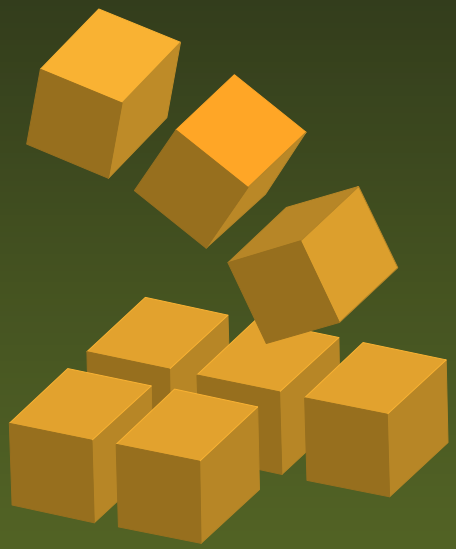
Translucent

Earth Abundant Materials Technology.



Integrated high reflectivity silicon substrates for GaN LEDs

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International Conference on Nitride Semiconductors- 9

Glasgow, UK

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Outline

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Introduction
- Problem
- Solution

Materials
- Epitaxial Rare Earth Oxide (REO) on Si (111)
- Lattice Engineering
- Applications

Mirrored Silicon for III-N LED industry
- Design of Embedded Mirrors on Silicon
- Growth by MBE
- Reflectivity

Conclusions

GaN Based LEDs

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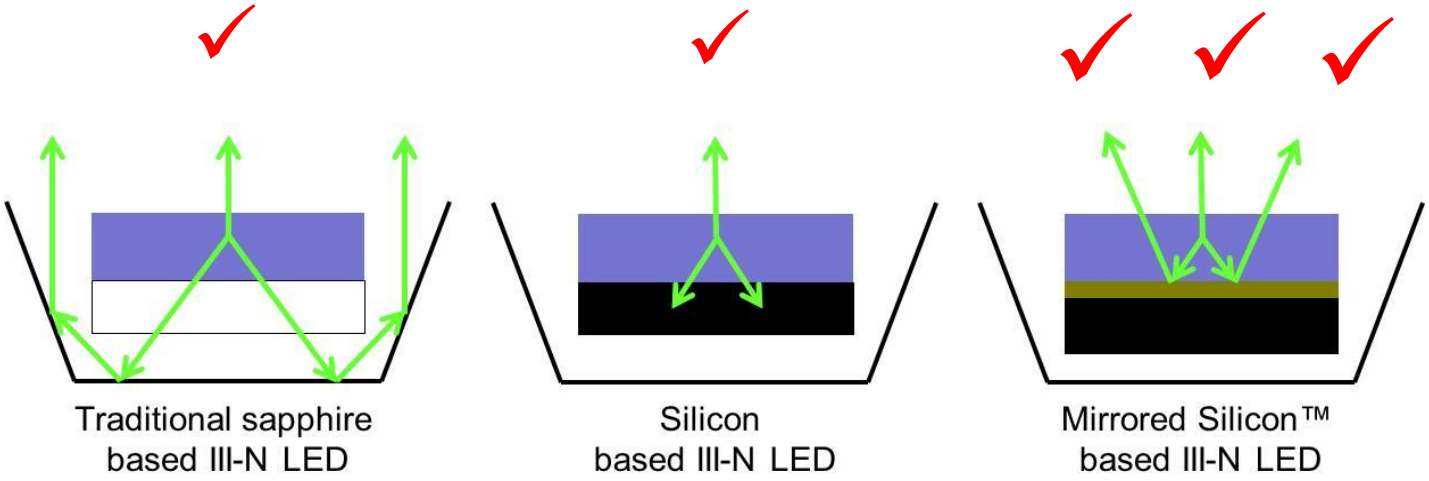
Problem: **Light absorption in silicon limits performance.**

Solution:

- **Mirrored Silicon substrate suitable for further GaN growth***
- **Rare Earth Oxide based Mirror solution possible**

HOW?



Solution: Embedded Mirror

Rare Earth Oxides (REO)

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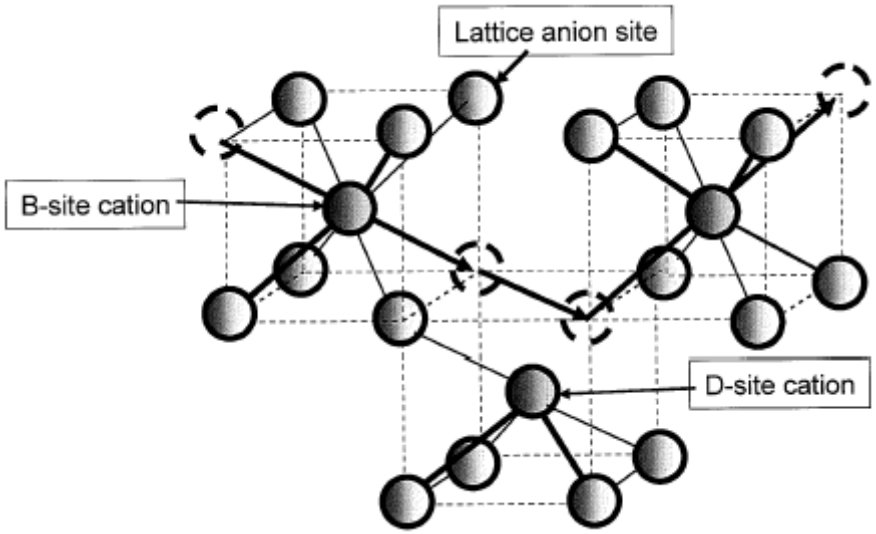
- Rare Earth Oxides (REO) RE: Gd, Er, Yb, Nd, Dy, Tb etc…
- Oxides of rare earth metals exhibit the “Bixbyite” structure.
- Space group Ia3, with 16 molecules per unit cell. Derived from the simple fluorite lattice by doubling the lattice parameter and leaving ¼ of the anion sites vacant
- Rare earth metals are earth abundant elements contrary to general belief.
- Growth of single crystal REO on silicon is possible due similar structural properties.



