IBAAS 2025
TECHNICAL LECTURE SERIES

4N HPA: SCIENCE, STRATEGY, AND SCALE – A MATERIAL AT THE CROSSROADS OF INNOVATION

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Contents

Introduction & Objective

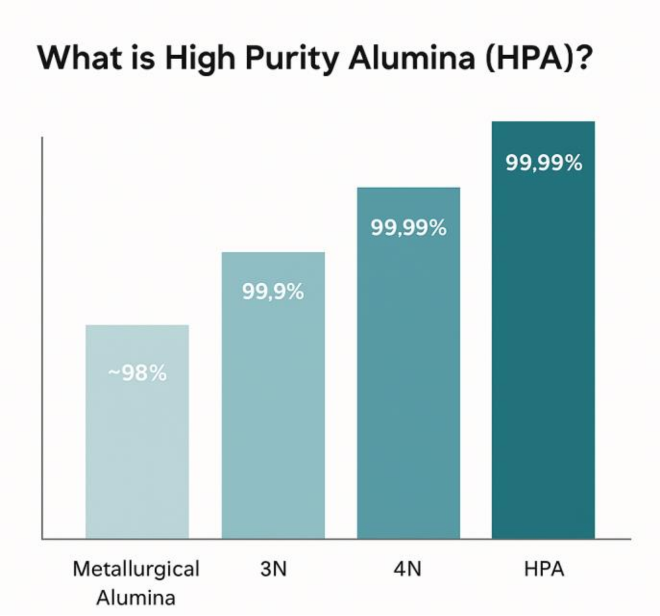
Introduction

- High Purity Alumina (4N, 99.99%)
- Chemical Stability, Optical transparency, high thermal resistance
- LED Phosphors, Lithium-Ion Batteries, Semiconductor substrates

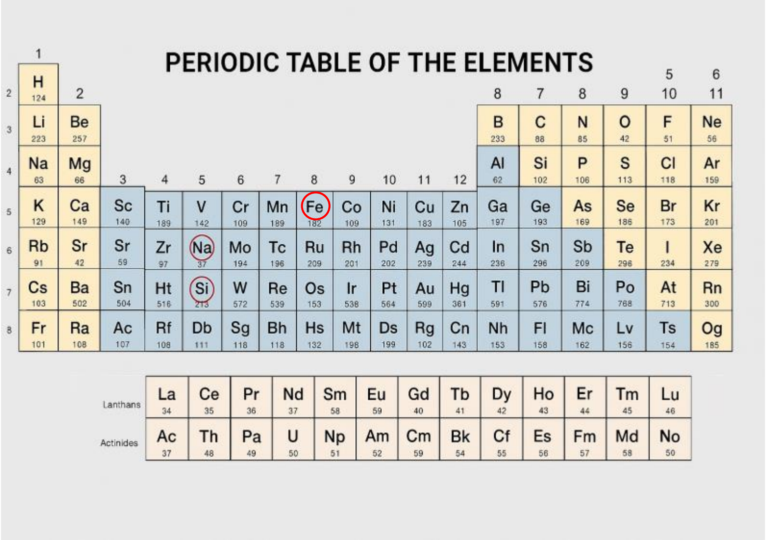
Objectives

- To introduce the science behind 4N HPA, its key properties and applications.
- To highlight the strategic and economic importance of developing domestic capability.
- To explore how investors and industry can leverage emerging opportunities.
- To present R&D efforts and breakthroughs achieved at JNARDDC, including a lab-scale validated process for producing 4N HPA.

High Purity Alumina (4N HPA)



Grade	Typical Use
3N (99.9%)	Ceramics, Phosphors
4N (99.99%)	LED, Sapphire Glass
5N (99.999%)	Semiconductors, Optics



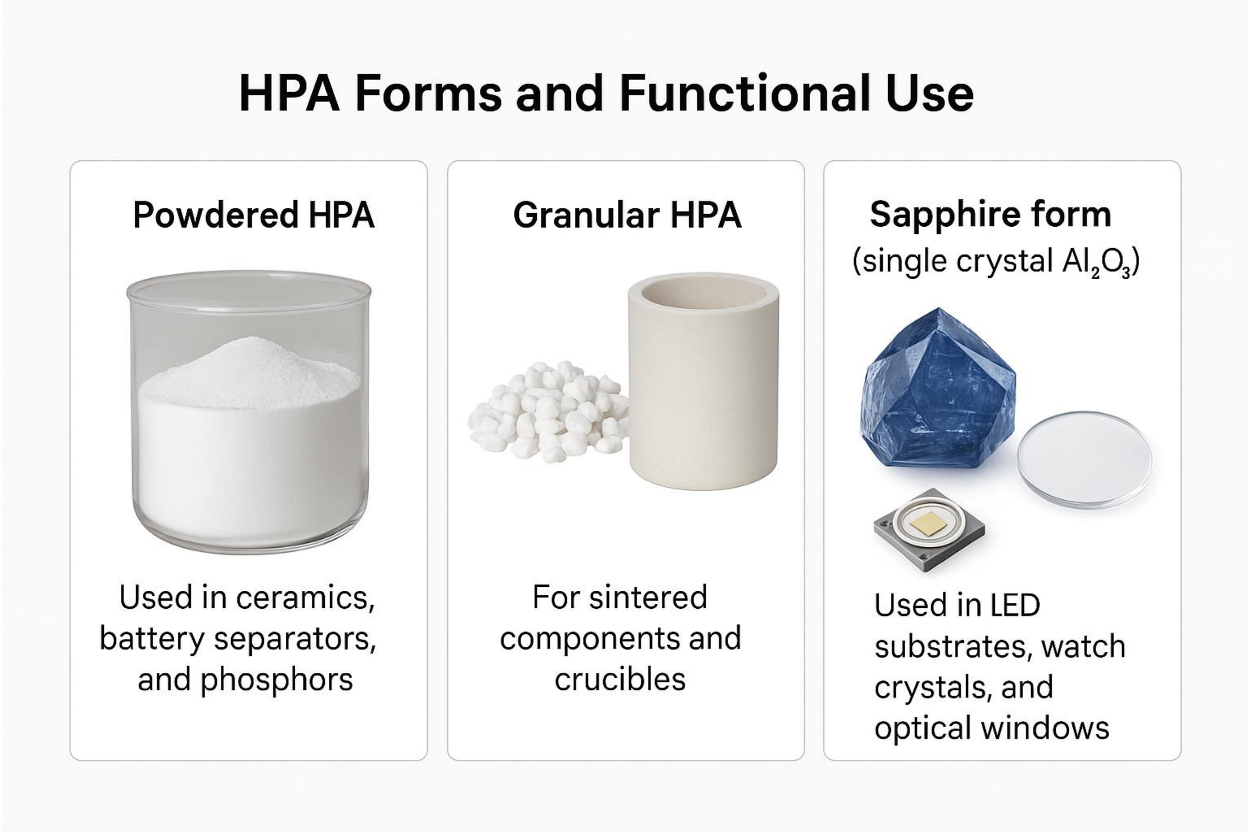
Why Purity Matters ?

