Point-contacting by Localised Dielectric Breakdown:
A new approach for contacting solar cells

SPREE Public Seminar
20th February 2014

Ned Western

Supervisor:
Stephen Bremner
Co-supervisor:
Ivan Perez-Wurfl

UNSW AUSTRALIA

ARENA

Australian Government
Australian Renewable Energy Agency

Outline

Motivation
Discovery
Device fab method
Basic results

- DIV
- TEM
- MS pics

Why self aligned

- dielectric leakage

Other applications

- Other gate metals
- Al BSF
- Other dielectrics
- n-type
- With emitter

Accurate measurement of R_c and S_{eff}

- p+ on n-type
- Array of point-contacts

Breakdown dynamics

- Weibull distribution
- Thickness dependence

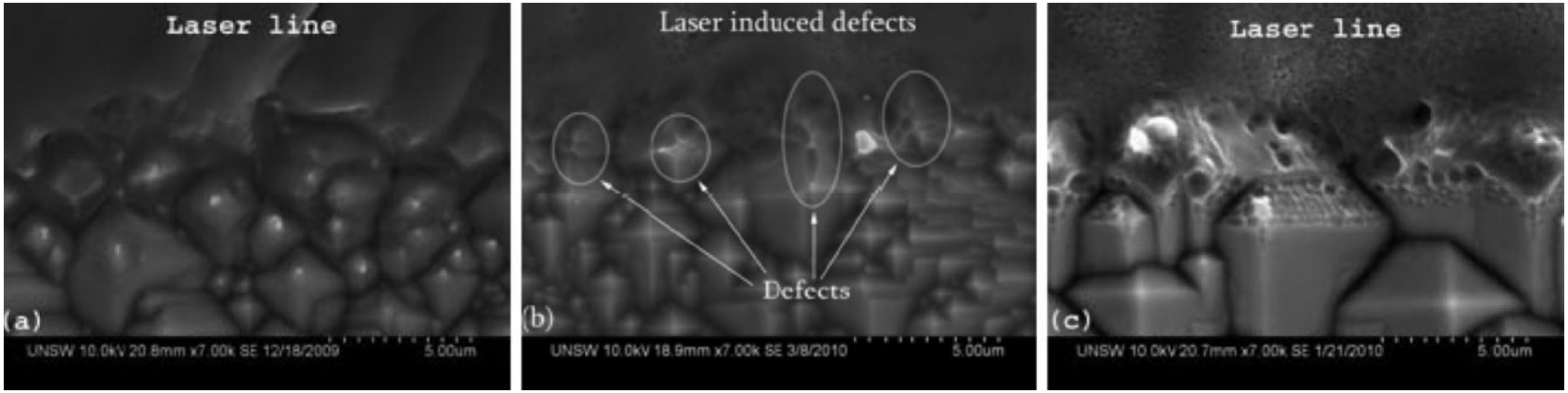
Motivation

Screen printed Aluminium Back Surface Field (BSF) has dominated for many years, improving this is next best way to boost cell efficiency. Various cell designs have been proposed to improve on this.

UNSW laser doping

- Laser damage to dielectric

UNSW laser doped selective emitter applied to rear surface *Xu et al.*



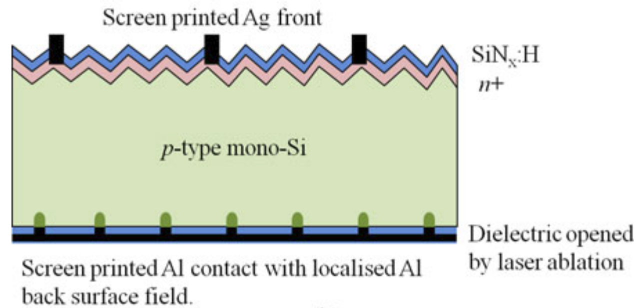
SEM images of crystal defects caused by laser doping with a) no SiN_x b) SiO_2/SiN_x stack c) SiN_x Hameiri *et al.*

Xu, G., et al. Energy Procedia 33 (2013): 33-40.
Hameiri, Z., et al. Progress in Photovoltaics: Research and Applications 19.4 (2011): 391-405.

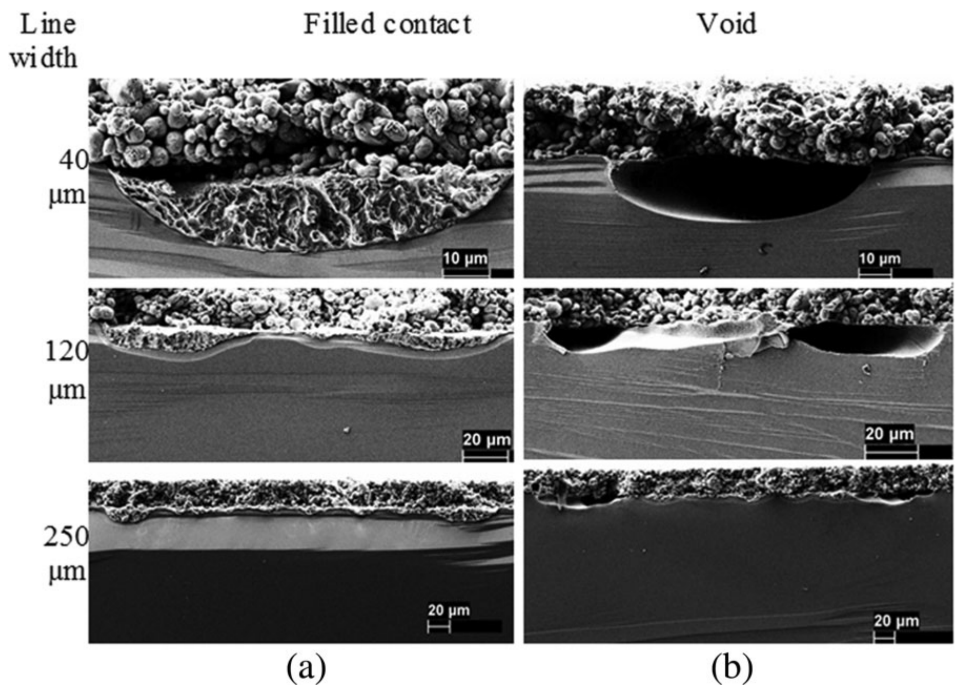
Motivation

PERC style Al BSF through patterned dielectric

- Voids a potential issue
- High temperature firing step



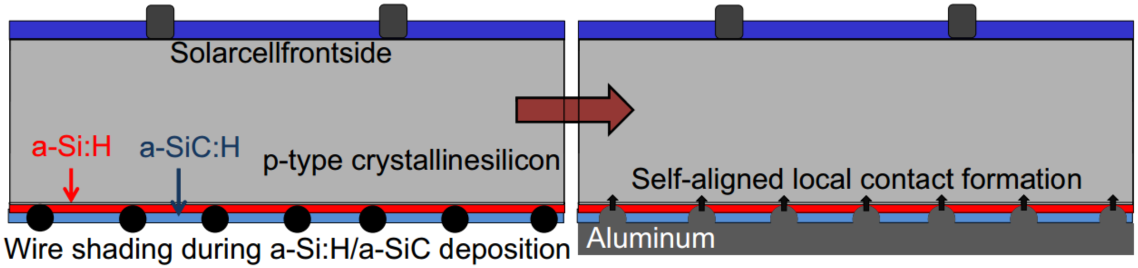
(b)



Void created during Al BSF of PERC structure Chen *et al.*

Chen, Jia, et al. "Investigation of Screen-Printed Rear Contacts for Aluminum Local Back Surface Field Silicon Wafer Solar Cells." (2013): 1-7.

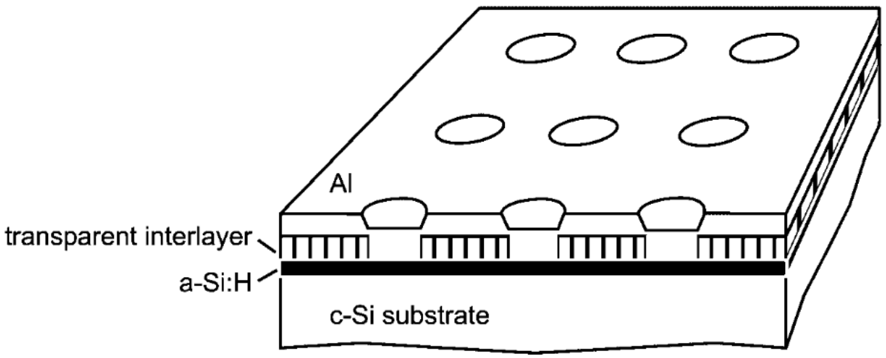
Motivation



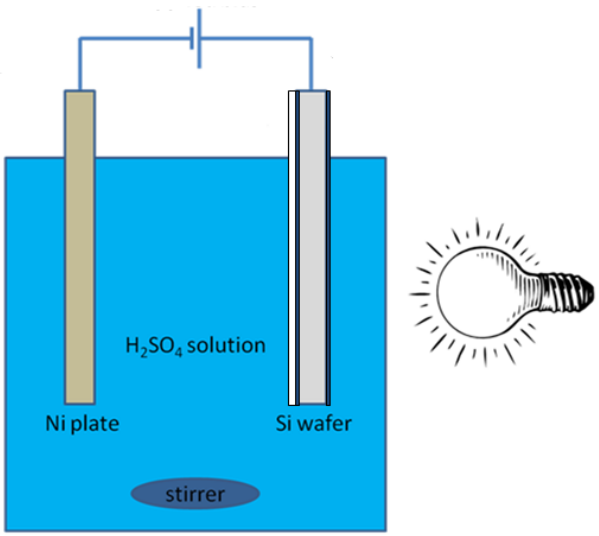
Aligned PECVD deposition by wire shading. Carstens *et al.*

Other designs,

- Some at low temperature
- Yet to demonstrate high performance



COSIMA process. Plagwitz *et al.*



Anodic Aluminium Oxide, Lennon *et al.*

Carstens, Kai, Shinsuke Miyajima, and Markus B Schubert. Solar Energy Materials and Solar Cells 106 (2012): 27-30.
Plagwitz, H., et alProgress in Photovoltaics: Research and Applications 12.1 (2004): 47-54.
Lennon, Alison, et al. *MRS Proceedings*. Vol. 1400. Cambridge University Press, 2012.

Motivation

Rear surface inherently difficult because:

- Low doped p-type surface sensitive to surface states
- Particularly for positively charged dielectric.
- Creating a doped region requires high temperature

Assume limited to industrial PERC or PERL type structure, we need 3 steps:

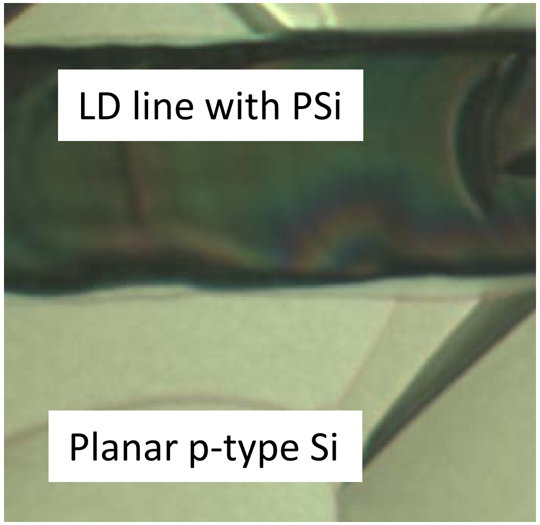
- Passivate surface with dielectric
- Dope Si (high temperature process, at least locally)
- Metal contact through dielectric to (only) the doped region

Ideally low temperature processing: cost, mc-Si, bulk hydrogenation

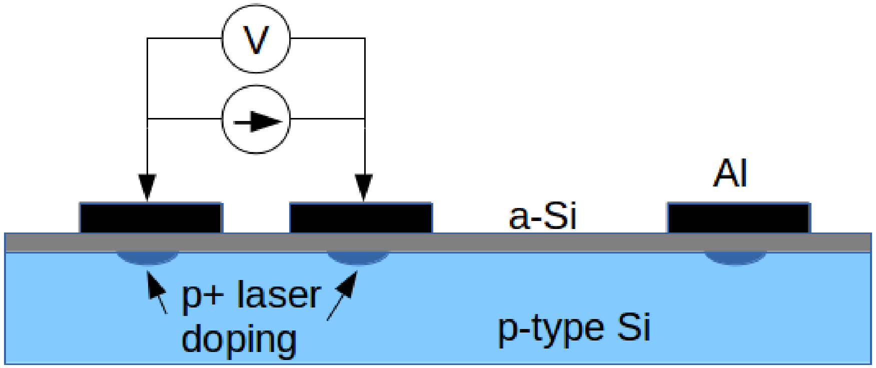
Dielectric deposition AFTER doping process avoids thermal damage, but then need a commercially relevant way of aligning contact through the dielectric.

