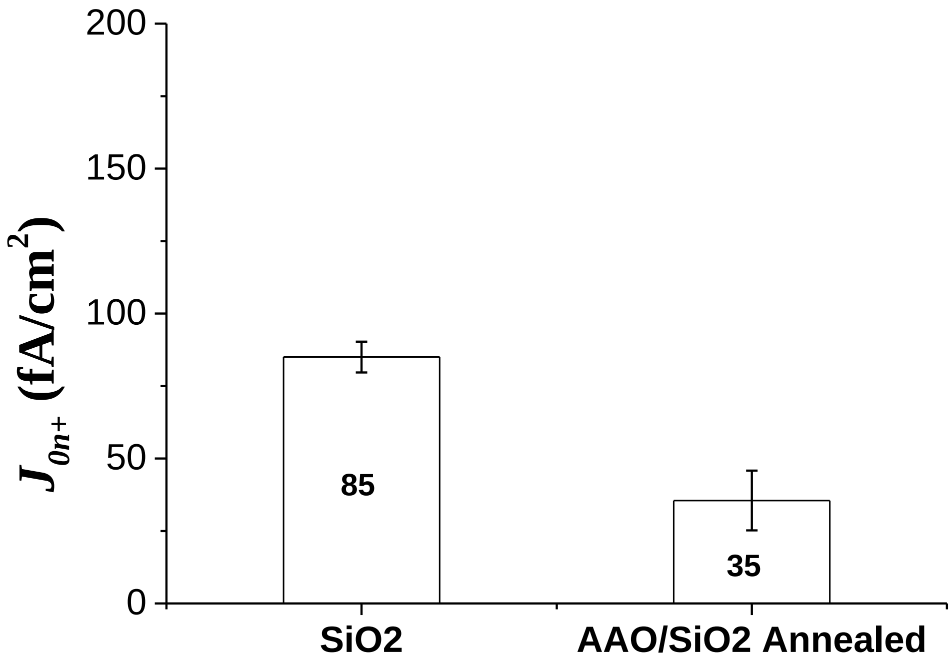
Outline

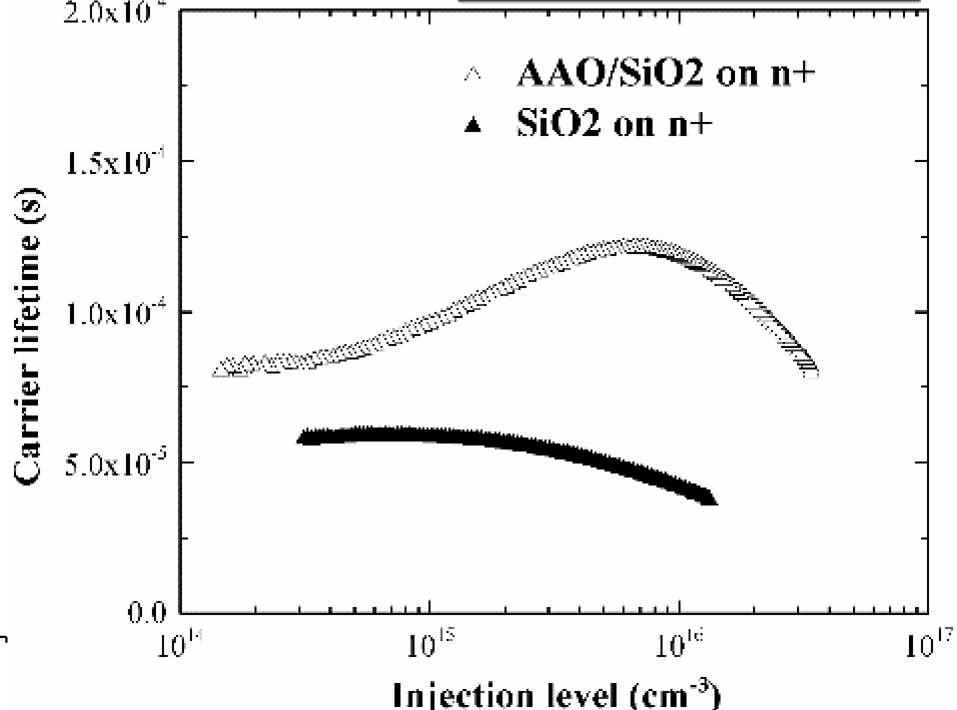
- Introduction to the Research Topic
  - *Objective and research area*
- Manipulation of stored charge in AAO
  - *Self-patterned localized metal contacts for silicon solar (motivation)*
  - *Manipulation of stored charge in AAO dielectric stacks*
  - *Investigation of stored charge distribution and stability*
  - *Impact of annealing*
- Passivation from AAO
  - *Passivation of AAO dielectric stacks on p^+ and n^+ surfaces*
  - *Improving the Passivation on p+ Surfaces by Charge Management*
  - *Demonstration of Bulk Passivation by Annealing AAO Stacks*
- Summary

