Electron Beam Crystallization of Amorphous Silicon Thin Films

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Outline

- Motivation
- Methods and numerical model
- Results and Discussion
- Conclusion and Outlook
Motivation

**kerfless** ~ 30-50\% high purity silicon \( (10^8 \text{ kg/year}) \) [1,2]

= huge saving potential for manufacturing costs

**kerfless** = no material waste + very thin wafers

= long-term future technology

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Motivation
- kerfless wafering Technologie am Fraunhofer FEP -

1. crystalline substrate
2. a-Si thin film
3. crystalline Si thin film
4. Si-thin film Wafer

**in situ dry clean process** [Bodenstein et al., 2015]

**splitting off crystallized c-Si layer** [Temmler et al., 2014]

**high rate EB-PVD** [Heinß et al., 2015]

**low defect electron beam crystallization** [Saager et al., 2014]
Methods and Numerical Model

- using a-Si coated Si-Wafers
- electron beam line scribing with different line scanning speed

![Graph showing electron penetration range and absorbed power density for different electron beam energies.](image)
Methods and Numerical Model

- For temperature field - solving 3D heat equation
  \[ c_p(T)\rho(T) \frac{\partial T(\vec{r}, t)}{\partial t} - \nabla [\lambda(T) \cdot \nabla T(\vec{r}, t)] \]

  \[ = p_A(\vec{r}, t) - \rho(T) \frac{\partial h_{fus}}{\partial t} \]

  \[ p_A(\vec{r}, t) = \eta_{th} U_B \cdot j_B(x, y, t) \frac{f_A(z)}{R_e} \]

  \[ T(\vec{r}, t = 0) = T_{ini} \quad \forall \vec{r} \in \mathcal{K} \]

  \[ -\lambda(T) \cdot \vec{n} \cdot \nabla T(\vec{r}, t) = \epsilon(T) \cdot \sigma_{SB}(T^4 - T^4), \quad \forall \vec{r} \in \partial \mathcal{K} \]

- For stress field – considering thermal and initial stress
  \[ \hat{\sigma} = \hat{\sigma}_{ini} + \hat{\epsilon}^{th} \]

  \[ \hat{\epsilon}^{th} = \hat{\alpha}(T) \cdot (T(\vec{r}) - T_{ref}) \]

  \[ \omega_{\sigma} = \frac{1}{2} \int_0^d \hat{\sigma} : \hat{\epsilon}^{th} \, dz \]
Experimental Results
- line scribing on a-Si coated Si-Wafer by electron beam-

![Image of experimental results]

- layer delamination at certain areas for $v_y \geq 50 \text{ m/s}$ and $e_A \leq 7 \text{ kJ/cm}^3$, resp.
- still attached layer regions are still amorphous
- detached layer regions shows a fine grained structure with long crystallites and with random crystal orientation $\rightarrow$ explosive solid phase crystallization
Numerical Results
- simulation of the temperature field -

\[ d_F = (0, 6 \pm 0, 66) \text{ mm} \]

\[ T_{\text{max}} < T_{a-l} \approx 1420 \text{ K} \text{ (crystallization temperature)} \]

\[ \Rightarrow \text{No crystallization phenomena would be expected} \]
Numerical Results
- simulation of the thermal stress field -

Initial tensile layer stress $\sigma_{ini}$ will be compensated by compressive thermal stress.

Maximum stress value of the $\sigma_{yy}$-component shows little variation in the a-Si layer.

$\Rightarrow$ Delamination phenomena can not be explained.
Numerical Results

- simulation of the thermal stress field -

⇒ energetic consideration of stress conditions -

Rising elastic strain energy desity \( \omega_\sigma \) with increasing absorbed electron beam energy \( e_A \)

Layer delamination will be expected if the stored mechanical energy exceeds the interface energy. This is the case for \( v_y \geq 50 \text{ m/s} \) and \( e_A \leq 7 \text{ kJ/cm}^3 \), respectively

⇒ plausible reason for layer delamination phenomena

\[
\omega_\sigma = \frac{1}{2} \int_0^d \sigma: \varepsilon' \mathrm{d}z
\]
Experimental Results
- additional crystallization tests with extended scanning pattern -

- Slowly heating up the whole sample to the maximum of $T_{\text{max}} \approx 1500$ K
- No layer delamination observed!
- Layer crystallizes with the same (001) crystal orientation from Si-substrate

⇒ epitaxial solid phase crystallization

- Glowing sample during electron beam processing
- Applied scanning pattern with high repetition rate at lower EB power line pitch $\ll d_F$
Conclusion and Outlook

- electron beam treatment on a-Si coated Si-substrates
  - epitaxial regrowth to (001) crystal orientation from Si-substrate
  - Increasing EB power density for enhancing throughput ➔ layer delamination

- COMSOL® simulation ➔ accumulation of strain energy up to interface energy
  - simulation results agree very well with experiment

- with FEM simulations ➔ an efficient process optimization is possible
  - undetectable process states can be find out
  - unexplainable processes phenomena can be understood

- Further working tasks ➔ further process optimization
  - determine process limits for enhancing throughput

- [Fraunhofer] FEP ➔ enhancing of competences for the simulation of thermal and mechanical processes
  - looking for project partners for extending further systematical studies
Thank you very much for your attention!

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