GE Healthcare

Gemstone – The Ultimate Scintillator for Computed Tomography

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Introduction

Gemstone™ is the newly developed scintillator from GE Healthcare. This material is a complex rare earth based oxide, which has a chemically replicated garnet crystal structure. Its superior performance characteristics over all existing CT scintillators enabled the successful launch of GE Healthcare's Discovery™ CT750 HD – an ultra premium CT product that delivers incremental clinical value to the diagnostic imaging community.

The demand for new CT technology has been accelerating. Customers are asking for higher image quality (spatial and contrast resolution), higher temporal resolution, faster patient workflow and lower dose. To reinvent the CT to set new clinical standards, GE Healthcare realized it had to start by redesigning the only element that had not changed within the past 20 years, the scintillator, thus, securing a technological leadership position. Eight years of research and development and a state-of-the-art, multi-million dollar clean room production facility have yielded a new CT scintillator with unprecedented performance and jewel-like material properties. The Gemstone detector platform was designed to exceed today's demanding needs as well as meet any foreseeable future requirements (Figure 1).

Research and development

GE has been at the forefront of developing transparent ceramics since 1959, when Robert Coble invented Lucalox (translucent aluminum oxide), which enables long-life, sodium vapor lighting. GE Healthcare also has a long history in the development and commercialization of transparent ceramics with the invention of the first polycrystalline CT scintillator. In 1988, GE released the first CT system with a ceramic scintillator, the HiLight, which was specifically designed to fill the performance gaps of cadmium tungstate. The origins of HiLight are over 35 years old and started with the pioneering work on the first ceramic laser. GE demonstrated that afterglow and radiation damage may be controlled with precision doping of the ceramic material. GE's release of Gemstone in November 2007 builds on decades of knowledge and experience at GE Healthcare and GE Global Research Labs.

The research on Gemstone began in October 2000, with the simple vision of delivering a CT detector that would provide a step-change improvement in image quality over the competitors in the market. By the end of 2001, GE examined over 150,000 possible material compositions and processed hundreds of unique compositions to converge on the origins of Gemstone. It took a full three years and more than $3 million in research to obtain a composition close to today's Gemstone performance. In late 2004, GE Healthcare started a pilot facility in Milwaukee. The pilot facility was later expanded to a $30 million state-of-the art, clean-room, full-scale manufacturing facility (Figure 2).

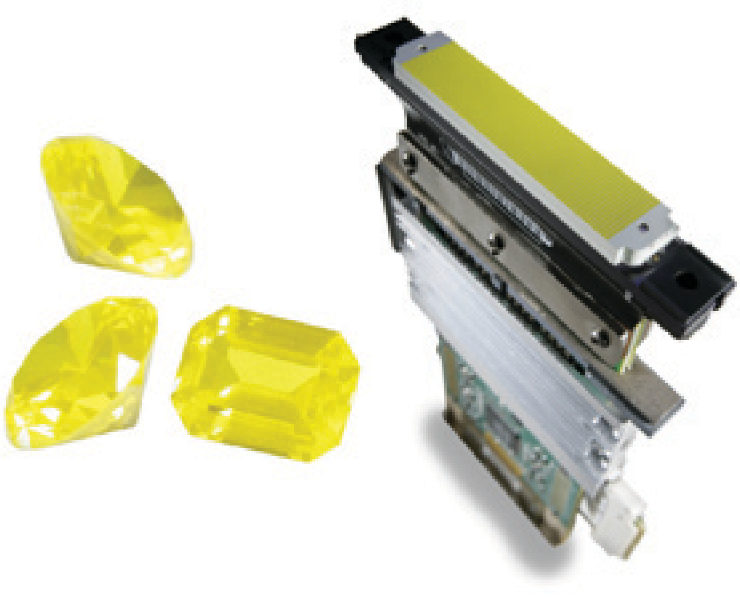

Figure 1. Gemstone scintillator material and detector module for Discovery CT750 HD

Figure 2. Partial view of the Gemstone scintillator synthesis facility at GE Healthcare

In late 2006, systems engineers began to leverage the unprecedented speed of Gemstone with seemingly unthinkable applications like fast energy switching and oversampling. The Discovery CT750 HD system equipped with Gemstone scintillator is capable of acquiring 2.5 times as many views per rotation at same rotating speed when compared to previous generation CT product. The significantly increased amount of information enhances the spatial resolution and enables electronically switching tube energies from 80 kVp to 120 kVp to acquire dual-energy images with a single X-ray tube during operation. Gemstone spectral imaging is accomplished with a single X-ray source that enables temporal registration of the dual-energy samples at 0.5 msec, which equates to 165 times faster than a dual-source CT scanner with tubes 90 degrees apart. Because Gemstone Spectral Imaging uses a single tube, single detector design, it delivers a full 50 cm material decomposition scan view.