Passivation on diffused surfaces



- AAO on the n+ surfaces

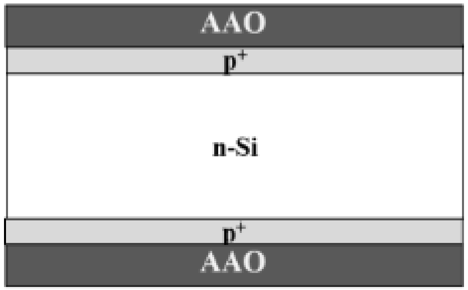




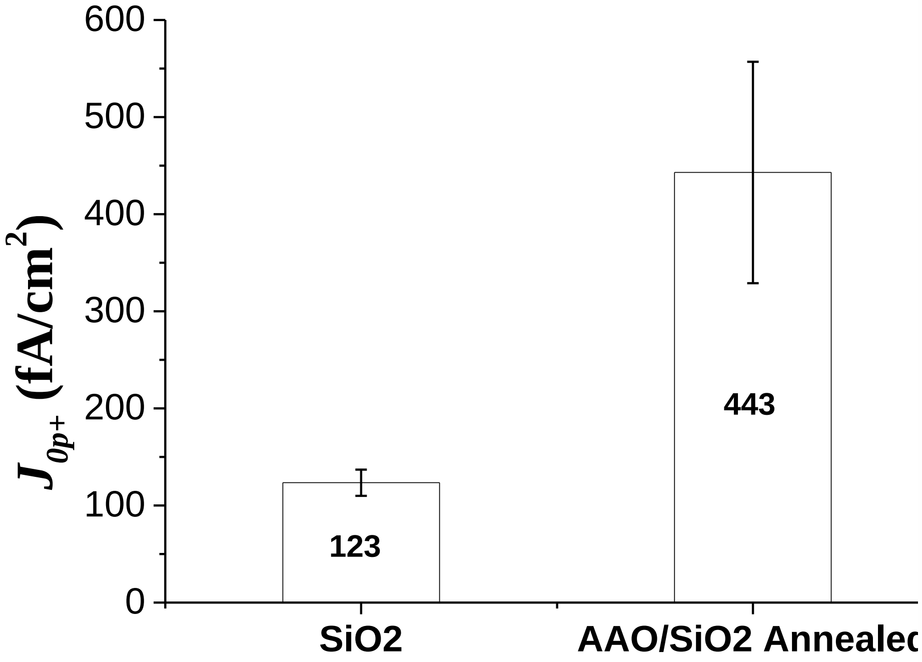
- Significant improvement in Jo is demonstrated when AAO applied on P diffused surface.
- Lifetime enhanced over the entire injection level