Anion Vacancy Ordered
Flourite crystal of type $RE^{3+}_2O_3$

REOs Have Cubic Crystal Structure

Materials- Rare Earth Oxides

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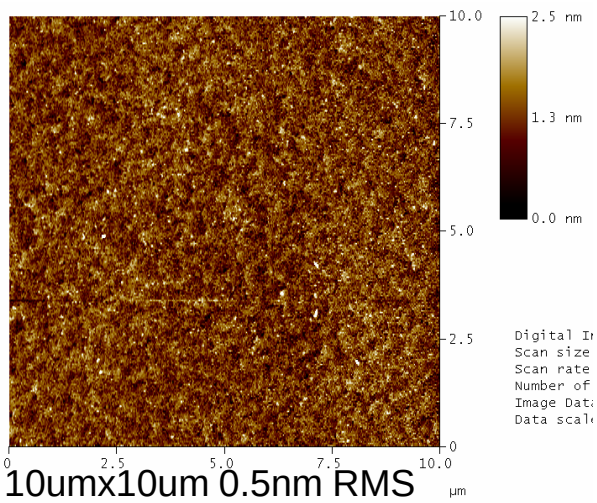
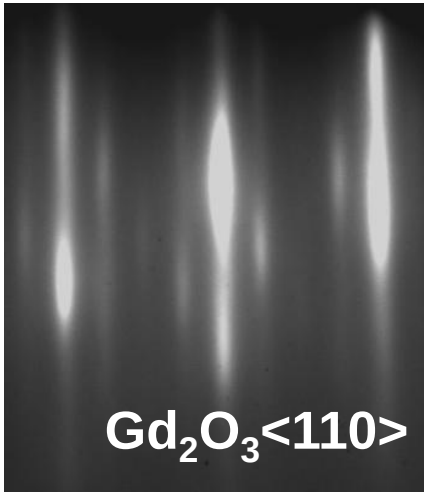
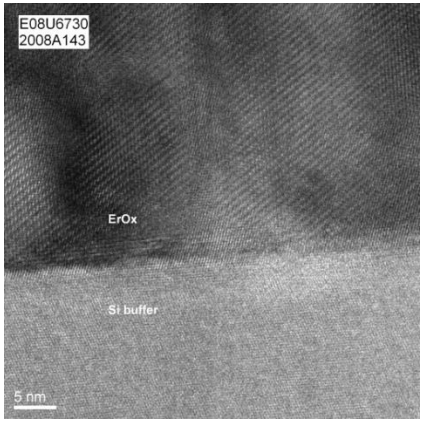
Simple process:
Metal + O_2 = oxide
Solid source **epi** (SSE)



10umx10um 0.5nm RMS





Epitaxial Growth of REO on Si(111) Possible

Lattice and Strain Engineered Oxides

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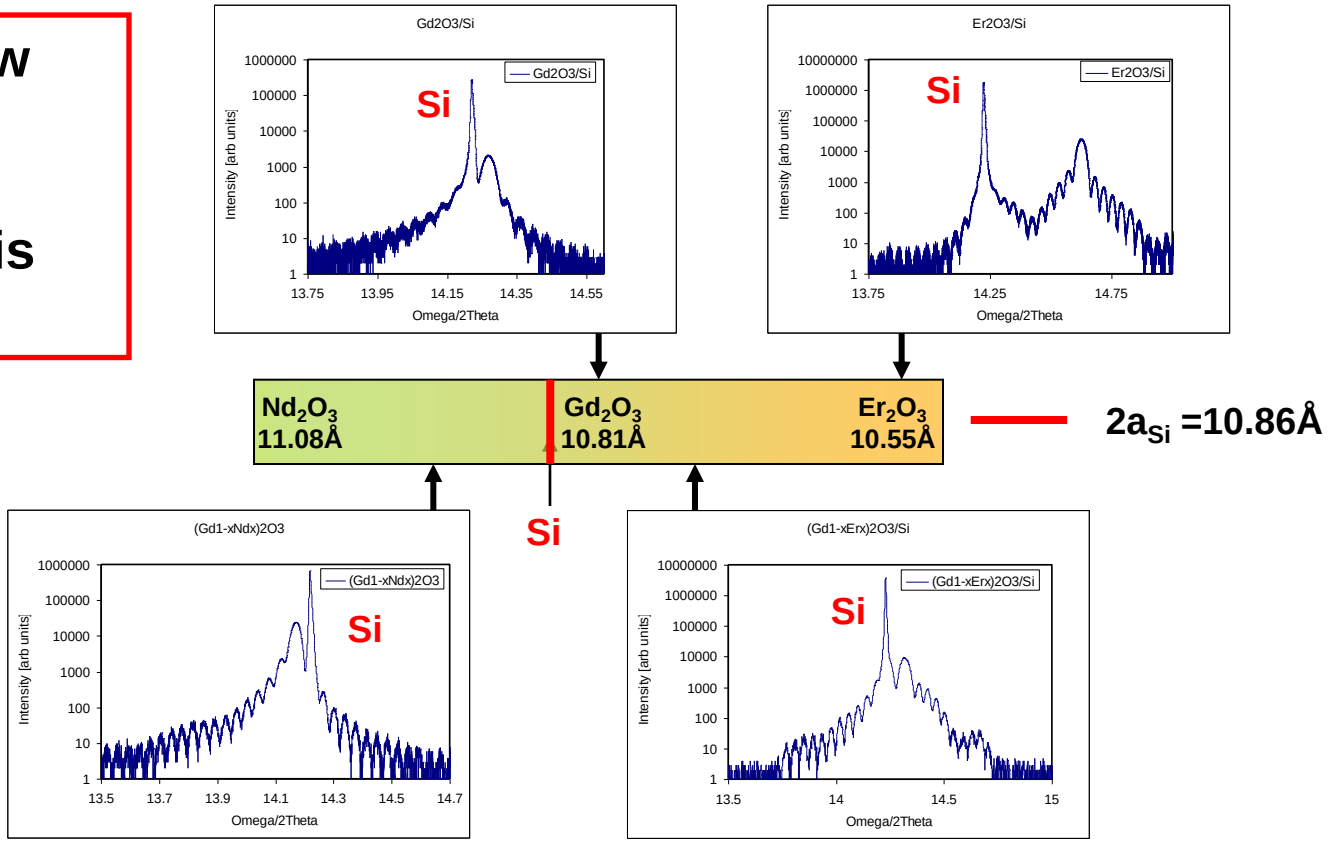
XRD Spectra show lattice parameter engineering possibilities in this material system.



