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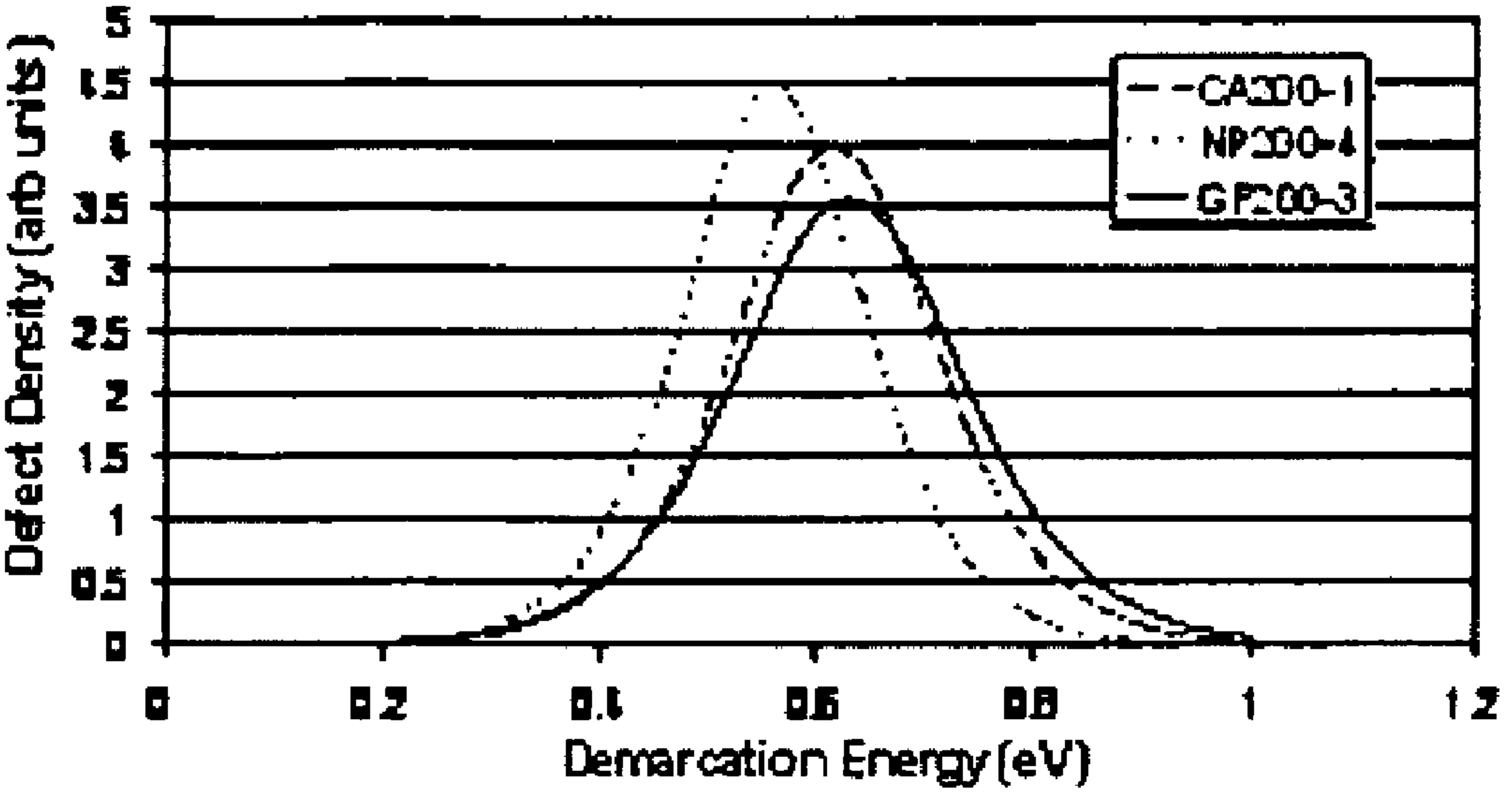
(54) Titre : PROCEDE ET SYSTEME DE FABRICATION DE RESEAUX DE BRAGG A FIBRES (FBG) STABLE
(54) Title: A PROCESS AND SYSTEM FOR MANUFACTURING STABLE FIBER BRAGG GRATINGS (FBGS)