Materials and manufacturing process

Material selection

The primary goal for this new scintillator is to have very fast speed while meeting other performance requirements. After evaluating hundreds of thousands of materials as potential candidates, we finally selected a rare earth-based garnet material as the new scintillator. This material has a cubic garnet structure that can enable high transparency without having to grow a single crystal. Cerium is selected as the activator to leverage its fast transition and its emission spectra, which is well matched to the silicon photodiode's sensitivity curve. Heavy rare earths are selected to increase stopping power of the scintillator to achieve higher quantum detection efficiency. Extensive research was conducted to optimize the composition in order to achieve the best performance for CT applications. The final composition of this material not only delivers performance, it also enables a robust manufacturing process. Moreover, this material provides a scalable platform for future technology upgrades.

Process design

A ceramic process was selected to produce the Gemstone scintillator. A CT scintillator material needs to have reasonable transparency in order to achieve good light output. For this purpose, one can choose to grow a single crystal via a melt-crystallization process or to sinter a transparent ceramic from highly engineered sub-micron powders. For example, $CdWO_4$ is a single crystal scintillator.

Compared to a single crystal, ceramic scintilators have a lot of advantages. First, a ceramic scintillator has much lower cost. Single crystal growth requires very high temperature and expensive crucibles. Additionally, the throughput for single crystal processes is usually very low. These issues with single crystals lead to very high investment, high-energy cost and other higher operating expenditures.

Second, a ceramic scintillator has much higher material uniformity, which is required for good CT image quality. The high uniformity is particularly important for controlled doping that is often required to reduce afterglow and increase radiation hardness. The required dopant levels are often in the 10 to 100 ppm levels and must be tightly controlled. The ability to arbitrarily dope nearly any composition with nearly ppm precision and uniformity is only possible with ceramics.

Third, for a ceramic scintillator material, the concentration of the activator dopant is not limited to low concentrations and hence low efficiency, and is also uniform from part to part. This is not achievable in single crystals due to the inherent concentration gradients that occur along the growth direction of the crystal. Lastly, a single crystal scintillator is more difficult to machine due to the cleavage planes.

GE is an industrial pioneer in transparent ceramic design and processing, and possesses the best talent in this area. HiLight is the first successful commercial transparent ceramic scintillator. The success of HiLight is attributed to the perfect combination of knowledge in both high performance phosphors and transparent ceramics. This knowledge and decades of experience resulted in the successful development of Gemstone.