Formation of solid solutions enable flexibility in tuning the lattice parameter of the oxide to match that of silicon.

Oxide Can be Tensile or Compressive Relative to Silicon

Engineered Substrates for GaN on Si

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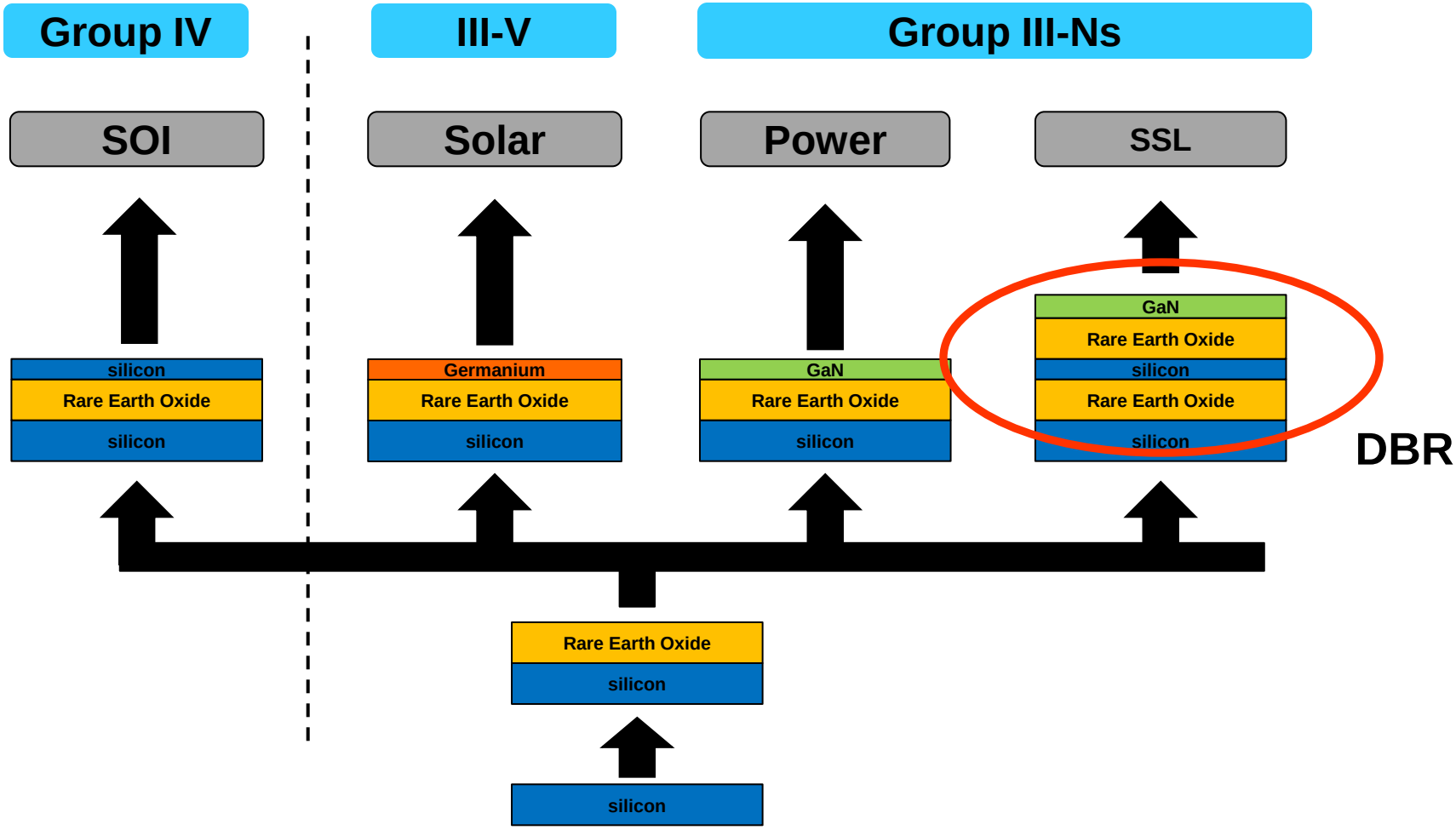

On-Silicon Platform Using REOs

Distributed Bragg Reflector

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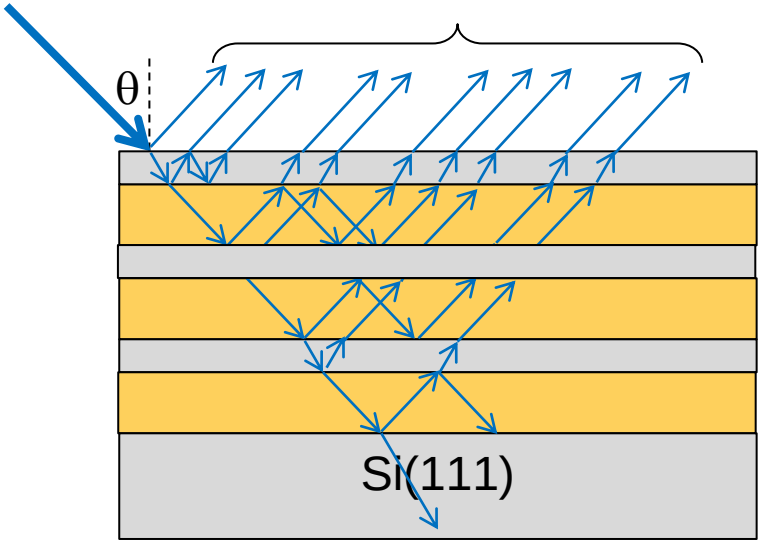
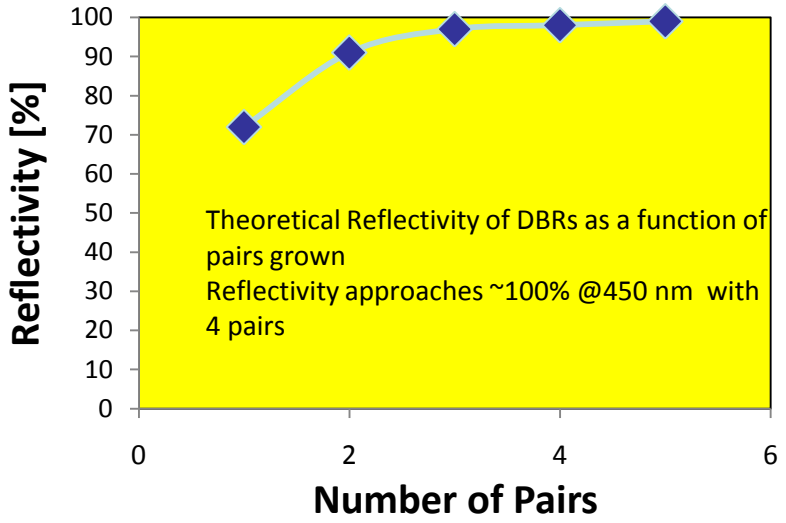
Incident **Reflected light**





