Ultrarapid Thermal Annealing Induced by DC Arc Discharge Plasma Jet Irradiation

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Outline

1. Background and Objectives
2. Experimental
   - Generation of Thermal Plasma Jet (TPJ) and Its Application to Ultrarapid Thermal Annealing (URTA)
3. Results and Discussion
   - Noncontact Temperature Measurement Technique with Millisecond Time Resolution
   - Crystallization of Amorphous Si Films & Its Application to Thin Film Transistor Fabrication
   - Formation of Si nanocrystals in SiO_x
4. Summary

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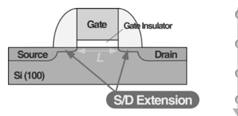
Background & Objectives

Ultrarapid Thermal Annealing (URTA) is one of the key process technologies

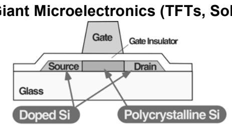
- ULSI Process : Shallow Junction



year / tech. node		Annealing Technology
2007 / 65 nm	1s	spike anneal
2010 / 45 nm	1ms	FLA (Flash Lamp Anneal)

Temperature Measurement in Milli- and Microsecond Time Domain

- Giant Microelectronics (TFTs, Solar Cells) : Crystallization, Dopant Activation



~10ns Excimer Laser Anneal (ELA)
>Limit in Output Power (~300W)
>Running Cost

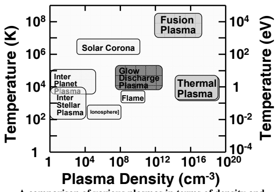
An Alternative High Power Heat Source with Simple Structure

Objectives of This Work are …

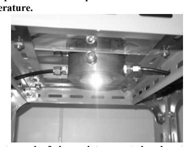
- To Develop a New URTA Technique and a Temperature Measurement Technique with Millisecond Time Resolution
- To Demonstrate the Application of URTA to Electronic Device Fabrication

About Thermal Plasma Jet (TPJ)

Thermal Plasma and Its Advantages as a Heat Source



A comparison of various plasmas in terms of density and temperature.



A photograph of plasma jet generated under atmospheric pressure DC arc discharge.

- Thermal Plasma
  - High density
  - ⇨ **Concentration of Electric Power**
- Thermal Plasma Jet (TPJ) As a Heat Source …
  - High power density (Thermal pinch effect) ~100 kW/cm^2
  - Simple structure
  - Atmospheric pressure discharge
  - ⇨ **Low Cost URTA Processing**

TPJ is a Very Attractive Heat Source for URTA

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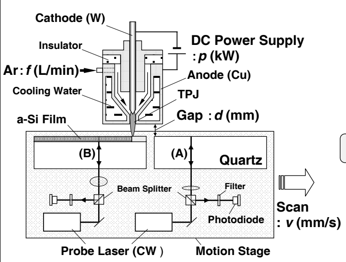
Experimental

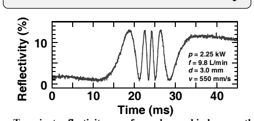
Application of TPJ to RTA



Experimental set up for thermal plasma jet (TPJ) annealing. Beam paths (A) and (B) are used to measure the temperature and phase transformation of a-Si film during anneal.

H. Kaku, *et.al.* Appl. Surf. Sci. 244, (2005) 8.

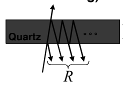
Oscillation in Transient Reflectivity



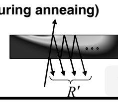
Transient reflectivity waveform observed in beam path (A) during TPJ irradiation.

Origin of the Oscillation

(before annealing)



(during anneaing)



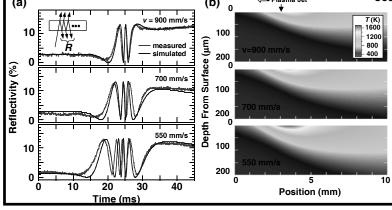
$$\frac{dn_Q}{dT} = 1.2\times10^{-5}$$

Noncontact Temperature Measurement Technique

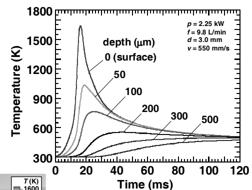
Procedure of Analysis

T. Okada, *et.al.* Jpn. J. Appl. Phys. 45 (2006) 4355.

- 2-d Heat Diffusion Simulation
  - > Effective power transfer efficiency : η (%)
  - > Width of plasma jet : w (mm)
- Optical Simulation
  - > $n_Q = 1.5 + 1.2\times10^{-5}\,T(°C)$
  - J. H. Wray, *et.al.* J. Opt. Soc. Am 59 (1969) 774.
  - > Multiple reflection and interference
- Comparison with Experimental Result
- Temperature Profile



