The Effect of SiO_2 Content Rate in Simulated Lunar Regolith on Ablation Plume Temperature and The Feasibility Assessment of Al_2O_3 Reduction

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1.Background

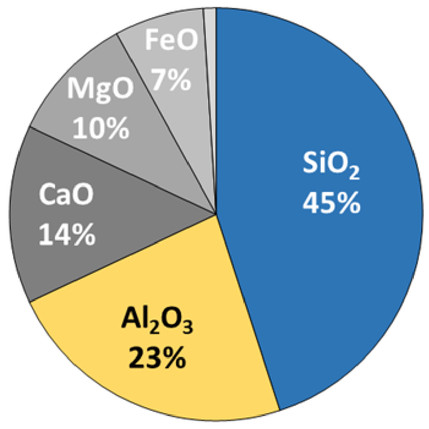
Lunar base construction

- ✓ High transportation cost from the Earth (100 million dollar/kg)

➡ **In-Situ Resource Utilization is important**

- ✓ Reduction of **23% Al_2O_3** in regolith
- ✓ Conventional method : Hall-Herout process

$Al_2O_3 + 3/2C \rightarrow 2Al + 3/2CO_2$ **No carbon On the Moon**



Composition of regolith

➡ **C-Free Alumina Reduction Method by Diode Laser Ablation**

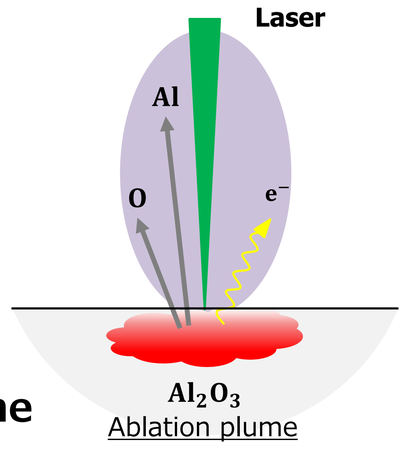
2. Principle

Laser Ablation

- ✓ Laser irradiation on the solid surface
  → Irradiated area melting, vaporizing, and generating plasma

Ablation Plume

- ✓ Plasma generated by ablation
  → consists of Electron, atoms etc…
- ✓ Irradiation part is High Temperature & Pressure
  → Plume injects vertically from surface



Ablation plume

➡ **Collecting reduced Aluminum in plume**
Reduction method with no consumables

3. Objectives

Previous Study

[1] Vacuum 167 (2019) 495-499
[2] K. Uesugi, R. Oishi, and M. Matsui, *Jpn. J. Appl. Phys.*, in press.

- ✓ **High plume temperature increased reduction rate** [1]
- ✓ **Thermal reduction by ablation was performed** [2]
  → Temperature was up to 5200 K
  → Temperature of SiO_2 mixed powder? Si in SiO_2 as a reducing agent?

$Al_2O_3 \rightarrow 2Al + 3O$: **Needs 5500 K**

Objectives

- ✓ Investigation of the effects of SiO_2 and Si on plume properties
- ✓ EDX analysis of the products of laser irradiation
- ✓ The feasibility study of SiO_2 laser reduction by emission spectroscopy and EDX