- Three period DBR mirror sufficient for high reflectivity
- Large Δn between REO and Silicon is key factor for high reflectivity
- Large Δn allows wide stop band.

DBR Mirrors Over 98% Reflective

Crystalline Silicon-on-REO

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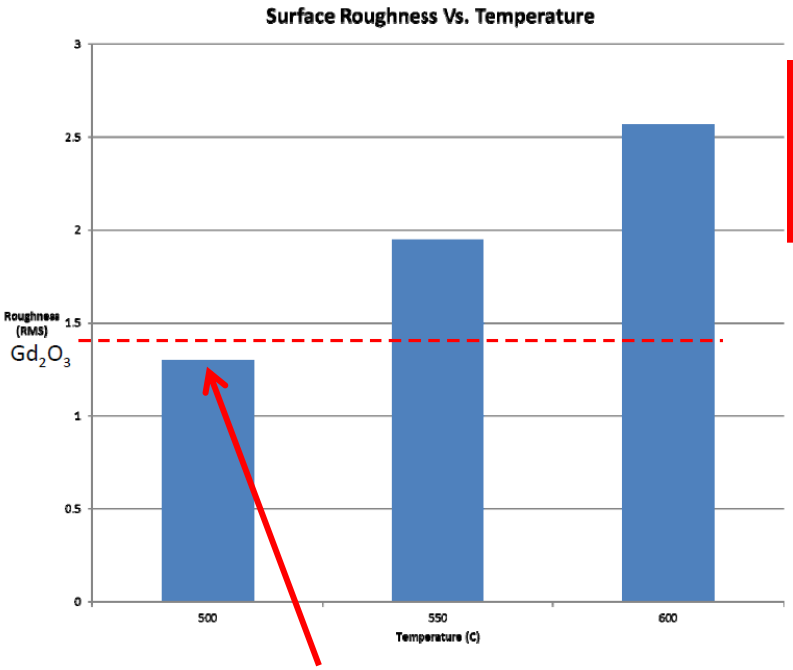
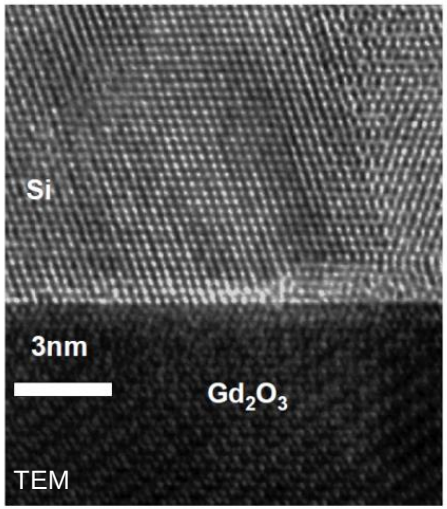
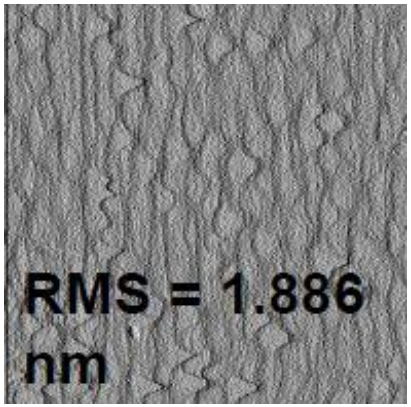


AFM results with Si epi on REO showing that the top silicon can be smoother than the REO

Excellent lattice matching





Source: ASU

Silicon Growth on Top of REO

Overgrowth of Si(111) on REO

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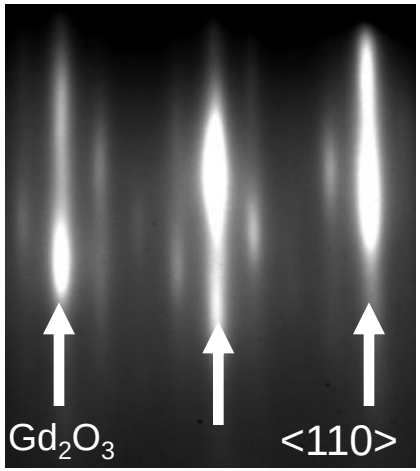
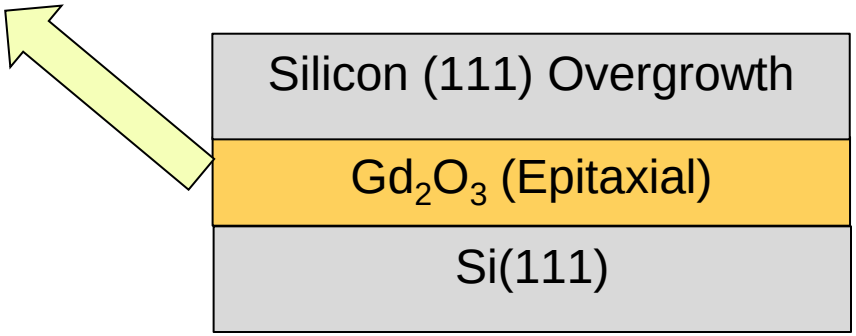