Discovery of self aligned breakdown

- Tunnelling through thin dielectric layer.
- TLM to measure change in contact resistance
- 1st IV sweep consistently showed noisy data
- Stable ohmic resistance from 2nd sweep onwards
- 'noise' in 1st sweep was in fact change in device resistance



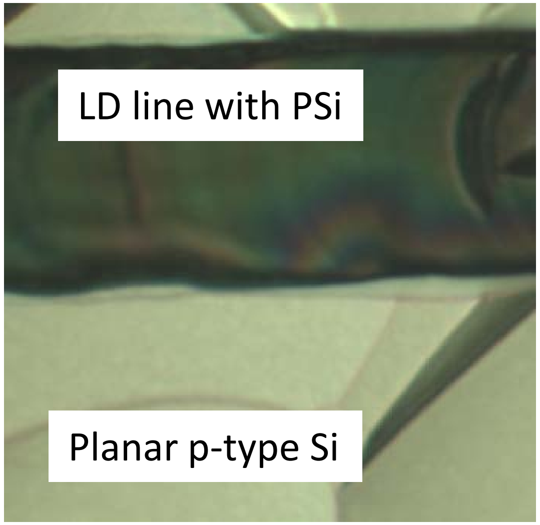
Microscope image of selective porous silicon formation over laser doped (LD) line



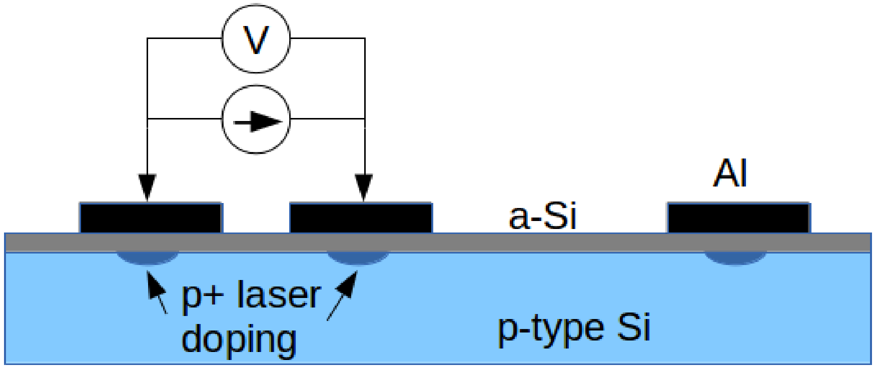
Selective tunnelling contacts on TLM structure

Discovery of self aligned breakdown

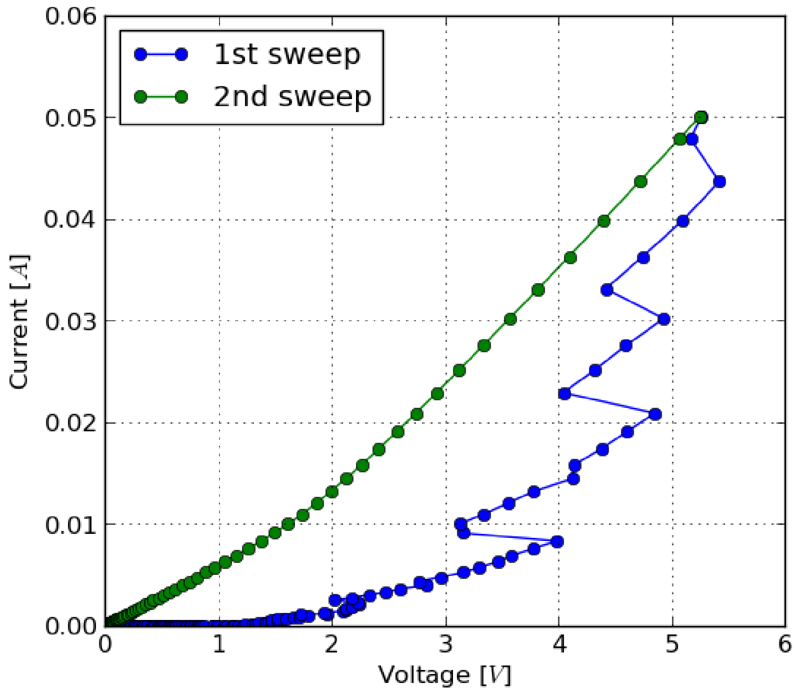
- Tunnelling through thin dielectric layer.
- TLM to measure change in contact resistance
- 1st IV sweep consistently showed noisy data
- Stable ohmic resistance from 2nd sweep onwards
- 'noise' in 1st sweep was in fact change in device resistance



Microscope image of selective porous silicon formation over laser doped (LD) line

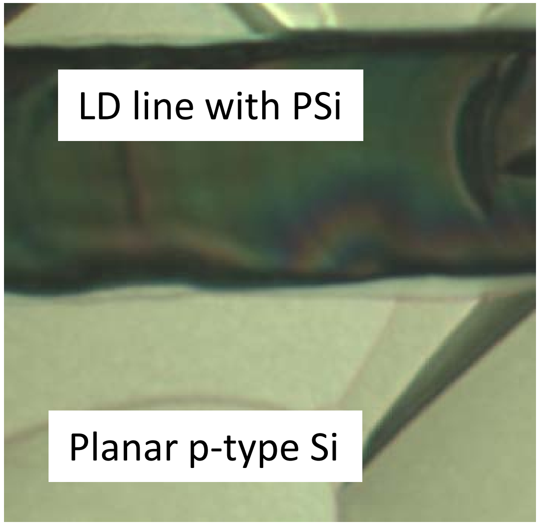


Selective tunnelling contacts on TLM structure

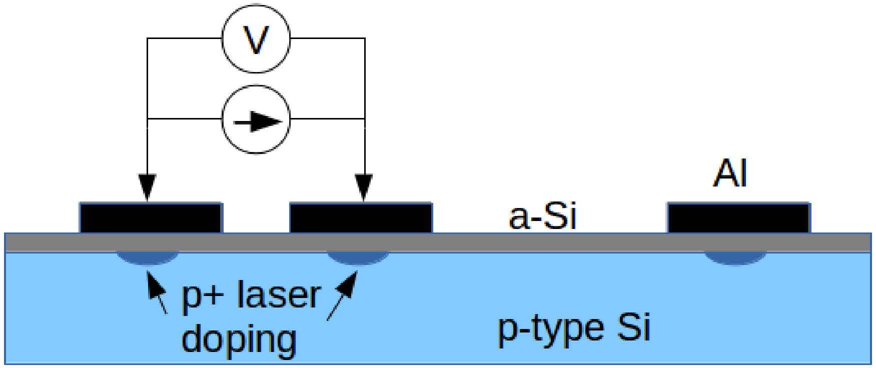


Discovery of self aligned breakdown

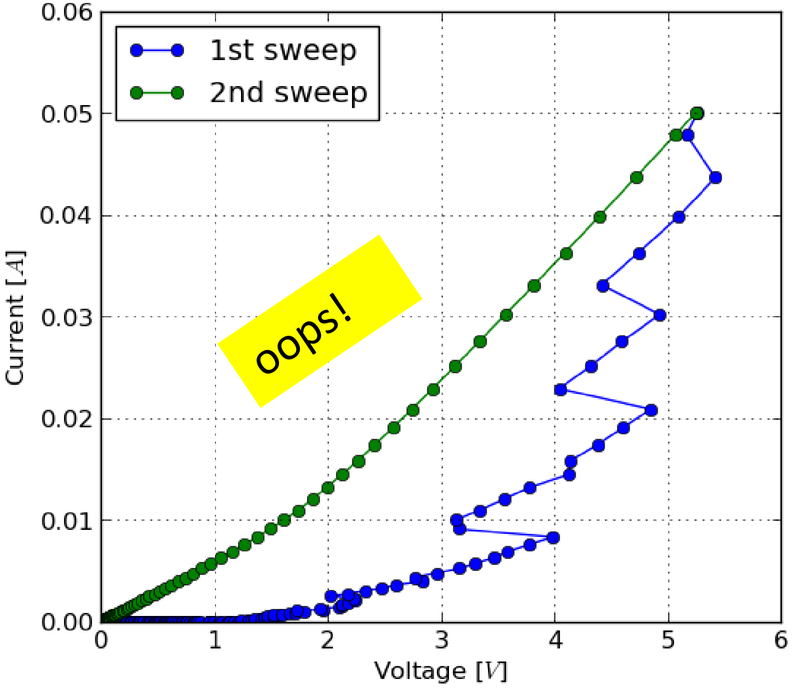
- Tunnelling through thin dielectric layer.
- TLM to measure change in contact resistance
- 1st IV sweep consistently showed noisy data
- Stable ohmic resistance from 2nd sweep onwards
- ‘noise’ in 1st sweep was in fact change in device resistance



Microscope image of selective porous silicon formation over laser doped (LD) line

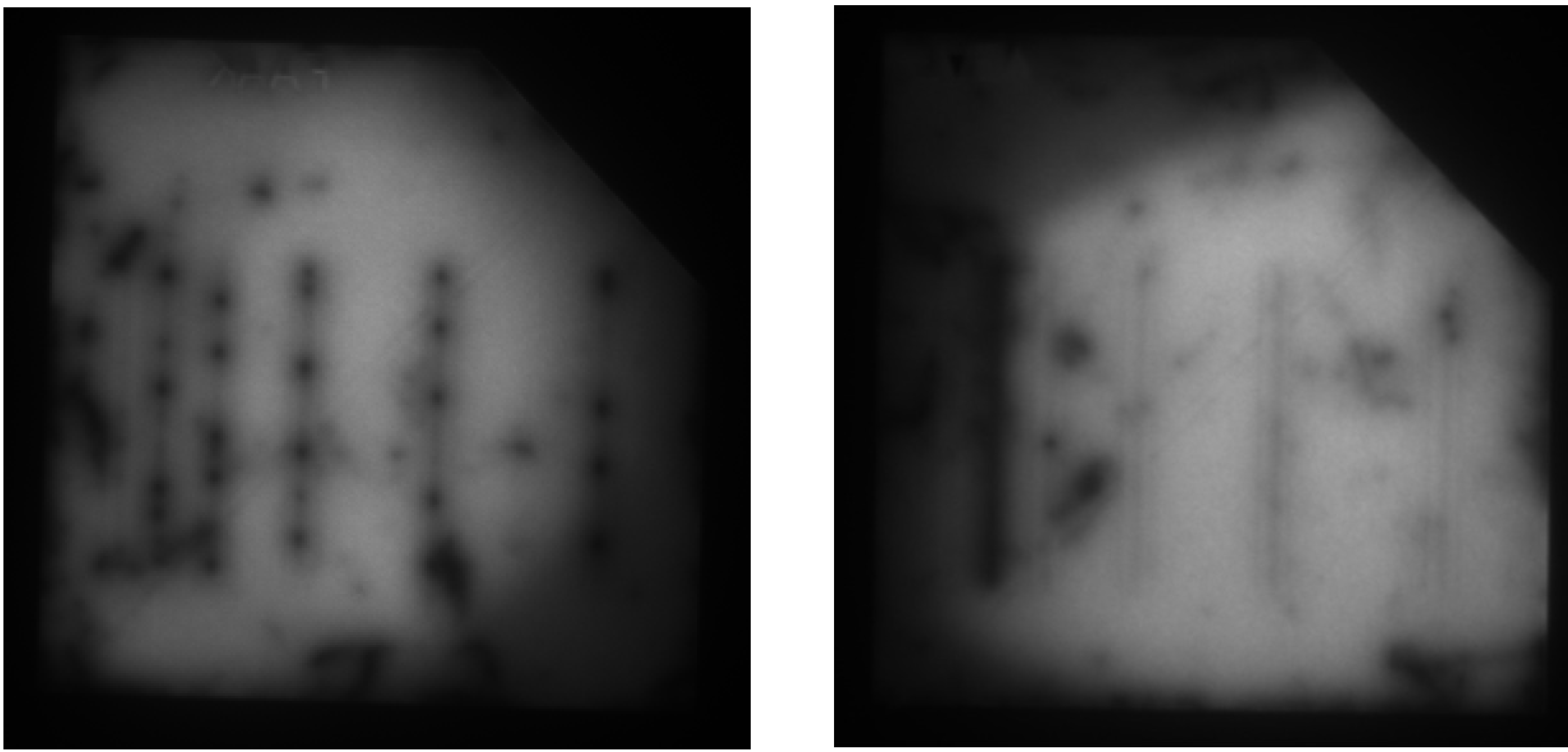


Selective tunnelling contacts on TLM structure



Discovery of self aligned breakdown

Darks spots show localised breakdown points.
Lifetime reduced for increasing current – gets ‘darker’

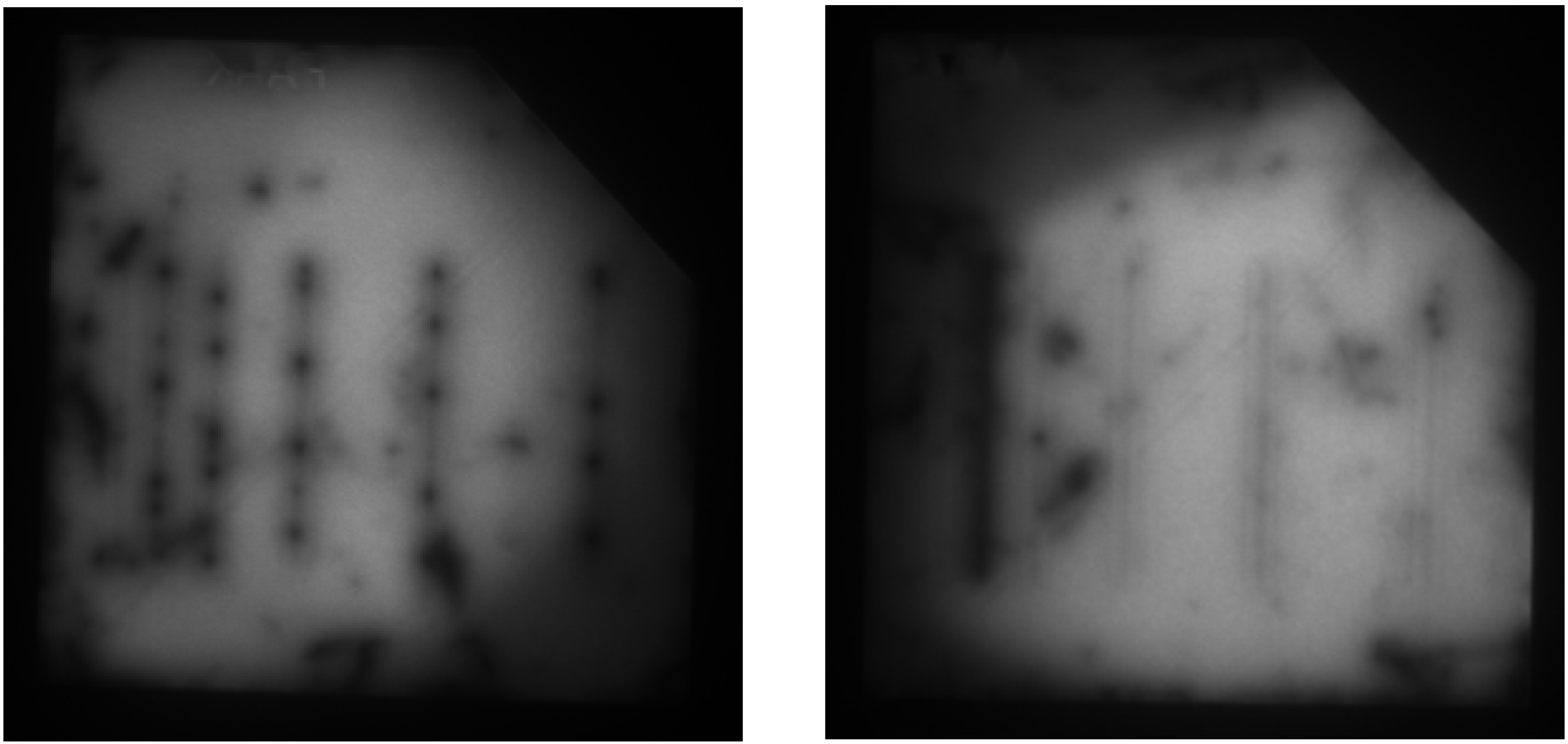


Photoluminescence images of TLM structure after IV measurement

Discovery of self aligned breakdown

Darks spots show localised breakdown points.
Lifetime reduced for increasing current – gets ‘darker’

Photoluminescence imaging = PhD!



Photoluminescence images of TLM structure after IV measurement

Trupke, T., et al. Applied Physics Letters 89.4 (2006): 044107-044107.