(57) **Abrégé/Abstract**:
The invention disclosed relates to a manufacturing process and system to produce high quality Fiber Bragg Gratings by calculating the decay behaviour of the FBGs from their growth and annealing the grown FBG under a temperature for a time decided on the

(57) Abrégé(suite)/Abstract(continued):

basis of the analysis done on the growth characteristics. This process excludes the need for expensive and time consuming accelerated aging testing experiments. This process also helps in discarding the gratings which may be determined to be unusable based on the writing data without further processing.

ABSTRACT

The invention disclosed relates to a manufacturing process and system to produce high quality Fiber Bragg Gratings by calculating the decay behaviour of the FBGs from their growth and annealing the grown FBG under a temperature for a time decided on the basis of the analysis done on the growth characteristics. This process excludes the need for expensive and time consuming accelerated aging testing experiments. This process also helps in discarding the gratings which may be determined to be unusable based on the writing data without further processing.

A PROCESS AND SYSTEM FOR MANUFACTURING STABLE FIBER BRAGG GRATINGS (FBGs)

FIELD OF THE INVENTION

The present invention relates to telecommunications, sensors, and related areas.

Particularly, the present invention relates to the field of fiber optics.

Still particularly, the present invention relates to a manufacturing process for highly stabilized Fiber Bragg Gratings (FBGs).

DEFINITIONS

In this specification, the following terms have the following definitions as given alongside. These are additions to the usual definitions expressed in the art.

A Fiber Bragg Grating (FBG) is a distributed Bragg reflector constructed in a segment of an optical fiber that reflects particular wavelengths of light, known as Bragg wavelength, and transmits all others. A fiber Bragg grating can therefore be used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector.

FBG Growing is the process of inscribing a periodic variation of refractive index into the core of an optical fiber, thereby creating an FBG by impinging the optical fibers with intense ultraviolet (UV) rays produced by laser sources.

An Excimer Laser (also termed as an exciplex laser) is a form of ultraviolet laser which is commonly used in eye surgery and semiconductor manufacturing. The term excimer is the short form of 'excited dimer', while exciplex is the short form of 'excited complex'. An excimer laser typically uses a combination of an inert gas (argon, krypton, or xenon) and a reactive gas (fluorine or chlorine). Under the appropriate conditions of electrical stimulation, a pseudo-molecule called an excimer (or in case of noble gas halides, exciplex) is created, which can only exist in an energized state and can give rise to laser light in the ultraviolet range.

Exposure Duration is the time for which the optical fiber is exposed to the UV rays during the growth of an FBG.

Exposure Intensity is the intensity of the UV rays impinging on the optical fiber during the growth of an FBG.

Exposure Conditions is the term used to define the different combinations of various parameters required for growing an FBG on a photosensitive material including the exposure intensity, exposure duration, wavelength of the UV laser rays, pulse energy of the UV laser rays and repetition rate of the UV laser rays.

Refractive Index (or index of refraction) of a medium is a measure of how much the speed of light (or other waves such as sound waves) is reduced inside the medium. The refractive index, n, of a medium is defined as the ratio of the velocity, c, of a wave phenomenon such as light or sound in vacuum to its velocity, v_p, in the medium itself as given by:

$$n = \frac{c}{v_p}$$

Reflectivity of a surface is the fraction of the radiation incident on the surface which is reflected by the surface.

Defects in an FBG: When the UV rays interact with the fiber during the FBG growing process, the energy of the UV photons is transferred to the fiber resulting in a change in the structure of the fiber. This change in structure is called a defect.

Activation Energy: The minimum energy required to re-transform a decayed defect to its original state is known as the activation energy.

Growth Characteristics of an FBG include the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength and the residual temperature as a function of exposure duration.

Decay Characteristics of an FBG include the normalized refractive index change, defect transformation rate and defect demarcation energy.

Defect Energy Distribution is the graph which shows the relationship between defect density and defect demarcation energy.