Material	Refractive Index (n)
Gd_2O_3	1.9
Silicon	4.25



Multi-Layer Growth Possible

Epitaxial GaN on Embedded Mirror

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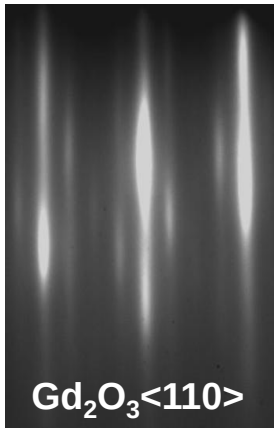
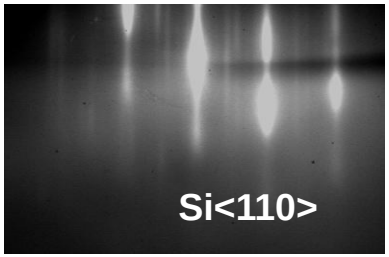
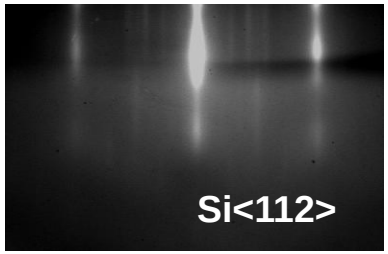
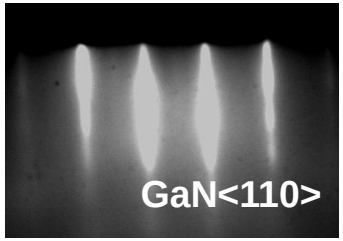
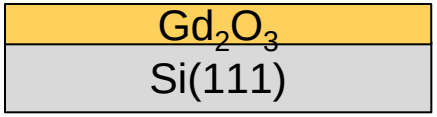


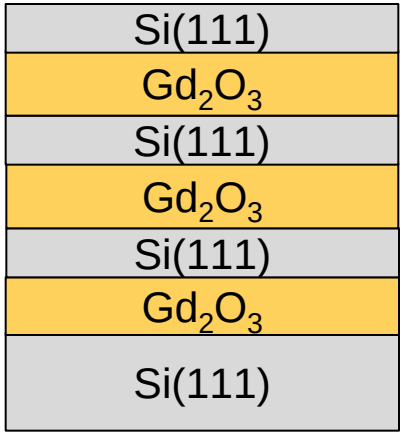




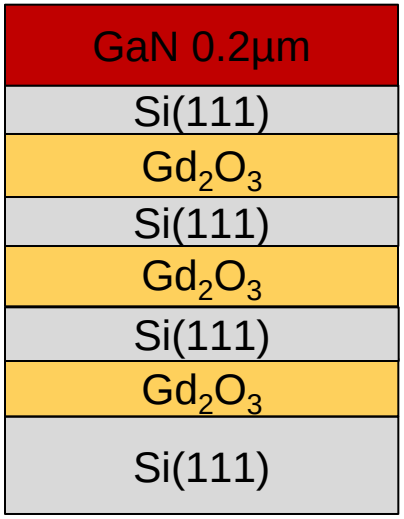




Gd_2O_3 on Silicon (111)



DBR on Si(111)



GaN on DBR

GaN Template on Mirror

Tunability of DBRs

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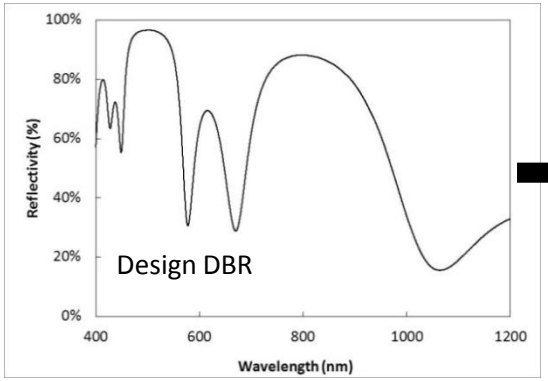
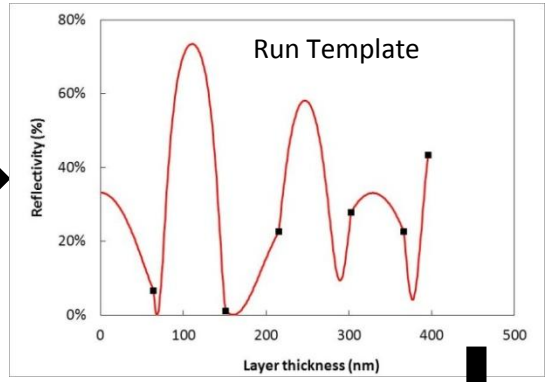
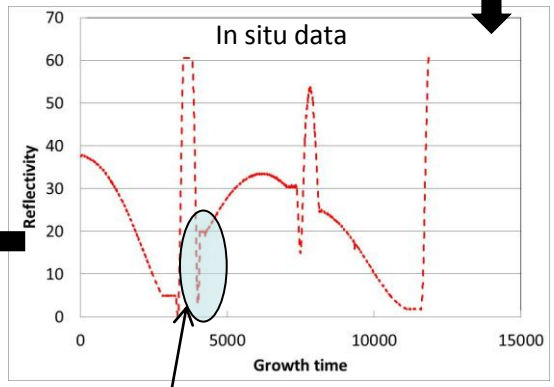


Start

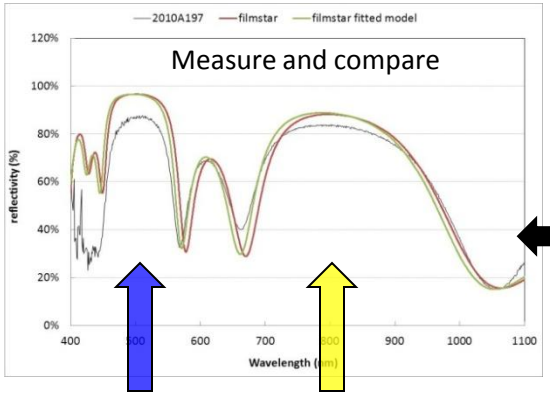


Layer by layer reflectivity data
Use to get end point %R for each layer
Calculated for 650nm, 15deg incident angle