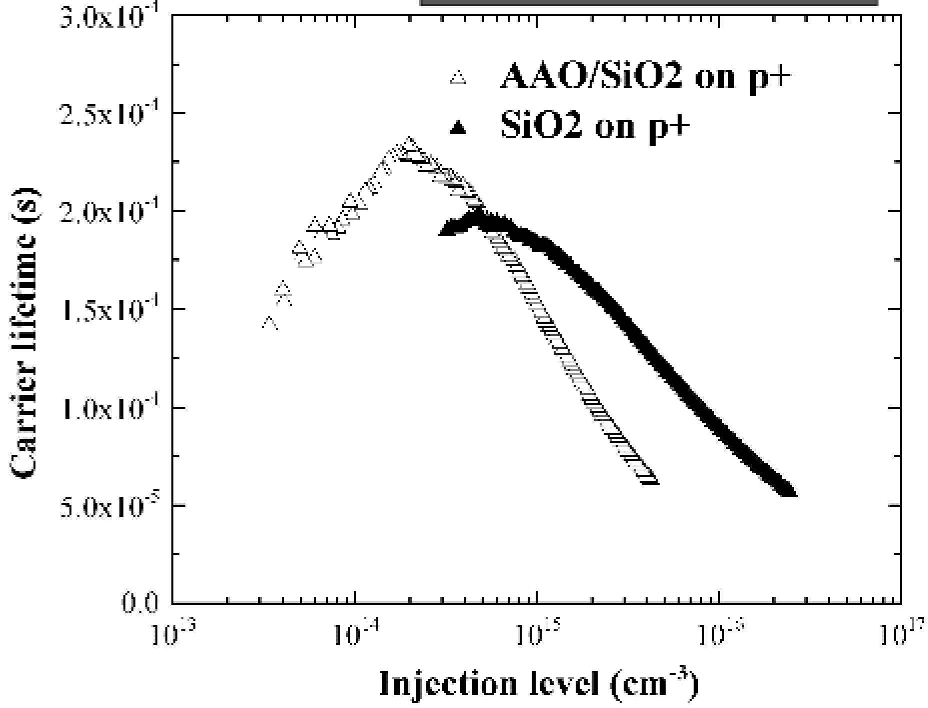
[6] Tao Wang (Co-superviised student), Bachelor's Thesis “Effects of Annealing Condition on AAO Passivation”, The University of New South Wales, Australia, 2013

Passivation on diffused surfaces



- AAO on the p^+ surfaces





- Surface recombination increased by AAO applied on B diffused surface.
- Lifetime enhanced at low injection level

