

**Aspects of Silicon Solar Cells:
Thin-Film Cells and LPCVD Silicon Nitride**

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Declaration

This thesis is an account of research undertaken between April 1998 and July 2002 at The Centre for Sustainable Energy Systems, The Department of Engineering, Faculty of Engineering and Information Technology, The Australian National University, Canberra, Australia.

Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university.

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Abstract

This thesis discusses the growth of thin-film silicon layers suitable for solar cells using liquid phase epitaxy and the behaviour of oxide/LPCVD silicon nitride stacks on silicon in a high temperature ambient.

The work on thin film cells is focussed on the characteristics of layers grown using liquid phase epitaxy. The morphology resulting from different seeding patterns, the transfer of dislocations to the epitaxial layer and the lifetime of layers grown using oxide compared with carbonised photoresist barrier layers are discussed. The second half of this work discusses boron doping of epitaxial layers. Simultaneous layer growth and boron doping is demonstrated, and shown to produce a $35\mu\text{m}$ thick layer with a back surface field approximately $3.5\mu\text{m}$ thick.

If an oxide/nitride stack is formed in the early stages of cell processing, then characteristics of the nitride may enable increased processing flexibility and hence the realisation of novel cell structures. An oxide/nitride stack on silicon also behaves as a good anti-reflection coating. The effects of a nitride deposited using low pressure chemical vapour deposition on the underlying wafer are discussed. With a thin oxide layer between the silicon and the silicon nitride, deposition is shown not to significantly alter effective lifetimes.

Heating an oxide/nitride stack on silicon is shown to result in a large drop in effective lifetimes. As long as at least a thin oxide is present, it is shown that a high temperature nitrogen anneal results in a reduction in surface passivation, but does not significantly affect bulk lifetime. The reduction in surface passivation is shown to be due to a loss of hydrogen from the silicon/silicon oxide interface and is characterised by an increase in J_{oe} . Higher temperatures, thinner oxides, thinner nitrides and longer anneal times are all shown to result in high J_{oe} values. A hydrogen loss model is introduced to explain the observations.

Various methods of hydrogen re-introduction and hence J_{oe} recovery are then discussed with an emphasis on high temperature forming gas anneals. The time necessary for successful J_{oe} recovery is shown to be primarily dependent on the nitride thickness and on the temperature of the nitrogen anneal. With a high temperature forming gas anneal, J_{oe} recovery after nitrogen anneals at both 900 and 1000°C and with an optimised anti-reflection coating is demonstrated for chemically polished wafers.

Finally the effects of oxide/nitride stacks and high temperature anneals in both nitrogen and forming gas are discussed for a variety of wafers. The optimal emitter sheet resistance is shown to be independent of nitrogen anneal temperature. With textured wafers, recovery of J_{oe} values after a high temperature nitrogen anneal is demonstrated for wafers with a thick oxide, but not for wafers with a thin oxide. This is shown to be due to a lack of surface passivation at the silicon/oxide interface.