Finish



Overshoot in 1st silicon layer



LED Phosphor

Plot of final measured R, original model and fitted model

Start = Finish

Structural Characterization

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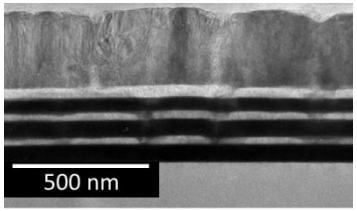
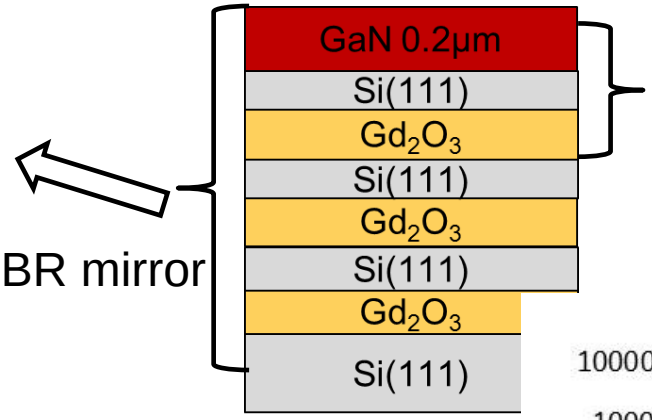
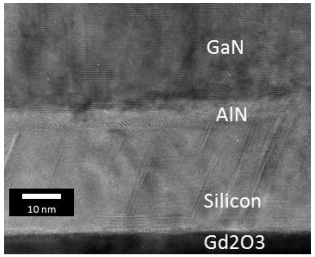
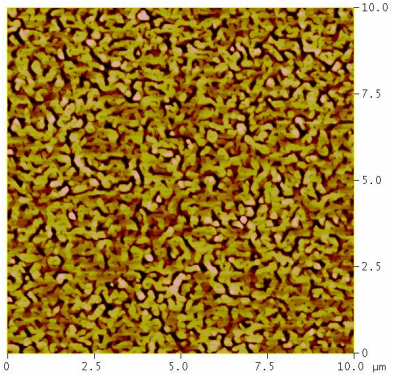
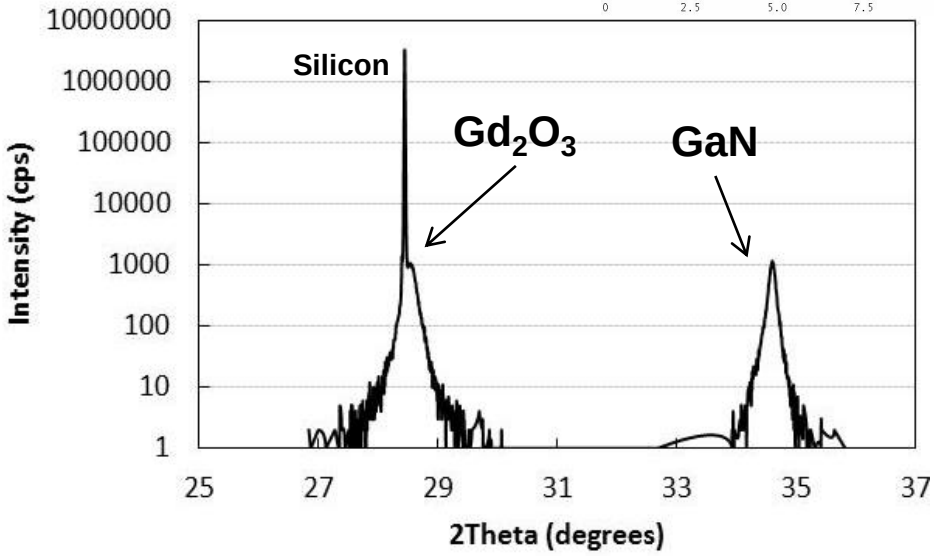


TEM of GaN on DBR mirror









- **XRD shows single crystal GaN on top of Mirrored Silicon™**
- **AFM scan show roughness of 6.64 nm with disconnected mesas**
- **GaN grown by MBE in-house is not optimized**
- **Further surface morphology optimization needed**

Structural Characterization Confirms Epitaxial GaN

Reflectivity Spectra

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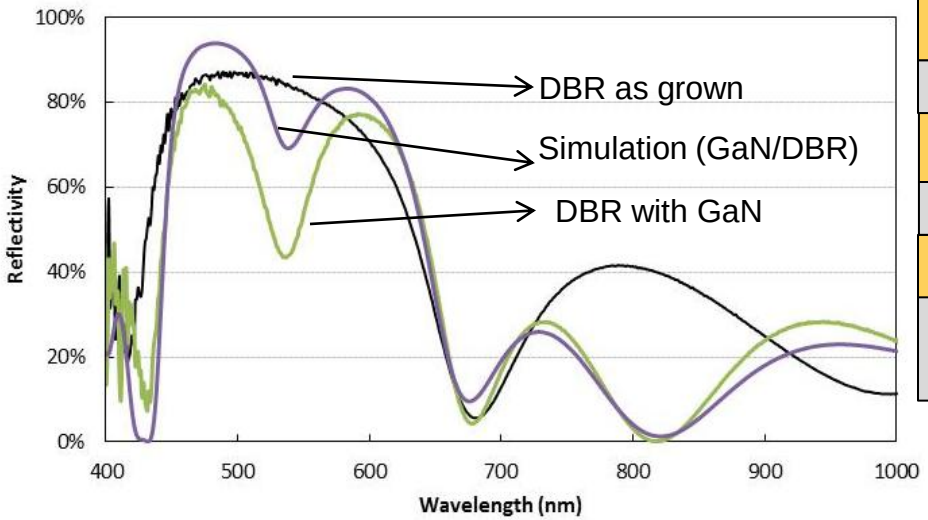
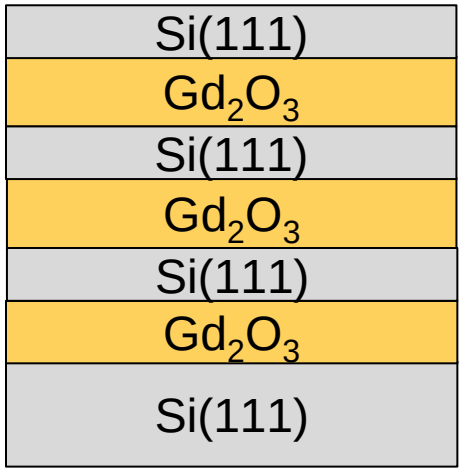
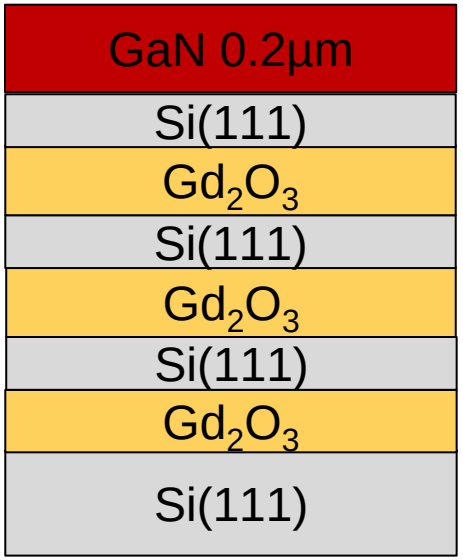
DBR Structure:
$(\lambda/4REO, \lambda/4Si)^2, \lambda/4REO, \lambda/4Si, 5\lambda/4GaN$