Scaling Factor is the factor by which the growth phase defect energy distribution of an FBG is to be sized to arrive at the decay phase defect energy distribution of the FBG.

BACKGROUND OF THE INVENTION AND PRIOR ART

Fiber Bragg gratings are created by "inscribing" (another term used for inscribing is writing) the periodic variation of refractive index into the core of optical fibers using intense ultraviolet (UV) sources such as excimer lasers. Special germanium-doped silica fibers are used in the manufacture of fiber Bragg gratings. The germanium-doped fibers are photosensitive wherein the refractive index of the core changes with exposure to UV light, with the amount of change depending on the exposure intensity and duration.

The reflected wavelength from the grating, called the Bragg wavelength (λ_B), is defined by the relationship $\lambda_B = 2n\Lambda$, where n is the effective refractive index of the grating in the fiber core and Λ is the grating period.

When the UV radiation interacts with the fiber during the FBG growing process, the energy of the UV photons is transferred to the fiber resulting in a change in the structure of the fiber via transformation of defects and hence modifying the refractive index in the exposed region as compared to the unexposed regions of the fiber. The defects so created in the fiber structure are not completely stable and end up decaying with different time constants and of different amplitudes. The minimum energy required to re-transform a defect to its original state is known as the 'Activation energy' E_a. Based on such a definition, the UV-induced defects can be broadly classified into two types:

1) **Shallow activation energy defects:** These are defects that re-transform to their original state with the application of relatively low energy (supplied thermally for a short time or through accumulation of thermal energy over longer time). The transformation process sustains until all the defects that have activation energy lower than demarcation energy (E_{da}) have been quenched. The demarcation

energy is defined as the energy corresponding to the desired lifetime at the field temperature of the application it is used for. The FBG can be stabilized by a process called 'Annealing', which involves heating the grating to high temperatures until the defects with activation energy lower than the demarcation energy are quenched. The recipe for this annealing process (the specific annealing temperature and time) are decided based on the results obtained via accelerated aging experiments.

2) **Deep activation energy defects:** These defects have activation energy higher than the demarcation energy and are relatively stable during the desired lifetime of the FBG. These defects are conserved even after the above annealing process, and hence are critical for the functionality of the FBG in the desired application.

Some applications of FBGs including telecommunication applications have very critical requirements. One example of such a requirement can be given as: the optical performance characteristics such as the insertion loss, Bragg wavelength and the like should be within the specified range when subjected to environmental tests simulating the field conditions. As such, thermal stability of FBGs written in photosensitive fibers is of critical importance for the devices to perform reliably within the specifications over a long period of time. Typically, this is ensured by annealing the gratings at an elevated temperature (for example, 150 deg C) for a short time (few minutes typically). High-temperature annealing of the FBGs written in photo sensitive fibers results in both the grating strength reduction and the shift in the Bragg wavelength. As a result, it is also important to quantify the grating strength reduction and the wavelength shift resulting from the annealing process before specifying the device performance characteristics. In addition, an optimal annealing process minimizes the performance degradation over the gratings' life. Thus, for the refractive index corresponding to the exposed region of the fiber to remain stable for a long-period of time, a critical requirement is stabilizing the UV-induced change in the refractive index.

After the FBG growing, the FBG has to be stabilized by removing some parts of it for improving the grating usability. To understand and optimize the defects, a sample grating is subjected to accelerated aging experiments, which may be through Iso-Thermal Annealing (ITA), Iso-Chronal Annealing (ICA) or a combination of both. The results of these experiments are used to obtain the defect details. The annealing methodology and recipe for the other gratings fabricated in the same batch are decided based on the above defect details. The FBG is then annealed to remove the shallow defects. As the accelerated aging process is a lengthy step, considerable amount of time and money are spent towards the stabilization of the grating.

Several attempts have been made to manufacture stabilized FBGs. The following are certain disclosures related to different stabilization techniques for FBGs.

