



# Highly Transparent and Highly Passivating Silicon Nitride for Solar Cells

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# Outline

- Motivation
- Reviews of SiNx properties
- Process development
- Recombination studies
  - Planar
  - Texturing
- Cell simulation and application



# Motivation

## Success of SiNx on silicon solar cells

PECVD SiN<sub>x</sub> is incorporated into most laboratory and industrial silicon solar cells, fulfilling three functions:

- i. it comprises the antireflection coating;
- ii. it provides surface and bulk passivation; and
- iii. it forms a chemical barrier to protect underlying interfaces from the degrading effects of moisture, humidity and sodium ions.



# Motivation

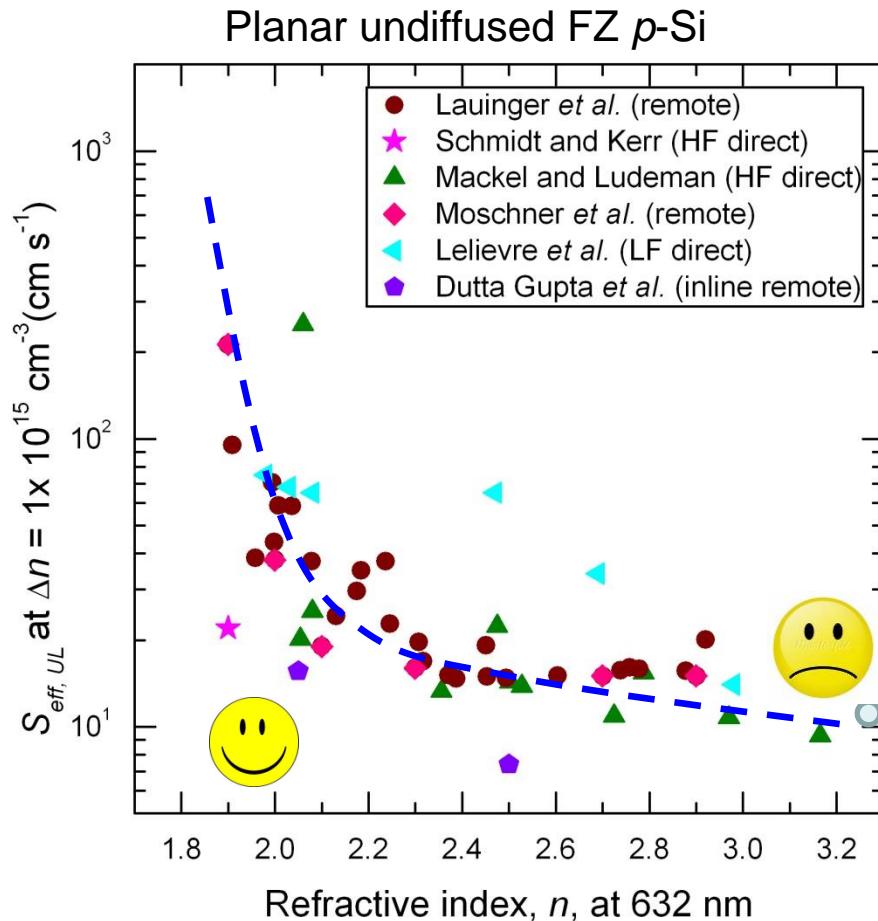
## Success of SiNx on silicon solar cells

PECVD SiN<sub>x</sub> is incorporated into most laboratory and industrial silicon solar cells, fulfilling three functions:

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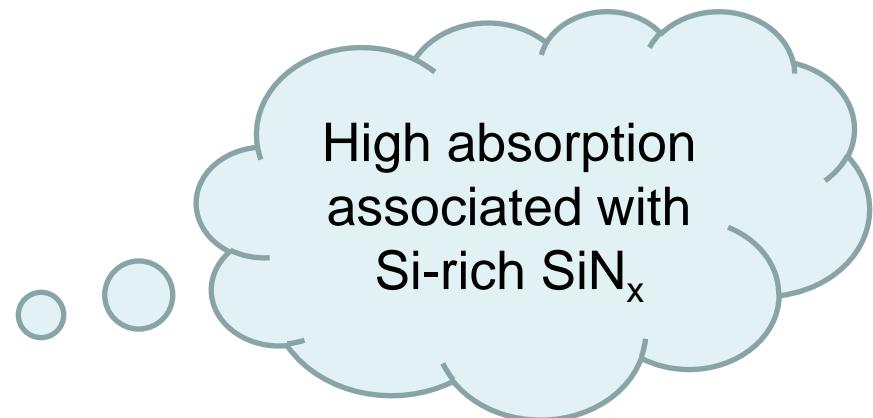
# Motivation

## Challenge of SiNx on silicon solar cells



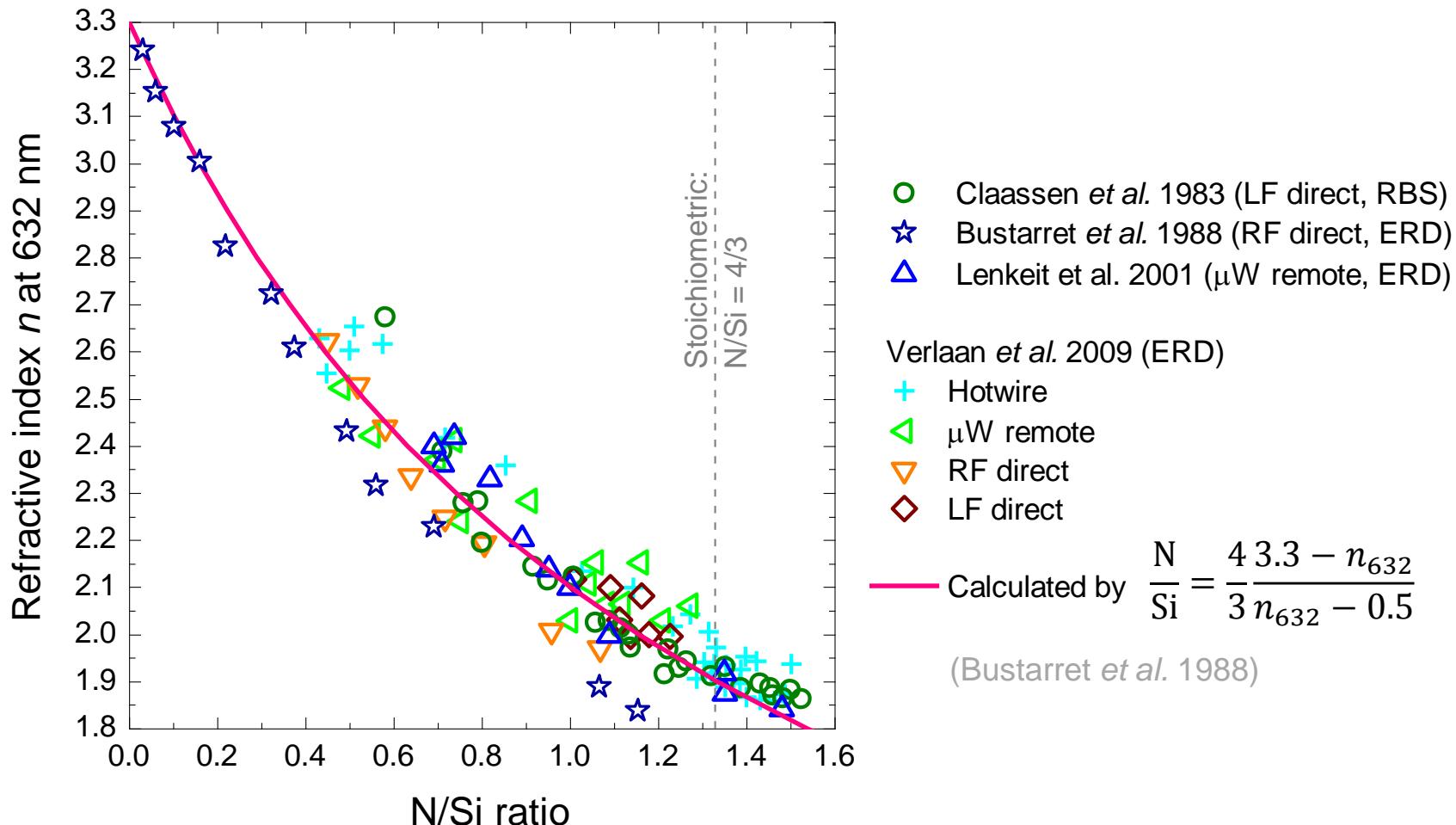
- **Classic trend:**

SRV decreases as  $n$  increases, irrespective of deposition techniques.