DBR as Grown



DBR with GaN

80% Reflective DBR with GaN Template

Angular Dependence

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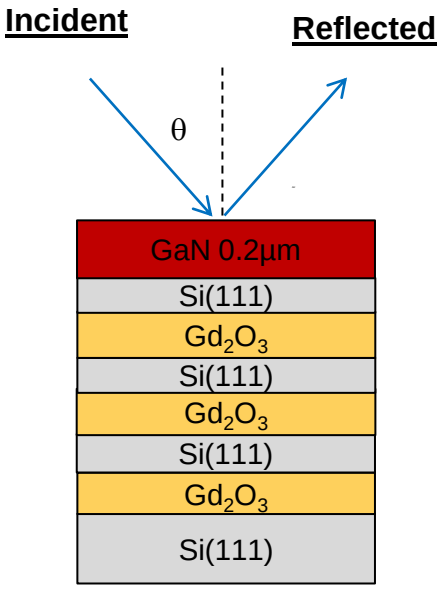
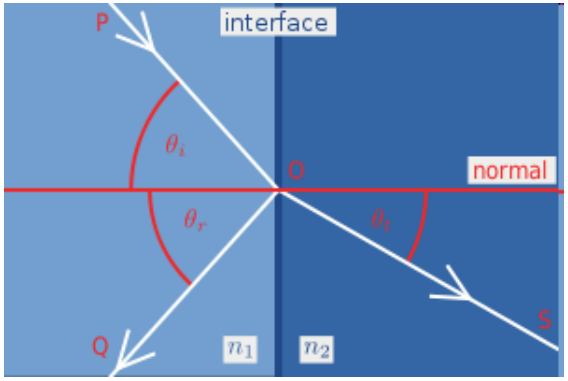
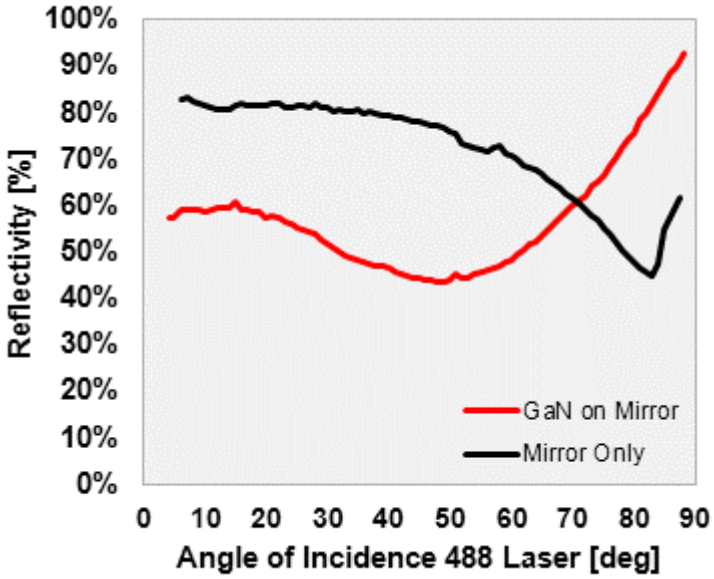
First generation mirror Reflectivity vs Angle







Angular Dependence Probed with 488 nm Laser

Device-Ready Substrates for LEDs

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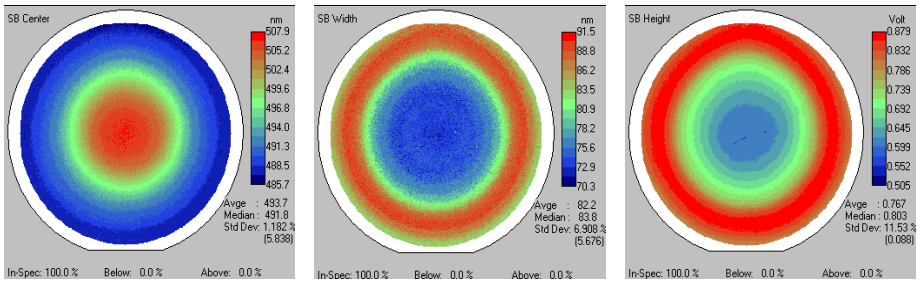
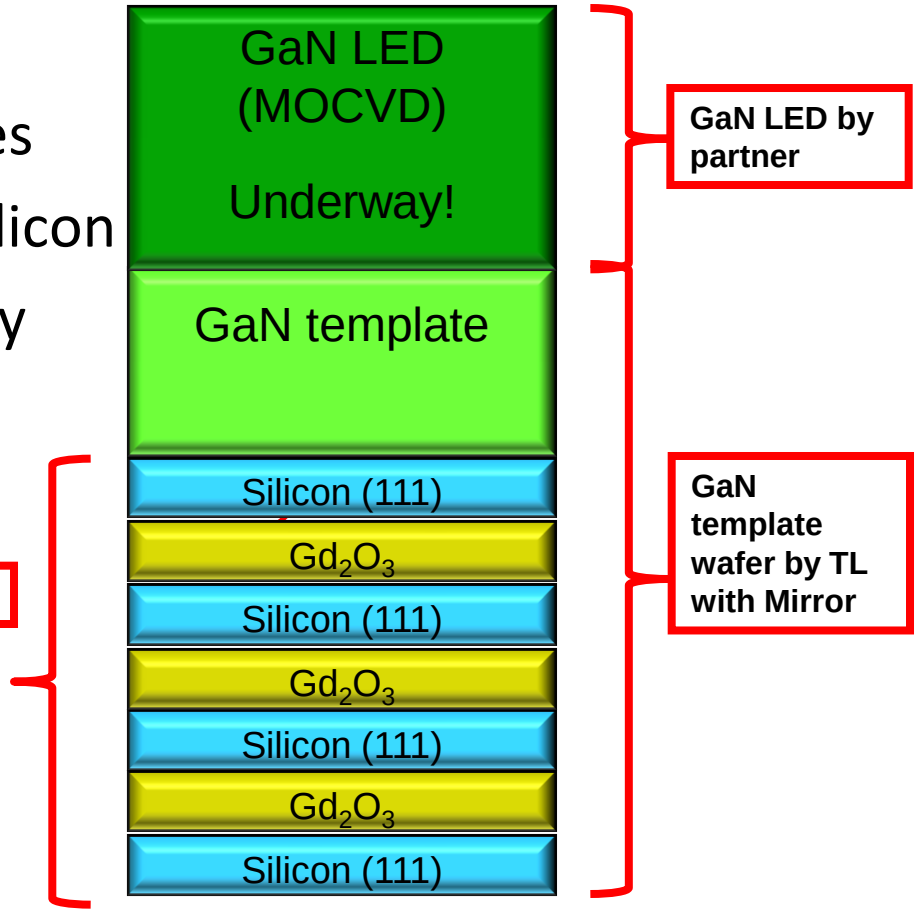
- DBR mirrors are single crystal and lattice matched to silicon substrates
- Mirrors reflect light absorbing in silicon
- Growth of LED structures underway
- Interested partners also welcome