PCT application WO0184191A2 published on 08.11.2001 discloses an apparatus for measuring environmental parameters comprising an optical fiber-based sensor having thermally-induced diffraction gratings which are stable at very high temperatures for many hours. The diffraction gratings are formed in an optical fiber by exposure to light from an infrared laser and they do not degrade at high temperatures. The optical fiber-based sensor is positioned within a high temperature environment having a parameter desired for measurement. The light source directs light into the optical fiber-based sensor. A detector measures the differential diffraction of the light output from the optical fiber-based sensor and determines a value of the environmental parameter based, at least in part, upon a known correlation between the differential diffraction and the environmental parameter. The diffraction gratings used in the apparatus disclosed in WO0184191A2 requires non-standard fabrication processes which increases the cost of manufacturing.

PCT application WO03005082 published on 16.01.2003 discloses a method and a device for tuning a Bragg grating in an optical fiber. Tuning of the grating is obtained by applying current to at least one longitudinal, internal electrode arranged along the core of the fiber. When current is passed through the electrode, thermal expansion occurs which in turn produces a stress on the fiber core. At the same time, the temperature of the core is increased. This leads to an electrically controlled tuning of the Bragg grating. The disclosure in WO03005082 deals only with the tuning of gratings and not with permanent correction of FBGs which is needed for the production of stabilized FBGs with tight tolerance levels.

United States patent application US20030133658 published on 17.07.2003 discloses a Bragg grating tuning method and apparatus. The Bragg grating is tuned with a heater which is used to adjust the temperature of the semiconductor substrate on which the grating is written using an optical beam. Again, the disclosure in US20030133658 deals only with the tuning of gratings and not with permanent correction of FBGs which is needed for the production of highly stabilized FBGs with tight tolerance levels.

United States patent application US20040161195 published on 19.08.2004 discloses a system and method for manufacturing FBGs. The different steps followed in the manufacturing process are: a) UV-writing an FBG in an optical fiber; b) monitoring characteristic data of the FBG; and c) generating a controlled complex temperature profile along the FBG with a heating means according to the characteristic data for providing an accurate controlled annealing process of the FBG, thereby providing an accurate trimming. The main drawback of the system and method disclosed in US20040161195 is that it requires a series of isochronal annealing steps with increasing temperature, thereby resulting in increasing the manufacturing cost considerably.

United States patent US7142292 published on 28.11.2006 discloses a method for improving optical properties of a Bragg grating having a spatial refractive index profile along a propagation axis. The method includes the following steps: i) characterizing defects of the spatial refractive index profile of the Bragg grating by measuring optical properties of the grating, reconstructing the spatial refractive index profile of the grating based on these measured optical properties and comparing the reconstructed spatial refractive index profile with a target spatial refractive index profile; ii) calculating an average index correction to the spatial refractive index profile as a function of the defects characterized in step i; and iii) applying this average index correction to the Bragg grating by controlling the light source characteristics and period of writing. The defects characterized in step i are period defects, apodization defects or both. But the method disclosed in US7142292 requires the reconstruction of the spatial refractive index profile of the grating for providing the necessary correction from the measured optical properties which makes the manufacturing process very complicated.

There is therefore felt a need for a process and a system for manufacturing highly stable FBGs, wherein:

- the defects are stabilized based on the grating growth process itself without going through the elaborate accelerated aging studies;
- the gratings which may be determined to be unusable based on the writing data can be discarded without further processing;
- the tight tolerance requirements of optical communication and sensor applications can be met; and
- the knowledge of decay phase defect energy distribution is obtained without the accelerated aging experiments, thereby reducing the manufacturing cost and time considerably.

OBJECTS OF THE INVENTION

It is an object of the present invention to provide a manufacturing process and system for high quality FBGs.

It is another object of the present invention to avoid going through expensive and time consuming accelerated aging studies used to characterize the decay behaviour of FBGs.

It is still another object of the present invention to meet the tight tolerance requirements of optical communication and sensor applications.

It is still another object of the present invention to discard unusable FBGs based on the writing data without further processing.