Improving the Passivation on p+ Surfaces

- Passivation on p^+ Surfaces with charge management

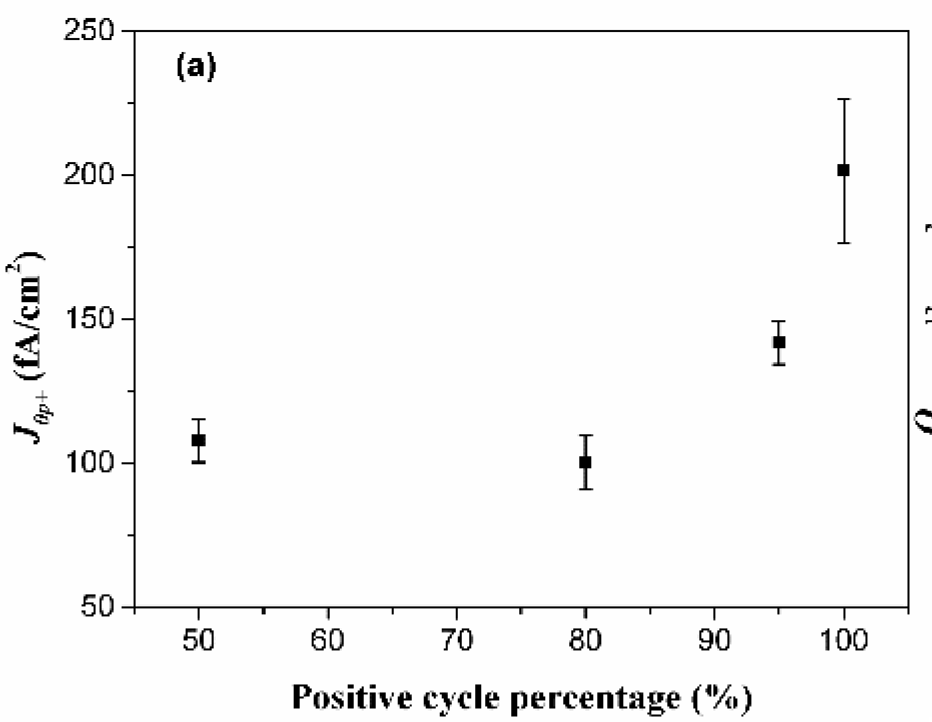


Fig. 7 J_o as a function of positive cycle percentage

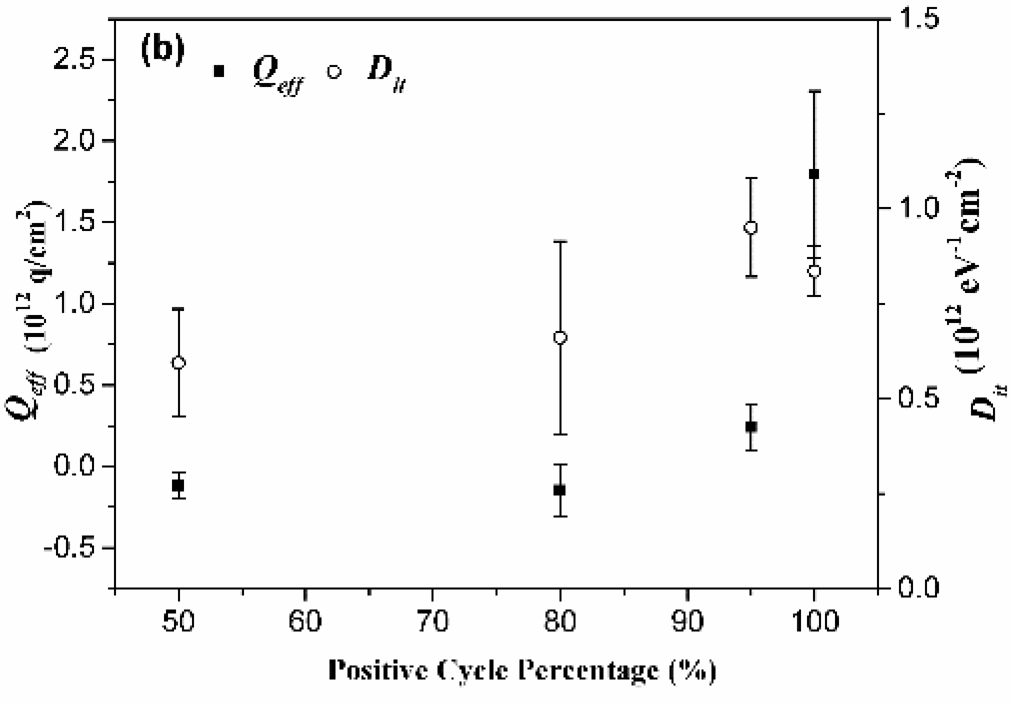
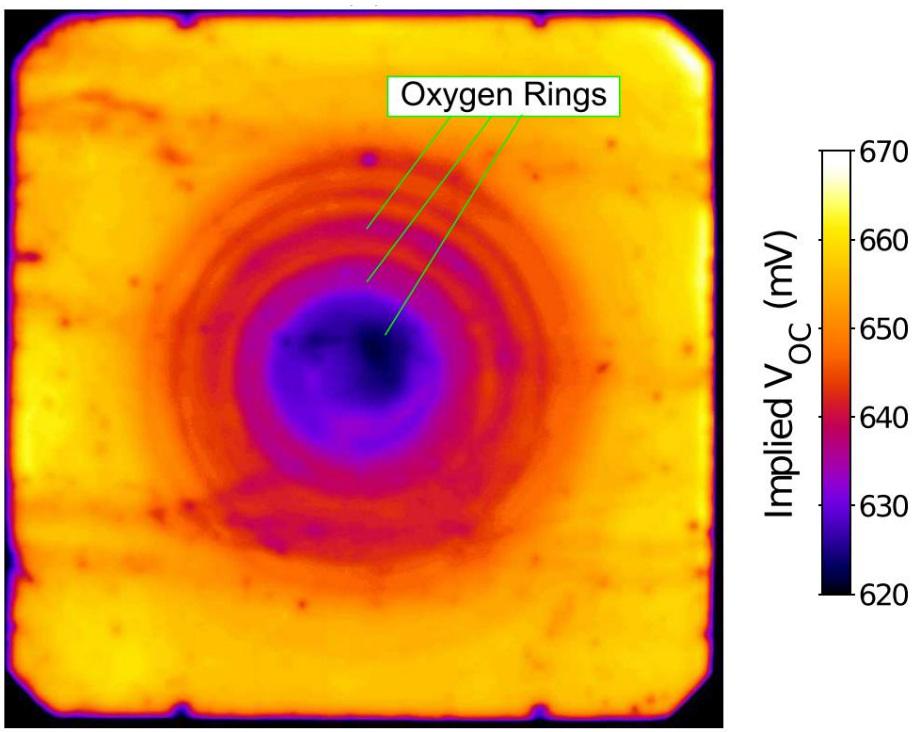