Point-contacting by Localised Dielectric Breakdown (PLDB)

- Low contact resistance < 1 mΩ.cm^2
- High effective lifetime > 700mV
- Processed at room temperature
- Fast
- Low tech
- Robust

Point-contacting by Localised Dielectric Breakdown (PLDB)

- Low contact resistance < 1 mΩ.cm^2
- High effective lifetime > 700mV
- Processed at room temperature
- Fast
- Low tech
- Robust

Punjab Livestock Development Board

Point-contacting by Localised Dielectric Breakdown (PLDB)

- Low contact resistance < 1 mΩ.cm^2
- High effective lifetime > 700mV
- Processed at room temperature
- Fast
- Low tech
- Robust

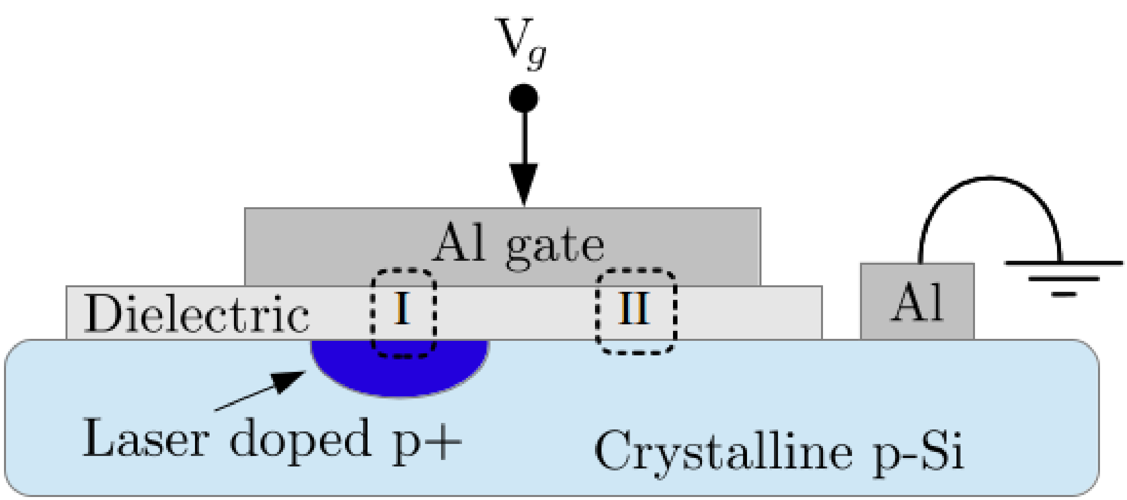
Punjab Livestock Development Board

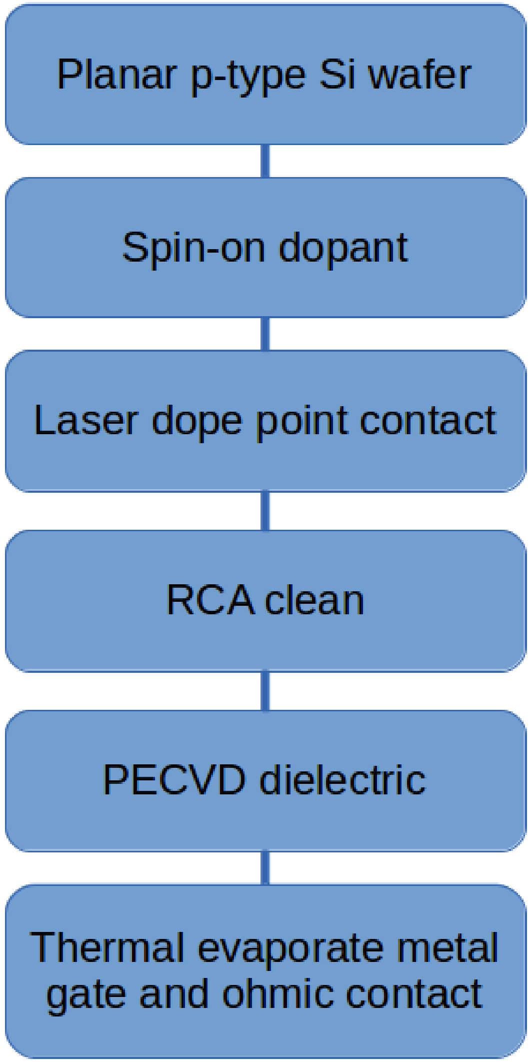
Device fabrication

- Single point contact measurement device imbedded in a MIS structure
- Dielectric deposition after laser doping preserves surface passivation

Region I: only over high doped point contact ~20x50um
Region II: everything else 1x1mm

Control samples omit laser doping step ie: no Region I





Outline

Motivation
Discovery
Device fab method
Basic results
- DIV
- TEM
- MS pics

Why self aligned
- dielectric leakage

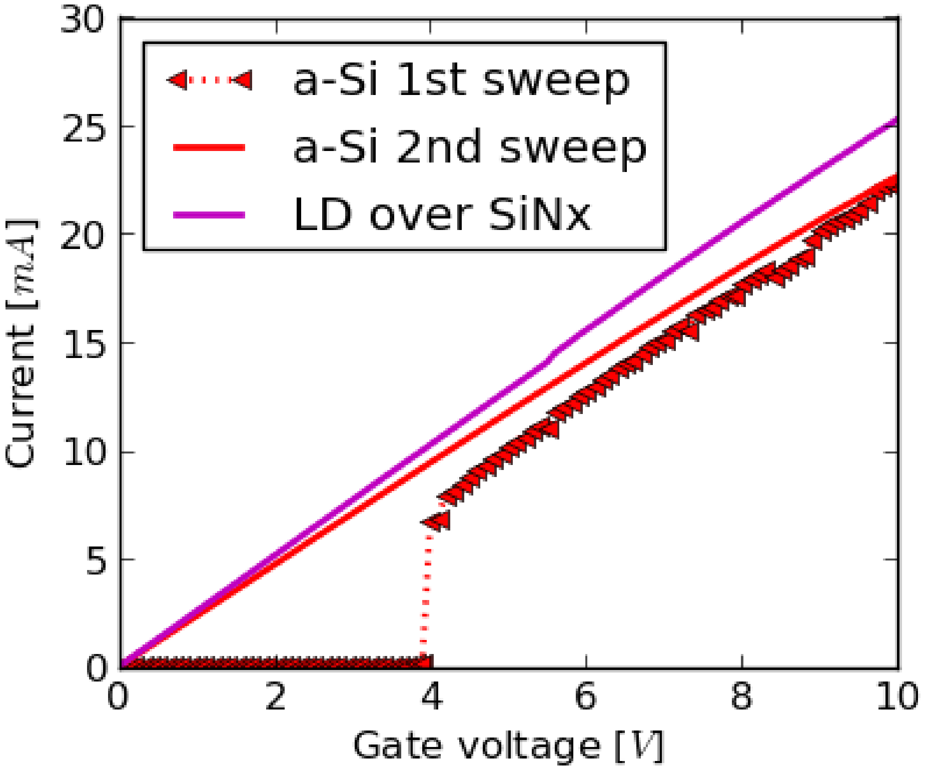
Other applications
- Other gate metals
- Al BSF
- Other dielectrics
- n-type
- With emitter

Accurate measurement of R_c and S_{eff}
- p+ on n-type
- Array of point-contacts

Breakdown dynamics
- Weibull distribution
- Thickness dependence

Typical IV results

- Sweep voltage from 0V
- Abrupt breakdown in dielectric seen as decrease in resistance
- Stable linear behaviour
- LD on SiN_x shows similar contact resistance compared to breakdown down technique

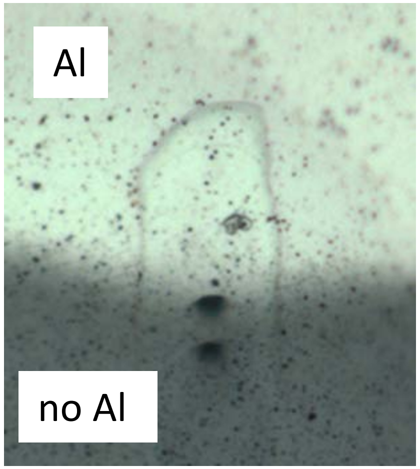


TEM - Transmission Electron Microscopy

- Difficult to determine what change was occurring in the a-Si

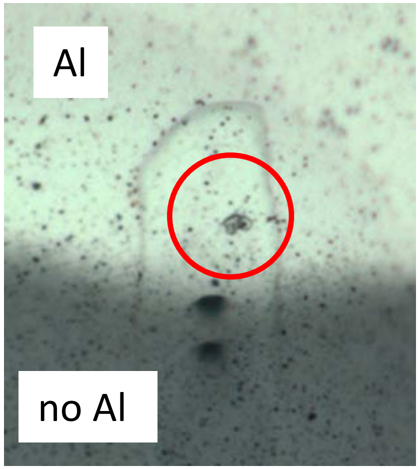
TEM - Transmission Electron Microscopy

- Difficult to determine what change was occurring in the a-Si



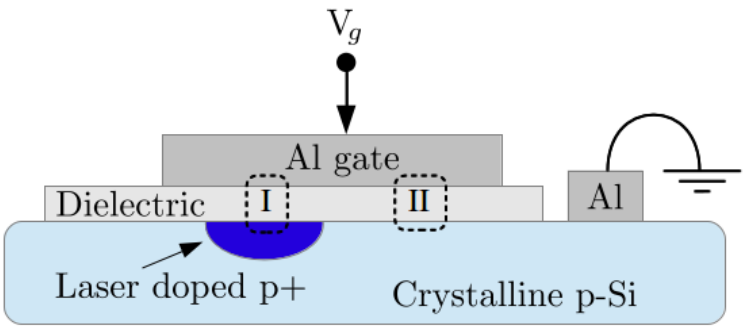
TEM - Transmission Electron Microscopy

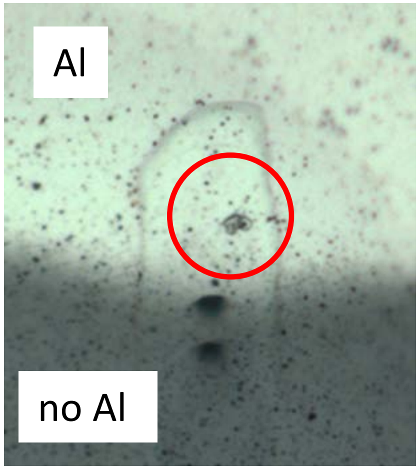
- Difficult to determine what change was occurring in the a-Si
- Surface deformation for thin metal layer, allows location of breakdown point

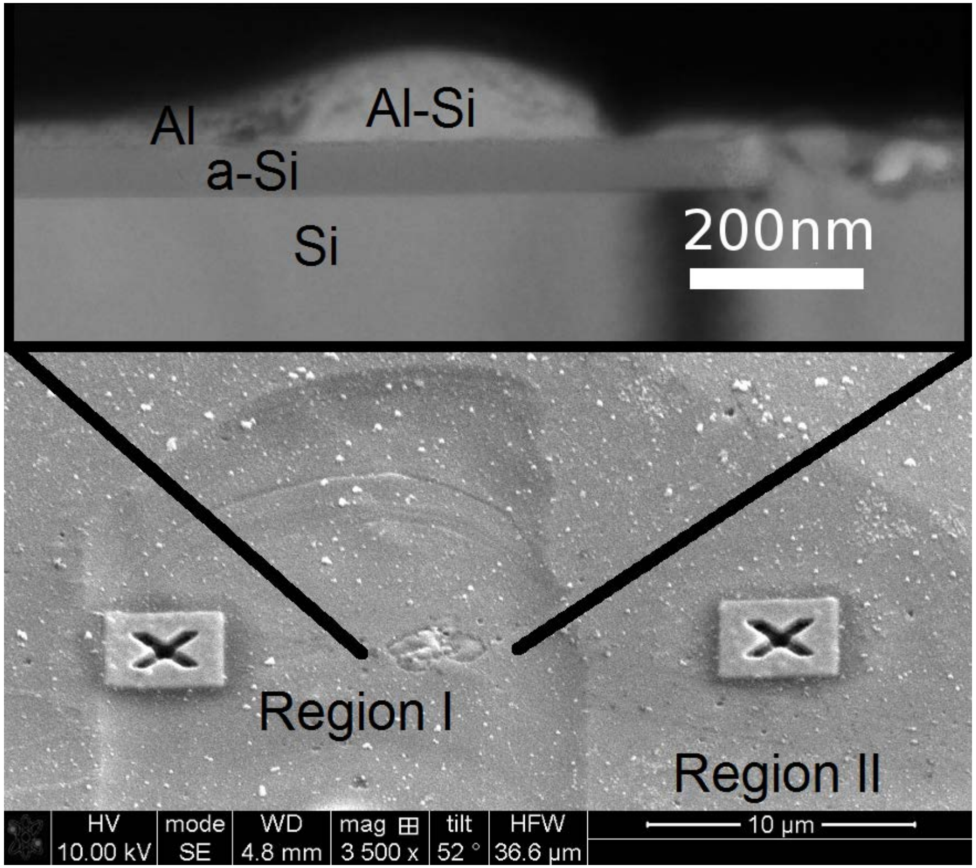


TEM - Transmission Electron Microscopy

- Difficult to determine what change was occurring in the a-Si
- Surface deformation for thin metal layer, allows location of breakdown point
- TEM confirms damage to a-Si and Al-Si eutectic



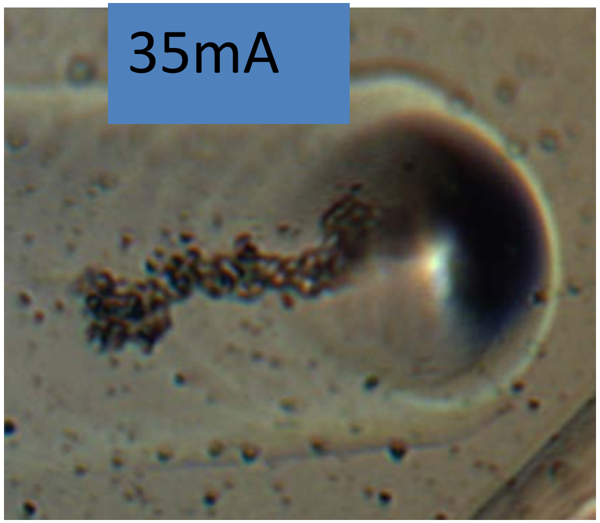


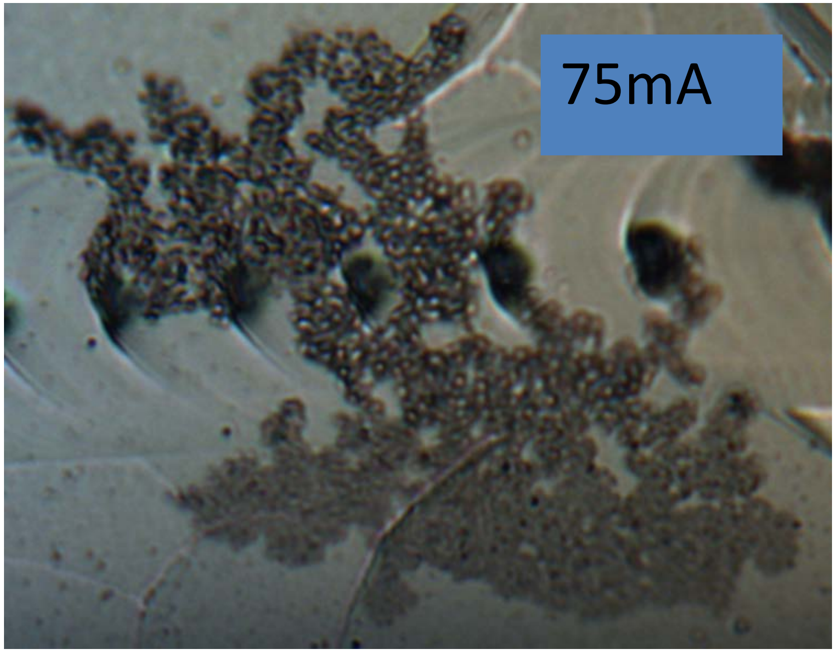


Western, Ned J., et al. Applied Physics Letters 102 (2013): 222105.