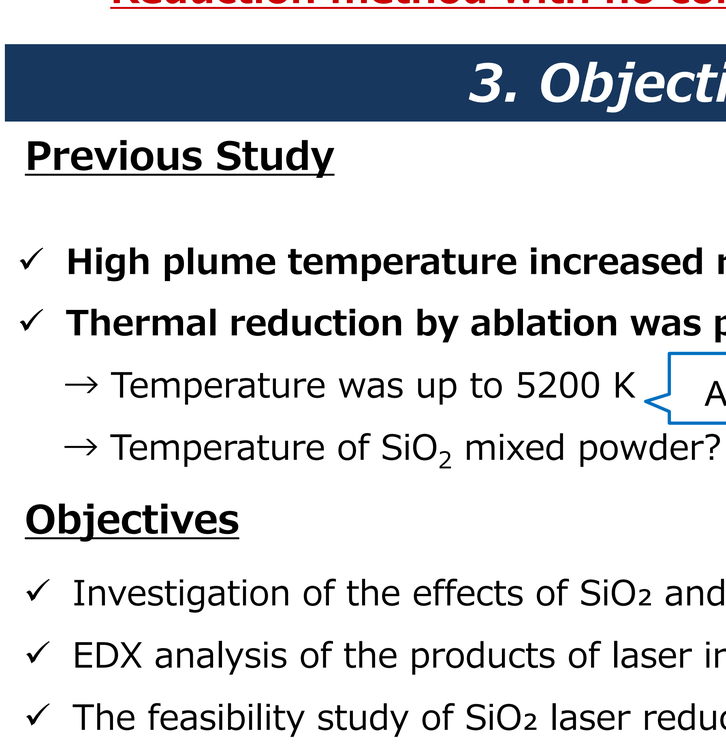
4. Experimental apparatus

High power laser diode

Laser output	1100 W (max.)
Wavelength	940 nm

Conditions

Working gas	Ar
Gas pressure	100 kPa
Laser intensity	1.3 GW/m²
Irradiation duration	1 sec
SiO_2, Si rate	25, 50 wt%



Experimental setup

- ✓ Emission spectra of plume at 2mm from the surface
- ✓ Planck curve fitting at continuous wavelength

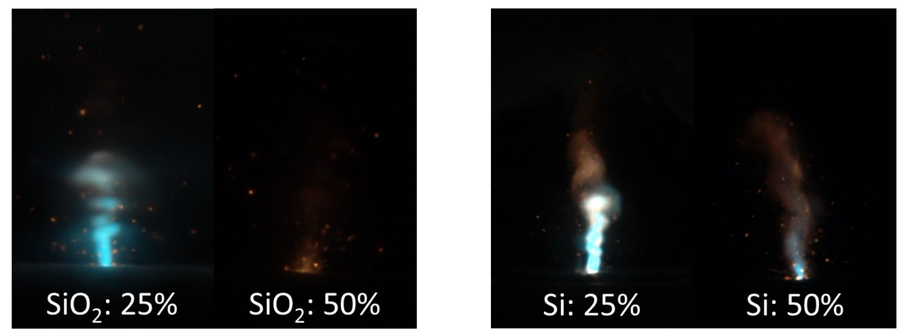
➡ **Estimating temperature**

Planck's law

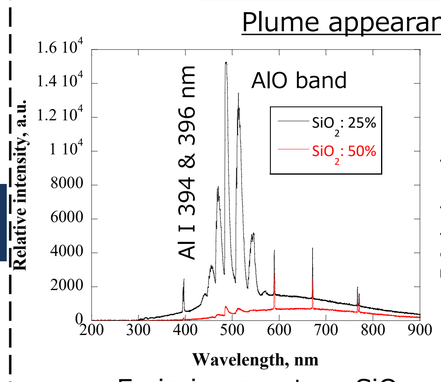
$$I(\nu,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}$$

5. Results & Discussions

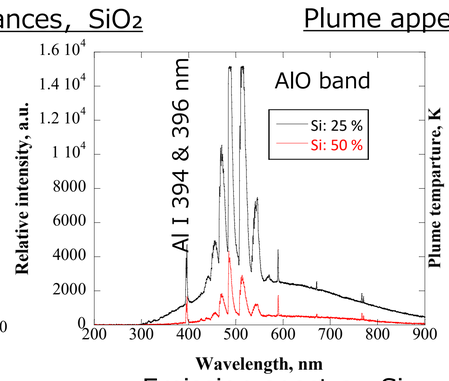
➢ Effects of SiO_2 & Si on plume temperatures



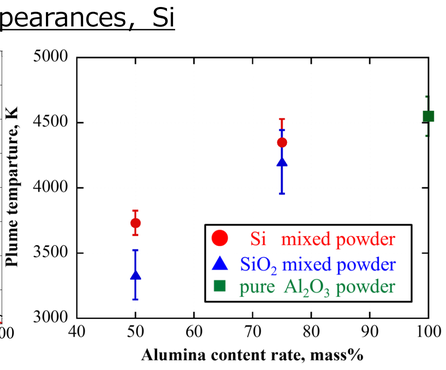
Plume appearances, SiO_2 Plume appearances, Si