Achieving high purity ensures that the following properties are maximized, allowing HPA to perform optimally in demanding applications:

- **High melting point: ~2050°C – suitable for extreme environments**
- **Excellent hardness and chemical stability**
- **High dielectric strength and thermal conductivity**
- **Transparent to visible and infrared light (especially sapphire form)**
- **Inert and non-reactive nature**

HPA Forms and their Uses

The form and purity of HPA determine its application and market value

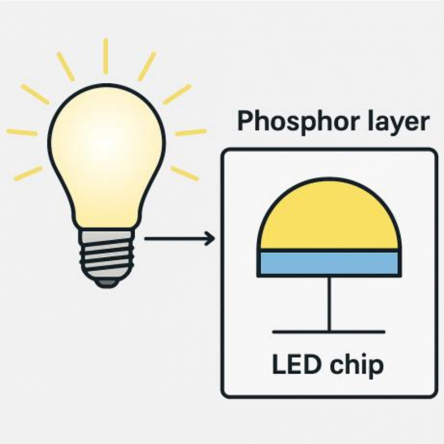


Global Demand and Its Applications

HPA use in LED Phosphors

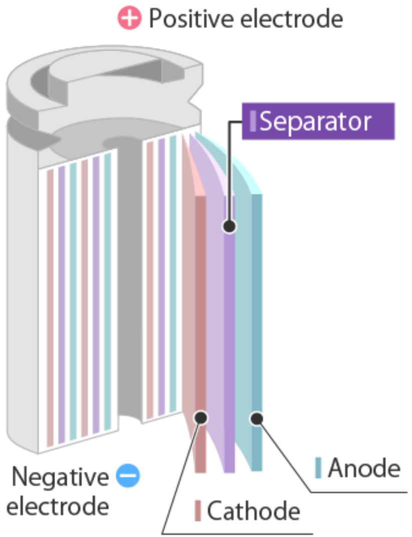
4N HPA in LED Phosphors:

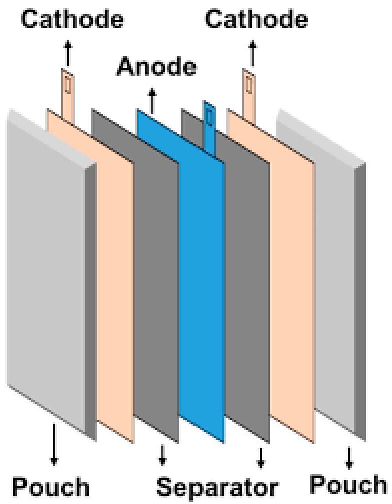
- **Application:** High-purity alumina (HPA) is used as a key component in the production of LED phosphors.
- **Role:** Enhances brightness and color efficiency in LED lights, making them more energy-efficient and long-lasting.
- **Market Demand:** As the LED industry grows due to energy-saving initiatives and lighting upgrades, the demand for HPA in this sector is expected to increase.



HPA for Lithium Ion Batteries Separator

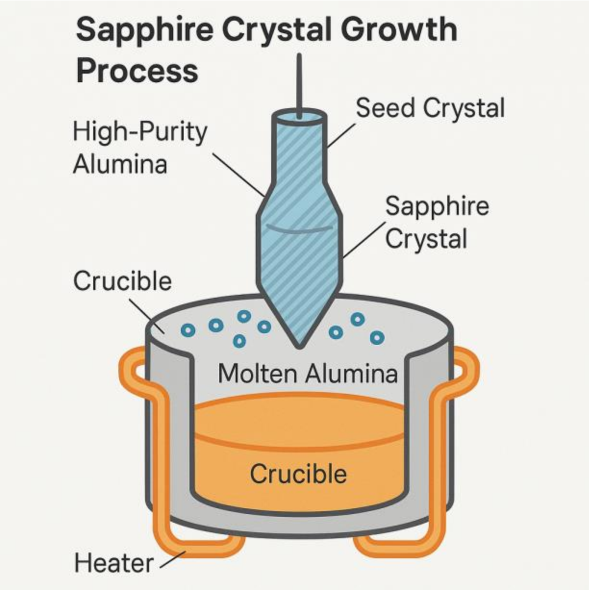
- **Application**: HPA is utilized in the production of separators for lithium-ion batteries, which are critical in electric vehicles (EVs) and portable electronic devices.
- **Role**: Provides high thermal stability, mechanical strength, and chemical resistance, improving battery life and safety.
- **Market Demand**: With the rise of electric vehicles and portable electronics, the demand for advanced battery technologies and separators is growing, driving the need for HPA.