Optical Microscopy

- Thin Al allows for convenient characterisation
- Size of breakdown area increases with increasing current
- Can exceed Region I if current too high
- Damage to adjacent surface passivation





Outline

Motivation
Discovery
Device fab method
Basic results
- DIV
- TEM
- MS pics

Why self aligned
- dielectric leakage

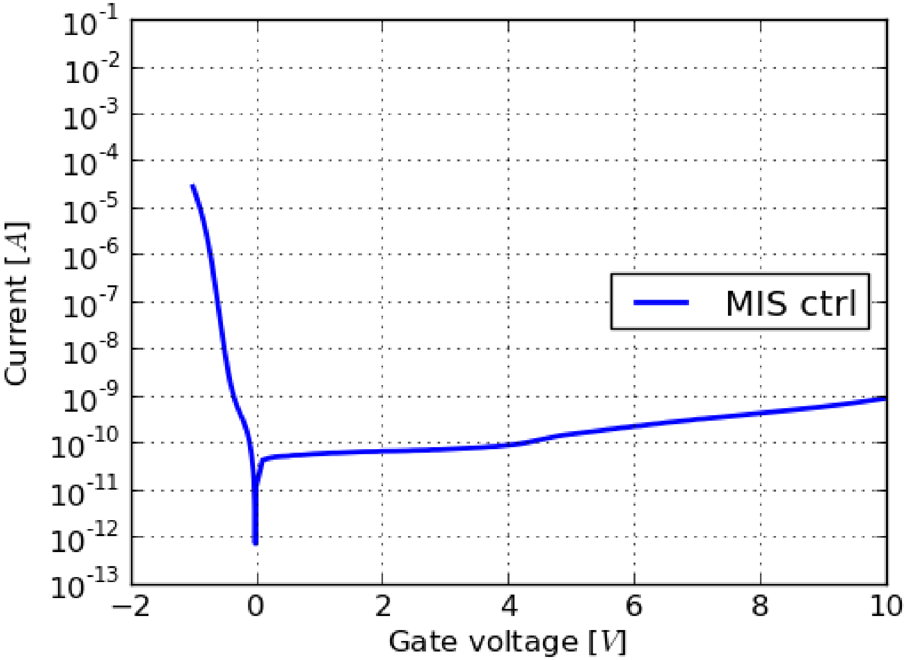
Other applications
- Other gate metals
- Al BSF
- Other dielectrics
- n-type
- With emitter

Accurate measurement of R_c and S_{eff}
- p+ on n-type
- Array of point-contacts

Breakdown dynamics
- Weibull distribution
- Thickness dependence

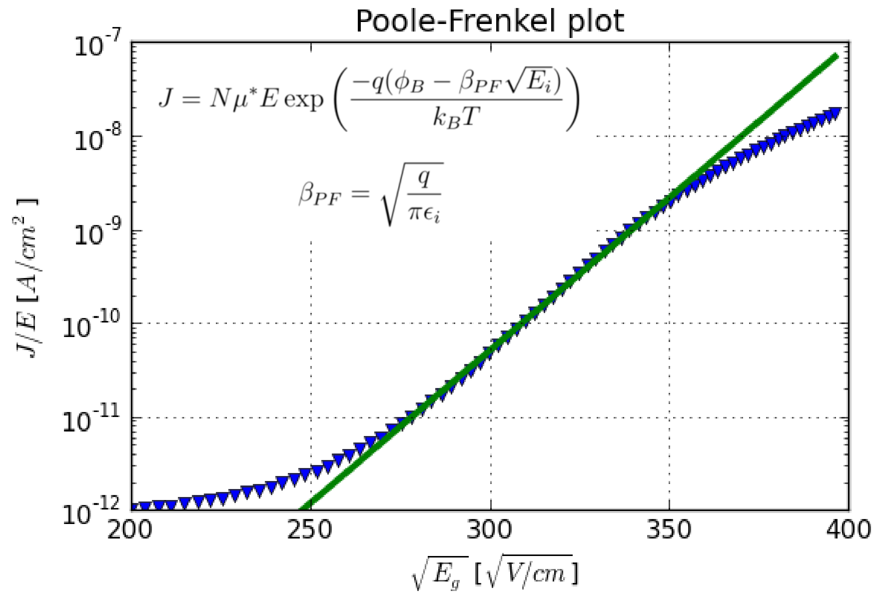
Typical IV results of control MIS devices

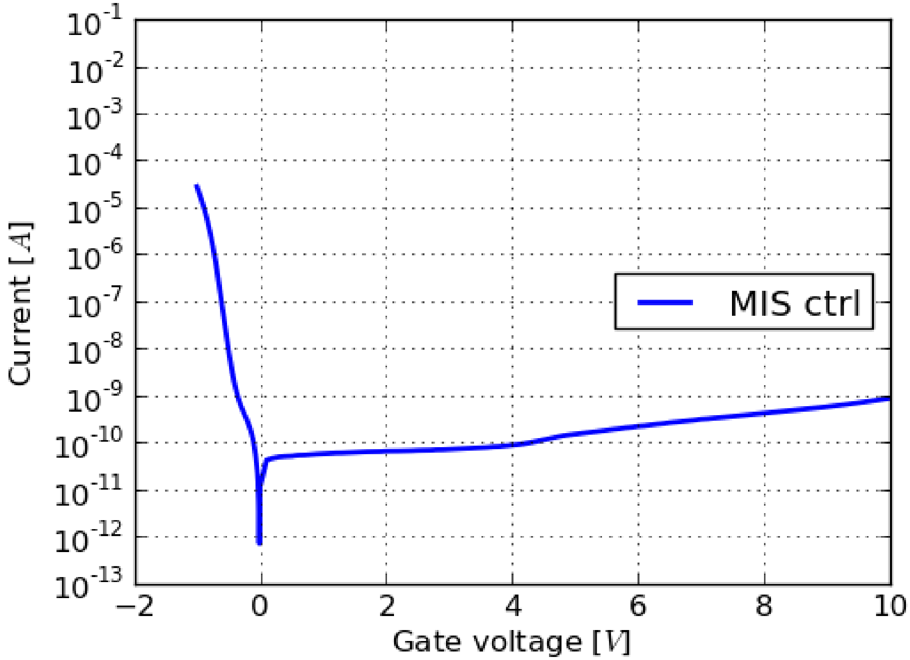
- IV curve of MIS like a reversed diode



Typical IV results of control MIS devices

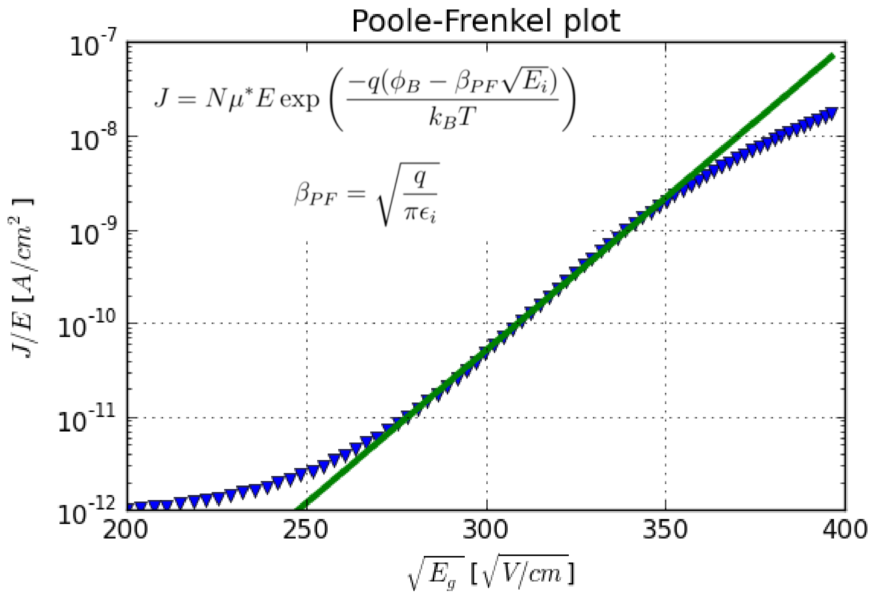
- IV curve of MIS like a reversed diode
- Why is there current for –ve voltage?
    - PF tunnelling

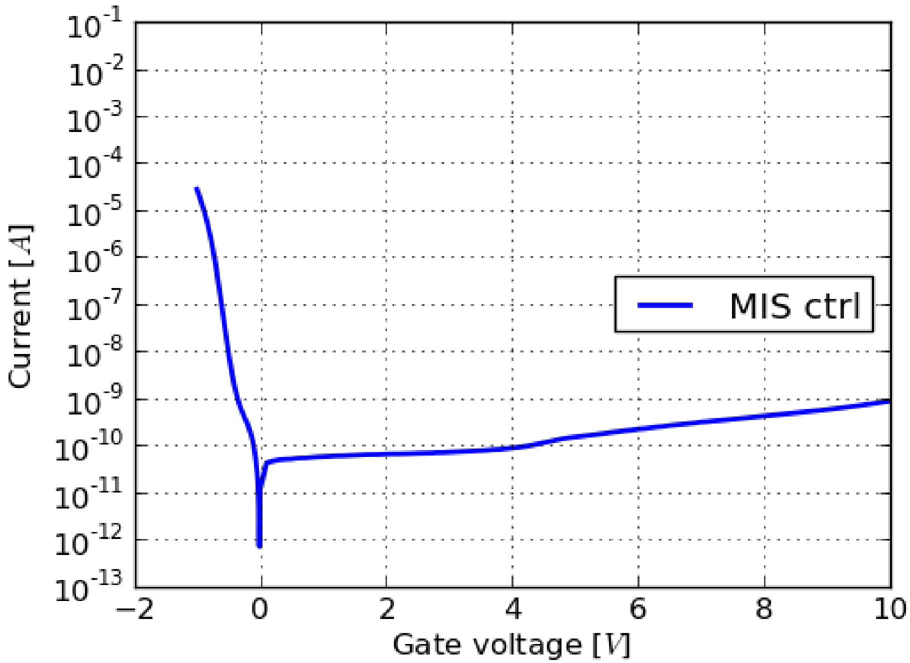




Typical IV results of control MIS devices

- IV curve of MIS like a reversed diode
- Why is there current for –ve voltage?
  - PF tunnelling
- Why is there less current for +ve voltage?
  - Thermal generation in depletion region





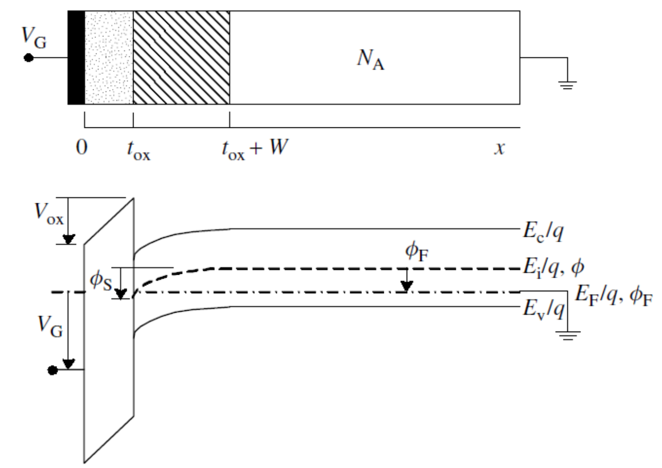
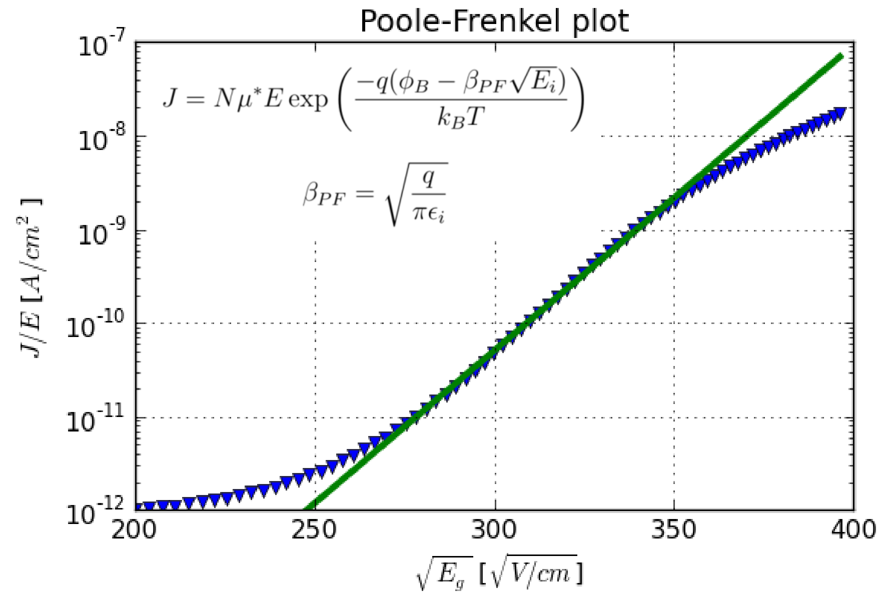
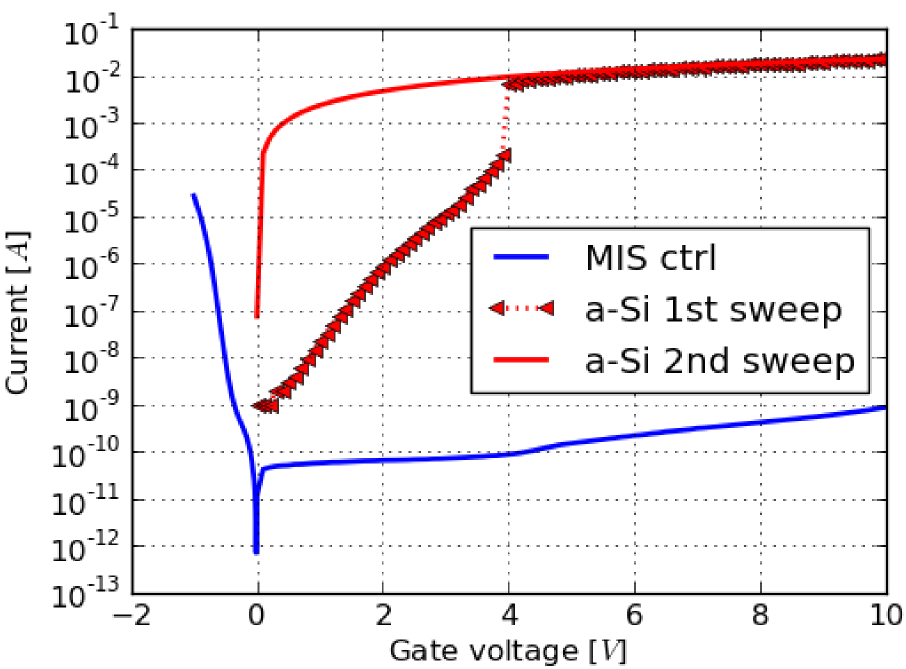


Fig. 6.3 Cross-section and potential band diagram of an MOS capacitor.