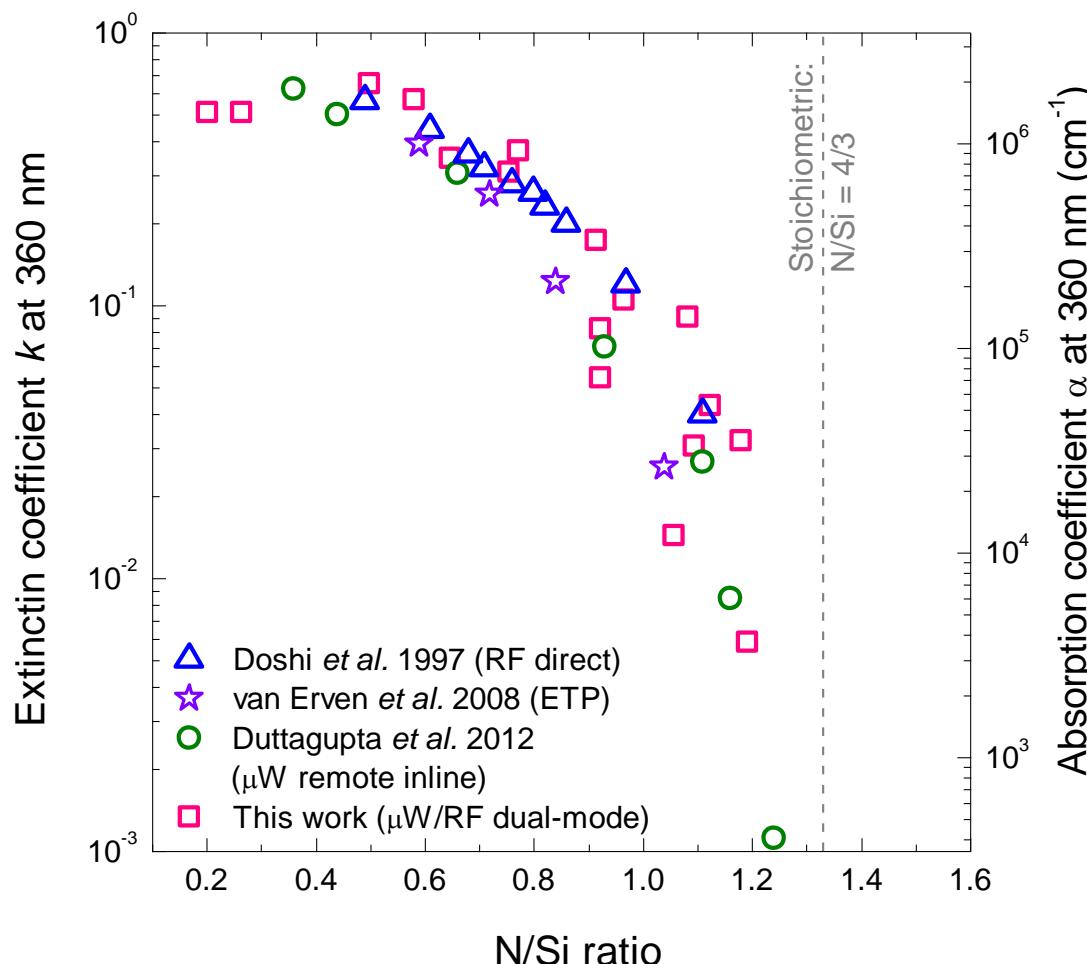
# Review of SiNx properties

## Optics: refractive index



# Review of SiNx properties

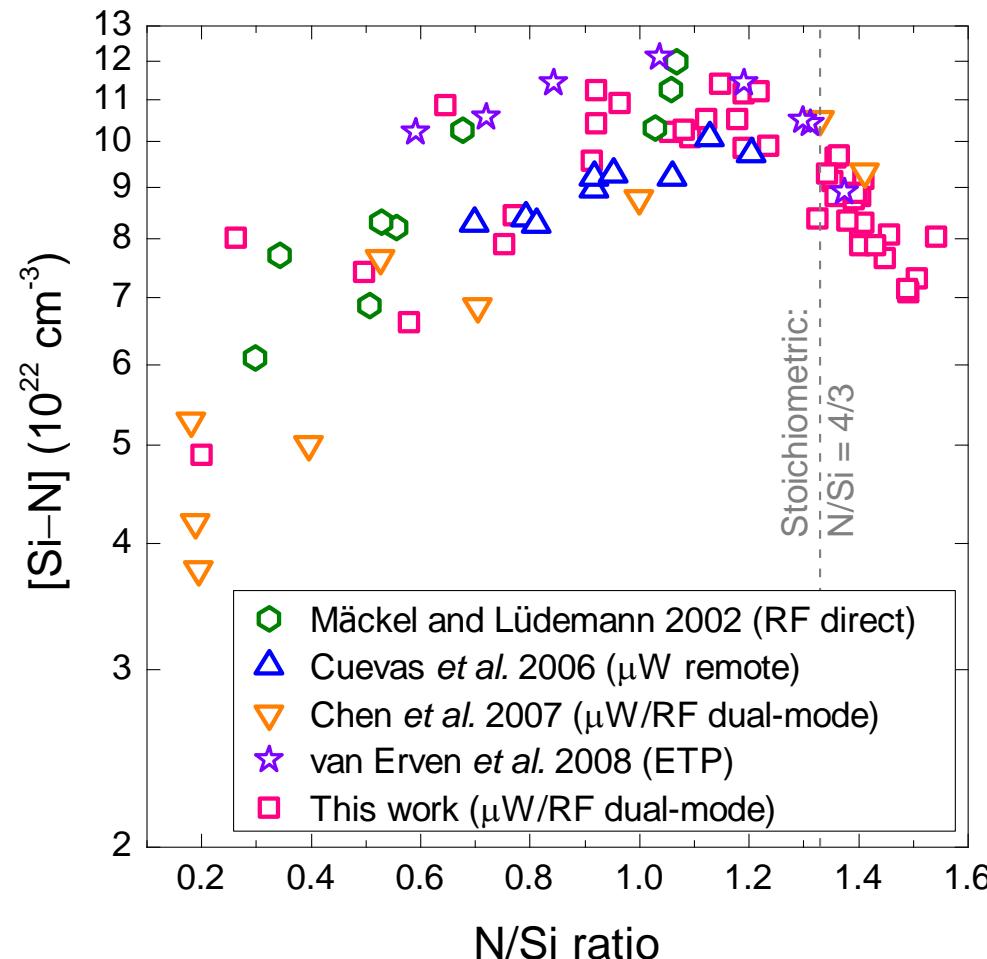
## Optics: extinction coefficient





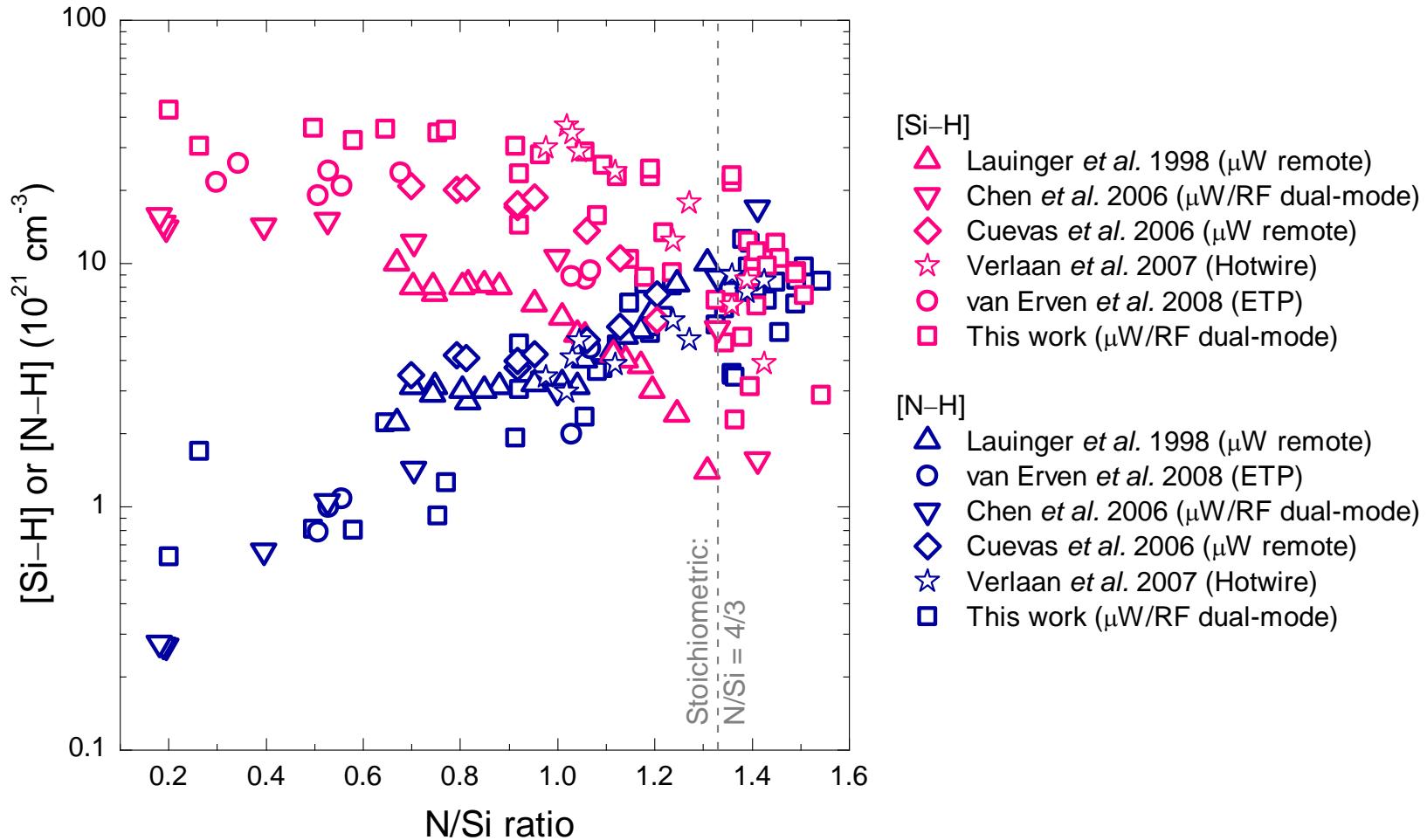
# Review of SiNx properties

## Structures: [Si–N]



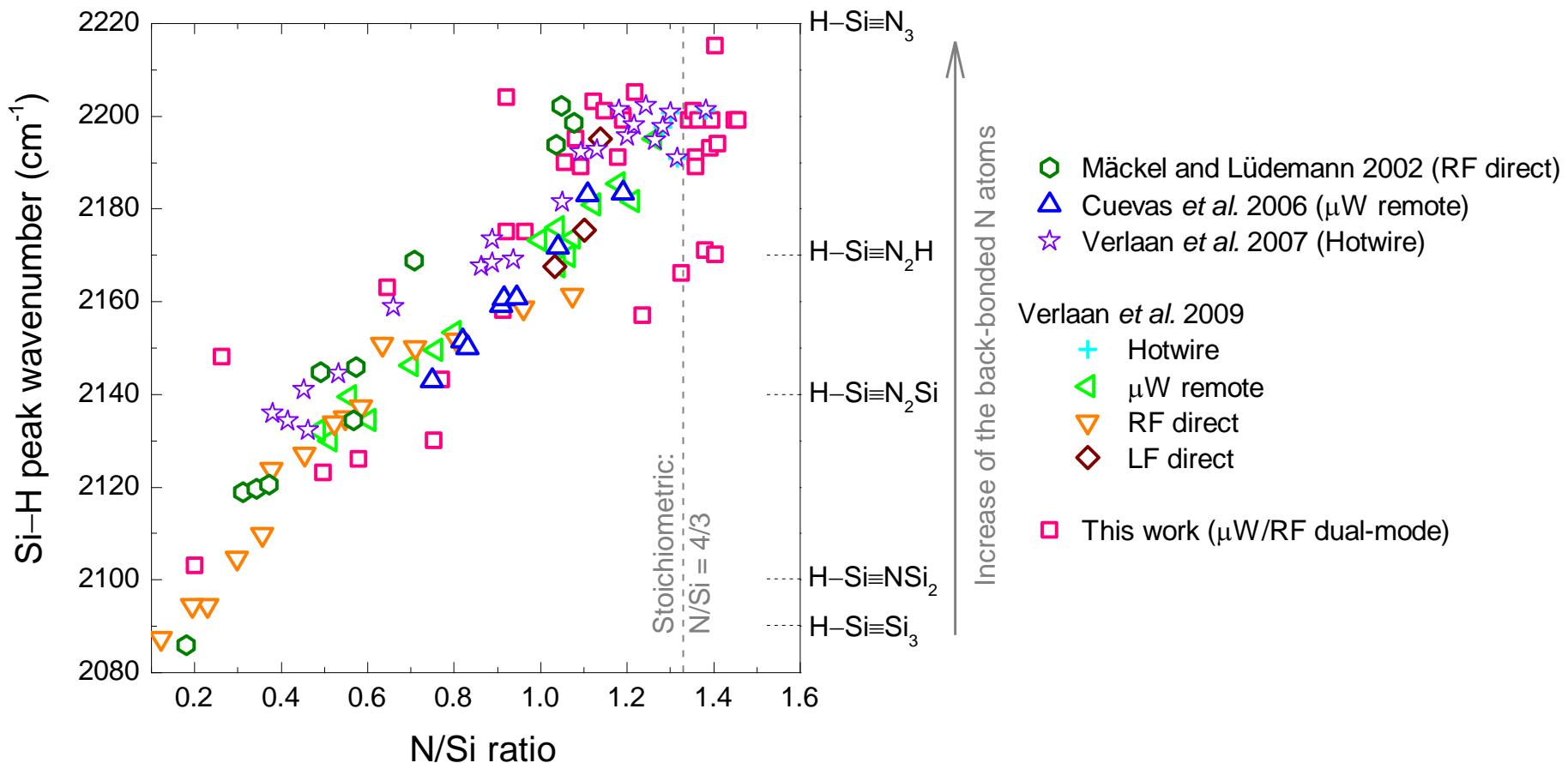
# Review of SiNx properties

## Structures: [Si–H] and [N–H]



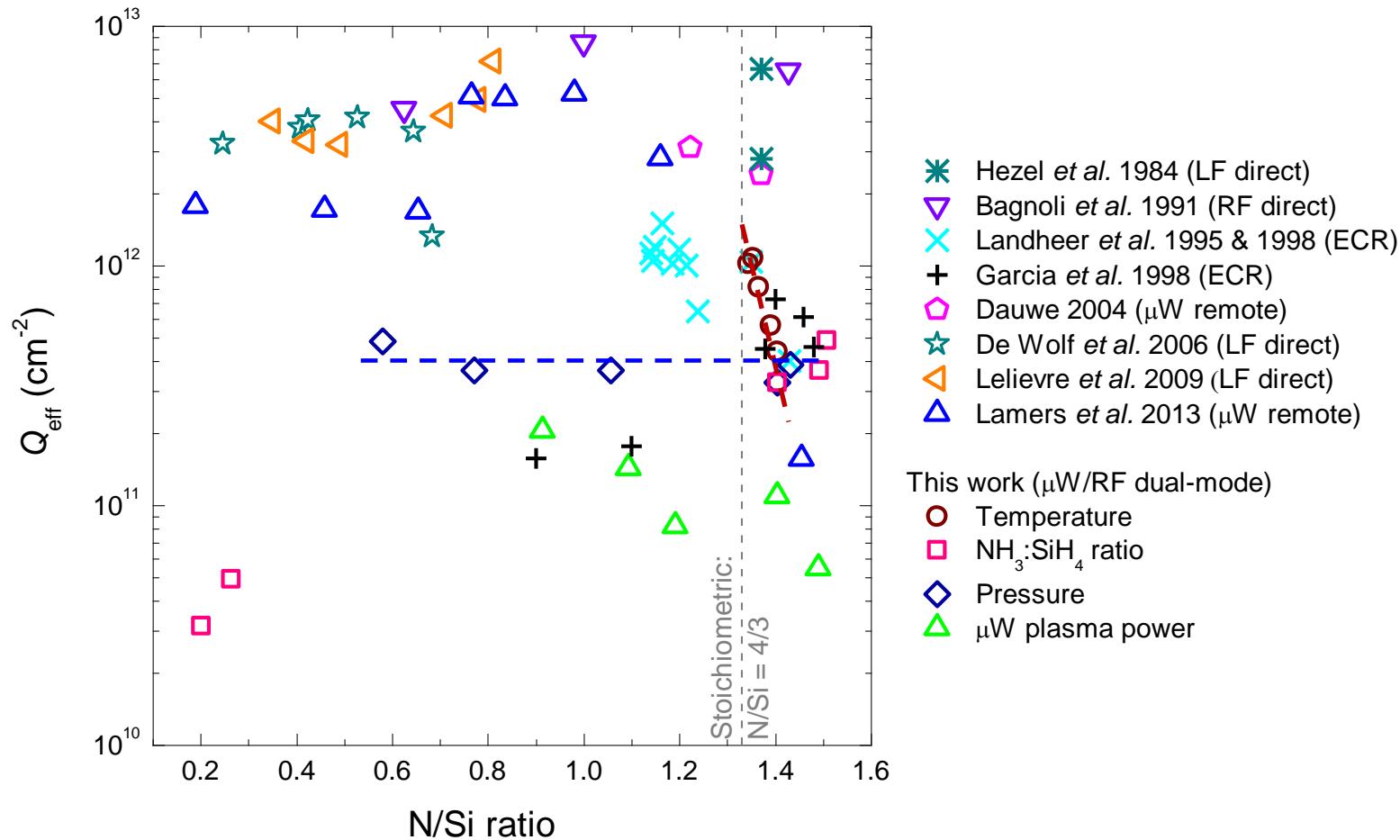
# Review of SiNx properties

## Structures: [Si–H] peak wavenumber



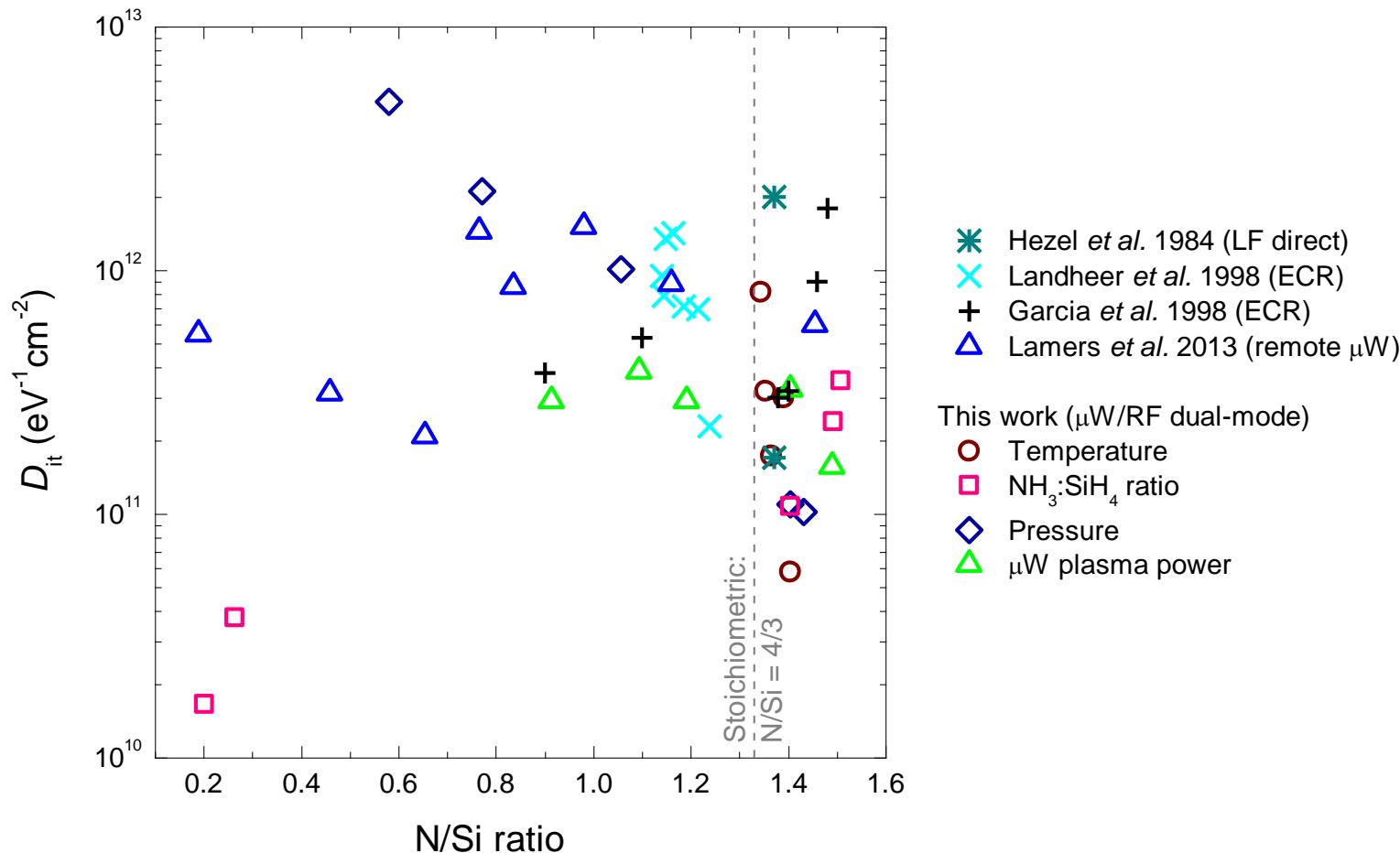