Fig. 8 D_{it} and Q_{eff} as a function of positive cycle percentage

[5] **Z. Lu,** Z. Ouyang, Y. Wan, N. Grant, D. Yan and A. Lennon. "Manipulation of stored charge in AAO/SiO_2 dielectric stacks by the use of pulse anodization", *Applied Surface Science*, 2015 (under review)

Demonstration of Hydrogen Passivation

- Hydrogen passivation on oxygen precipitation ?



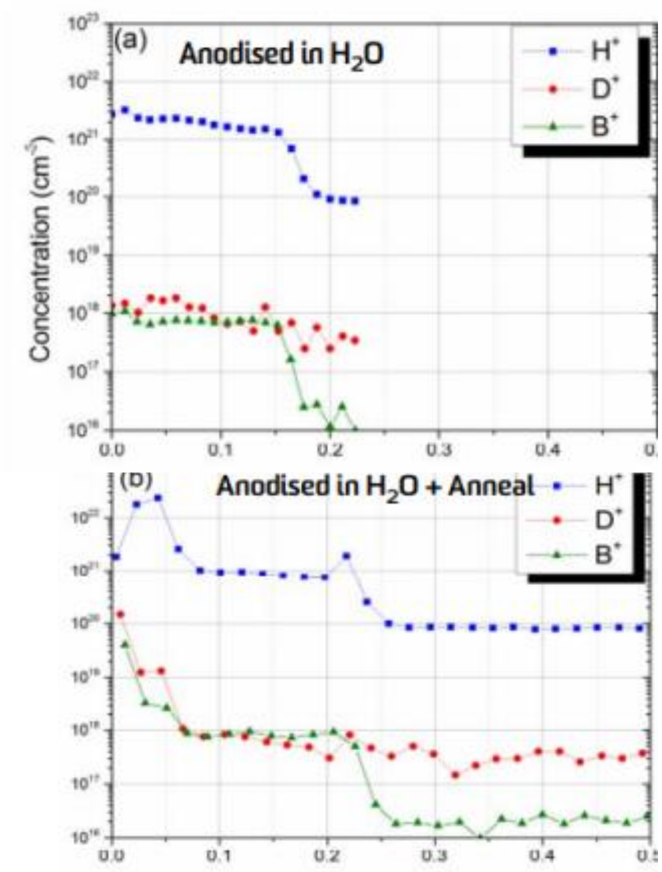


Figure 9. (a) PL images of Oxygen precipitation; (b) Hydrogen incorporation in AAO[P.H. Lu]

[7] B. Hallam, B. Tjahjono, T. Trupke, and S. Wenham, "Photoluminescence imaging for determining the spatially resolved implied open circuit voltage of silicon solar cells," *Journal of Applied Physics,* vol. 115, p. 044901, 2014.
[8] J. D. Murphy, R. E. McGuire, K. Bothe, V. V. Voronkov, and R. J. Falster, "Minority carrier lifetime in silicon photovoltaics: The effect of oxygen precipitation," *Solar Energy Materials and Solar Cells,* vol. 120, Part A, pp. 402-411, (2014)

Demonstration of Hydrogen Passivation

- Hydrogen passivation on oxygen precipitation ?