Typical IV results of control MIS devices

- IV curve of MIS like a reversed diode
- Why is there current for –ve voltage?
  - PF tunnelling
- Why is there less current for +ve voltage?
  - Thermal generation in depletion region
- Why is there high current through Region I?
  - High current density, high stress
  - Leads to breakdown in Region I





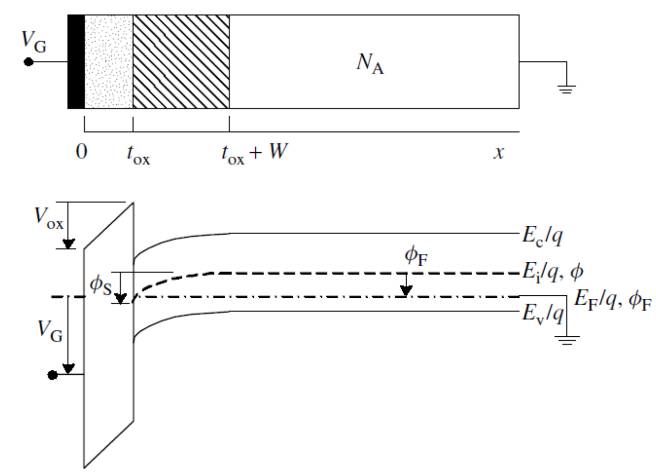


Fig. 6.3 Cross-section and potential band diagram of an MOS capacitor.

Outline

Motivation
Discovery
Device fab method
Basic results
- DIV
- TEM
- MS pics

Why self aligned
- dielectric leakage

Other applications
- Other gate metals
- Al BSF
- Other dielectrics
- n-type
- With emitter

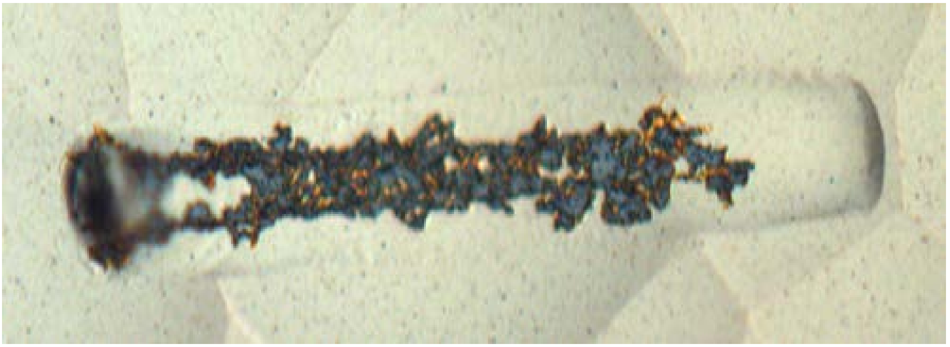
Accurate measurement of R_c and S_{eff}
- p+ on n-type
- Array of point-contacts

Breakdown dynamics
- Weibull distribution
- Thickness dependence

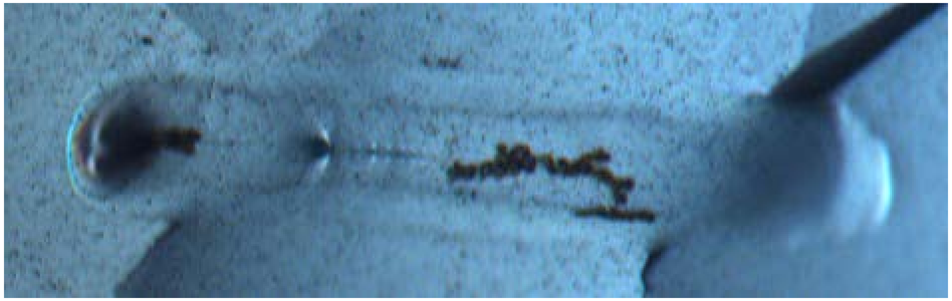
Different gate metals

	Eutectic T with Si
Au	377'C
Al	577'C
Ti	1330'C

- a-Si very reactive with Al
- Metal induced crystallisation occurs at 70% of eutectic temp Herd *et al.*
- Electric field increases reactivity Jang *et al.*
- Repeat with Au and Ti
- If sensitive to gate metal, the breakdown process should change with gate metal type
- Shows a robust process, works with different gate metals



20nm Au



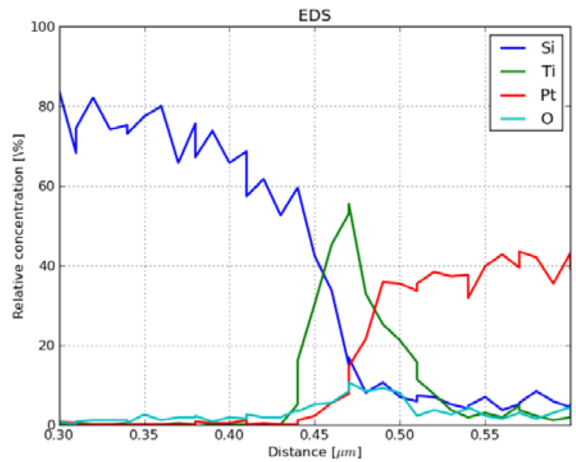
25nm Ti

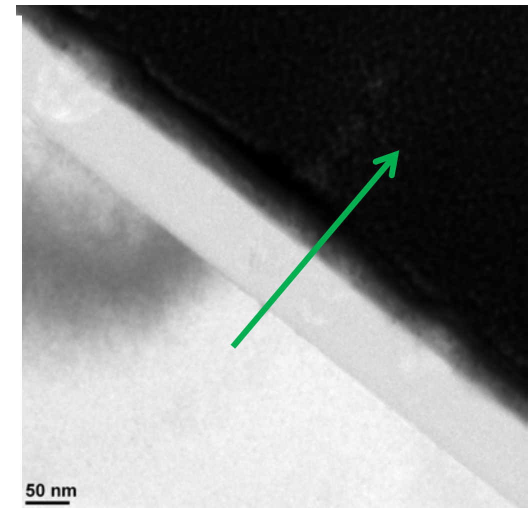
Herd, S. R., P. Chaudhari, and M_H Brodsky. Journal of Non-Crystalline Solids 7.4 (1972): 309-327.
J Jang et al. “Electric-field-enhanced crystallization of amorphous silicon”. In: Nature 395.6701 (1998), pp. 481–483.

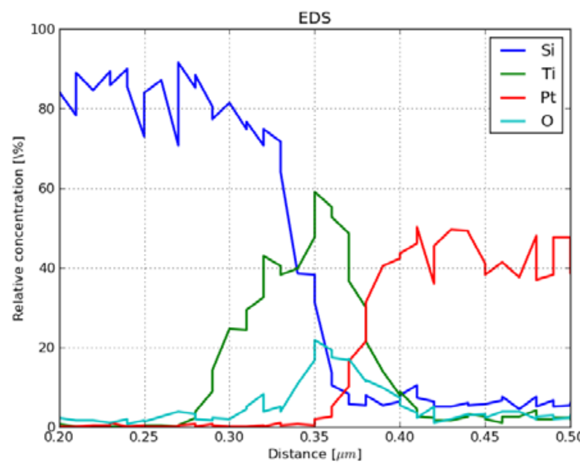
TEM and EDS - Energy Dispersive X-ray Spectroscopy

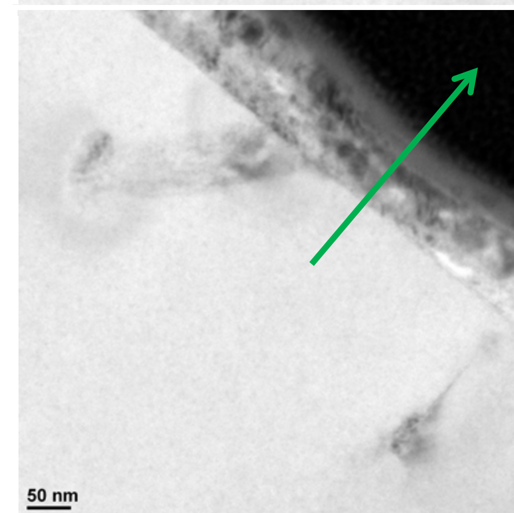
Breakdown process demonstrated with high eutectic gate metal

- TEM of breakdown site with 25nm Ti
- EDS shows Diffusion of Ti gate into a-Si
- Confirms high temperatures reached > 1330’C









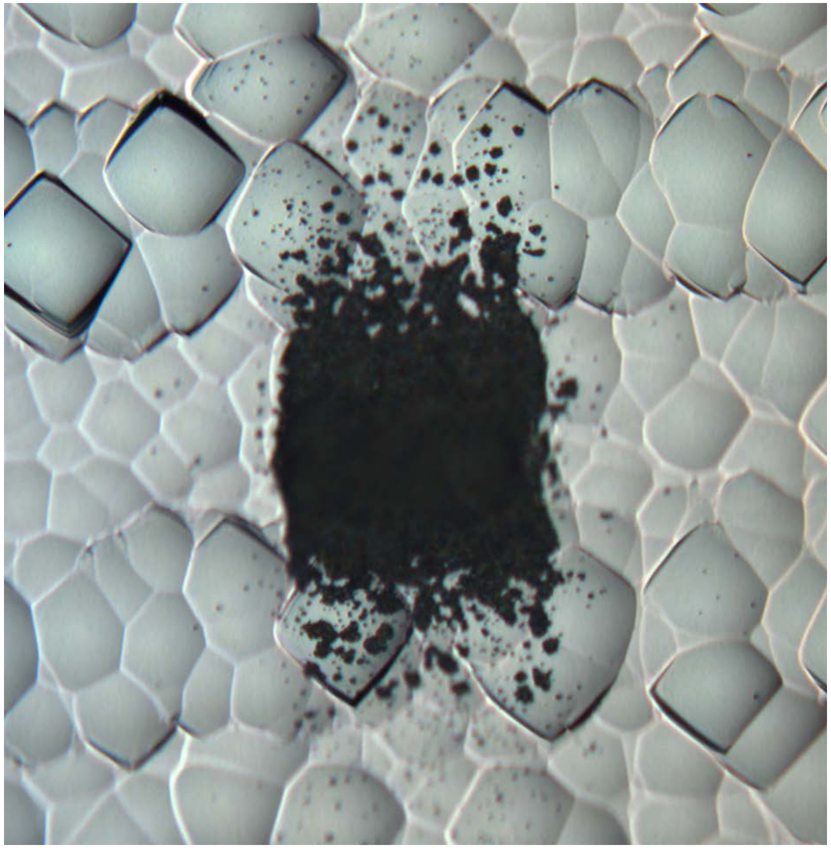
Al doped BSF

Not limited to boron doping

Processing steps:

- Injet printed Al paste lines through Si mask to create point contact.
- Belt furnace fired to create Al BSF
- Wet chemistry removal of residual Al paste
- Processed as for laser doped samples

IV results show dielectric breakdown occurs in same way



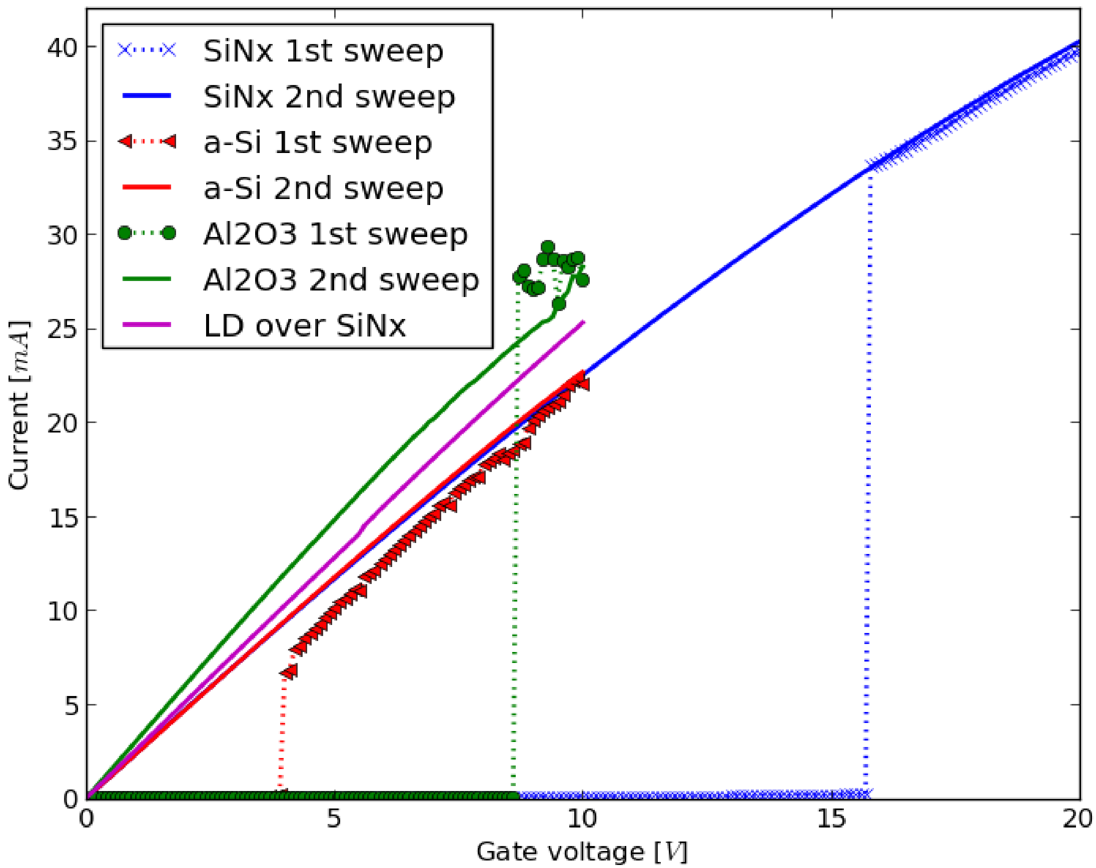
Microscope image of injet printed Al paste on planar p-type Si