# Review of SiNx properties

## Electronics: insulator charge density $Q_{\text{eff}}$



# Review of SiNx properties

## Electronics: interface defect density $D_{it}$





## Conclusion 1

Irrespective of deposition techniques,

- (i) the bulk structural and optical properties are universally correlated to the N/Si ratio; and
- (ii) the electronic properties ( $Q_{\text{eff}}$  and  $D_{\text{it}}$ ) appear independent of the N/Si ratio.

- Promoting an opportunity of decoupling  $\text{SiN}_x$  surface passivation and optical transmission properties; and therefore
- Circumventing the trade-off between the two properties.

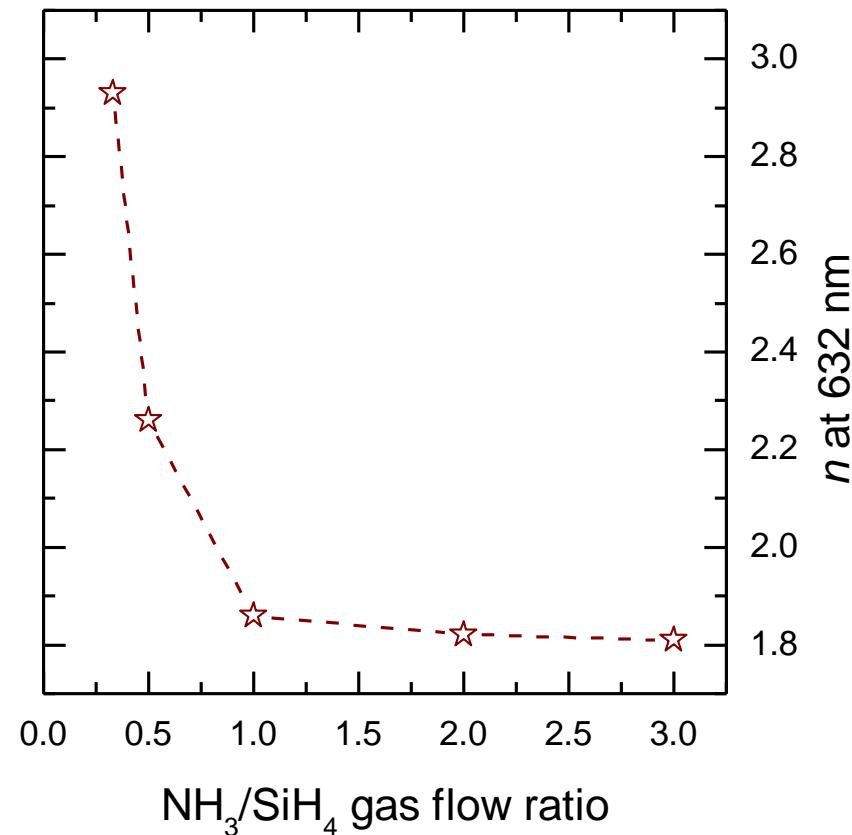
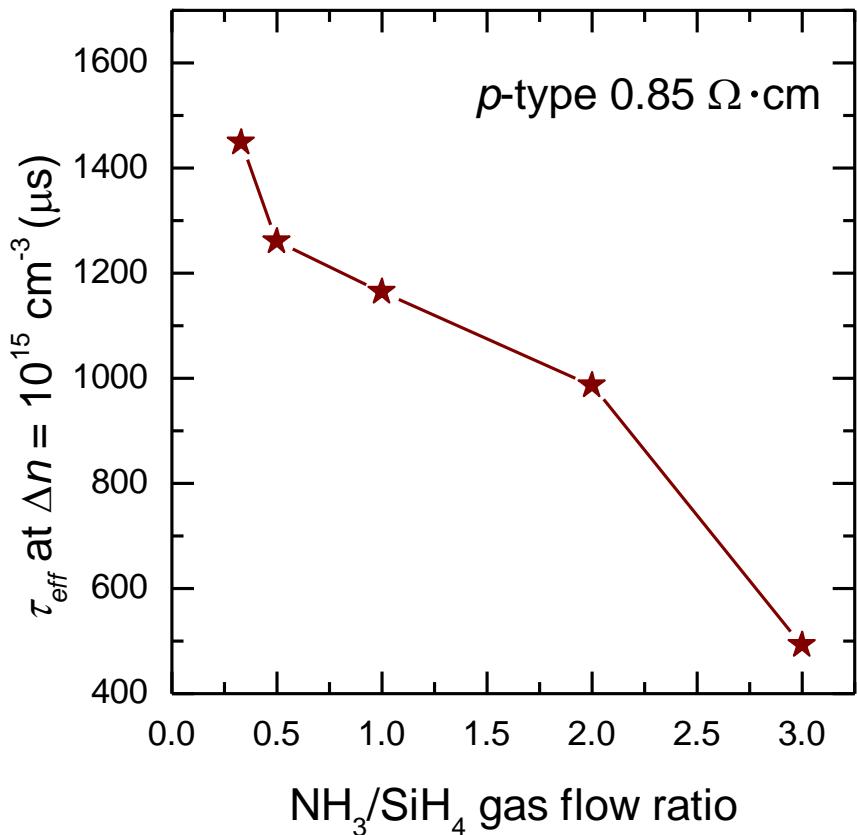