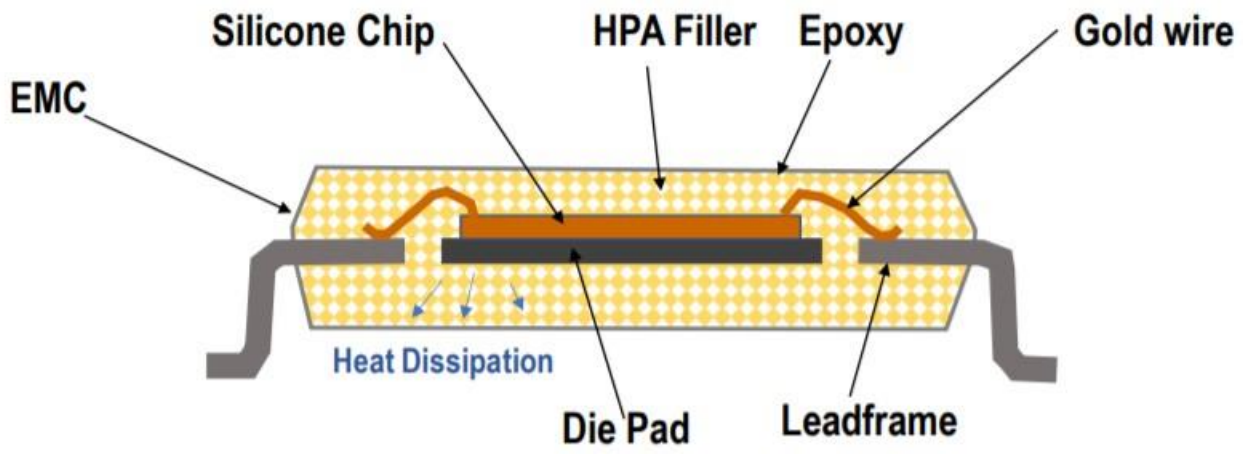
HPA for Sapphire Substrates

- **Application:** HPA is used to produce high-quality sapphire substrates for use in semiconductor and optical applications.
- **Role:** Provides a stable, high-quality substrate that is essential for the production of blue and white LEDs, as well as for use in advanced electronic devices.
- **Market Demand:** The continued advancement of the electronics and LED industries, alongside emerging applications in photonics, is driving the demand for sapphire substrates.



HPA for Semiconductor and Optical Applications

- **Application:** HPA is used in the manufacturing of semiconductor devices and optical components, including lenses and windows for high-performance lasers.
- **Role:** Offers excellent purity, high thermal stability, and optical transparency, making it essential for next-generation electronic and optical devices.
- **Market Demand**: With the increasing demand for high-performance semiconductors in data centers, telecommunications, and emerging technologies like quantum computing, the need for HPA in these sectors is expected to grow.



Current HPA Production Technologies

Bayer's Process: Traditional Alumina Route

Pros:

•**Mature Technology**: Well-established process with a global presence.

•**High Yield**: Efficient at producing alumina from bauxite.

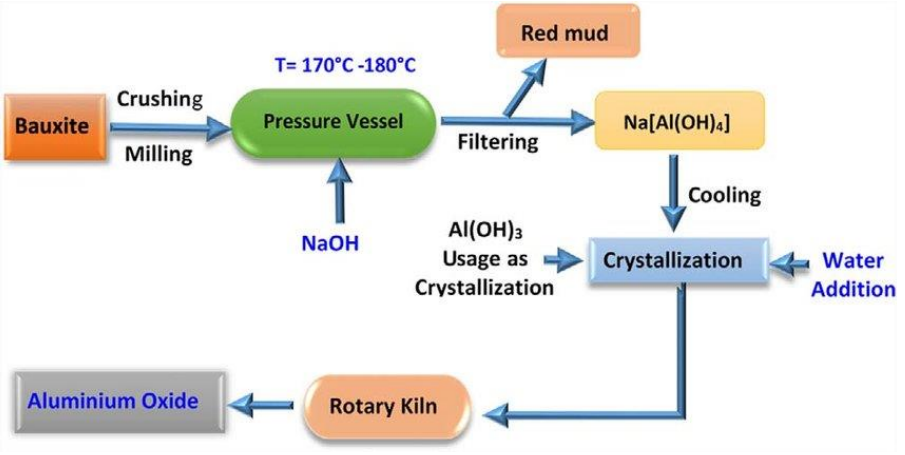
•**Scalable**: Suitable for large-scale industrial production.

Cons:

•**Energy-Intensive**: Requires significant energy for calcination.

•**Environmental Impact**: Large amounts of red mud (waste byproduct) are generated.

•**Limitations for HPA**: Not directly suited for high-purity alumina, additional purification steps are needed.



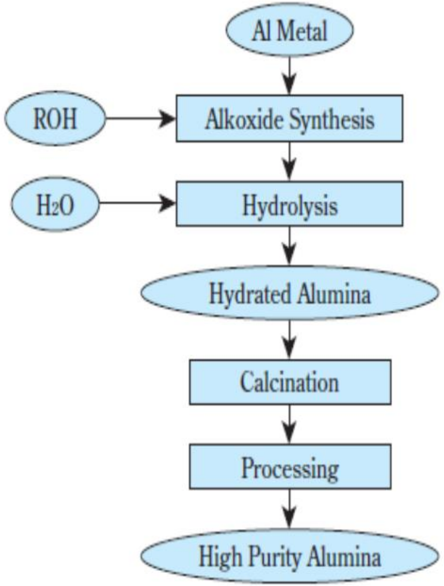
Alkoxide Process

Pros:

- **High Purity:** Direct production of HPA with minimal impurities.
- **Control over Purity:** Allows precise control over the purity level of alumina.
- **Suitability for Specialty Applications:** Ideal for producing ultra-high purity materials used in LEDs and semiconductors.

