Translucent

Earth Abundant Materials
Technology.

Crystalline

Rare Earth Oxide

Crystalline rare earth oxides are an interesting subset of the materials initially developed for high k dielectrics. At a time when earth abundance is an important consideration in the selection of material, published data shows that the rare earths are as abundant as other common industry accepted elements such as Hf, Ga and As [1]. Whereas amorphous rare earth compounds are known to be hydroscopic, the crystalline versions of the same materials are not. The fact that crystalline rare earth oxides (cREO™) are lattice coincident on silicon and can be epitaxially grown on silicon substrates (preferred orientation is <111>, with <100> and <110> under development) is the driving force for developing this class of dielectric materials.

What is lattice coincident? As is shown in figure 1, in the case of the cREO™ the unit cell of the oxide is equivalent to twice that of silicon. The rare earth series (lanthanides) within the periodic table encompass a number of elements, most notable Er (erbium), Gd (gadolinium), Nd (neodymium) and La (lanthanum), each with a slightly different sized unit cell. Despite the complex nature of the crystal it is fundamentally of a cubic nature, hence its compatibility with silicon, another cubic material

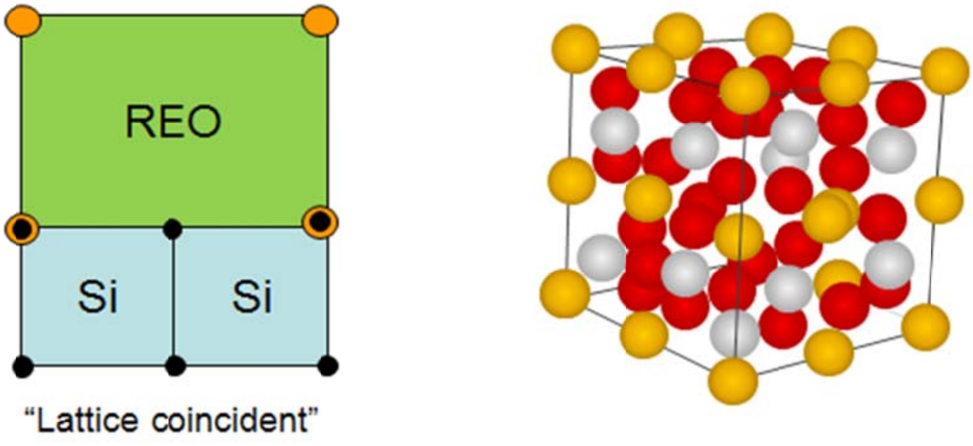
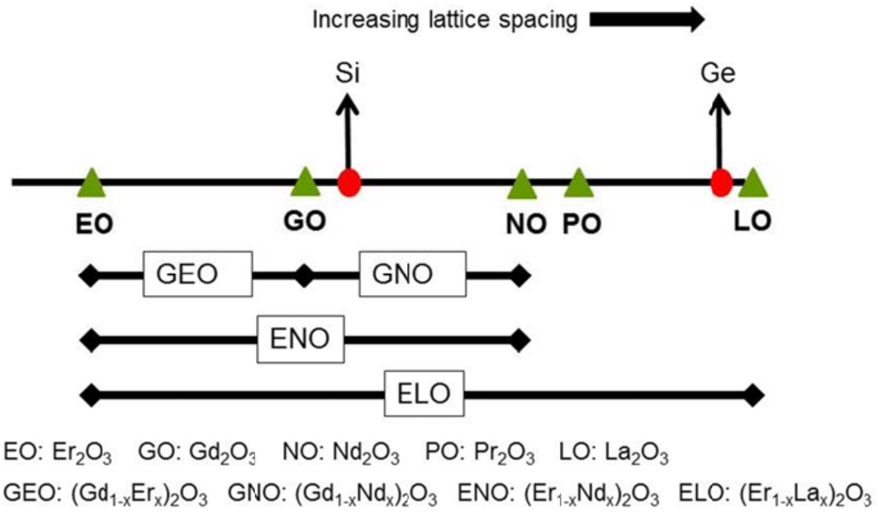


Figure 1: Concept of lattice coincident and the crystalline model for cREO™

By combining two of these rare earths in a ternary cREO™ the dielectric can not only be made lattice coincident to silicon but also potentially to Ge. Figure 2 shows the relative lattice spacing for both binary and ternary oxide options relative to the unit cell of Si and Ge.