Emission spectra, SiO_2



Emission spectra, Si

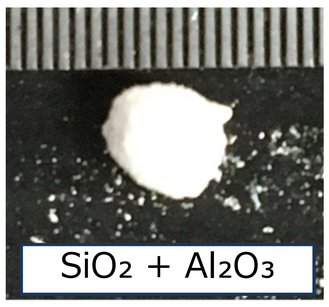


Plume temperatures

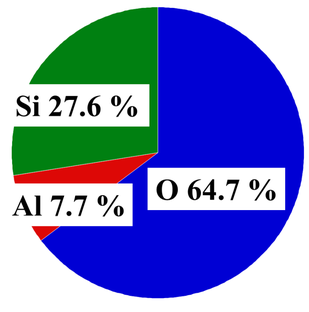
- ✓ SiO_2 rate increasing → AlO band & Al I spectra decreasing
- ✓ Si rate increasing → AlO band & Al I spectra confirmed
- ✓ Plume temperature : Al_2O_3 > Si + Al_2O_3 > SiO_2 + Al_2O_3
  - **Binding energy ⇒ (Al–O: 481 kJ/mol, Si–O: 628 kJ/mol)**
  - Al_2O_3 > Si + Al_2O_3 ⇒ Heat loss because of chemical reaction

→ $Al_2O_3 + 3/2Si \rightarrow 2Al + 3/2SiO_2$ (endothermic reaction)

➢ EDX analysis of the products of laser irradiation

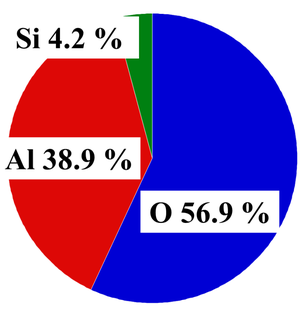


$SiO_2 + Al_2O_3$



White sphere (left), Atomic ratio (right)

Si + Al_2O_3

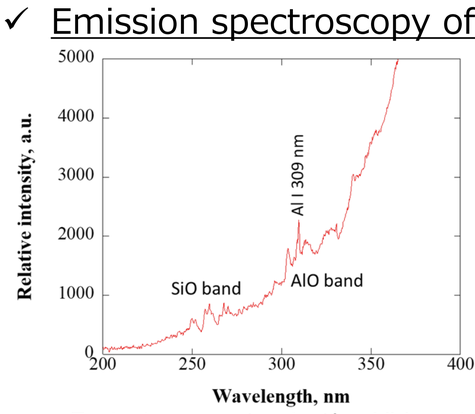


Spheres with metallic luster (left), Atomic ratio (right)

- ✓ A few μm from the surface : EDX results
  → ・White sphere was a mixture of **SiO_2 & Al_2O_3**
  ・Spheres with metallic luster were estimated to **Al_2O_3**
- ✓ Analysis of the lower layer : Reaction with hydrochloric acid
  → Hydrogen gas generated only from Si + Al_2O_3 products
  → **The reduced Al was produced by silicon**

➢ Feasibility study of SiO_2 reduction

- ✓ Emission spectroscopy of SiO_2 ablation & EDX analysis



Emission spectra in the UV region

- ✓ Emission spectra
  → Si I 255 & 288nm could not be confirmed
- ✓ EDX analysis
  → **$SiO_{1.4\text{-}1.5}$**: Oxygen defect structure

➡ **SiO_2 reduction by laser ablation to produce Si was impractical**
Reusable reductants will be needed for SiO_2 & Al_2O_3 Reduction

6. Conclusions

- ✓ Plume temperatures: **Under the condition of mixing SiO_2, plume temperature decreased up to 1500 K.**
- ✓ Products of laser irradiation: **Alumina reduction with Si was confirmed, but reduction with SiO_2 was not.**
- ✓ SiO_2 reduction by laser ablation: **The production of Si could not be confirmed from the results of emission spectroscopy and EDX.**