## Methodology

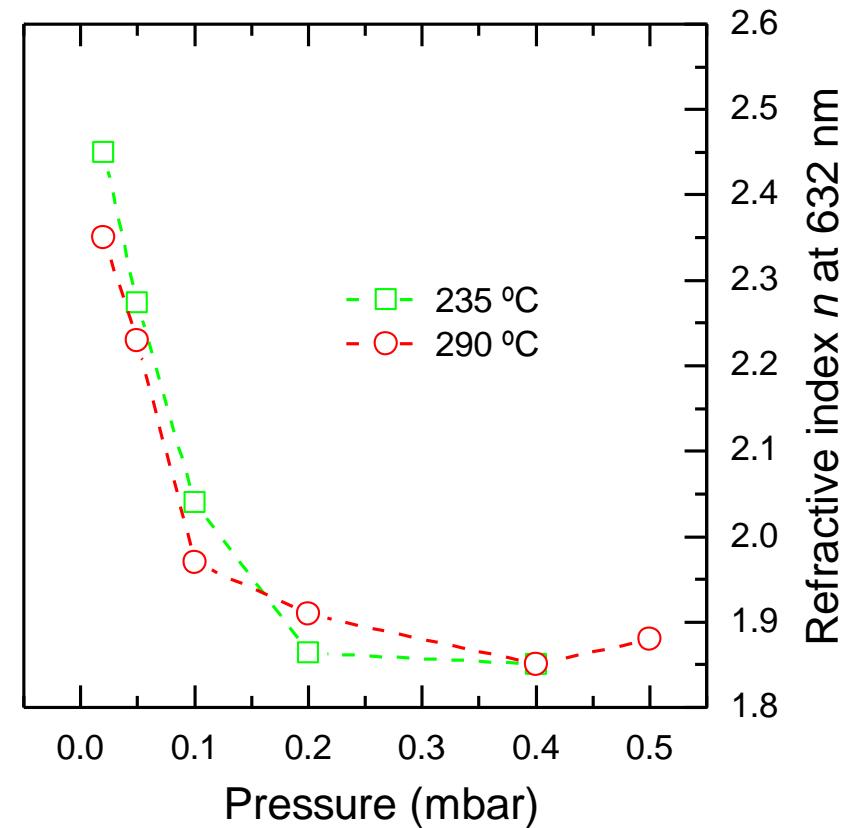
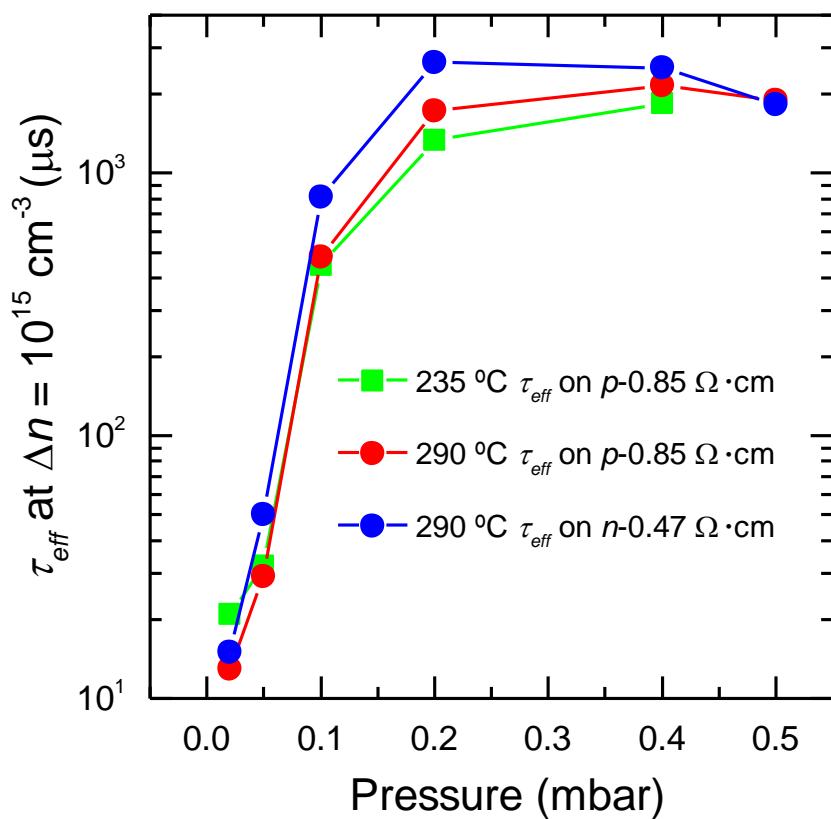
- 1) Varying deposition parameters in Roth & Rau AK400:
  - NH<sub>3</sub>:SiH<sub>4</sub> ratio
  - Pressure
  - Temperature
  - Microwave plasma
  - RF plasma
- 2) Monitoring surface passivation  $\tau_{\text{eff}}(\Delta n)$
- 3) Monitoring optical properties  $n$  &  $k$



## Results – NH<sub>3</sub>:SiH<sub>4</sub> ratio

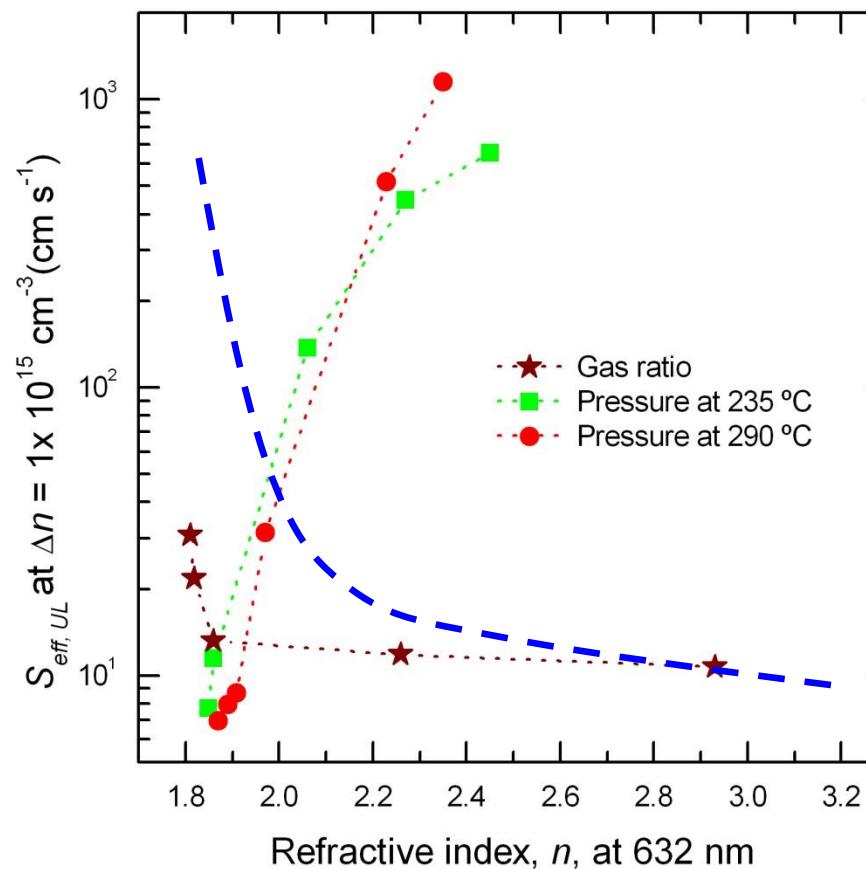


## Results – Pressure and temperature



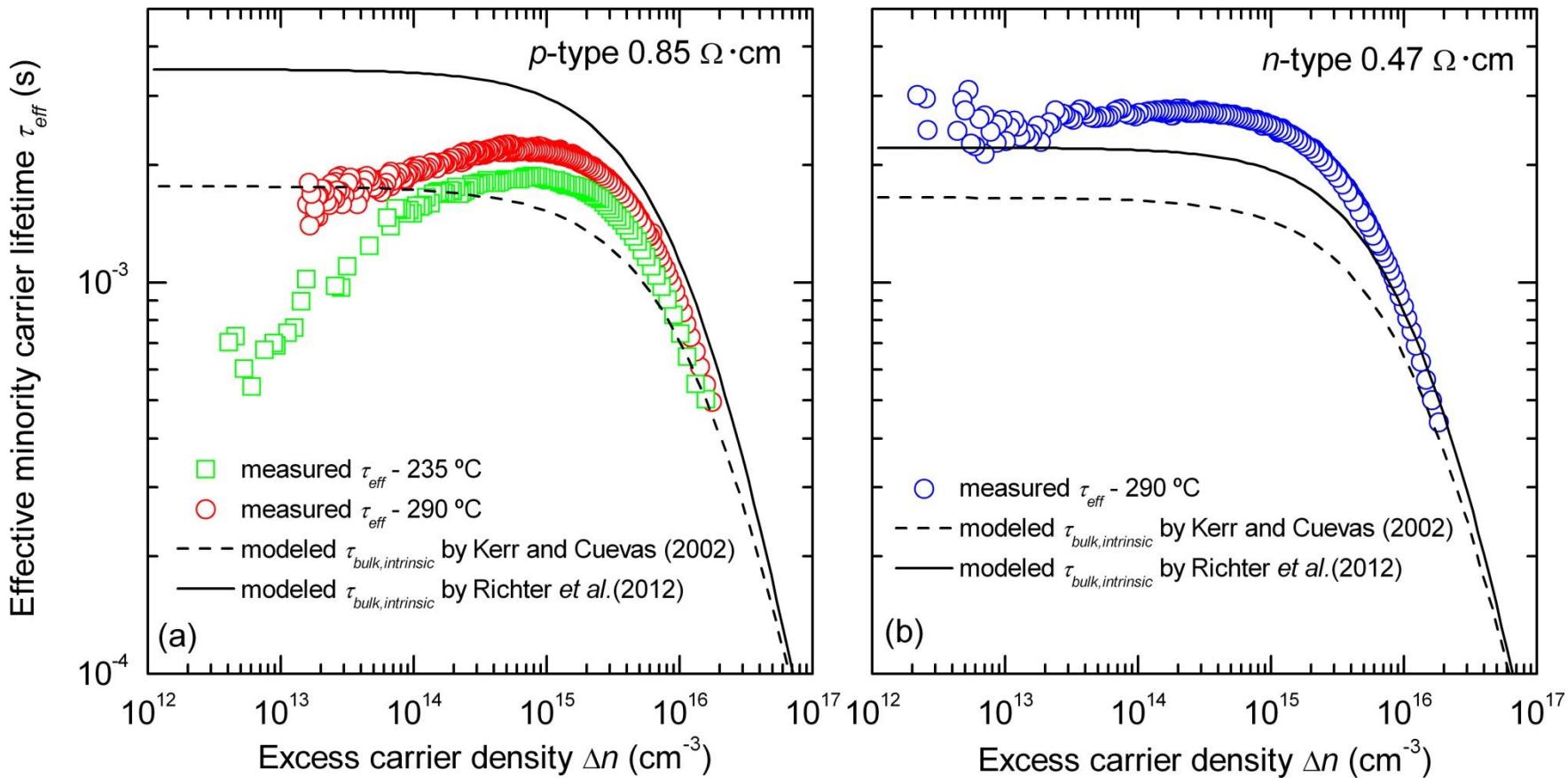


## Results – $S_{\text{eff},\text{UL}}$ vs. $n$



# Process development

## Surface passivation: $\tau_{\text{eff}}(\Delta n)$

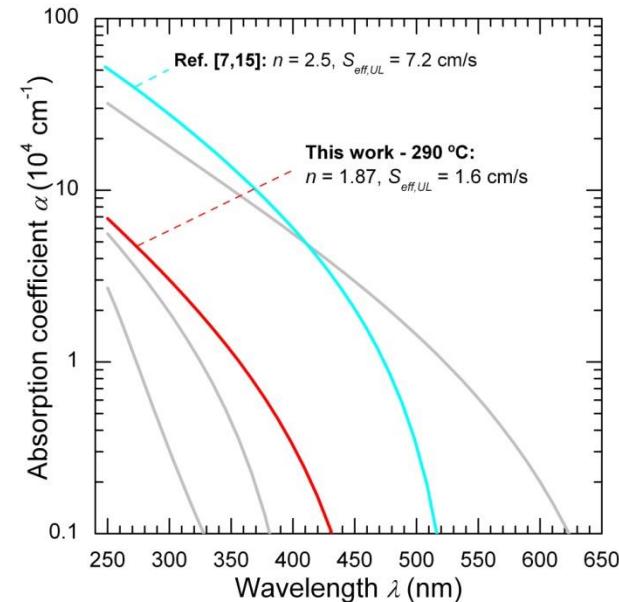




# Process development

## Optical transmission

- OPAL 2
- Random textured Si surface
- Si thickness: 180  $\mu\text{m}$



Ref.	$n_{632\text{nm}}$	$S_{\text{eff},UL}$ (cm/s)	<u>Cell under air</u>					<u>Cell encapsulated beneath glass/EVA</u>				
			$J_{\text{inc}}$	$t_{\text{SiNx}}$ (nm)	$J_{\text{gen}}$	$J_{\text{Abs}}$ (mA/cm <sup>2</sup> )	$J_{\text{refl}}$	$J_{\text{inc}}$	$t_{\text{SiNx}}$ (nm)	$J_{\text{gen}}$	$J_{\text{Abs}}$ (mA/cm <sup>2</sup> )	$J_{\text{refl}}$
DuttaGupta <i>et al.</i>	2.5	7.2		58	38.98	1.45	0.83		40	37.58	0.69	0.42
This work at 290 °C	1.87	1.6	41.27	80	40.38	0.21	0.67	38.69	88	38.24	0.11	0.34