EO: Er_2O_3 GO: Gd_2O_3 NO: Nd_2O_3 PO: Pr_2O_3 LO: La_2O_3
GEO: $(Gd_{1-x}Er_x)_2O_3$ GNO: $(Gd_{1-x}Nd_x)_2O_3$ ENO: $(Er_{1-x}Nd_x)_2O_3$ ELO: $(Er_{1-x}La_x)_2O_3$

Figure 2 – Alignment of cREO and group IV semiconductors

Figure 3a includes X-ray diffraction data for a range of binary and ternary oxides confirming both the crystallinity of the material and the tunability of the oxide lattice relative to that of silicon. Figure 3b shows similar data but for a set of $(Er_{1-x}Nd_x)_2O_3$ oxides precisely lattice engineered to match various SiGe compositions, as indicated by the vertical graduations which are in units of "10% Ge" starting at 10% (ie $Si_{0.9}Ge_{0.1}$).

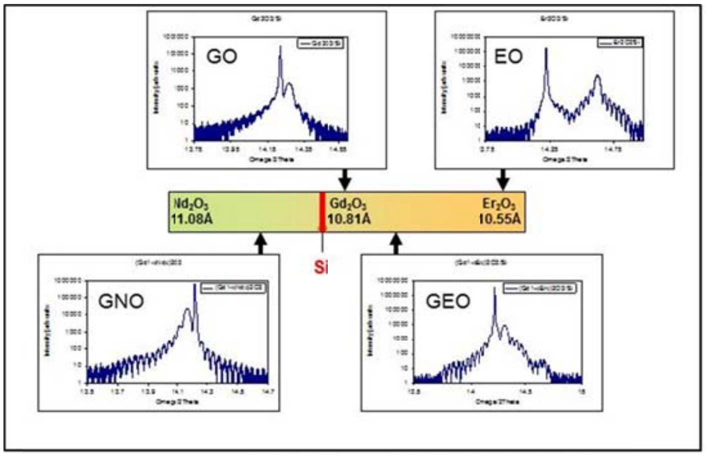


Figure 3a – Lattice Engineering

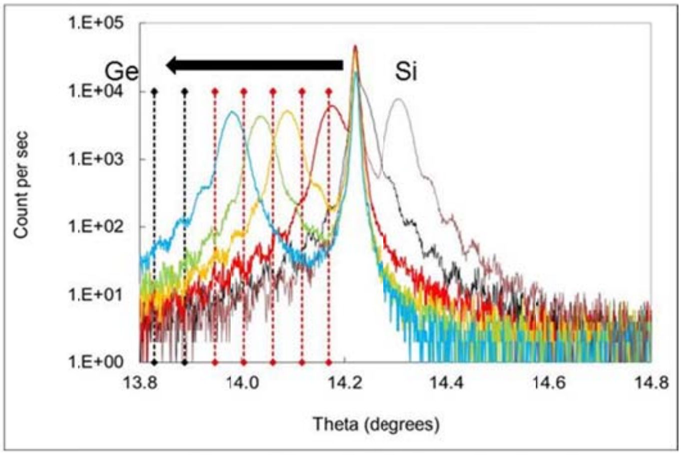


Figure 3b – ENO Lattice Engineering

The growth method employed to produce cREO™ on silicon is solid source epitaxy that uses 5N rare earth metals and O_2 as the source materials, in a vacuum of ~10^{-6} torr. Typical thermal budget for the process is 750-900degC. The process specific reactors are designed according to standard tool design rules in silicon CMOS fabs and are maintained as per typical production fab procedures. The process can be scaled today to 200mm, and supports in-situ monitoring (RHEED, reflectometry) for real time control of the epitaxial growth.

TEM studies of the crystalline oxide on silicon highlight one of the key differentiators between these oxides and some of the other high k dielectrics currently in manufacturing development, namely the suppression of interfacial oxide. As can be seen in the TEM of figure 3, the oxide (in this case Er_2O_3) exhibits a sharp interface with the underlying silicon and there is no observed silicate in between the substrate and the cREO.