Cons:

- **High Cost:** Requires expensive chemicals and energy for the reaction.
- **Scale-Up Challenges:** Less proven at industrial scale compared to Bayer process.
- **Complex Process:** Involves multiple steps requiring precise control.



Hydrothermal and Hydrochloric Acid Leaching

Pros:

•**Efficient Extraction**: Effective for processing a variety of raw materials, including low-grade ores.

•**Flexible**: Can use alternative raw materials, not just bauxite.

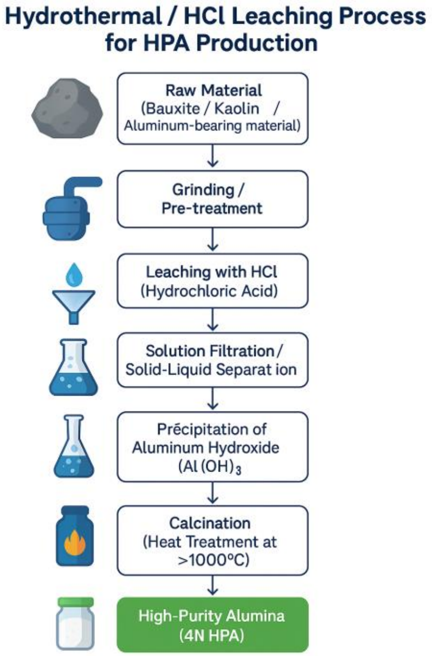
•**Low Energy Consumption**: Potential for lower energy consumption compared to Bayer process.

Cons:

•**Complexity in Purification**: Requires additional purification steps to achieve high purity.

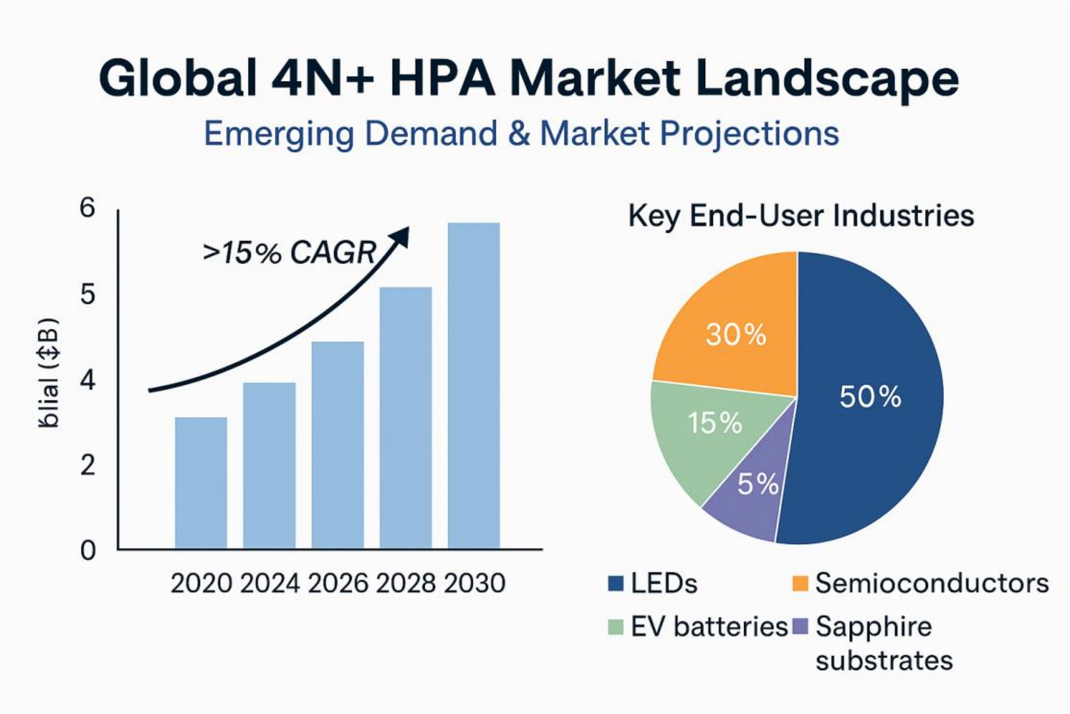
•**Corrosive Chemicals**: Use of hydrochloric acid can lead to equipment corrosion and environmental concerns.

•**Scalability Issues**: Less established for large-scale commercial production.



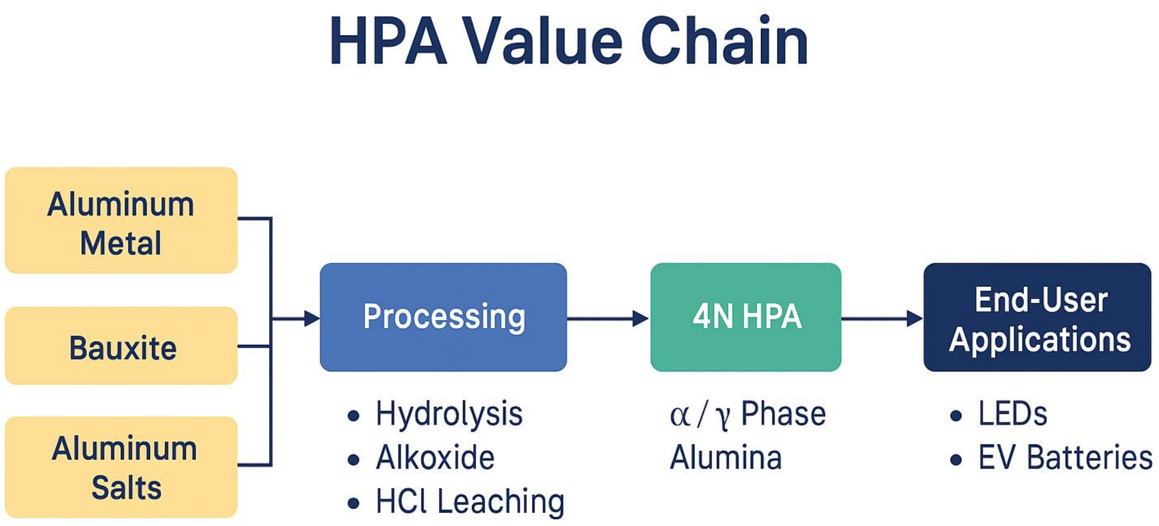
Industrial Value Chain & Market Landscape