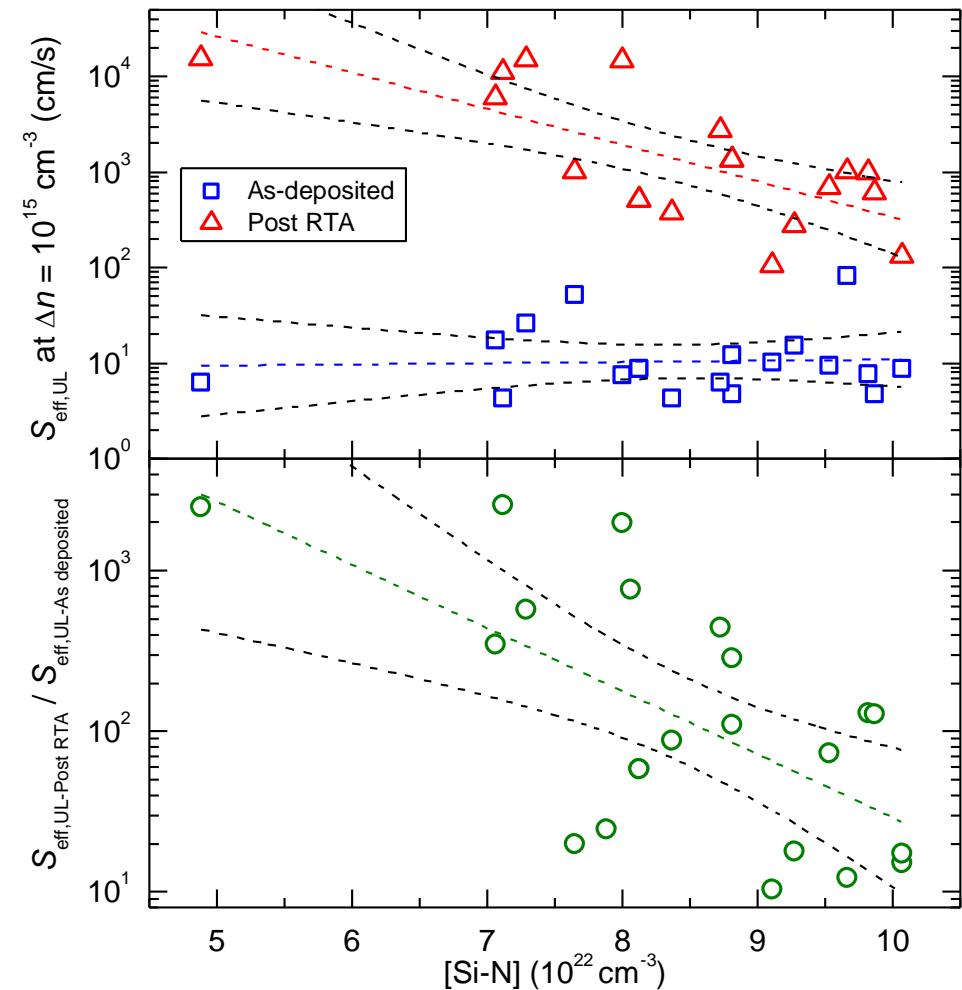
$\Delta J$  **1.40** - 1.24 - 0.16

$\Delta J$  **0.66** - 0.58 - 0.08

# Process development

## Thermal stability

- Poor thermal stability
- Correlated to [Si–N]
- Further studies required



RTA 800 °C for 5 seconds



## Conclusion 2

A single  $\text{SiN}_x$  layer can provide both

- ✓ high passivation of c-Si surface
- ✓ high transmission at short wavelength

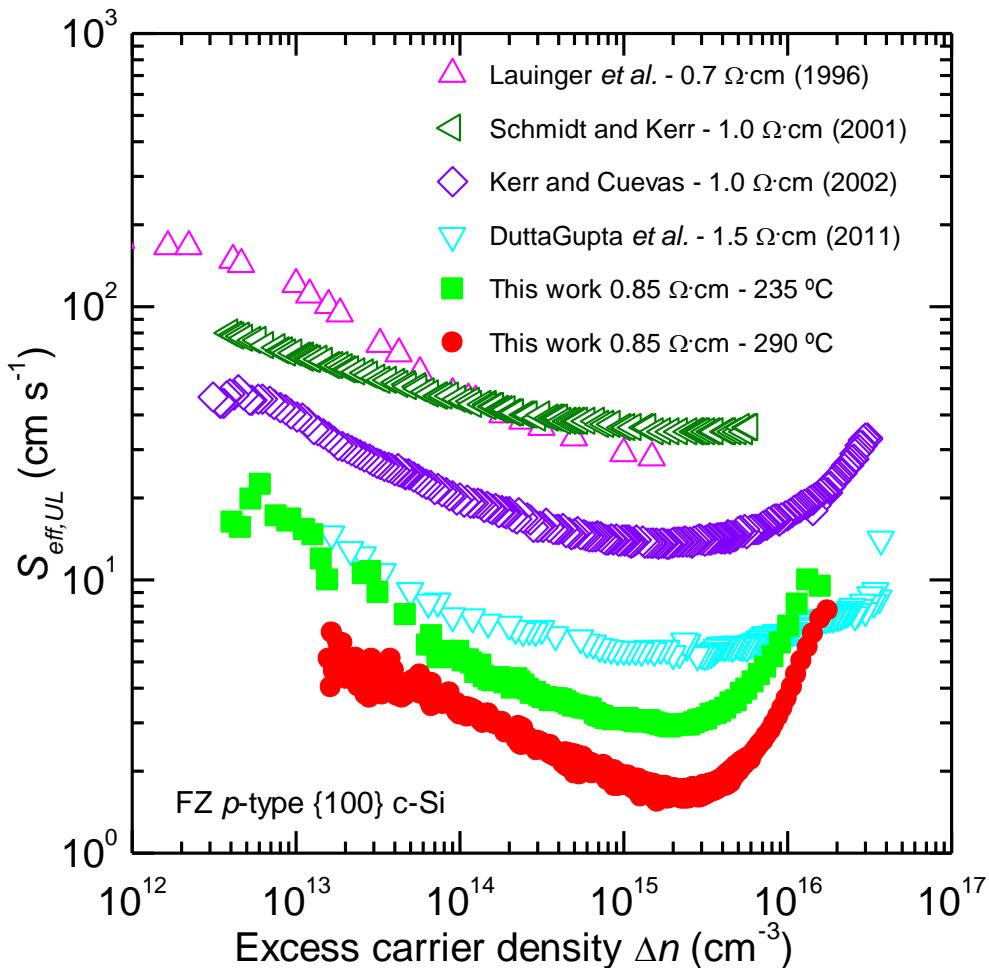


## Methodology

- 1) Extracting  $S_{\text{eff},\text{UL}}(\Delta n)$  from measured  $\tau_{\text{eff}}(\Delta n)$
- 2) Probing electronic properties by C-V measurements:  $D_{\text{it}}$  and  $Q_{\text{eff}}$
- 3) Modeling  $S_{\text{eff},\text{UL}}(\Delta n)$



## Extracting $S_{\text{eff},\text{UL}}(\Delta n)$



$$S_{\text{eff}}(\Delta n) = \frac{w}{2} \left( \frac{1}{\tau_{\text{eff}}(\Delta n)} - \frac{1}{\tau_{\text{bulk}}(\Delta n)} \right)$$

$w$  : Si wafer thickness

$\tau_{\text{eff}}(\Delta n)$  : effective minority carrier lifetime

$\tau_{\text{bulk}}(\Delta n)$  : Si bulk lifetime

- Similar injection-level dependence
- Lowest Auger-corrected  $S_{\text{eff},\text{UL}}$  ( $1.6 \text{ cm/s}$ )

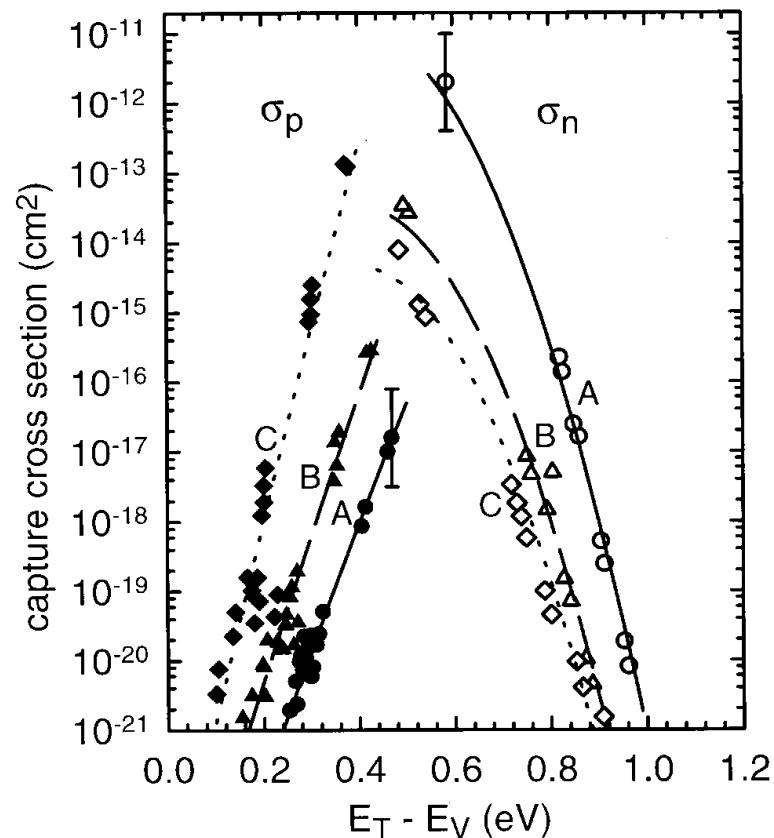


# Recombination studies – planar

## Probing electronics: $D_{it}$ , $Q_{eff}$ and $\sigma_{n/p}$

$D_{it-Midgap}$ ( $\text{cm}^{-2}\text{eV}^{-1}$ )	$3.0 \times 10^{11}$
$Q_{eff}$ ( $\text{cm}^{-2}$ )	$5.6 \times 10^{11}$

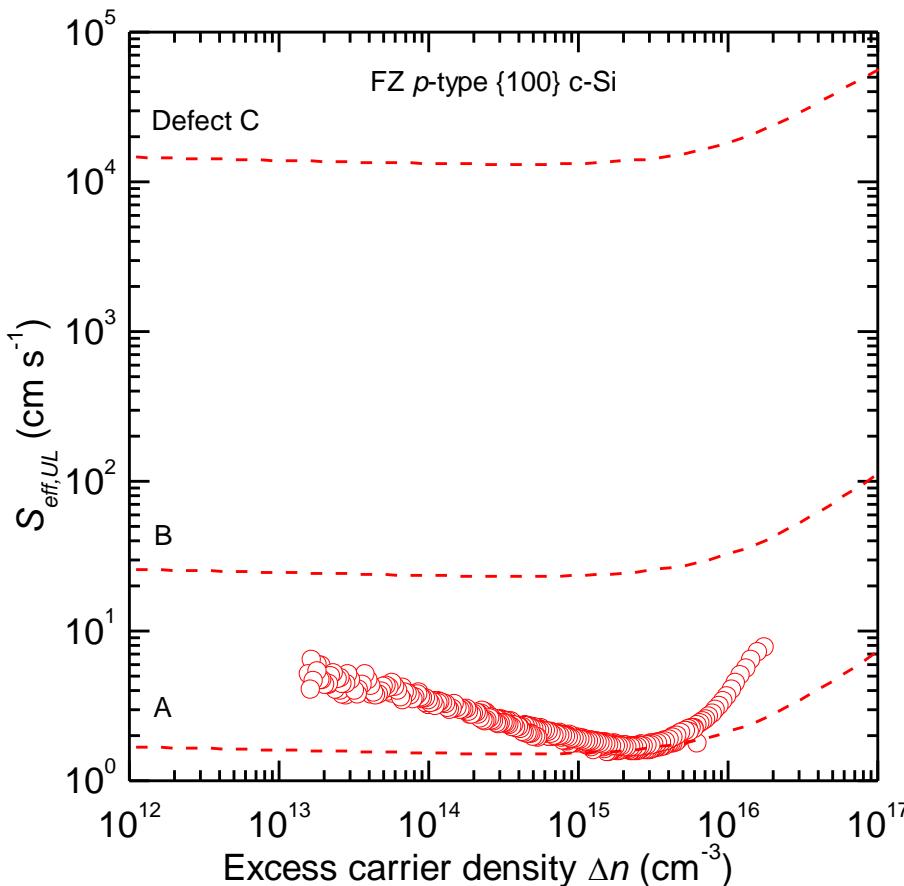
Extracted from quasi-static (QS) and high-frequency (HF) capacitance-voltage (C-V) measurements



Schmidt *et al.* (1997)



## Modeling $S_{\text{eff},UL}(\Delta n)$



Notes for the  $S_{\text{eff},UL}(\Delta n)$  modeling:

- Adapting the latest Si intrinsic bulk lifetime model—Richter *et al.* (2012)
- Assuming a single defect at a single energy level (midgap)
- Assuming  $\sigma_n$  &  $\sigma_p$  saturate and constant for the unmeasured gap regions
- Defect A or B (or both) is likely to dominate the recombination at the Si– $\text{SiN}_x$  interface.
- Defect C is excluded.



## Conclusion 3

- We obtained a low  $S_{\text{eff,UL}} = 1.6 \text{ cm/s}$  on  $0.8 \Omega\text{cm}$  p-type FZ Si, with  $D_{it} = 3.0 \times 10^{11} \text{ eV}^{-1} \text{ cm}^{-2}$  at midgap, and  $Q_{\text{eff}} = 5.6 \times 10^{11} \text{ cm}^{-2}$ .
- Defect A or B (or both) is likely to dominate the recombination at the Si–SiN<sub>x</sub> interface, and
- Defect C is excluded.