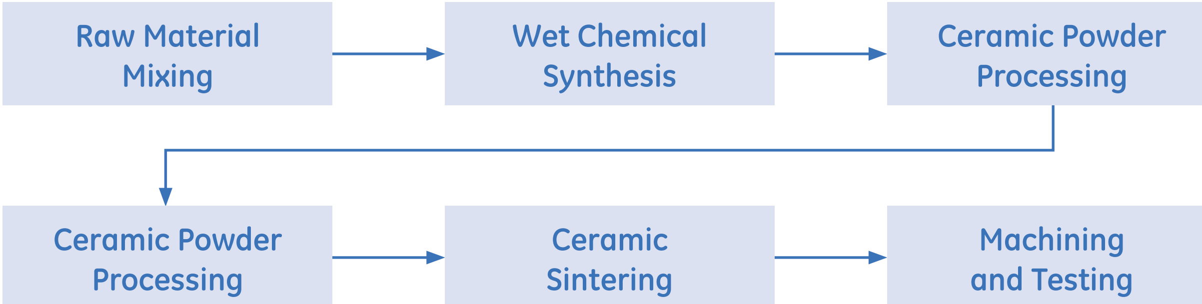

Figure 3. The key processing steps for Gemstone scintillator

Figure 3 shows the key processing steps for Gemstone scintillator material. All processes were developed to tailor the unique behavior of the material, maximize the performance of the scintillator and ensure manufacturing robustness. Wet chemical synthesis was employed to ensure the homogeneous mixing of the component elements at the atomic level, which in turn, provides the best material uniformity. A unique powder process was invented to control the powder agglomeration and particle size distribution, so the ceramic is highly sinterable and free of contaminants that may decrease its performance. A novel sintering process was developed to deliver the ultimate in highly transparent ceramic scintillators. Gemstone has high light output, very low afterglow and almost undetectable radiation damage.

Figure 4. A portion of the state-of-the-art quality control equipment

During the process development, GE's Six Sigma methodology such as DOE, Robust Design and Optimization was widely used to drive innovation and efficiency.

In order to produce a highly consistent quality scintillator, we developed and implemented many in-process measurements and characterization techniques to control the manufacturing processes. These measurements provide real time feedback of the process outputs and enable the engineers to reliably predict the quality of the product. Figure 4 shows some of the state-of-art quality control equipment.

Superior performance attributes and clinical values

Primary speed

Primary speed is critical to image quality. When the decay is slower, there is more information carry-over from view to view and from voxel to next neighboring voxels. The information carry-over will blur the image and reduce resolution. Software correction is employed for slower scintillators to deal with this problem, but there is a penalty of increased noise or reduced signal to noise ratio. These effects are minimized with the speed of CT750 HD Gemstone scintillator.

Primary speed describes how fast the scintillator responds to X-ray excitation. Primary speed includes two components: the rise time of the output signal in response to a constant X-ray input, and the fall time for the first component of exponential decay of that output after the input is turned off. Usually the rise time is on the order of a few nano-seconds, so the focus is primarily on the decay component. The scintillation decay is described by equation 1 as follows:

$$I = I_0 \exp\left(-\frac{t}{\tau}\right) \quad (1)$$

Scintillator	Primary speed
Gemstone	0.03μs
GOS (Gd_2O_2S)	2μs

where I_0 is the initial light intensity with constant X-ray source excitation, I is the light intensity at time t after the X-ray source is turned off, τ is the primary decay time constant or primary speed.

With a decay time of only 0.03 μs, Gemstone is 100 times faster than GOS and is the fastest scintillator in CT industry.

The extremely fast speed of Gemstone enables many new CT applications that provide desired clinical values to CT customers. For instance, the Discovery CT750 HD built on the Gemstone platform is capable of faster sampling and dynamic focal spot deflection, thus significantly improving the spatial resolution. It also has the capability of fast KV switching – dynamic switching between two different energy levels of X-rays during a single rotation. With fast KV switching or dual "energy imaging, one can perform material decomposition, monochromatic imaging, etc. These capabilities bring a series of revolutionary applications in cardiology, oncology and other diagnostic imaging areas without the trade-offs associated with dual tube and dual detector designs.

In addition, the exceptional fast speed of Gemstone makes it possible to design future CT systems with faster rotation and higher viewing rate without any correction, thus enabling high temporal resolution as well as spatial resolution and better image quality. It provides a long-term platform that one can continuously build new technologies and capabilities for many years or decades to come.

Afterglow

Afterglow is one of the most important properties of a scintillator that will have direct impact on image quality. Higher afterglow leads to image artifacts and higher noise.

Afterglow is the secondary time component of the exponential decay of the output after the X-ray source is turned off. In practical terms, afterglow refers to the remaining light from the scintillator at several milliseconds or longer since the X-ray source is turned off. Afterglow caries a part of the signal from one view and passes into next views during scanning. Therefore, high afterglow without correction will cause arching artifacts extending from low attenuation anatomy into areas of higher attenuation and will decrease in-plane spatial resolution. In order to achieve good image quality, low afterglow is desired.

Compared to GOS, Gemstone has much lower afterglow. At 40ms, the afterglow of Gemstone is 0.001%, only 25% of GOS. This very low afterglow of Gemstone will enable higher spatial resolution and lower image noise. The high image quality can contribute to improved low-contrast detectability and potential lower dose applications.