Emerging Demand & Market Projections



The global market for High Purity Alumina was valued at US$17.3 Billion in 2024 and is projected to reach US$52.6 Billion by 2030, growing at a CAGR of 20.3% from 2024 to 2030.

Strategic Overview of the HPA Value Chain



Investment Opportunities & Challenges

Key Players & Cost Benchmarks

Global Market Dynamics: Players, Costs & Competitive Edge

Major Global Players:

- Altech Chemicals (Australia)
- Sasol (South Africa)
- Sumitomo Chemicals (Japan)
- Orbite Technologies (Canada)

Typical Production Routes:

- Hydrochloric Acid Leaching
- Alkoxide Process
- Thermal decomposition of Aluminium Salts

Cost Benchmarking (for 4N HPA):

- Global Average Cost - $ 14-20/Kg
- Indian R&D based Cost- ₹ 500-600/kg (approx. $ 6-7 excluding manpower and scale-up factors)

Work Done on HPA at JNARDDC- Project Overview

Project Details

Title: Development of Process for 4N High Pure Alumina (HPA) and Substrate Making for its Validation in LED Applications

OBJECTIVES

Develop a process know-how for 4N HPA preparation

Preparation of sapphire

Validation of sapphire for LEDs

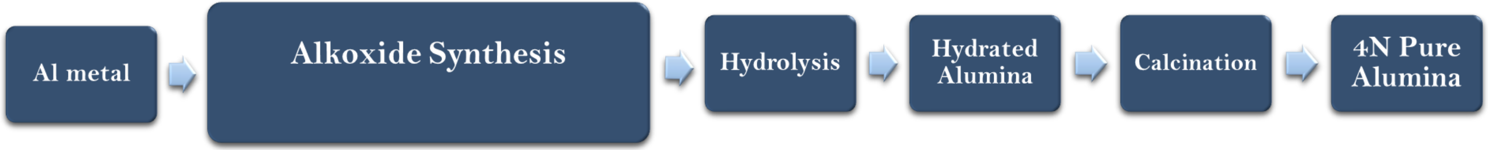
Cost Economics for developed process

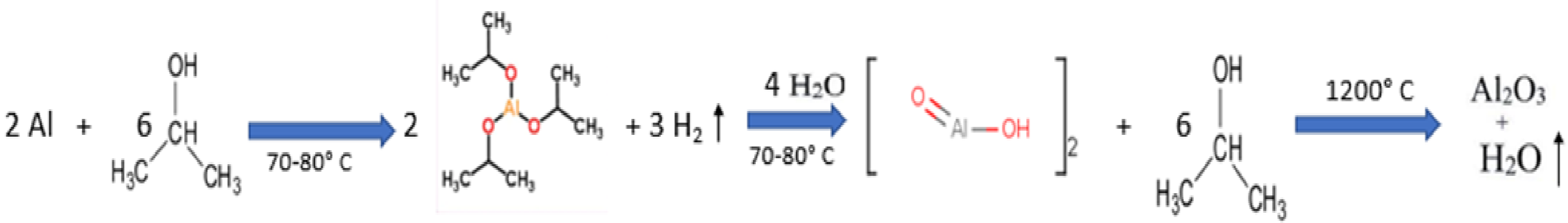
JNARDDC, Nagpur

IIT Bhubaneswar

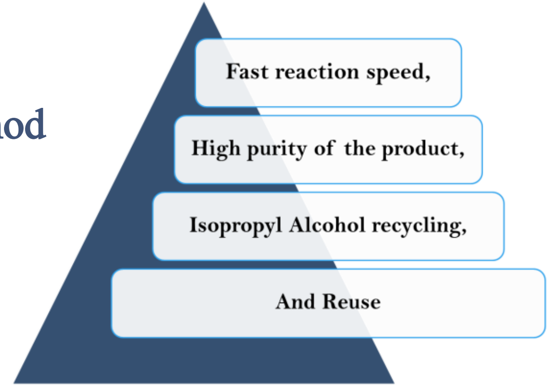
Anna University

Process Methodology – Alkoxide Route Using Aluminum Metal





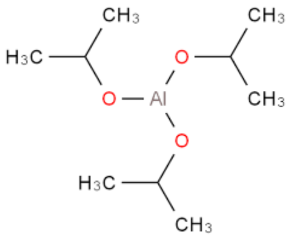
Advantages of Alkoxide Hydrolysis Method



Precursor Advantage: Role of AIP in HPA Purity

- **Precursor Purity**: AIP can be synthesized with high purity and if used as a precursor, initial purity carries through to the final product i.e HPA.
- **Controlled Reaction Pathways**: Precise manipulation of reaction conditions
- **Reduced contaminant introduction**: With its well defined chemical structure, introduction of unwanted contaminants can be reduced
- **Fewer Purification steps**: Highly pure precursor reduce the need for extensive purification steps means less potential for contamination
- **Tailored Synthesis routes**: AIP provides flexibility in defining synthesis routes
- **Optimized Reaction Conditions**: Temperature and Pressure optimization leads to more efficient reaction with fewer unwanted products

The central Aluminium is octahedral surrounded by three bidentate (O--Pr)4 ligands, each featuring tetrahedral Al.