Temporal Variation of Temperature

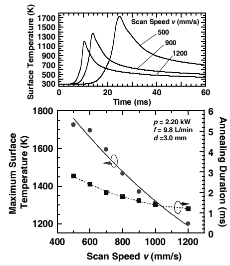


A Noncontact Temperature Measurement Technique with Millisecond Time Resolution has been Successfully Developed

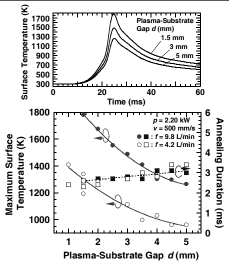
Accuracy < 30 K @~1670K

Annealing Condition & Surface Temperature

Scanning Speed (v) Dependence



Plasma-Substrate Gap (d) and Ar Flow Rate (f) Dependence under constant v of 500 mm/s



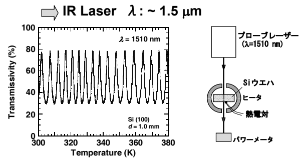
Characteristic Values of TPJ Annealing at Different Gap (d)

d (mm)	T_{max} (K)	t_a (ms)	R_h ($\times 10^5$ K/s)	R_c ($\times 10^5$ K/s)
1.5	1781	2.6	3.87	1.47
3.0	1488	2.8	2.93	1.00
5.0	1266	3.0	2.23	0.69

Application to Si Wafer

Oscillation of Transmissibility

- Probe CW Laser
  - ⇨ IR Laser λ : ~ 1.5 μm



Transmissivity of d = 1 mm Si wafer measured at a wavelength of 1510 nm under varying temperature. $n(T) \sim 2 \times 10^{-4}$ K^{-1} was obtained.

G. Cocorullo *et. al.* Appl. Phys. Lett. 74 (1999) 3338.

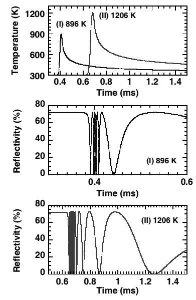
Comparison between Quartz & Si

- Thermal Properties of Quartz & Si

	Quartz	Si
κ (Wcm^{-1}K^{-1})	2.2×10^{-2}	3.3×10^{-1}
dn/dT (K^{-1})	1.3×10^{-5}	1.4×10^{-4}

⇨ Higher Sensitivity in Si

Simulated Transient Reflectivity

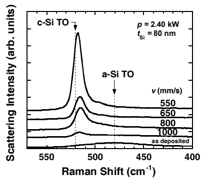


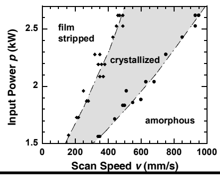
Simulated transient reflectivity of Si wafer under URTA.

Noncontact Temperature Measurement is Applicable to Si Wafer with Higher Time Resolution of μs.

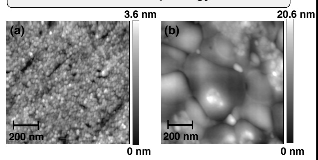
Crystallization of a-Si Films by TPJ Irradiation

Crystallinity & Process Window



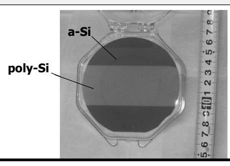


Surface Morphology



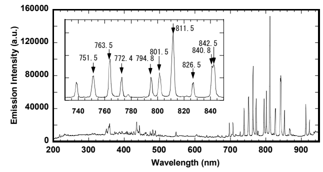
(a) Solid Phase Crystallization d=20~30 nm, RMS=0.5 nm (b) Melting and Resolidification d=300~600 nm, RMS= 3.4 nm

Crystallization by Step & Repeat Method



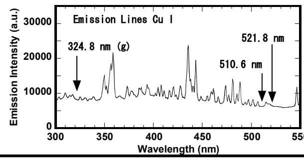
OES of Ar Thermal Plasma Jet

Strong Emission Lines From Atomic Ar are Observed in NIR



Optical emission spectrum of thermal plasma jet.
Most of the significant lines are identified to be emission from Ar atoms as indicated in the inset. From the Boltzmann's plot of the Ar lines, the temperature of the plasma was roughly estimated to be **8300 K**.

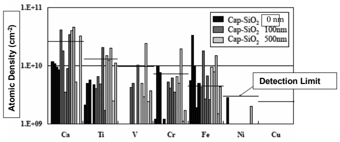
No Emission Lines From Cu was Detected



Identification of emission lines from Cu in thermal plasma jet.
No emission lines from Cu was observed in the optical emission spectrum of thermal plasma jet.