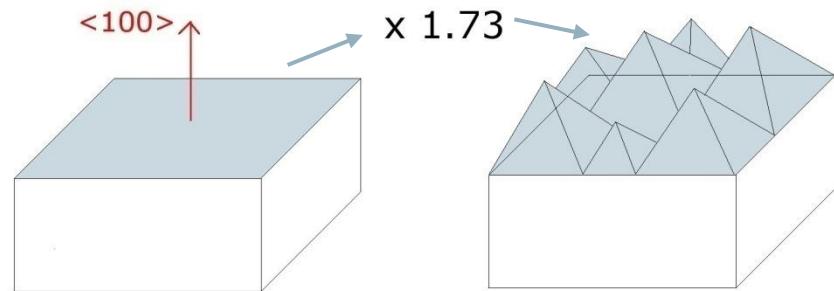
## Methodology

- 1) Employing the optimum deposition condition and varying the  $\text{NH}_3:\text{SiH}_4$  ratio to obtain a wide range of film refractive indices ( $n$  at 632nm = 1.83 – 4.1)
- 2) Monitoring  $S_{\text{eff},\text{UL}}$  as a function of  $n$  at 632nm on three types of Si surfaces:
  - i. Planar {100}
  - ii. Planar {111}
  - iii. Texturing with random upright pyramids
- 3) Probing electronic properties at textured surfaces by depositing corona charge



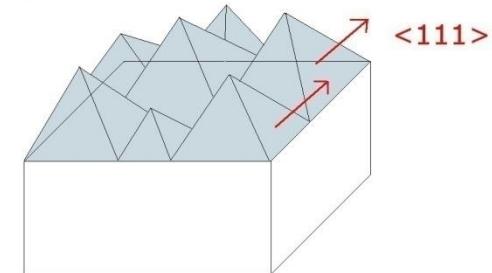
## Drivers of enhanced recombination

1. Enlarged surface area

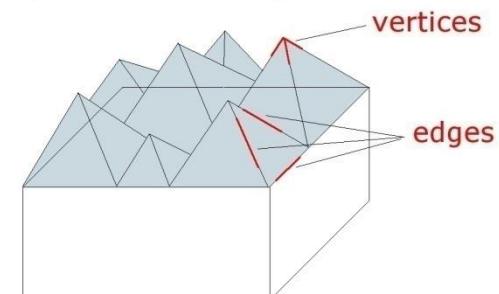


2. Orientation of surface planes:

$$f_O = \{111\}/\{100\}$$



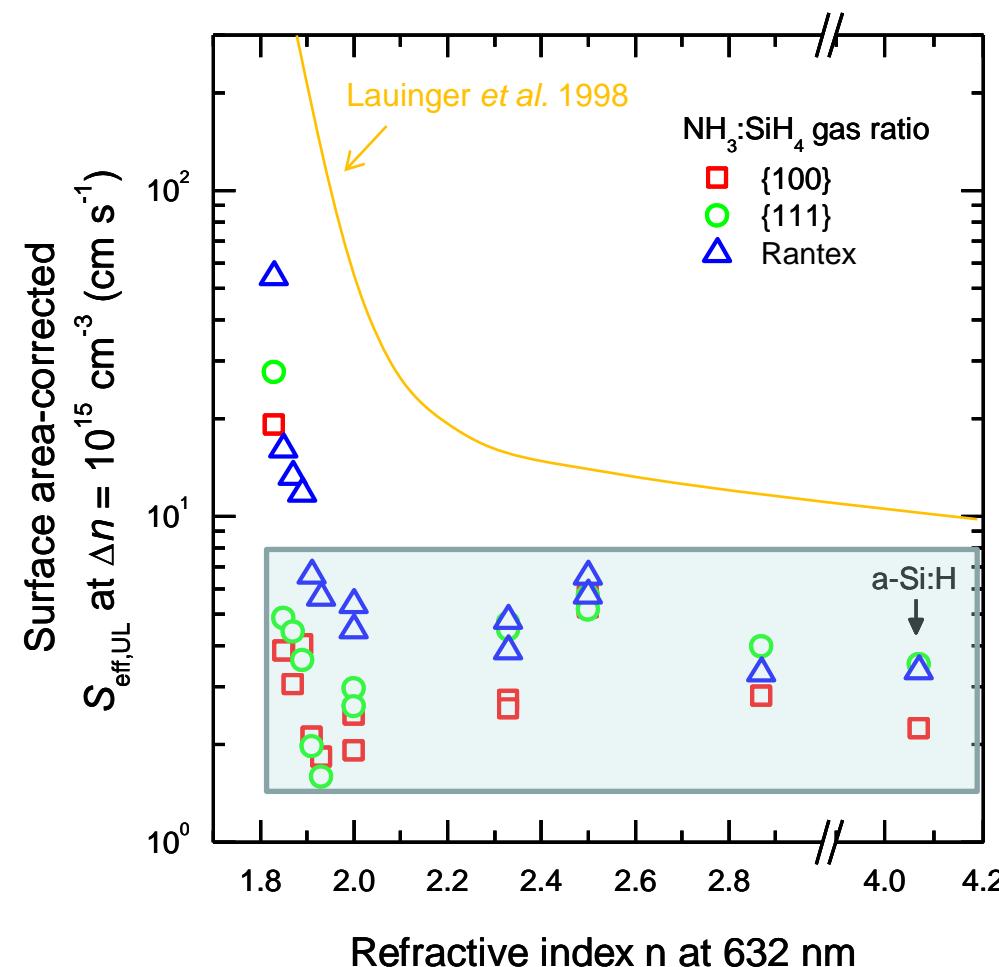
3. Presence of concave and convex surface features:  $f_V = \text{texture}/\{111\}$



# Recombination studies – texturing

## Results: surface area-corrected $S_{\text{eff},\text{UL}}$

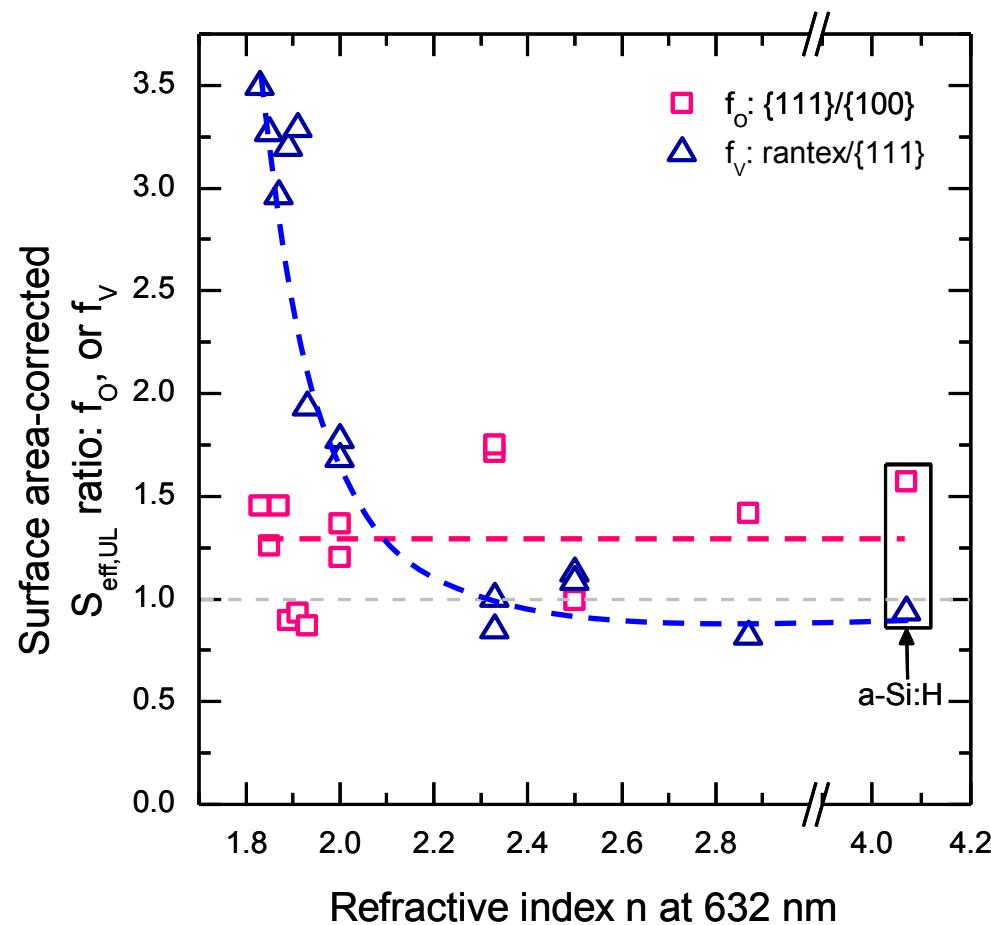
- Consistent trend:  $S_{\text{eff},\text{UL}}$  first decreases and then saturates
- Two exceptions:
  - low  $S_{\text{eff},\text{UL}}$
  - saturates at lower  $n$
- Low and constant  $S_{\text{eff},\text{UL}}$  over a range of
  - $n$  (1.85 – 4.1 at 632 nm)
  - surface morphologies



# Recombination studies – texturing

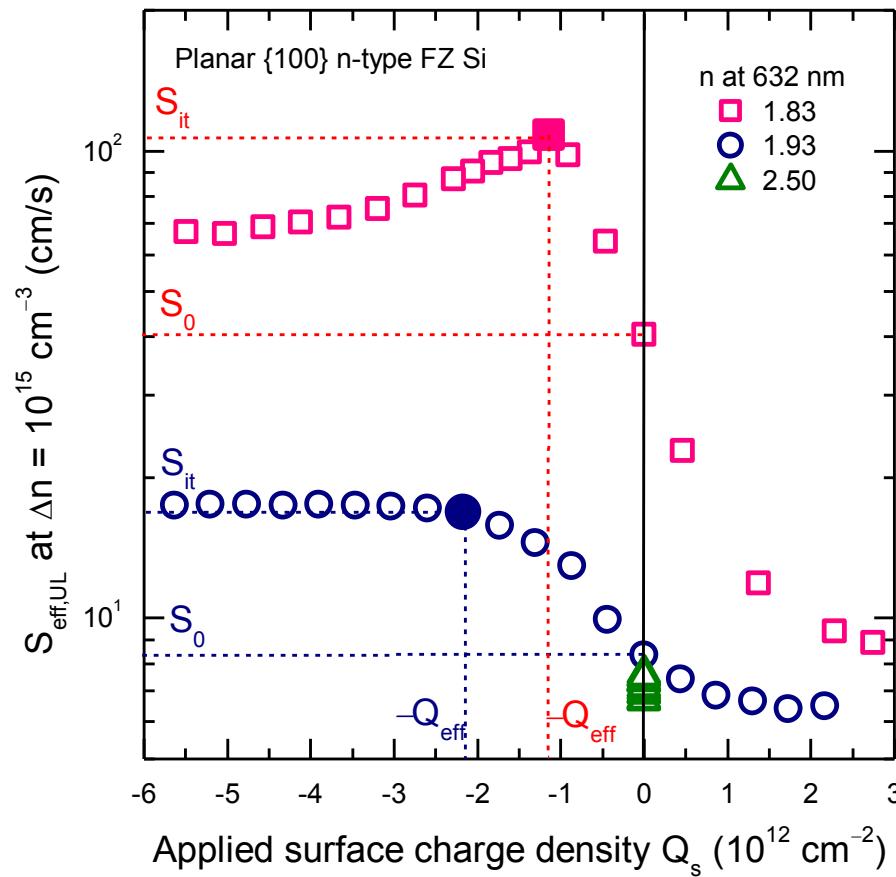
## Results: surface area-corrected $S_{\text{eff},\text{UL}}$ ratio

- $f_o$  is constantly low (0.9-1.7) → less orientation dependence
- $f_v$  relates strongly to  $n$ 
  - high at low  $n$
  - sensitive to morphology
  - close to 1.0 when  $n \geq 2.3$
  - negligible increase at texture, after area-correction