Unique chemical structure of AIP

Catalyst-free Approach: Cleaner, Safer Pathway

Why It Matters:

Traditional synthesis methods for HPA often rely on toxic catalysts like **iodine** and **mercury chloride**, posing safety, environmental, and regulatory challenges.

Our Breakthrough:

JNARDDC's catalyst-free route eliminates hazardous chemicals while maintaining ultra-high purity.

- **Controlled temperature for precise reaction kinetics**
- **Regulated pressure to maintain reaction equilibrium**
- **Optimized reaction time for purity + efficiency**

Advantages Over-Catalyst Based Methods

Catalyst-Based (Iodine, $HgCl_2$)	Catalyst-Free (JNARDDC)
Uses Toxic and hazardous substances	Environmentally Benign
Requires additional removal steps	Simplified Process
Risk of catalyst contamination in final product	Cleaner, higher purity
Higher cost due to catalyst handling and disposal	Lower operational cost
Regulatory challenges for toxic chemicals	Safer, scalable, compliant

How Pure Are Our Raw Materials?

Purity analysis of aluminium metal received from NALCO

Elements	Iron (Fe) Wt %	Silicon (Si) Wt %	Copper (Cu) Wt %	Manganese (Mn) Wt %	Zinc (Zn) Wt %	Vanadium (V) Wt %	Gallium (Ga) Wt %	Titanium (Ti) Wt %	Magnisium Mg Wt %	Chromium (Cr) Wt %	Nickel (Ni) wt %	Barium (B) wt %	Calcium (Ca) wt %	Sodium (Na) wt %	Strontium (Sr) wt %	Total Purity
NALCO	0.061	0.018	0.007	0.002	0.003	0.003	0.007	0.004	0.002	0.001	0.004	0.001	0.001	0.006	0.001	99.878 %
JNARDDC	0.040	0.025	0.0003	0.0007	0.0018	0.0030	0.0075	0.005	0.0007	0.0007	0.0008	0.0011	0.0002	0.005	ND	99.905%

Purity analysis of Iso Propyl Alcohol

Water	Fe	Ti	Ca	V	P	Ga	Mg	Si
0.01%	0.093 ppm	ND	0.036 ppm	ND	0.031 ppm	ND	ND	ND

Intermediate and Final Purity Milestones

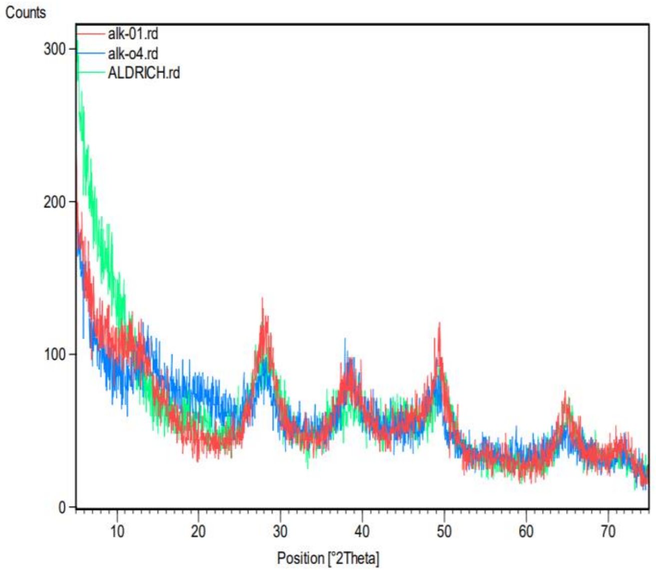
ICP-Analysis of Intermediate Products

Elements %	Fe_2O_3	SiO_2	Cu_2O_3	Mn_2O_3	Mg_2O_3	Zn_2O_3	TiO_2	V_2O_5	P_2O_5	CaO	Purity
AIP	0.0404	0.0246	0.00044	0.00023	0.00081	0.00199	0.0049	0.00030	0.00119	0.0076	99.9053
Al Hydrate	0.037	0.0223	0.00023	0.00021	0.00092	0.00174	0.0051	0.00035	0.00328	0.00054	99.90921

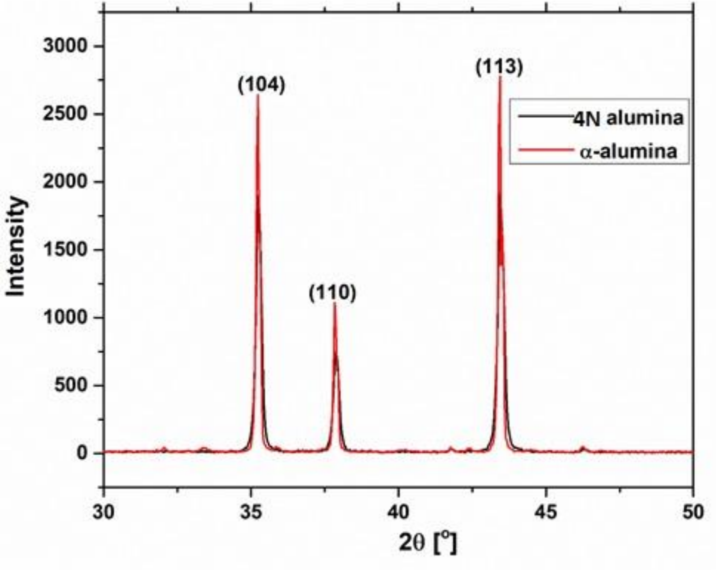
ICP-Analysis of final Product

Sample ID	SiO_2 (%)	TiO_2 (%)	Fe_2O_3 (%)	CaO (%)	P_2O_5 (%)	V_2O_5 (%)	Al_2O_3 (%)
ALK-52	0.0023	0.001	0.007	0	0.0003	0.0004	99.989
Al_2O_3 Sigma Aldrich	0.0011	0.001	0.007	0	0	0.0019	99.989