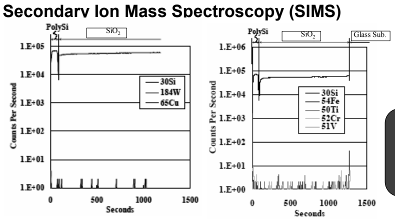
Impurity Concentrations in TPJ Crystallized Si Films

- **Total Reflection X-Ray Fluorescence (TXRF)**



Mn, Zn, Mo, Pd, Sn, Ba, As, Rb were Below Detection Limit.

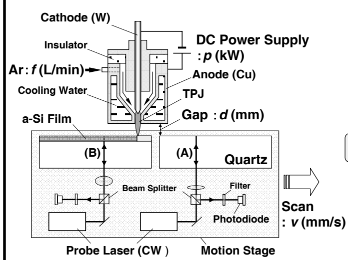
- **Secondary Ion Mass Spectroscopy (SIMS)**



No Metal Contamination was Detected from TPJ Crystallized Si Films

Experimental

Application of TPJ to RTA



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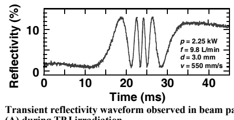
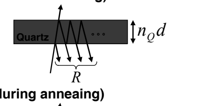


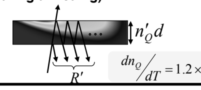
Transient reflectivity waveform observed in beam path (A) during TPJ irradiation.

Origin of the Oscillation

(before annealing)



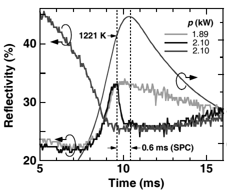
(during anneaing)



$$dn_Q/dT = 1.2\times10^{-5}$$

Crystallization of a-Si Films

In-situ Observation of Solid Phase Crystallization (SPC)



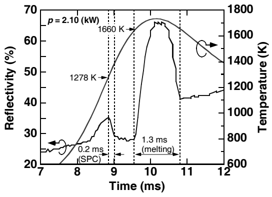
Annealing conditions :

f = 7.0 L/min, d = 3.3 mm, v = 770 mm/s

> Solid Phase Crystallization (SPC)

> 1220 K, 0.6 ms

In-situ Observation of Melting & Resolidification



Annealing conditions :

f = 7.0 L/min, d = 0.8 mm, v = 770 mm/s

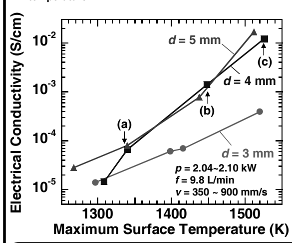
> SPC at 1278 K within 0.2 ms followed by melting and resolidification at 1660 K within 1.3 ms.

Electrical Properties of TPJ Crystallized Si Films

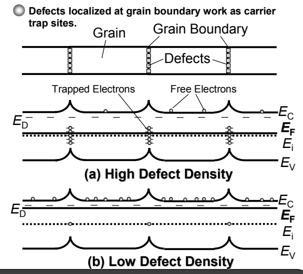
Electrical Conductivity of TPJ Crystallized lightly-doped Si Films

Average P Concentration : 4.3 x 10^{17} cm^{-3}

Electrical conductivity as functions of annealing temperature



Defects localized at grain boundary work as carrier trap sites.



> Carrier Concentration in TPJ Crystallized Si Films Increases with Increasing Annealing Temperature.

> Defect density in Si Films is Decreases with Annealing Temperature

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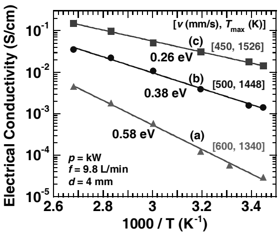

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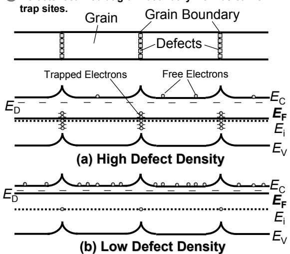


> Carrier Concentration in TPJ Crystallized Si Films Increases with Increasing Annealing Temperature.

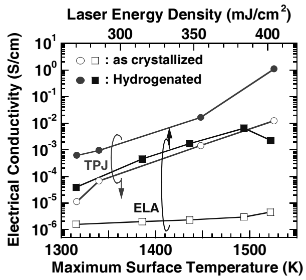
> Defect density in Si Films is Decreases with Annealing Temperature

Electrical Properties of TPJ Crystallized Si Films

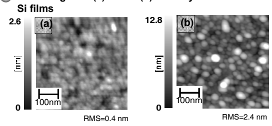
Defect Reduction by Hydrogen Plasma Treatment @ 250C, 60s

Average P Concentration : 4.3 x 10^{17} cm^{-3}

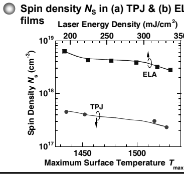
Electrical conductivity of TPJ & ELA crystallized Si films before and after hydrogenation