List of Acronyms and Symbols

| | |
|--------------|---|
| AIC | Aluminium Induced Crystallisation |
| AR | Anti-Reflection |
| ARC | Anti-Reflection Coating |
| a-Si | amorphous Silicon (no crystal structure) |
| BSF | Back Surface Field |
| BSR | Back Side (or Surface) Reflector |
| CVD | Chemical Vapour Deposition |
| APCVD | Atmospheric Pressure CVD |
| cat-CVD | Catalytic CVD |
| CC CVD | Closed Chamber CVD |
| EBEP CVD | Electron Beam Excited Plasma |
| ECR CVD | Electron Cyclotron Resonance CVD |
| ECR PACVD | Electron Cyclotron Resonance Plasma Assisted CVD |
| HR CVD | Hydrogen Radical CVD |
| HWCVD | Hot Wire CVD |
| LPCVD | Low Pressure CVD |
| PACVD | Plasma Assisted CVD (also called Plasma CVD) |
| PCVD | Plasma CVD (also called PECVD and PACVD) |
| PECVD | Plasma Enhanced CVD (also called plasma CVD) |
| remote PECVD | Plasma CVD with a remote plasma source |
| RF PECVD | Radio Frequency Plasma Enhanced CVD |
| RTCVD | Rapid Thermal CVD |
| SA CVD | Sub-atmospheric CVD |
| Cz | Czocholaski grown silicon |
| Dessis | a 2 dimensional computer program for solar cell simulation |
| DLARC | Double Layer Anti-Reflection Coating |
| EBIC | Electron Beam Induced Current |
| efficiency | (for solar cells) output energy/input energy |
| EFG | Edge-defined Film-fed Growth |
| ELO | Epitaxial Layer Overgrowth |
| EQE | External Quantum Efficiency |
| EWT | Emitter Wrap Through |
| FF | Fill Factor, equal to $I_{sc} V_{oc} / P_{max}$ |
| FGA | Forming Gas (5% hydrogen in argon) Anneal |
| FZ | Float Zone |
| IAD | Ion Assisted Deposition |
| IC | Integrated Circuit |
| I_{sc} | Short Circuit Current |
| ITO | Indium Tin Oxide, commonly used as an anti-reflection coating |

| | |
|---------------|---|
| i-type | intrinsic (undoped) |
| IQE | Internal Quantum Efficiency |
| J_{oe} | emitter saturation current density |
| J_{sc} | short circuit current density |
| LBL | Layer-By-Layer |
| L_{diff} | diffusion length |
| LPE | Liquid Phase Epitaxy |
| L/W | the ratio of diffusion length to wafer width |
| mc-Si | multi-crystalline Silicon, the non-crystalline material with the largest grains |
| MG-Si | Metallurgical Grade Silicon |
| μc -Si | micro-crystalline silicon, grain sizes smaller than poly-crystalline silicon, but larger than nano-crystalline silicon |
| MIRHP | Microwave Induced Remote Hydrogen Passivation |
| n^+ | heavily doped n-type |
| n^{++} | very heavily doped n-type |
| n-type | doped with atoms with single electron in their valance band, eg. phosphorous, arsenic or antimony |
| nc-Si | nano-crystalline silicon |
| ONO | a triple stack; SiO_2 , SiN_x , SiO_2 |
| p^+ | heavily doped p-type |
| p^{++} | very heavily doped p-type |
| PC1D | a 1 dimensional computer programme for solar cell performance simulation [32] |
| P_{max} | the maximum operating power output |
| poly-Si | poly-crystalline Silicon, grain sizes in between multi and micro-crystalline silicon |
| p-type | doped with atoms with a single hole in their valance band, eg boron, aluminium or gallium |
| QMS | Quasi Mono-crystalline Silicon, mono crystalline silicon that has been electrochemically etched to form porous silicon. |
| R_{\square} | sheet resistance, typically measured after a diffusion or drive-in step using a 4-point probe. |
| P RTP | Pulsed Rapid Thermal Processing |
| RGS | Ribbon Grown on Ssubstrate |
| RTP | Rapid Thermal Process |
| sc-Si | single (or mono) crystalline Silicon |
| SEM | Scanning Electron Microscope |
| S_{front} | front surface recombination velocity |
| Si:H | Hdrogenated Silicon (usually amorphous or very small grained) |
| SiO_2 | Slicon Oxide |
| SiN | Silicon Nitride |
| SOI | Silicon On Insulator |
| SPC | Solid Phase Crystallisation |
| S_{rear} | rear surface recombination velocity |
| SRH | Schottky-Read-Hall |
| SRV | Surface Recombination Velocity |
| SSP | Silicon Sheets from Powder |
| τ | lifetime |

| | |
|---------------------|-------------------------------------|
| τ_{eff} | effective lifetime |
| UHV sputtering | Ultra-High Vacuum sputtering |
| UMG-Si | Ugraded Metallurgical Grade Silicon |
| VHF-GD | Very-High Frequency Glow Discharge |
| V_{oc} | open circuit voltage |
| ZMR | Zone Melt Recrystallisation |

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