Crystallographic Match: Synthesized vs Standard Materials

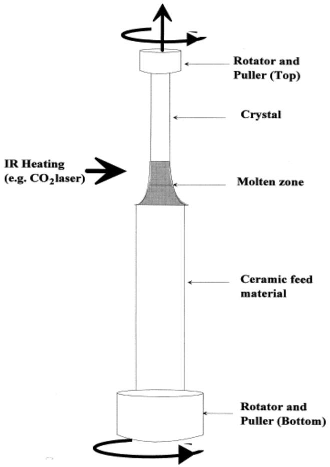


Comparative diffractogram of prepared AIP with the one procured commercially



Comparative Diffractogram of prepared HPA with the commercially procured

From HPA to Sapphire



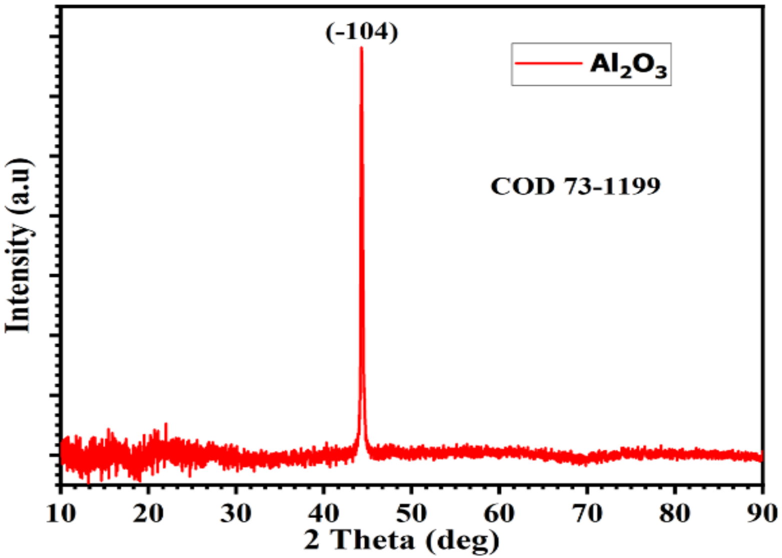
Schematic of Float zone method

Sapphire Growth facility installed at Anna University

Float Zone growing the crystal from melt

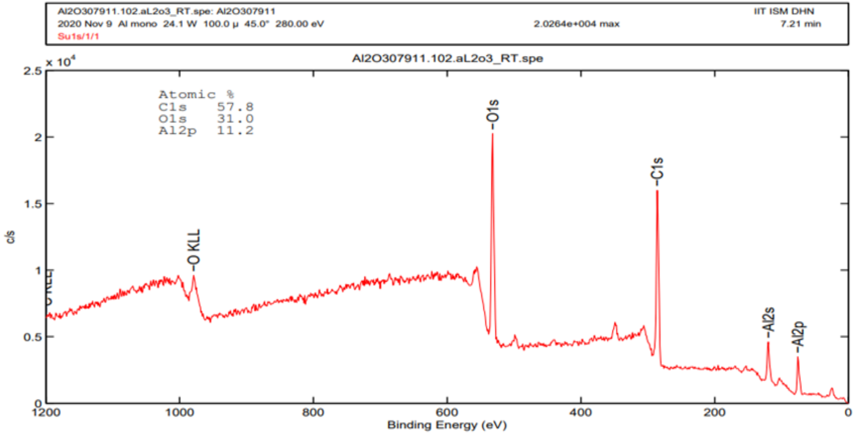
Single crystal grown (5 cm x 1cm) →

Structural and Surface Purity of Sapphire

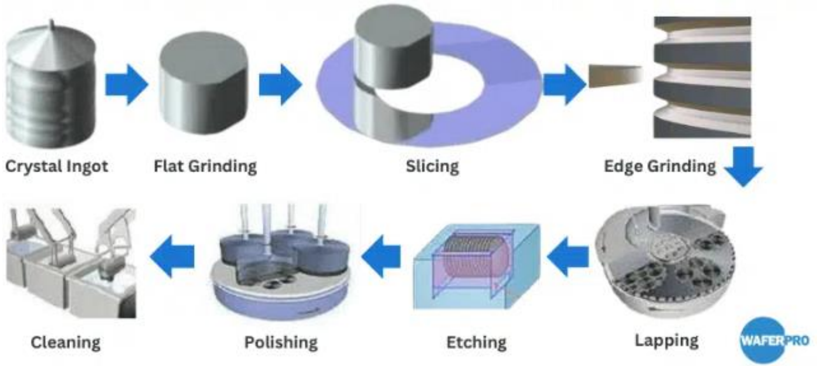


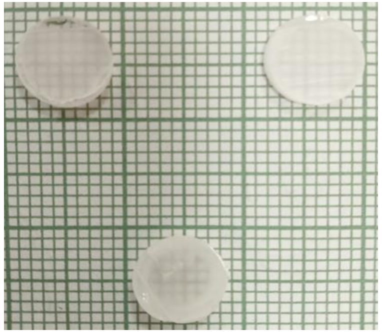
HRXRD

XPS



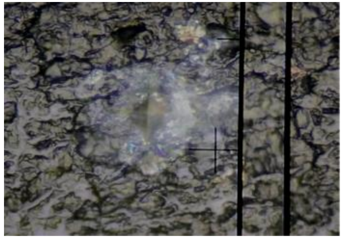
Alumina Wafer Fabrication

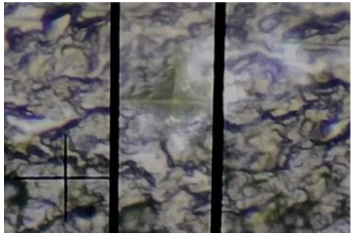




Single crystal grown → **Wafer Manufacturing Process** → **Al_2O_3 wafers (Dia.10 mm and thickness 1.5 mm)**