Figure 4

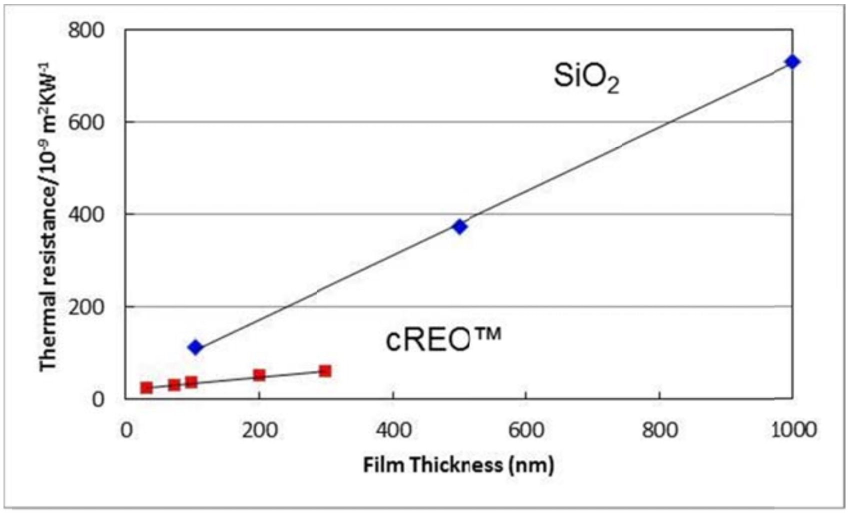
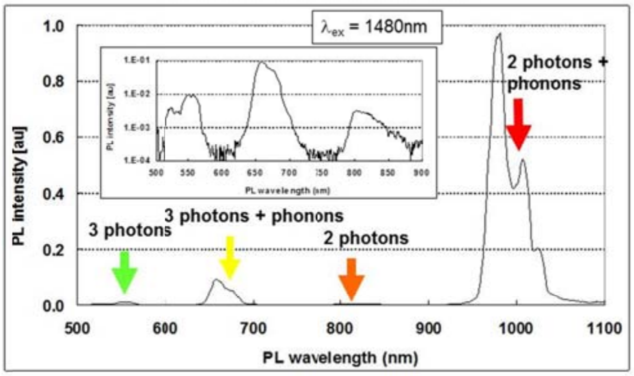


Figure 5: thermal resistance data

From a mechanical perspective the other oxide property of substantial interest is its thermal conductivity. In measurements done both internally and verified by leading experts in the field, the cREO™ was shown to have a bulk thermal conductivity >3x that of thermal SiO_2. In the plot of figure 5 a lower slope is indicative of better thermal conductivity whilst the smaller intercept for cREO™ is representative of this materials lower, interface thermal resistance with the underlying silicon substrate.

A number of the ternary alloys also exhibit interesting optical properties. With cREO™ the crystallinity is used to control the placement of the RE metal, thereby avoiding the quenching phenomena observed in RE implanted technologies. The characteristics of the cREO emission are predominantly the same as the RE metal, i.e. Er in $(Gd_{1-x}Er_x)_2O_3$ still has dominant PL emission at 980nm and demonstrates the same up conversion properties first observed in erbium doped fiber amplifiers (see figure 6). Further details on the optical properties of crystalline rare earth oxides can be found at www.Translucentinc.com/Applicationnotes/Opticall Properties of cREO™.pdf



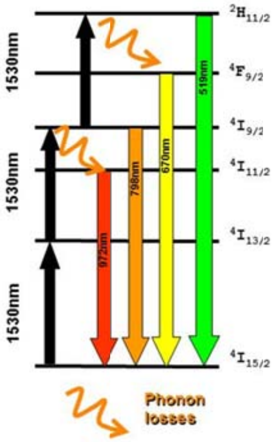


Figure 6: Photoluminescence from Er in $(GdEr)_2O_3$

Having grown a high quality crystalline oxide what then? Under the right growth conditions the oxides can support the growth of additional semiconductors and other dielectrics, for example silicon, opening up the potential for "on-silicon" platform technologies as shown in figure 7 and various virtual substrates and templates as shown in figure 7 and described further in application notes located at www.translucentinc.com/media

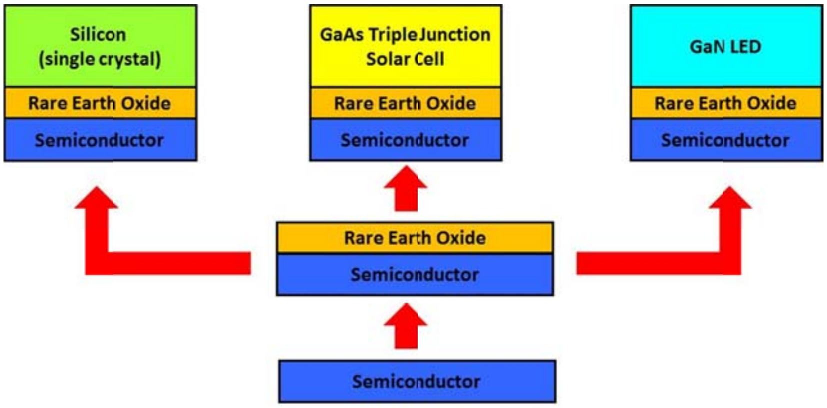


Figure 7: "on-silicon" platform technology

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[1] – P.H. Stauffer et al, Rare Earth Elements – Critical resources for high technology, USGS (2002)