Scintillator	Afterglow (40ms)
Gemstone	0.001%
GOS (Gd_2O_2S)	0.004%

In general, afterglow results from the electronic defects that are associated with material composition and processing. Such defects act as traps for the excited electrons and delay the charge/energy transfer to the luminescence centers and lead to a small portion of light that decays slower than the primary component. The low afterglow of Gemstone is a result of deeply understanding the dependence of scintillation properties on the material composition and processing parameters. Over the years, systematic studies have been carried out to build a transfer function between afterglow and the chemical composition using DOE techniques. Similar studies were also done on the various processing techniques. As a result of such optimization, the defects are minimized and the lowest afterglow for a commercial CT scintillator has been achieved for Gemstone.

Radiation damage

When exposed to high-energy photons such as X-ray, many high-energy electron-hole pairs are created. The transfer of this energy from atoms (or ions) to atoms can generate many defects such as vacancies, interstitials, or atomic displacement. A certain amount of such defects will not be healed in a short time and will cause darkening of the scintillator material. This darkening results in optical self-absorption of the light generated by scintillation and causes a shift in gain or a shift in light output for a given X-ray exposure. High radiation damage will require frequent calibration. It may also cause Z-axis non-uniformity, and thus images will have ring and spot artifacts when scanning anatomical regions with high variation along the Z-axis such as the top of the head.

Considerable attention to composition and process optimization has ensured that Gemstone remains completely stable under exposed CT dose levels. As shown in Table 2, Gemstone is fully 20 times less sensitive to radiation dose or 20 times more stable than GOS.

Scintillator	Vendor	Radiation Damage (%)
GE Gemstone	GE	0.03%
GOS (Gd_2O_2S)	Siemens, Toshiba, Philips	0.65%

Table 2. The radiation damage of Gemstone compared to GOS.

Light output

Light output is an important scintillator characteristic because it directly affects the signal-to-noise ratio of the images at a given radiation dose. For CT applications, low light output can result in performance being electronic noise versus quantum noise limited for thin-slice, large-patient, and low-dose applications.

In a strict definition, light output is the number of light photons generated and subsequently collected at the photodiode per unit energy of X-ray photons. It is a result of scintillation efficiency, but also depends on the transparency of the scintillator and how the scintillator array is constructed and what reflector material is used. In practical CT system design, other performance characteristics such as crosstalk and quantum detection efficiency (X-ray stopping power) need to be considered along with optimizing light output. As a result, trade-offs will be made to optimize the system performance, not just light output. One needs to be aware of how the light output is measured because the reported light output value is highly dependent on the measurement itself. In the optimized scintillator array design for Discovery CT750 HD, the measured light output for Gemstone is about 5% higher than HiLight and less than 10% lower than GOS when measured with the same reflector. Practically, such difference is so small that the effective signal-to-noise ratio will not be affected by these differences. Therefore it is concluded that Gemstone has equivalent light output when compared to HiLight and GOS scintillators.

Emission spectrum and diode matching

Emission spectrum is the relative intensity distribution of light generated by scintillation as a function of wavelength. It is highly dependent on the luminescence center in the scintillator material. The luminescence center is created by the small amount of dopant elements. When considering the HiLight scintillator, Eu is the luminescence center and its emission is a relatively sharp peak at around 610 nm, thus matching the maximum silicon photodiode efficiency very well. In GOS, the emission from Pr has a peak at about 510 nm and is not as well matched as HiLight. In Gemstone, the emission is a broad peak from about 500 nm to 700 nm with a maximum at about 585 nm. This spectrum matches the silicon diode very well, thus providing very high conversion efficiency and light output.

Transparency and material uniformity

Similar to HiLight, Gemstone has a cubic crystal structure. In a polycrystalline ceramic material, the grains (or the smallest single crystallites) are randomly oriented. The grains sharing one grain boundary can have different crystalline orientation. For a non-cubic crystal structure as found in GOS, the refractive index is different along different crystal orientations, therefore resulting in light scattering at the grain boundaries. For this reason, ceramics such as GOS (hexagonal structure) can not be made fully transparent due to grain boundary scattering unless the grain size is small compared to the wavelength of interest (in the nanometer scale). However, this is not an issue for Gemstone and HiLight because they have isotropic refractive indices. Their cubic structure makes it possible to produce a fully transparent and uniform scintillator material. The tailored transparency for Gemstone results in high light collection efficiency and spectral linearity, and subsequently improves image quality by reducing spectral artifacts and increasing signal-to-noise ratio.