Different dielectrics

So far demonstrated with:

- a-Si
- Si rich SiN_x
- Stoichiometric SiN_x
- ALD Al_2O_3

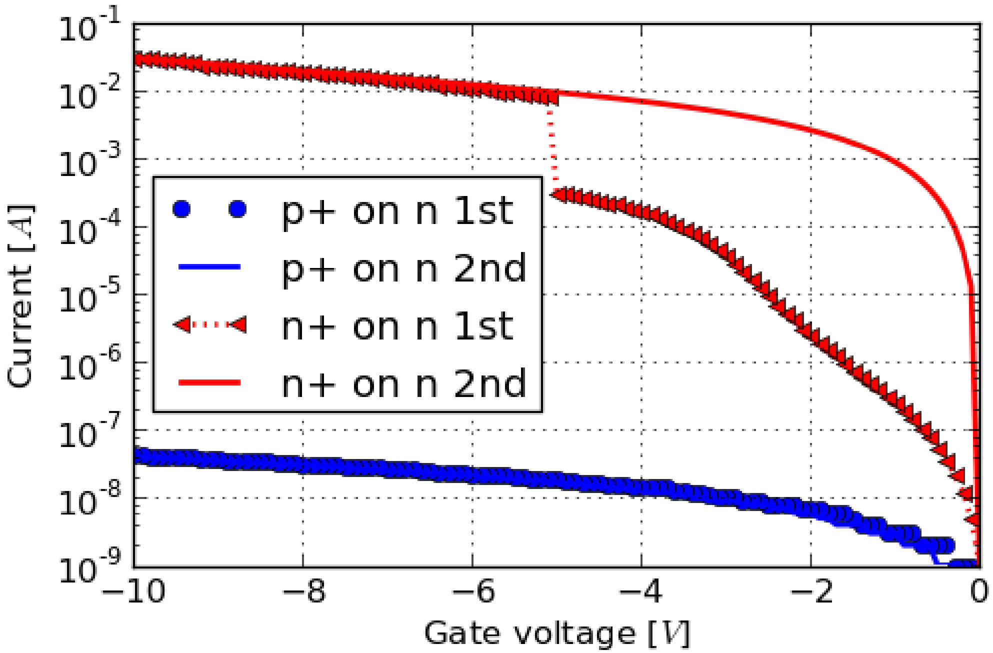
Different films breakdown at different voltages -why?



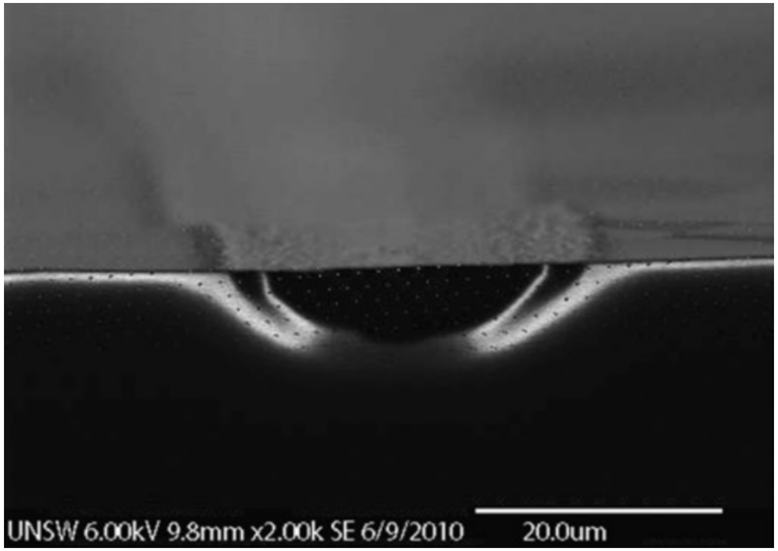
Different polarities

bulk\ LD	p+	n+
p-type	y	n
n-type	n	y

Also works with n-type with appropriate change in bias polarity but not for a change in type. Assumed to be due to reverse bias of p-n junction limiting current



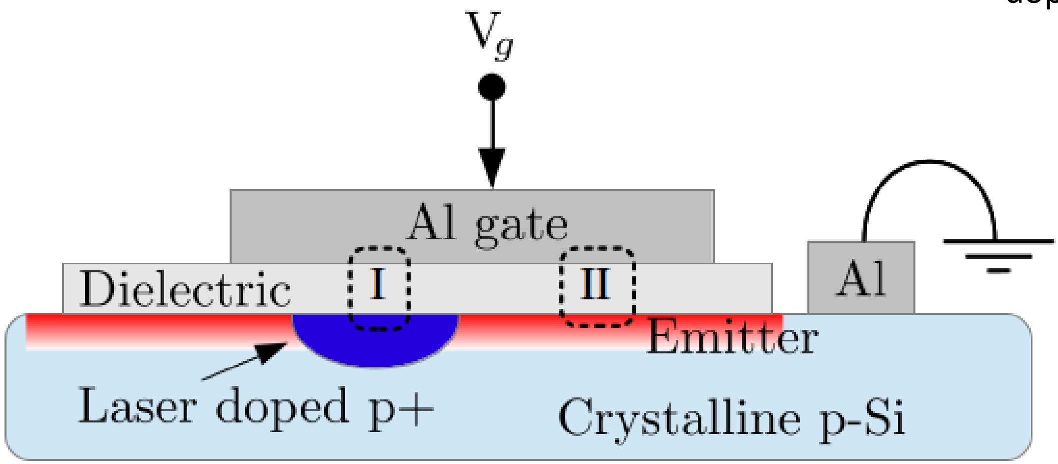
Phosphorous diffusion



Electron Beam Induced Current (EBIC) of laser doping through an n-type emitter

Laser doping through an n-type emitter is possible due to depth of LD junction.
Applications to:

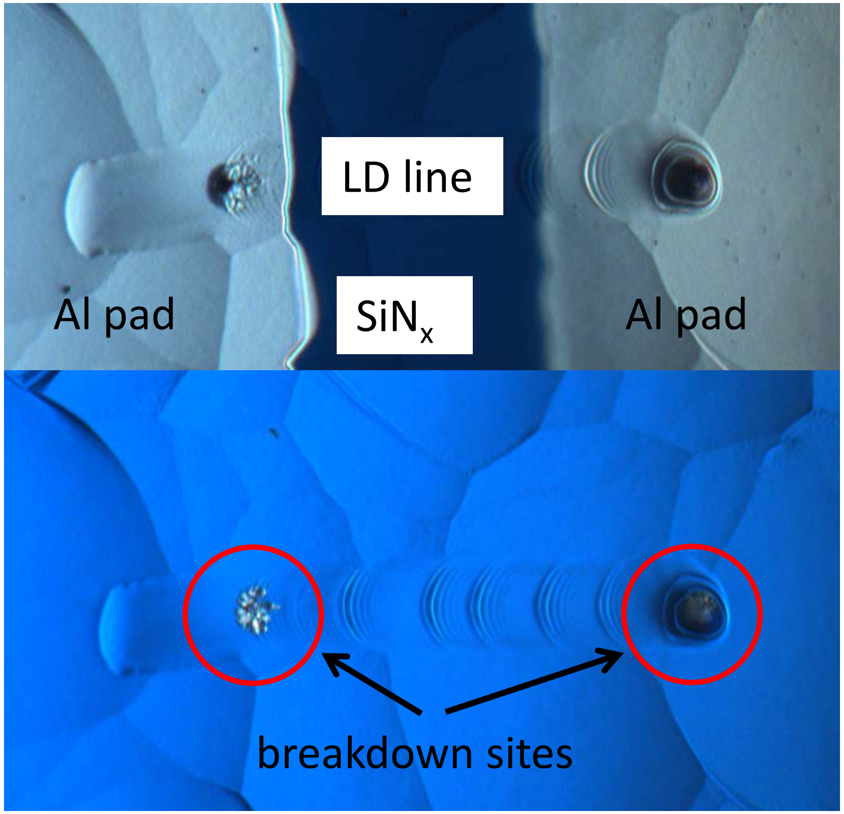
- Floating junction surface passivation
- Interdigitated back contact without a patterned emitter



Change in type

Contact possible for change in doping type:

- p+ laser doping on n-type wafer
- Two contacts to same LD line
- Breakdown still restricted to Region I!
- Current limited along line
- Provides method for measuring contact resistance using TLM



Outline

Motivation
Discovery
Device fab method
Basic results

- DIV
- TEM
- MS pics

Why self aligned

- dielectric leakage

Other applications

- Other gate metals
- Al BSF
- Other dielectrics
- n-type
- With emitter

Accurate measurement of R_c and S_{eff}

- p+ on n-type
- Array of point-contacts

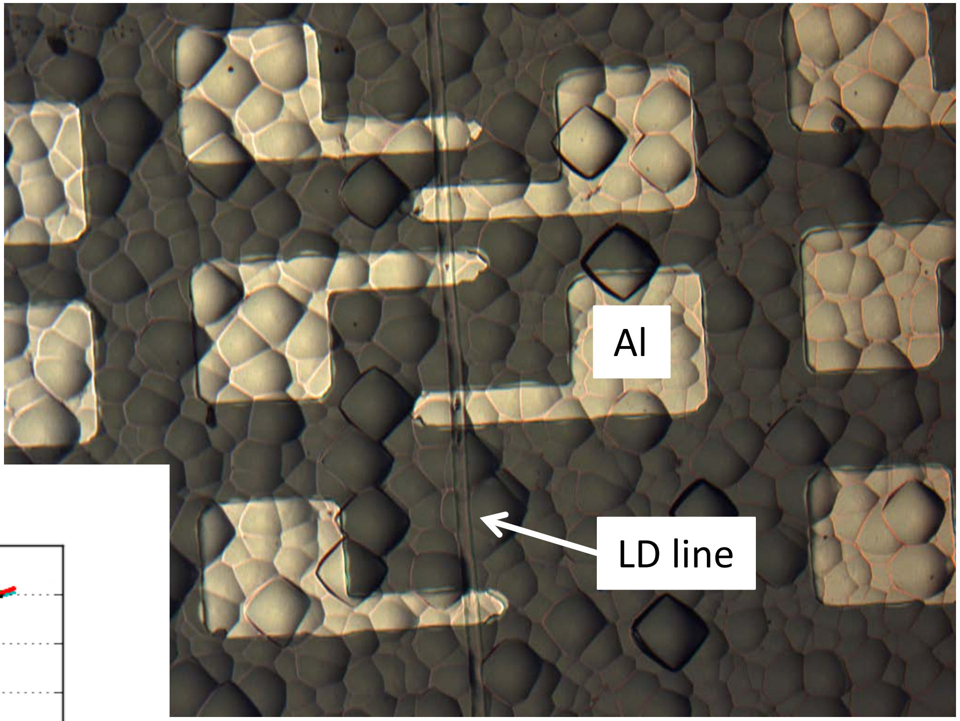
Breakdown dynamics

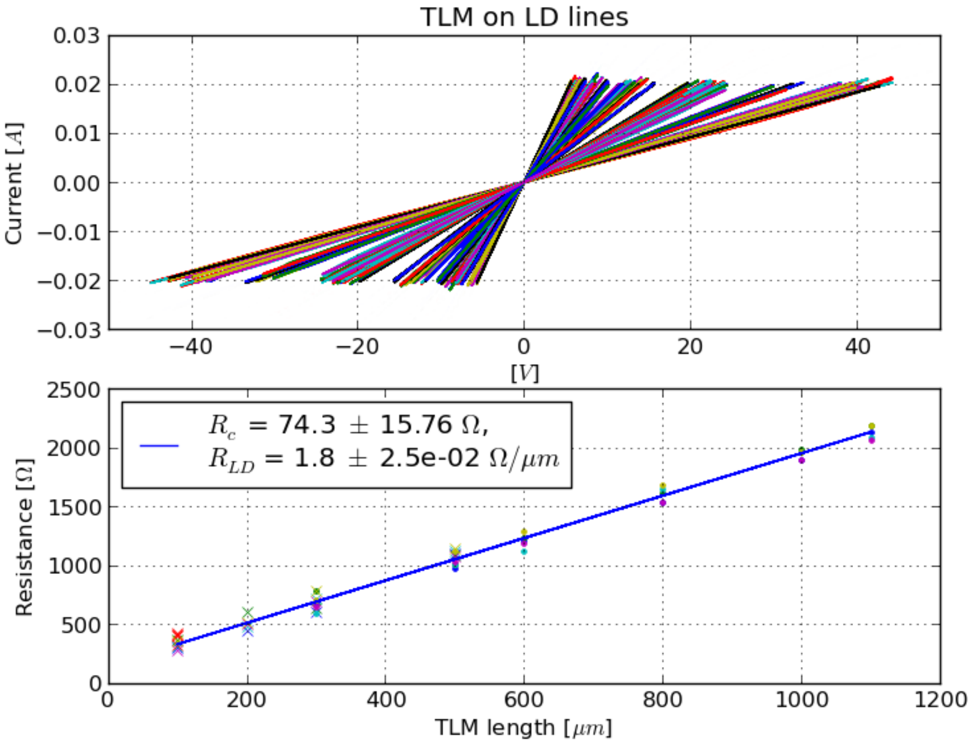
- Weibull distribution
- Thickness dependence

TLM – transmission line method

Multiple contacts to a single line in TLM structure.

Also allows for accurate measurement of LD line conductivity!