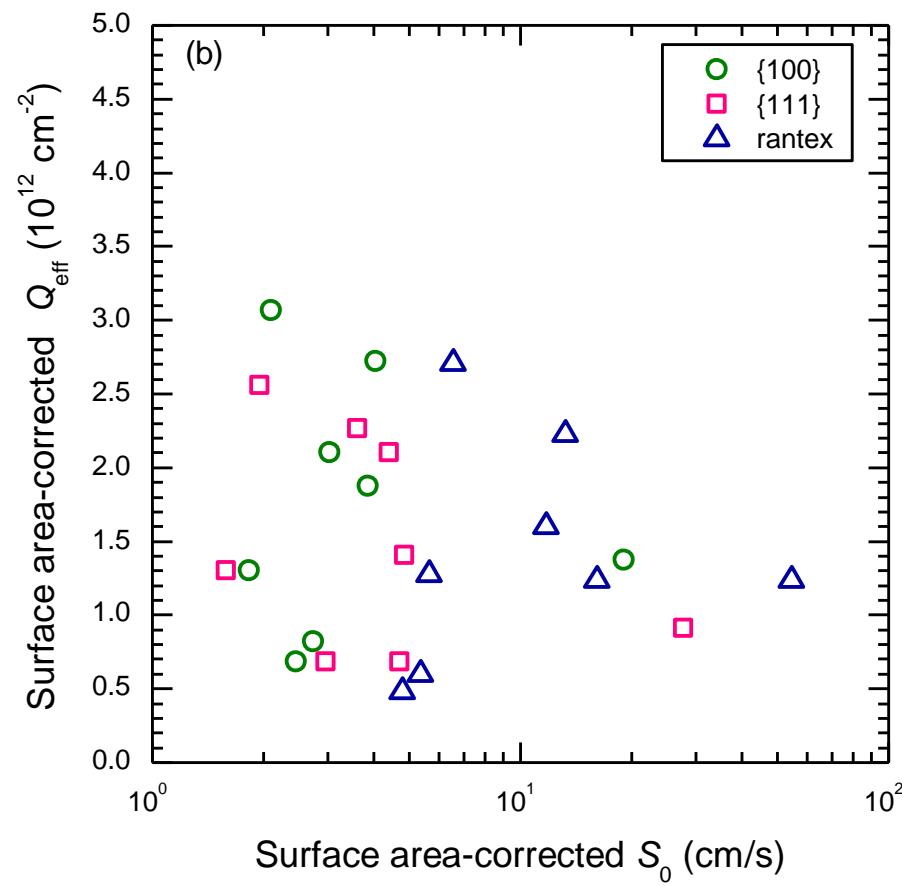
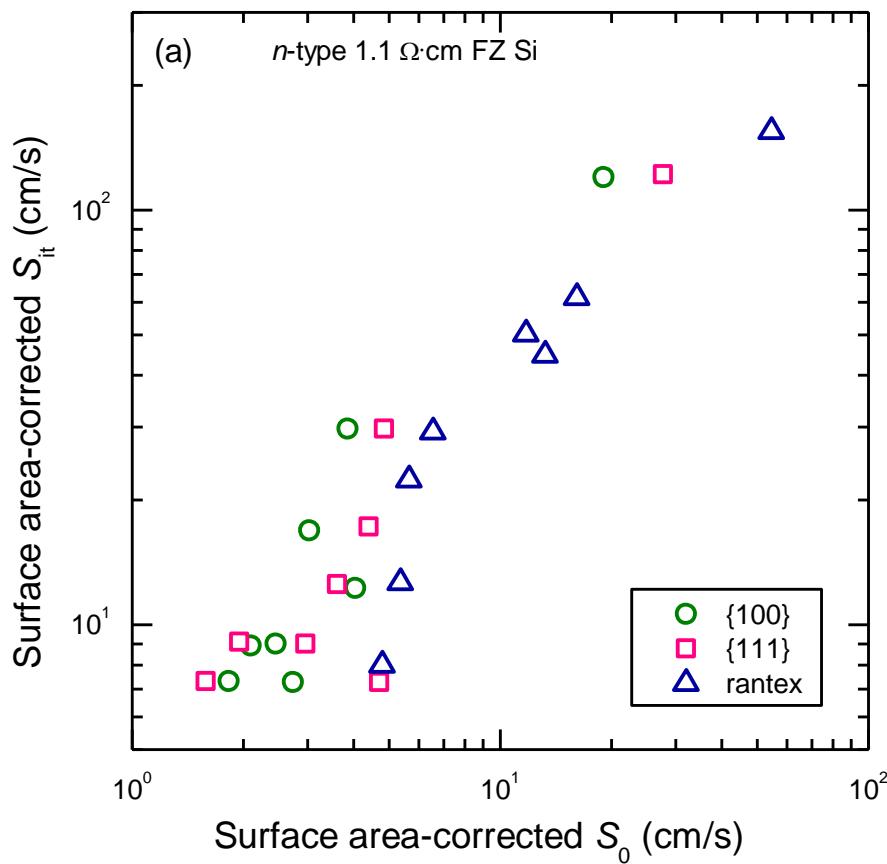


## Probing electronics by corona-lifetime technique





## Results: $S_{it}$ or $Q_{eff}$ versus $S_0$





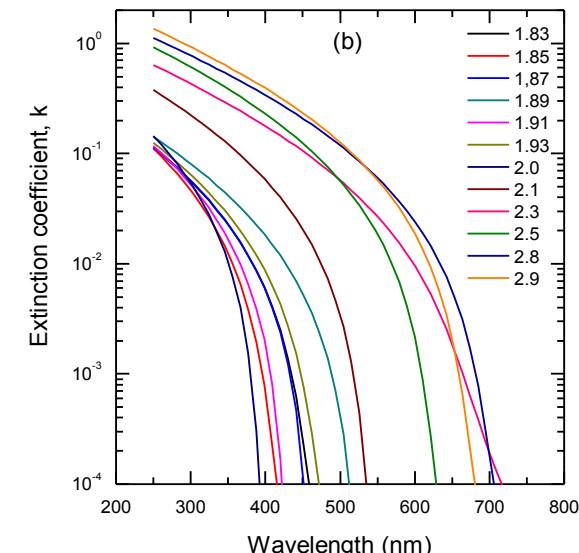
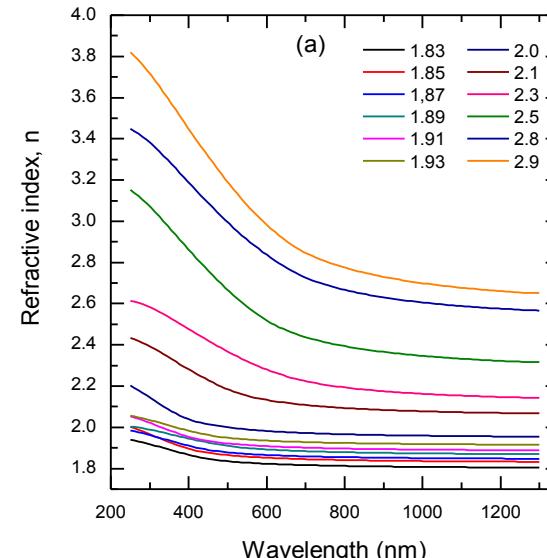
## Conclusion 4

- A constant and low SRV is achieved on planar and textured Si surfaces over a wide range of  $n$  (1.85-4.1),
- When passivated by N-rich SiNx, the increase in recombination at textured surfaces is high, and it is
  - i. due to the presence of vertices/edges on pyramids rather than due to the {111} orientation (i.e., high  $f_V$  and low  $f_O$ ), and
  - ii. primarily caused by an increase in  $D_{it}$  rather than a reduction in  $Q_{eff}$ .
- When passivated by Si-rich or a-Si:H, the increase in recombination at textured surfaces is negligible after are-correction (i.e.,  $f_V$  and  $f_O$  are close to unity).

# Cell simulation and application

## Simulating impact of $\text{SiN}_x$ on cells

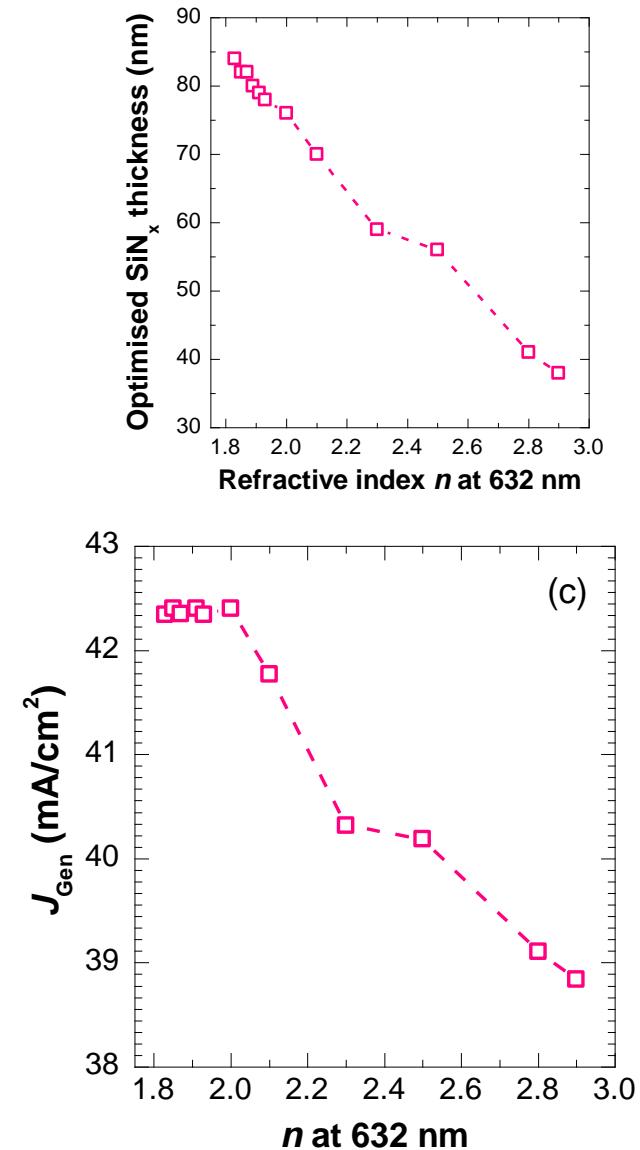
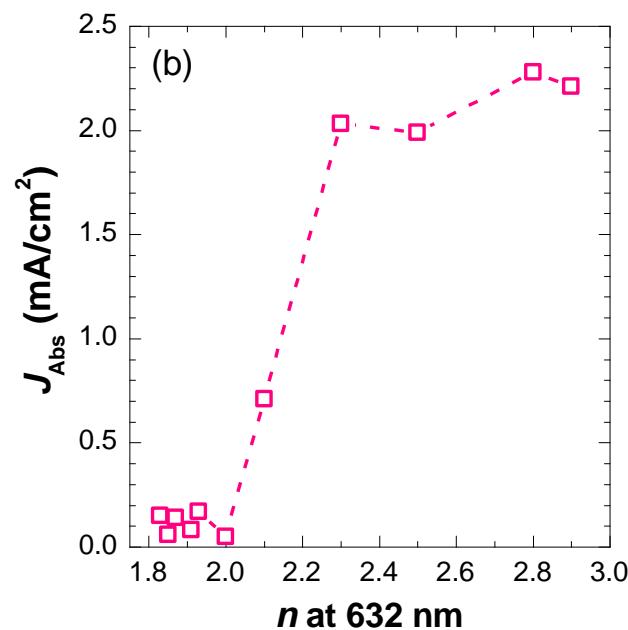
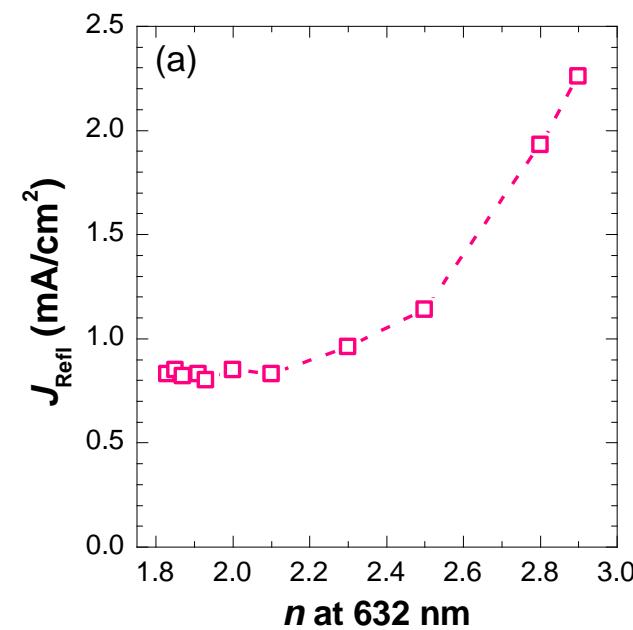
- $\text{SiN}_x$  functions as front surface passivation and ARC layer
- p-type PERC ( $n^+$ -diffused front) and n-type IBC (undiffused front)
- Cell simulation using Quokka 2 [Fell 2012]
- Optical simulation using OPAL 2 [McIntosh *et al.* 2012]
  - Random upright pyramids
  - Spectrum AM 1.5g
  - Operating in air