AFM images of (a) TPJ & (b) ELA crystallized Si films



Spin density N_S in (a) TPJ & (b) ELA crystallized Si films



ELA

R_C~10^{10} K/s

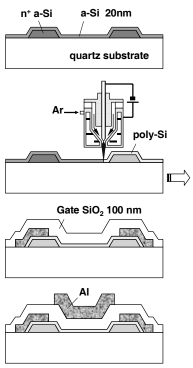
TPJ

R_C~10^5 K/s

> TPJ Crystallized Films Have Lower Defect Density Compared to ELA Films

> Defect Reduction Process Works Efficiently to TPJ Si Films

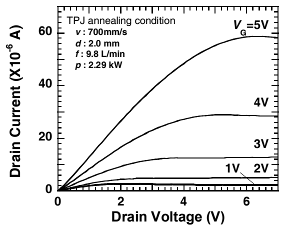
TFT Fabrication Process Flow



- **a-Si Deposition**
  - > S/D n+ a-Si (PECVD)
  - > Channel a-Si deposition(PECVD)
- **Crystallization**
  - > Thermal Plasma Jet
  - 2.3kW 700mm/s (SPC condition)
  - > Excimer Laser Annealing (ELA) :Reference
- **Channel Isolation**
  - > Dry Etching (SF_6)
- **Source/Drain Electrode Formation**
  - > Thermal Evaporation Al
- **Gate SiO_2 Formation**
  - > SiO Evaporation in Oxygen Radical
- **Gate Electrode Formation**
  - > Al Evaporation
- **Defect Reduction**
  - > High-Pressure H_2O Vapor Anneal

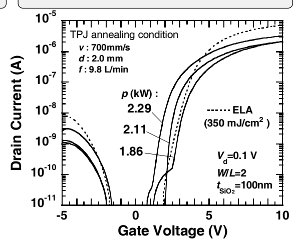
TFT Performances

Output Characteristics



μ_{FE} ($cm^2V^{-1}s^{-1}$)	62
V_{th} (V)	3.4
I_{ON} / I_{OFF}	>10^6
Process Temperature (C)	260

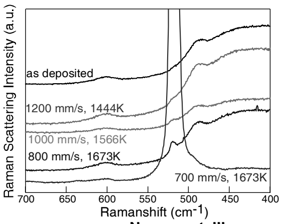
Transfer Characteristics



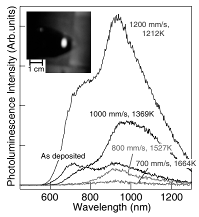
S. Higashi , *et.al.* Jpn. J. Appl. Phys. 44, (2005) L108.

Formation of Nanocrystals in SiOx

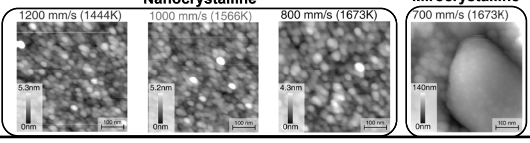
Raman Scattering Spectra of TPJ Annealed SiO_x Films



PL Spectra of TPJ Annealed SiOx Films (excitation : 325 nm)



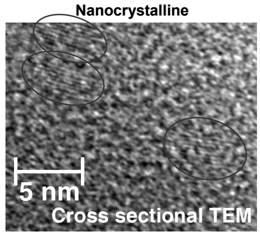
Nanocrystalline **Mirocrystalline**



Formation of Nanocrystals in SiOx

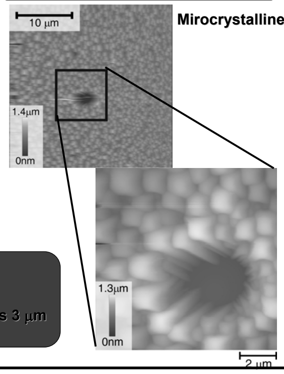
Cross sectional TEM of a TPJ annealed SiOx film

Nanocrystalline



Large lateral grain growth from SiOx film with trench structure

Mirocrystalline



- Si nanocrystals are formed in TPJ annealed SiOx
- Lateral crystalline growth as long as 3 μm is achieved.

Conclusions

1. A New RTA Technique Utilizing Thermal Plasma Jet (TPJ) and Noncontact Temperature Measurement Technique with Millisecond Time Resolution have been Developed.
2. Substrate Surface Temperature is Controlled From 960 to 1781 K with Typical Annealing Duration of 3 ms.
3. Amorphous Si (a-Si) Films are Crystallized Through Solid Phase or Melting & Resolidification Depending on the Annealing Condition.
4. TFTs Fabricated Using TPJ Crystallization Technique Show Good Electrical Performance with μ_{fe} of 62 cm^2/Vs and V_{th} of 3.4 V.
5. Nano- and Micrometer Sized Si Crystalline Growth is Achieved by TPJ Annealing of SiOx Films.