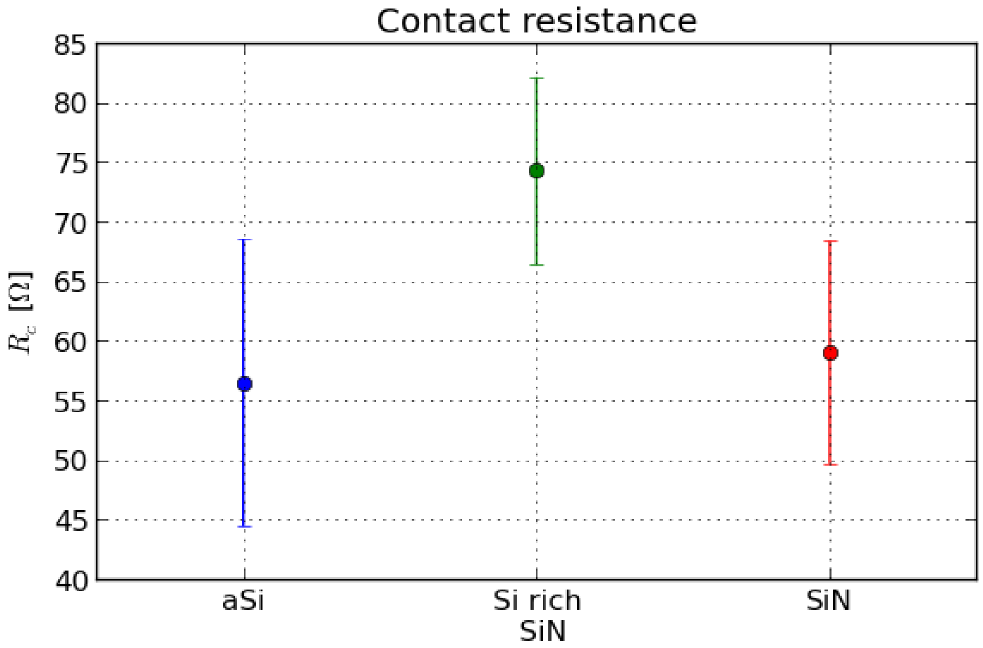


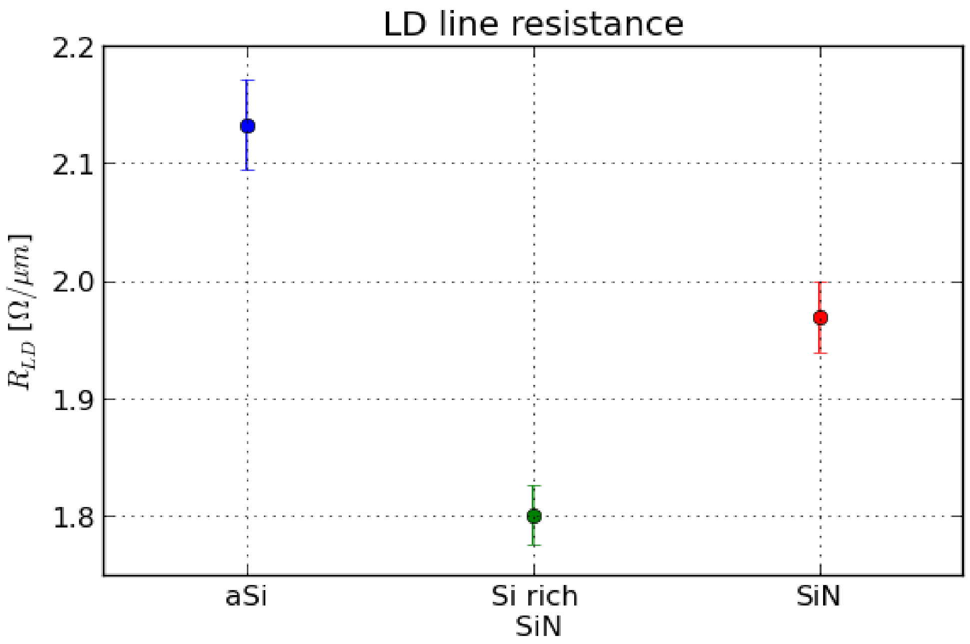
Contact resistance
Comparing dielectrics

~ 1 order lower contact resistivity compared to screen printed contacts.

< 1 mΩ.cm² for area estimate

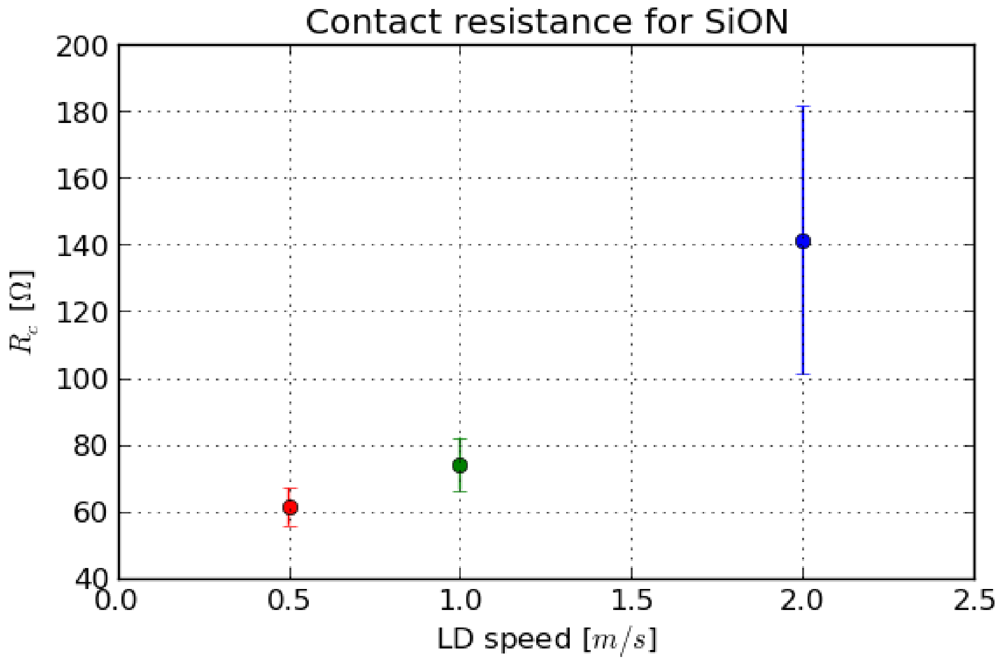
Comparable results between dielectrics, robust process.

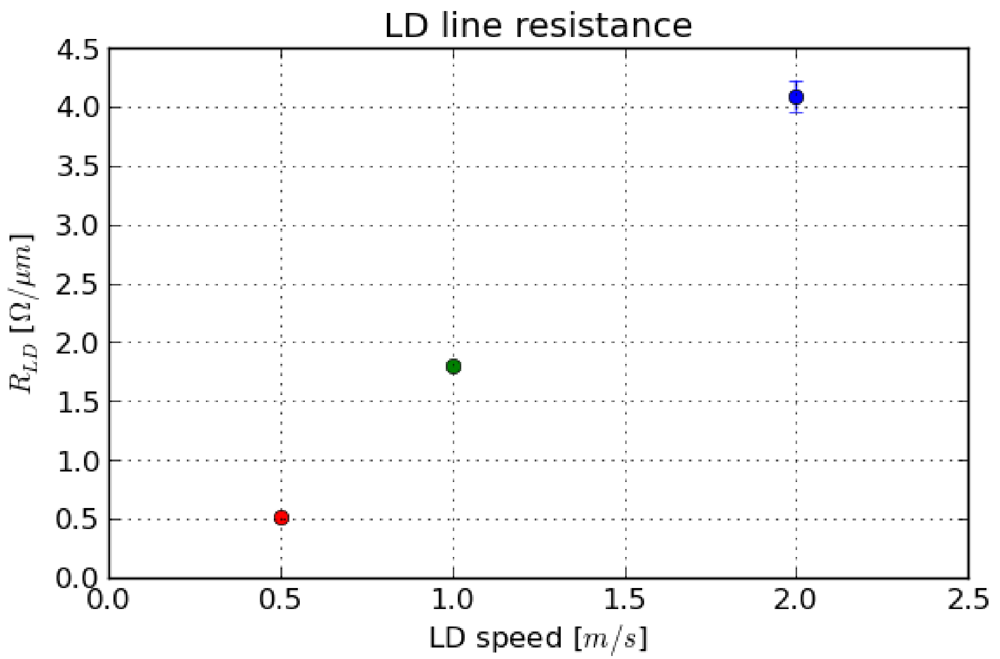




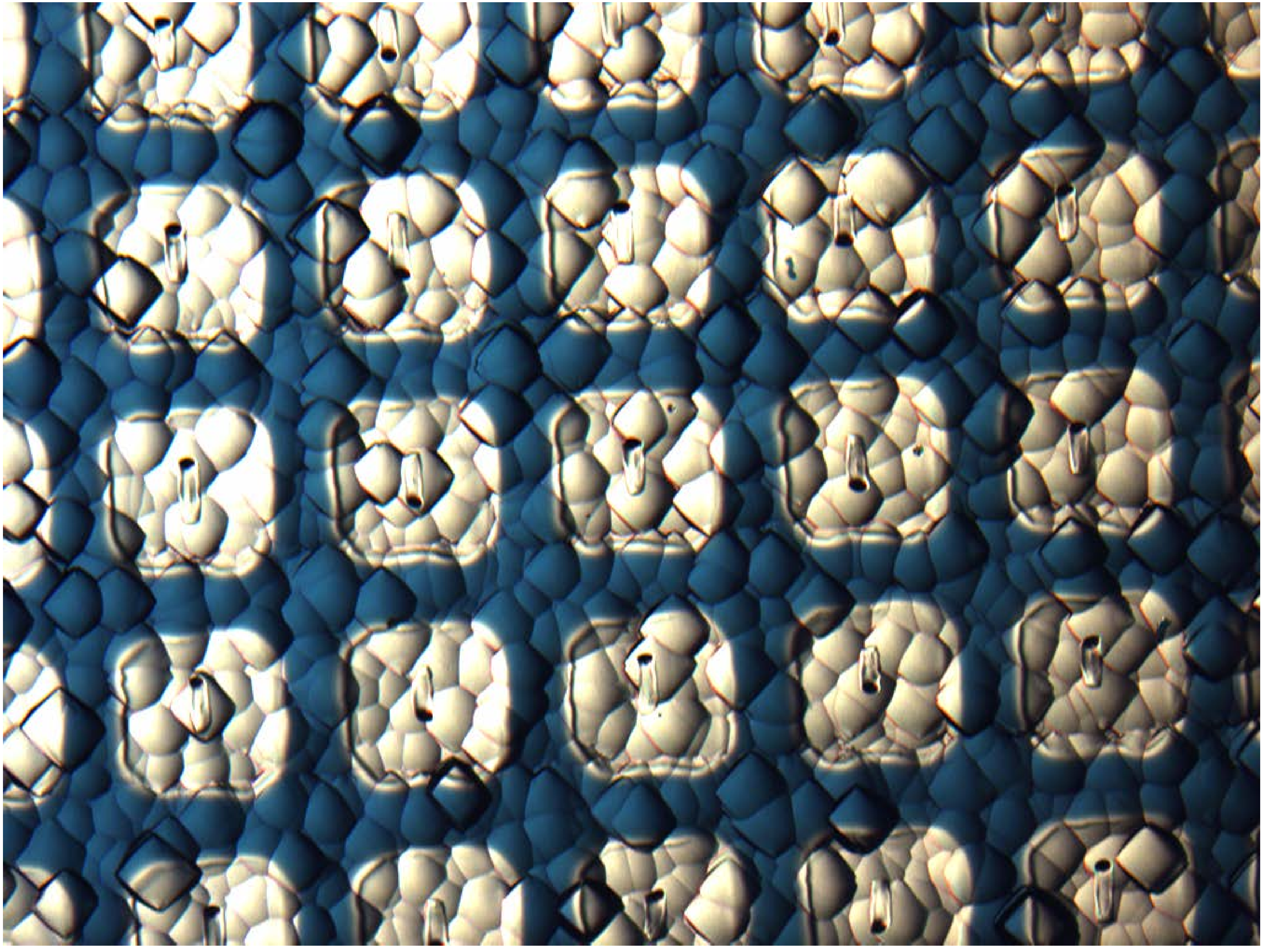
Contact resistance
Comparing LD speed

Increase in R_c and LD line resistance for faster speeds – lower doping concentration