Functional Characterization of Alumina Wafers





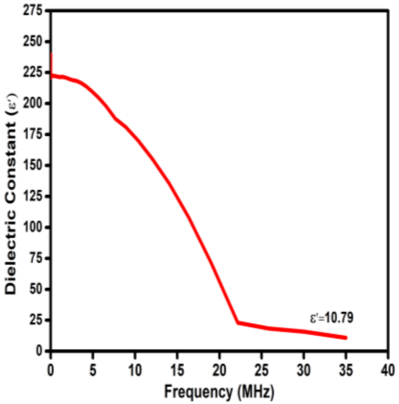
1 kgf

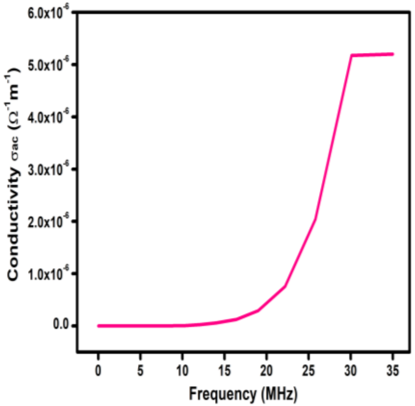
76.56 GPa

0.5 kgf

31.72 GPa

Vicker's Hardness: $$HV = \frac{2F \sin\frac{\propto}{2}}{gd^2}$$





$$\varepsilon_r = \frac{Cp\ d}{\varepsilon_o A}$$

ε_r =9.5 at 1 MHz

C_p= Capacitance
d = thickness of the sample
A= area of the sample
ε_o= Absolute permittivity of free space ($8.854 \times 10^{-12}\ C^2N^{-1}m^{-2}$)

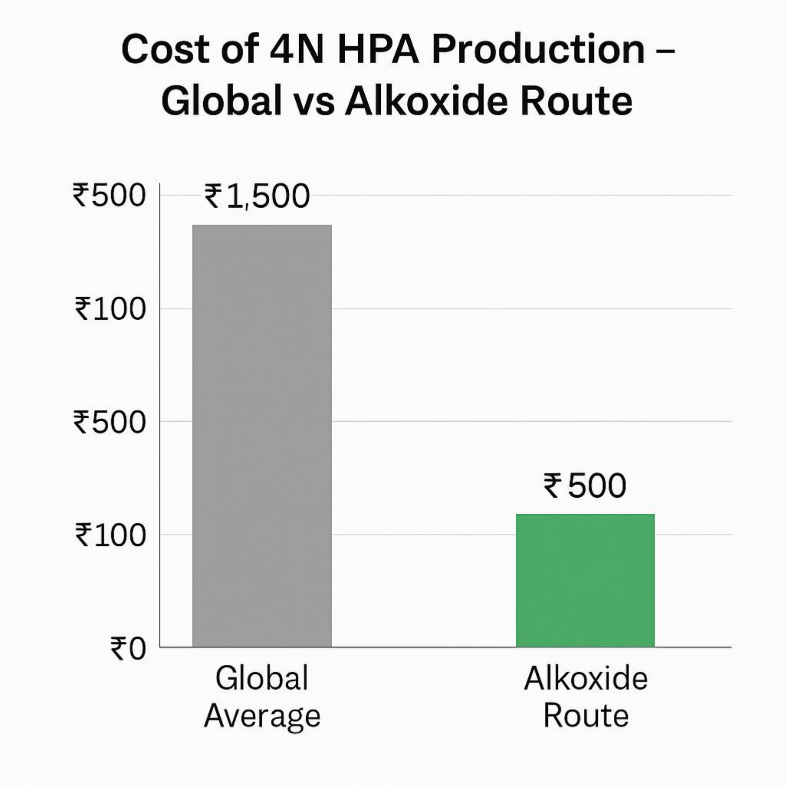
$$\sigma_{ac} = \varepsilon_o\, \varepsilon_r\, \omega \tan\delta$$

$\sigma_{ac} = 5.2\times10^{-7}\ \Omega^{-1}\ m^{-1}$

ε_o= absolute permittivity
$\varepsilon_{r=}$ Dielectric constant
$\omega = 2\pi f$
$\tan\delta$ = Dielectric loss

Dielectric Properties

Cost Advantage of Alkoxide Route



From Lab Success to Bench-Scale Reality

- Scale-up of Alkoxide Based HPA Process
- Design and Set up of Bench-Scale Reactor System
- Optimization of Process Parameters
- Material Characterization at Larger Scale
- Evaluation of End-Use Suitability
- Proposal for Funding and Industry Partnership

Key Takeaways and The Road Ahead

- **4N High Purity Alumina is a strategic material**
  Critical for advanced applications like LEDs, semiconductors, and sapphire substrates

- **Growing global demand presents investment opportunities**
  Especially for India to emerge as a self-reliant supplier.

- **Lab-scale success at JNARDDC validates the potential**
  Alkoxide-based HPA process offers promise for scale-up

- **Next phase: Bench-scale production & industry partnerships**
  Aimed at commercialization, cost-efficiency, and application testing

- **Collaboration is key**
  Investors, industry partners, and R&D institutes can jointly unlock value

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