# Cell simulation and application

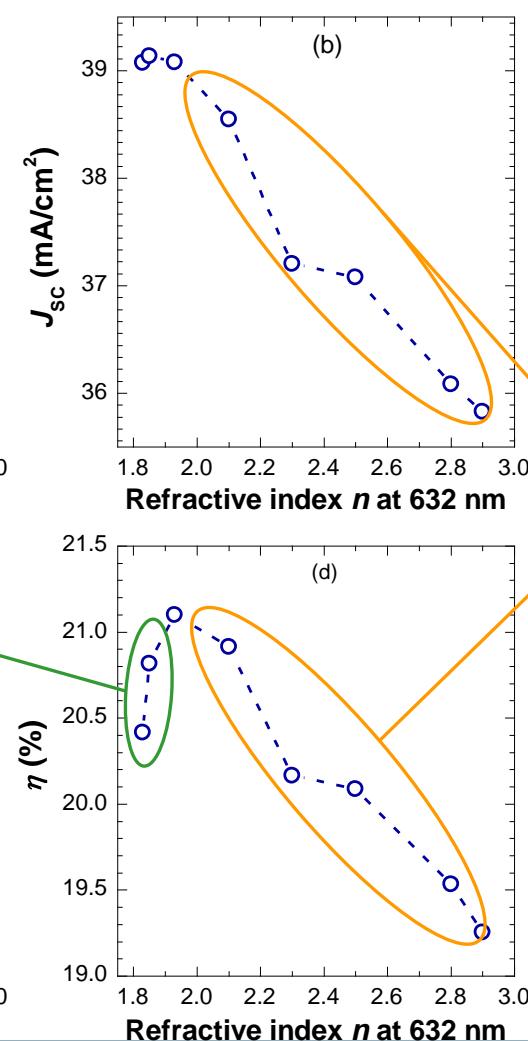
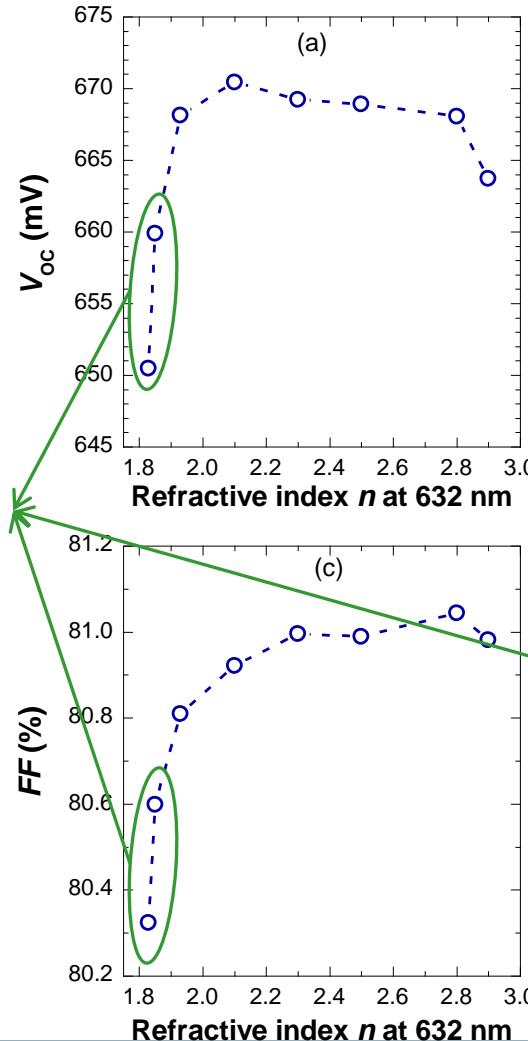
## Simulation results (1/3): ARC





## Simulation results (2/3): *p*-PERC cell

High recombination

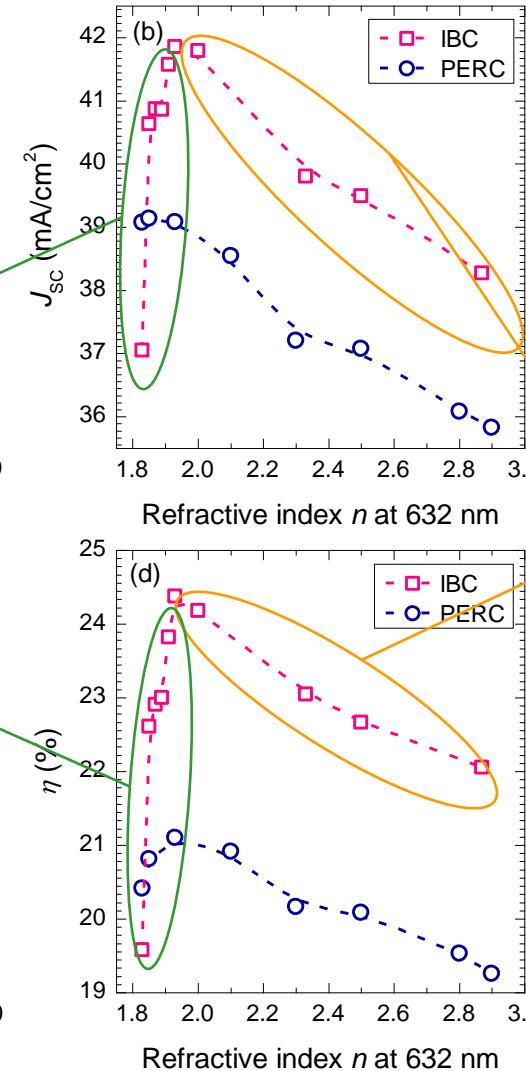
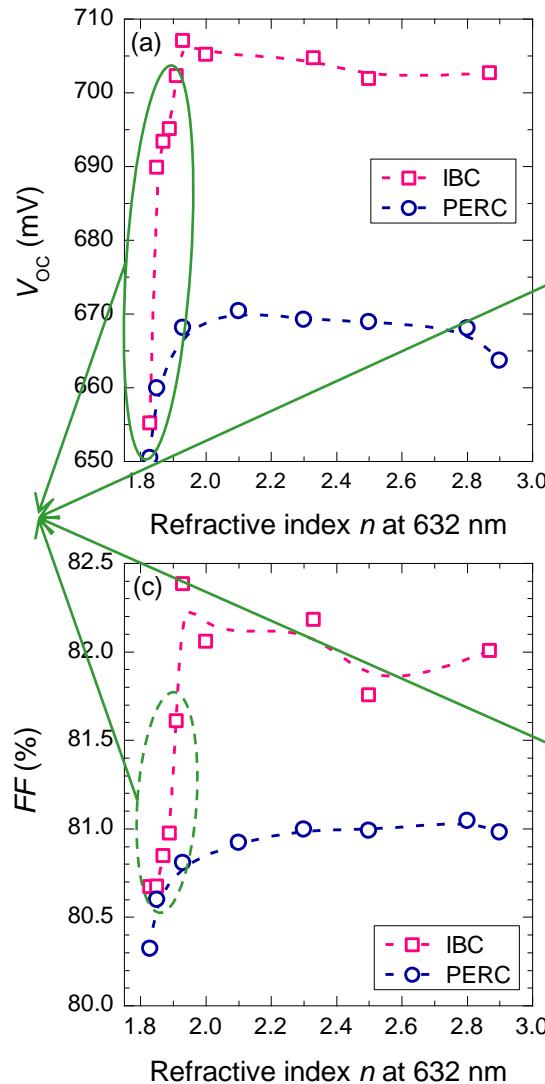


High absorption

# Cell simulation and application

## Simulation results (3/3): $n$ -IBC cell

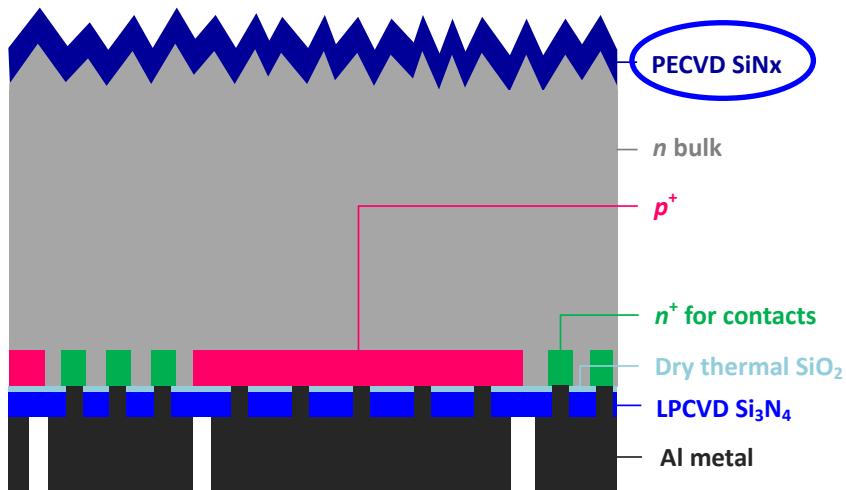
High recombination



High absorption

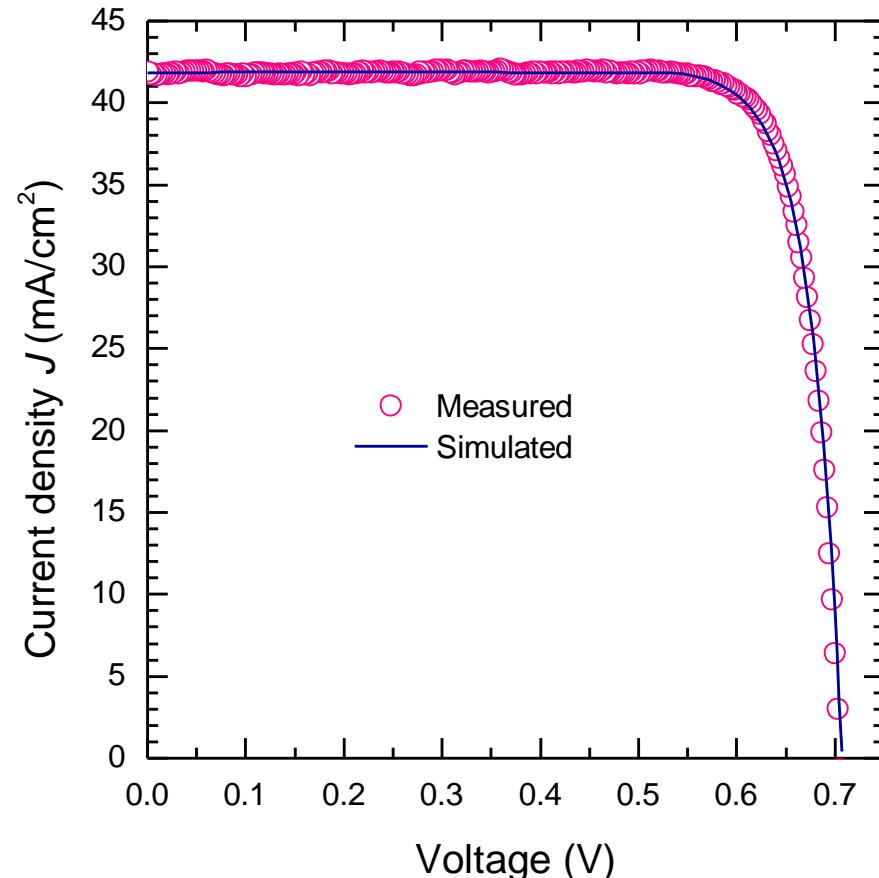


## Application on n-type IBC



V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	η (%)
705	41.9 ± 0.7	82.7	24.4 ± 0.5

Under standard testing conditions (25°C, AM1.5G spectrum)





## Conclusion 5

- The optimum  $\text{SiN}_x$  for both p-type PERC and n-type IBC has  $n = 1.9$ , owing to:
  - high surface recombination when  $n < 1.9$
  - high film absorption when  $n > 1.9$
- Application of the optimum  $\text{SiN}_x$  onto the front textured undiffused surface of an n-type IBC cell enabled a conversion efficiency of  $24.4 \pm 0.5\%$ .



# Summary

- No universal correlation exists between surface recombination and bulk structural/optical properties.
- A highly transparent and highly passivating SiNx is attained, enabling a 24.4%-efficient n-type IBC cell.
- An increase in recombination of the textured surfaces is
  - i. related to the presence of vertices and/or edges of the pyramids rather than to the presence of {111}-orientated facets, and;
  - ii. primarily attributable to an increase in  $D_{it}$  rather than a decrease in  $Q_{eff}$ .



# Thank you!