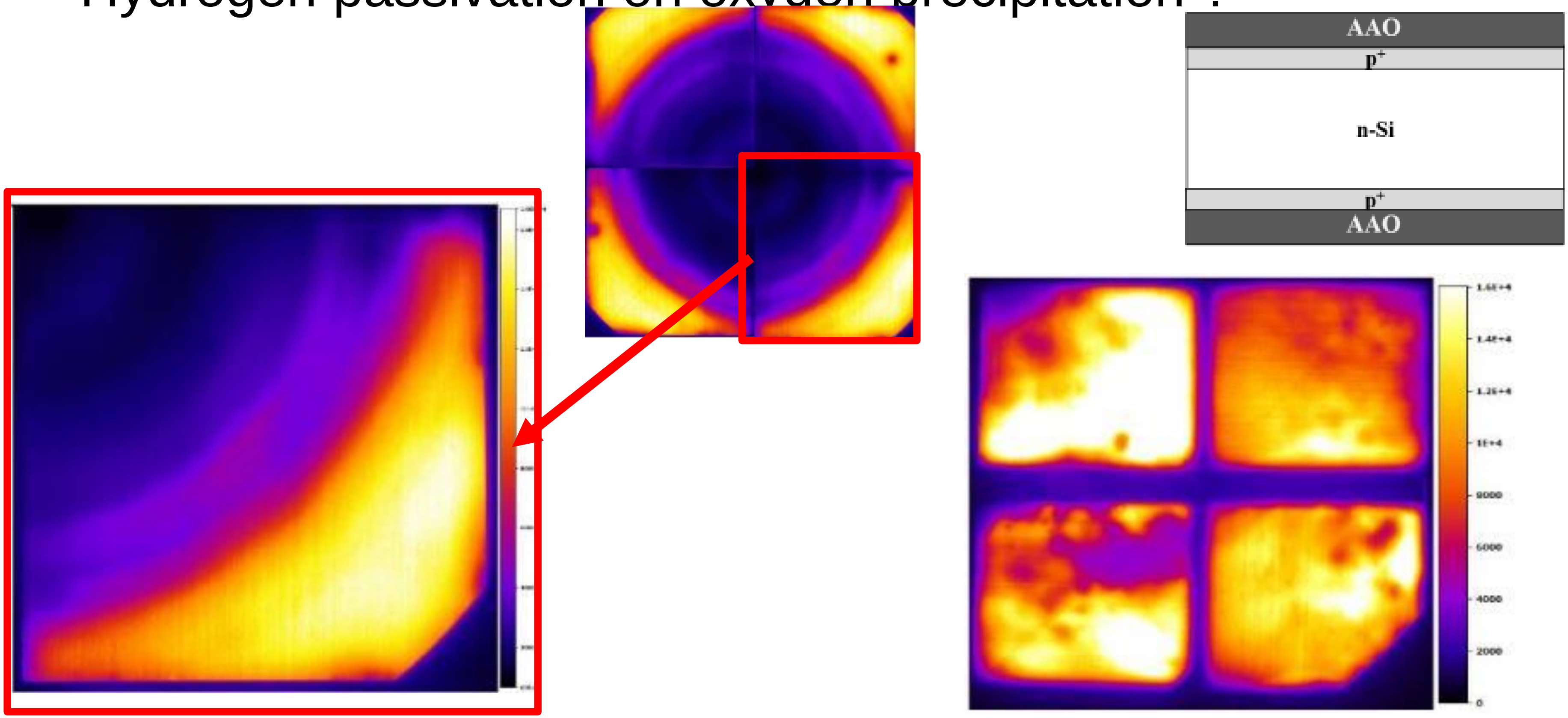


Figure 10. PL images after (a) oxidation and diffusion; (b) anodization and annealing in N_2

[7] B. Hallam, B. Tjahjono, T. Trupke, and S. Wenham, "Photoluminescence imaging for determining the spatially resolved implied open circuit voltage of silicon solar cells," *Journal of Applied Physics,* vol. 115, p. 044901, 2014.
[8] J. D. Murphy, R. E. McGuire, K. Bothe, V. V. Voronkov, and R. J. Falster, "Minority carrier lifetime in silicon photovoltaics: The effect of oxygen precipitation," *Solar Energy Materials and Solar Cells,* vol. 120, Part A, pp. 402-411, (2014)

Summary

- Localized contacts achieved by self-pattern AAO are demonstrated in this work, but result in low device voltage.
- Stored charge manipulation in AAO was achieved using pulsed anodization, with Q_{eff} ranging from 2×10^{12} to -5×10^{11} q/cm^2
- The Q_{eff} and D_{it} were found to be affected by annealing and it is suggested that O_2 annealing can reduce the bulk positive Q_{eff} while FG anneal is most effective in reducing D_{it}.
- AAO provides good passivation for phosphorus diffused Si surface, but results in higher SRV when applied on boron diffused Si surface
- Charge manipulation was demonstrated to enhance passivation on boron-diffused surfaces

Thank you!