Chemical durability and mechanical properties

As a rare earth garnet ceramic, Gemstone has very high mechanical strength and hardness. This enables a high precision machining process to produce the pixelated scintillator array. More importantly, Gemstone is one of the most stable ceramic materials, and like any gemstone, it can maintain optical luster in nearly any harsh environment for geological timescales. Gemstone can withstand immersion in boiling water for unlimited life. Only very strong acid at very high temperatures can have a slight etching effect on Gemstone. It is also chemically and mechanically stable at a wide range of temperatures. In comparison, GOS is very sensitive to environmental conditions. Even during machining such as grinding or slicing, GOS will react with water from humidity and oxygen in the air to form H_2S gas and leave a white, opaque coating of gadolinium oxide and gadolinium sulfate on the surface. The lower fracture strength of GOS makes defect-free machining to fine pixels challenging. The superior mechanical properties and chemical durability of Gemstone will provide and ensure excellent stability for the life of the CT detector.

Manufacturability

Manufacturability describes how robust a process can be used to produce the material consistently. The robustness of the process defines the quality predictability as well as process complexity, cost, scalability, and flexibility. Gemstone scintillator is a pure oxide material. Although it requires a great deal of attention to control composition and other process parameters, Gemstone can be produced repeatedly in large quantities with consistent quality. There is no loss of any components during the process, thus the end composition is exactly what goes into the material at the beginning. Moreover, there is favorable flexibility in the Gemstone processing techniques. For instance, Gemstone is compatible with most of the net shape ceramic processes such as injection molding and gel casting. The net shape process can provide a finer pixel design with reasonable cost and quality.

In contrast, GOS suffers from its complex crystal structure and the volatile nature of sulfur, one of its primary ingredients. It is very difficult to retain the sulfur during the ceramic processing for GOS because sulfur tends to decompose, sublime, or simply evaporate from the material composition. A very complex process is needed to keep the sulfur in the material and it is even more challenging to maintain the correct ratio of sulfur in the final GOS ceramic scintillator. The process includes using H_2S atmosphere during sintering, which is a challenge to prevent corrosion of furnace equipment and to ensure safety for personnel. As previously mentioned, the hexagonal crystal structure with anisotropic indices of refraction of GOS makes it very difficult to achieve reasonable translucency. Very strict control of particle size during powder synthesis is required for GOS. As a result of above-mentioned drawbacks, the batch size of GOS is usually limited and the consistency of quality is not easy to maintain. Additionally, the processing techniques for GOS are not compatible with any of the above-mentioned net shape processes, thus any future direction toward finer pixels as a function of scintillator array design will be completely dependent on machining processes.

Summary

As the newest CT scintillator, Gemstone has succeeded in meeting the goals defined by the GE CT business in October of 2000 – to deliver a CT detector that provides a step-function improvement in image quality over anything in the market. It enables the launch of GE's Discovery CT750 HD – a revolutionary ultra-premium CT product that has many new exciting capabilities in cardiology, oncology, and low-dose applications, as well as supports advanced acquisition techniques such as dual-energy imaging, etc. Gemstone's superior performance meets any foreseeable future requirements for a CT scintillator and provides a long-term platform upon which many new designs and new technologies can be built for years or decades to come. Gemstone is truly an imagination breakthrough and a great example of GE's commitment to innovation and focus on customer values.

Healthcare Re-imagined

GE is dedicated to helping you transform healthcare delivery by driving critical breakthroughs in biology and technology. Our expertise in medical imaging and information technologies, medical diagnostics, patient monitoring systems, drug discovery, and biopharmaceutical manufacturing technologies is enabling healthcare professionals around the world to discover new ways to predict, diagnose and treat disease earlier. We call this model of care "Early Health." The goal: to help clinicians detect disease earlier, access more information and intervene earlier with more targeted treatments, so they can help their patients live their lives to the fullest.
Re-think, Re-discover, Re-invent, Re-imagine.

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