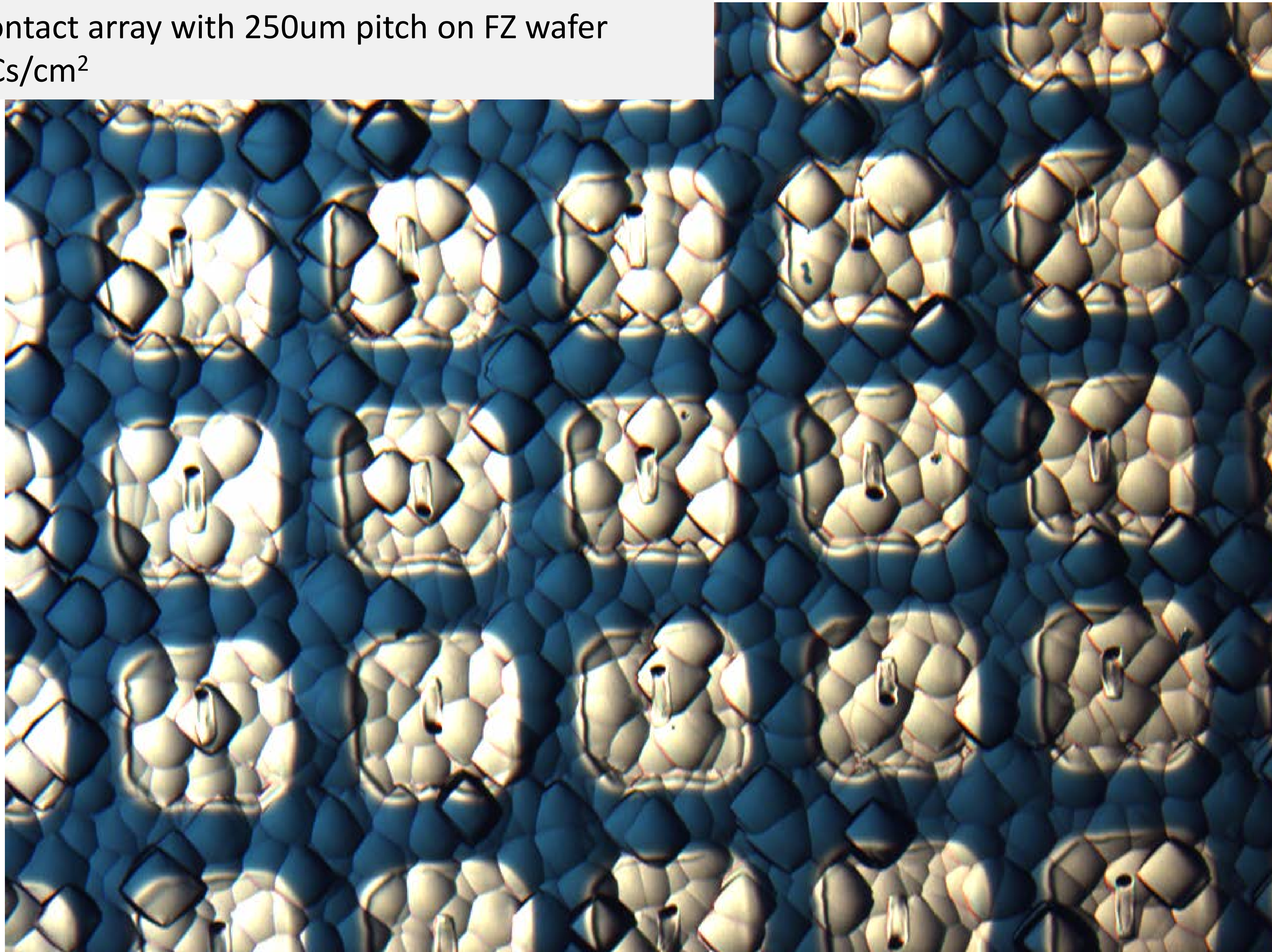


Surface passivation



Surface passivation

Point contact array with 250um pitch on FZ wafer
1600 PCs/cm^2

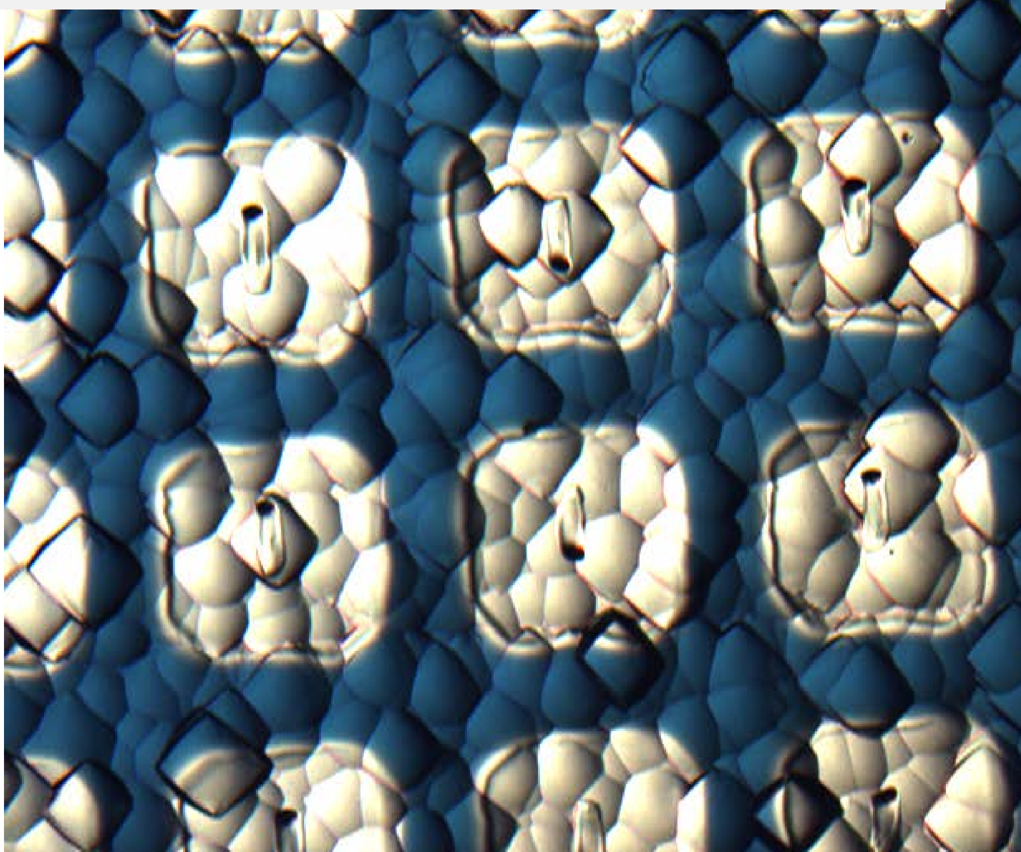


Surface passivation

Point contact array with 250um pitch on FZ wafer
1600 PCs/cm^2

Breakdown 2 columns of contacts, no change in tau$_{eff}$
tau$_{eff}$ = 300us, iV$_{oc}$ ~= 700mV, S$_{eff}$ < 50cm/s

1st try! Not optimised yet.



Outline

Motivation
Discovery
Device fab method
Basic results
- DIV
- TEM
- MS pics

Why self aligned
- dielectric leakage

Other applications
- Other gate metals
- Al BSF
- Other dielectrics
- n-type
- With emitter

Accurate measurement of R_c and S_{eff}
- p+ on n-type
- Array of point-contacts

Breakdown dynamics
- Weibull distribution
- Thickness dependence

Percolation model

Percolation model well established in IC industry describing breakdown distribution for thin gate dielectrics.

- We know current through dielectric limited by PF tunnelling
- Total charge passed linked to breakdown of 'thick' PECVD dielectrics – Allers *et al.*
- Breakdown distribution determined by Weibull function:

$$F(x) = 1 - \exp\left((x/\alpha)^{\beta}\right)$$

J. Appl. Phys., Vol. 90, No. 5, 1 September 2001

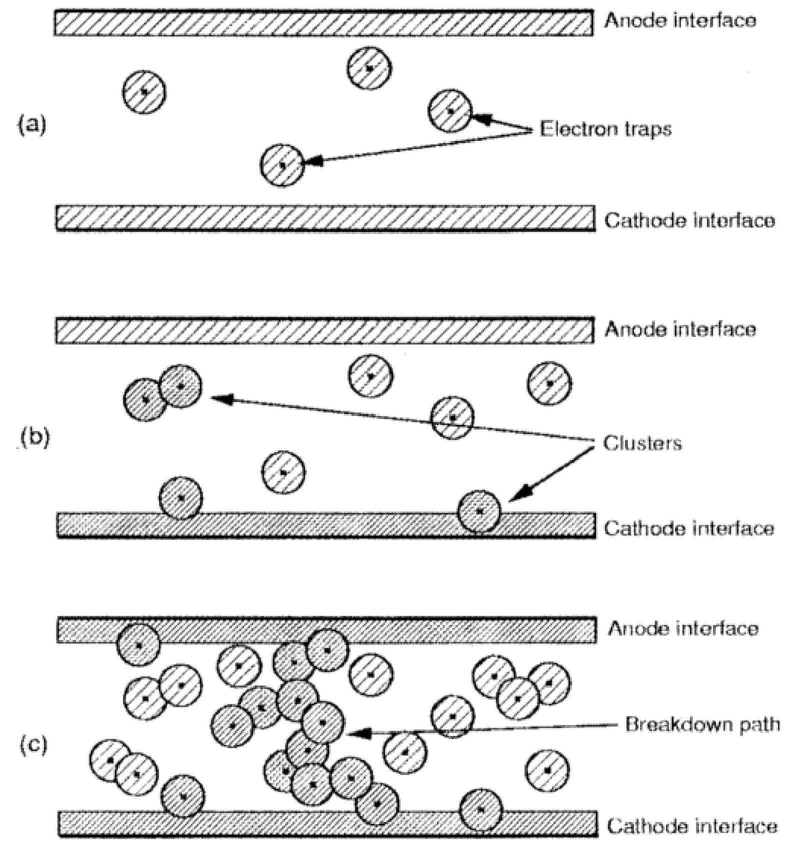
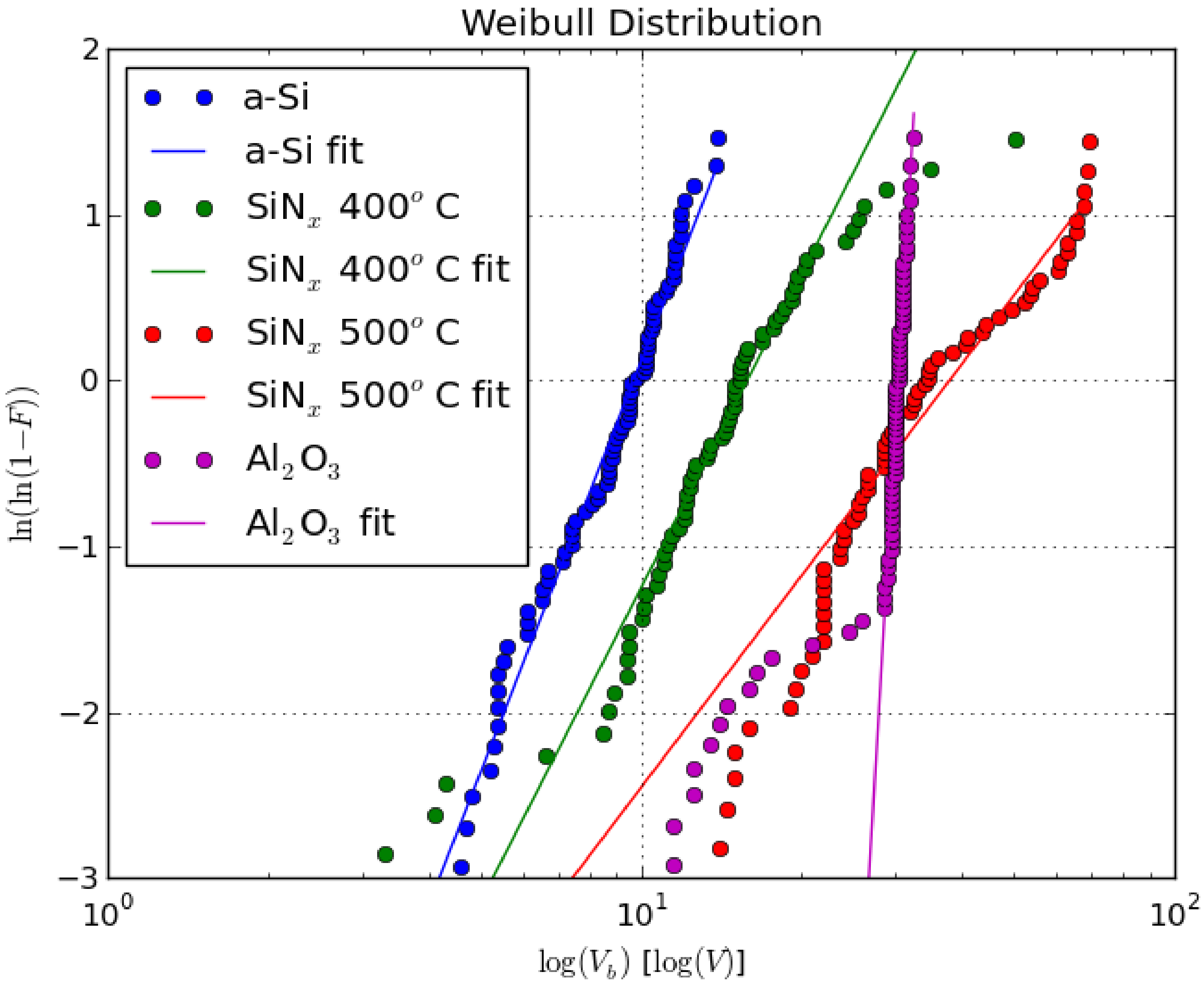


FIG. 61. Various steps of the percolation model for oxide breakdown. As the density of neutral electron traps increases, conductive clusters of traps are formed, ultimately leading to the creation of a conductive breakdown path from anode to cathode [from Degraeve *et al.* (Ref. 3)].

Green, M. L., et al. Journal of Applied Physics 90.5 (2001): 2057-2121.
Allers, K-H. Microelectronics Reliability 44.3 (2004): 411-423.

Weibull distribution

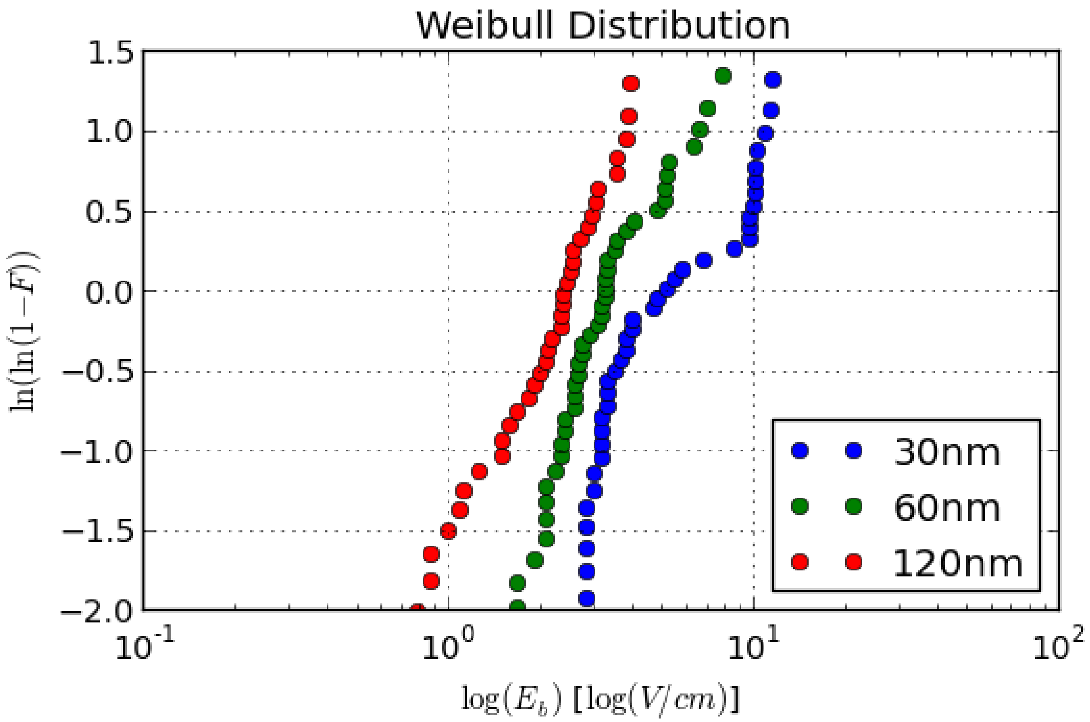
Breakdown voltage extracted from each IV sweep, then added to 'Weibull plot'.
Fit to function, can extract Weibull parameter β



Weibull distribution

Dielectric thickness dependence:

- Same dielectric, different thickness
- Average E_{BD} not constant



There may be a way to predict Weibull distribution parameters from PF parameters, but there are hurdles:

- Thickness dependence
- Poole-Frenkel model
- Uniformity of laser doping
- Uniformity of dielectric

Is this even useful?

Future Work

- Link leakage current to breakdown characteristics (maybe)
- Optimise for S_{eff} and R_c
- Apply to a rear surface of high efficiency solar cell
- Transfer to industry
- Apply to IBC cell
- Apply to high performance mc-Si
- Get working for front surface selective emitter structure

Acknowledgements

- The authors acknowledge the facilities, and the scientific and technical assistance of the Australian Microscopy & Microanalysis Research Facility at the Electron Microscope Unit, The University of New South Wales.
- This work was performed in part at the NSW Node of the Australian National Fabrication Facility
- This Program has been supported by the Australian Government through the Australian Renewable Energy Agency (ARENA). Responsibility for the views, information or advice expressed herein is not accepted by the Australian Government.

ammrf Australian Microscopy & Microanalysis Research Facility

ANFF

ARENA Australian Government Australian Renewable Energy Agency

Questions?