DBR Mirrors Lattice Matched to Si Wafers

Conclusion

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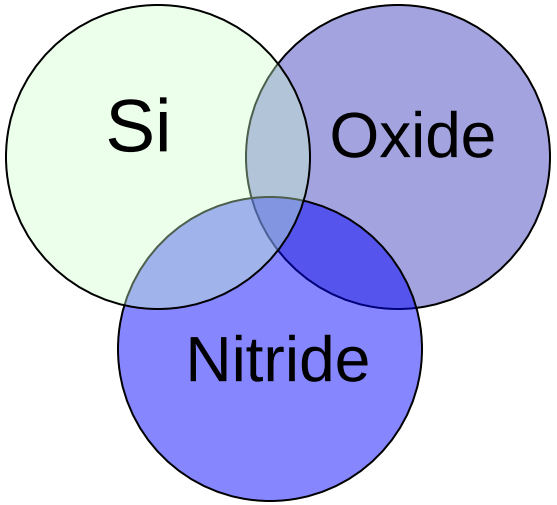
- “On-silicon” solutions available through Rare Earth Oxides
- Mirrored silicon provides embedded reflectors for GaN Based LEDs.
- REOs can be used for lattice and strain engineering
- Field screening for GaN power devices possible
- REOs can be used as high-k dielectrics to passivate GaN
- 3x100mm or 1x200 mm systems currently in operation



Engineered GaN on Silicon Using Oxides

Rare Earth Metals- Abundancy

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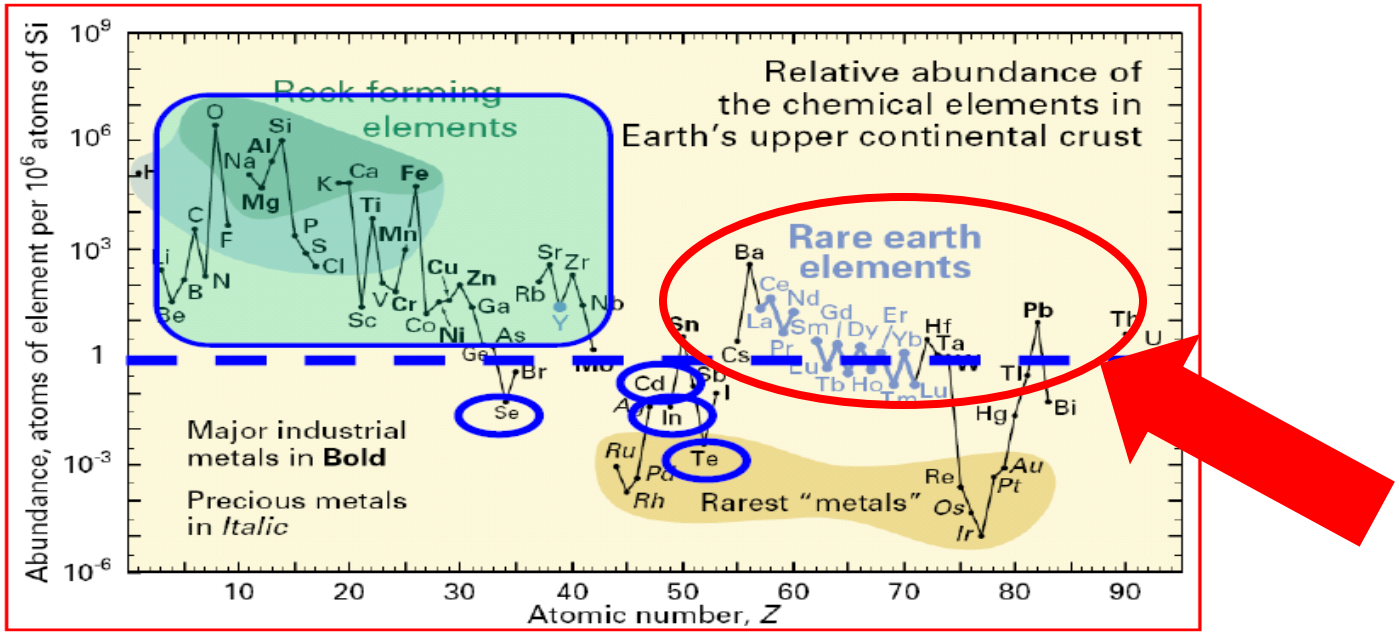
Relative abundance of elements vs. atomic number*



**from P.H. Stauffer et al, Rare Earth Elements - Critical Resources for High Technology, USGS (2002)*

Rare Earth Metals are Actually Abundant…