SUMMARY OF THE INVENTION

In accordance with the present invention, there is provided a process for manufacturing stable Fiber Bragg Gratings (FBGs) using different types of photo sensitive fiber materials under different exposure conditions, said FBGs having specific growth and decay characteristics, said process comprising the following steps:

- growing an FBG on a selected photo sensitive fiber material by exposing said fiber material to Ultra Violet (UV) laser rays produced by a laser source under predetermined exposure conditions defined by selected combinations of exposure duration, exposure intensity, wavelength of said UV laser rays, pulse energy of said UV laser rays and repetition rate of said UV laser rays;
- monitoring the growth of said FBG to determine the different growth characteristics thereof including the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength and the residual temperature as a function of exposure duration;
- determining the growth phase defect energy distribution of said FBG using said monitored growth characteristics;
- deducing the decay phase defect energy distribution of said FBG by scaling said growth phase defect energy distribution of said FBG by a scaling factor determined by a step of comparing said FBG with an

FBG grown on a similar photo sensitive fiber material under exposure conditions similar to said predetermined exposure conditions;

- obtaining the percentage of the shallow activation energy defects and the deep activation energy defects in said compared FBG from said deduced decay phase defect energy distribution;
- analyzing said percentage of the shallow activation energy defects by comparing it with a threshold value for determining whether said compared FBG is to be retained or discarded;
- analyzing said deduced decay phase defect energy distribution of said retained FBG to determine the annealing temperature and annealing time; and
- annealing said retained FBG using said determined annealing temperature for said determined annealing time to remove all shallow activation energy defects and to obtain a stable, high quality FBG.

Typically, the process for manufacturing stable FBGs includes:

i. a step of creating a database populated with the growth and decay characteristics of FBGs grown on different types of photo sensitive fiber materials under different exposure conditions according to the following steps:
    - growing an FBG on a selected photo sensitive fiber material by exposing said fiber material to Ultra Violet (UV) laser rays produced by a laser source under predetermined exposure conditions defined by selected combinations of exposure duration, exposure intensity,

wavelength of said UV laser rays, pulse energy of said UV laser rays and repetition rate of said UV laser rays;

- monitoring the growth of said FBG to determine the different growth characteristics thereof including the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength, and the residual temperature as a function of exposure duration;
- determining the growth phase defect energy distribution of said FBG using said monitored growth characteristics ;
- carrying out accelerated aging experiments on said FBG to obtain the decay characteristics including the normalized refractive index change, defect transformation rate, and defect demarcation energy, and thereby determining the decay phase defect energy distribution; and
- obtaining a scaling factor between decay phase defect energy distribution and growth phase defect energy distribution; and

ii. a step of providing a comparator adapted to compare said FBG being manufactured with an FBG grown on a similar photo sensitive fiber material under exposure conditions similar to said predetermined exposure conditions and retrieving the scaling factor corresponding to said compared FBG from said database.

Typically, the step of growing said FBG includes a step of impinging said photo sensitive fiber material with UV rays produced from an excimer laser source.

Typically, the step of growing said FBG includes a step of exposing said photo sensitive fiber material to said UV rays until the refractive index change of said photo sensitive fiber material reaches saturation.

Typically, the step of growing said FBG includes a step of controlling the spatial distribution of the exposure intensity by a photo mask.

Typically, the step of growing said FBG includes a step of controlling the spatial distribution of the exposure intensity by a diffractive phase photo mask.

Typically, the step of monitoring the growth of said FBG includes a step of said FBG using radiations emitted by a compact broadband light source.

Typically, the step of monitoring the growth of said FBG includes a step of analyzing the rays reflected from said FBG by an optical spectrum analyzer.

In accordance with the present invention, there is provided a system for manufacturing stable Fiber Bragg Gratings (FBGs) comprising: i) an FBG growing mechanism having a UV laser source adapted to produce UV rays directed to impinge on a photo sensitive fiber material under predetermined exposure conditions controlled by a photo mask, thereby growing an FBG;

ii) an FBG stabilizing mechanism; and iii) an FBG annealing mechanism, said FBG stabilizing mechanism comprising:

- a monitoring mechanism adapted to monitor different growth characteristics of said FBG including the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength and the residual temperature as a function of exposure duration;
- a comparator adapted to:
    i. compare said FBG grown on said photo sensitive fiber material with an FBG grown on a similar photo sensitive fiber material under exposure conditions similar to said predetermined exposure conditions; and
    ii. obtain the scaling factor corresponding to said compared FBG; and
- an analyzing mechanism adapted to:
    i. obtain the growth phase defect energy distribution of said FBG using said monitored growth characteristics;
    ii. deduce decay phase defect energy distribution of said compared FBG by scaling said growth phase defect energy distribution with said scaling factor;
    iii. obtain the percentage of the shallow activation energy defects and the deep activation energy defects in said compared FBG using said deduced decay phase defect energy distribution;

iv. analyze said percentage of shallow activation energy defects by comparing it with a threshold value for determining whether said compared FBG is to be retained or discarded; and

v. analyze said deduced decay phase defect energy distribution of said retained FBG to determine the annealing temperature and annealing time.

Typically, said FBG stabilizing mechanism co-operates with a database populated with the growth characteristics, decay characteristics and the scaling factor of FBGs grown on different types of photo sensitive fiber materials under different exposure conditions.

Typically, said predetermined exposure conditions include exposure conditions selected from a group consisting of different combinations of the exposure duration, exposure intensity, wavelength of said UV rays, pulse energy of said UV rays and repetition rate of said UV rays.

Typically, said monitoring mechanism comprises a compact broadband light source adapted to produce radiations directed to fall on said FBG.

Typically, said monitoring mechanism comprises an optical spectrum analyzer adapted to analyze the rays reflected from said FBG.

Typically, said comparator is adapted to co-operate with said database to compare said FBG grown on said photo sensitive fiber material with an FBG grown on a similar photo sensitive fiber material under exposure conditions similar to said predetermined exposure conditions.

Typically, said comparator is adapted to retrieve the scaling factor corresponding to said compared FBG from said database.

In accordance with yet another aspect of the present invention, there is provided an FBG manufactured in accordance with the process which is substantially described herein above.

In accordance with yet another aspect of the present invention, there is provided an FBG manufactured by the system which is substantially described herein above.

BRIEF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

The manufacturing process steps of FBGs in accordance with this invention is now described with the help of accompanying drawings, in which:

Figure 1 illustrates a flow chart of the manufacturing process to obtain a highly stabilized FBG;

Figure 2 illustrates a block diagram of the system used for the manufacture of a highly stabilized FBG;

Figure 3 illustrates defect distributions calculated from FBGs in different photosensitive fibers during growth phase; and

Figure 4 illustrates defect distributions calculated from FBGs in different photosensitive fibers during decay phase.

DETAILED DESCRIPTION OF THE INVENTION

The drawings and the description thereto are merely illustrative of a manufacturing process and system to obtain a highly stabilized FBG in accordance with this invention and only exemplify the process and system of the invention and in no way limit the scope thereof.

The present invention relates to a manufacturing process and system to produce high quality Fiber Bragg Gratings by calculating the decay behaviour of the FBGs from their growth and annealing the grown FBG under a temperature for a time decided on the basis of the analysis done on the growth characteristics. This process also excludes the need for expensive and time consuming accelerated aging testing experiments.

Figure 1 illustrates a flow chart of the manufacturing process to obtain a highly stabilized FBG. The different steps involved in the manufacturing process are explained with respect to Figure 1 as given below.

Creating a database is the first step of the FBG manufacturing process as represented by the reference numeral **102**. The database is used to store the growth and decay characteristics of the FBGs grown on different types of photo sensitive fiber materials under different exposure conditions. During the creation of the database in step **102**, the decay characteristics and defect details corresponding to the growth characteristics of an FBG are stored by establishing proper relationships with each other. The different steps involved in creating the database are:

- growing an FBG on a selected photo sensitive fiber material by exposing the fiber material to Ultra Violet (UV) laser rays produced by a laser source under predetermined exposure conditions defined by selected combinations of exposure duration, exposure intensity, wavelength of the UV laser rays, pulse energy of the UV laser rays and repetition rate of the UV laser rays;

- monitoring the growth of the FBG to determine the different growth characteristics including the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength, and the residual temperature as a function of exposure duration;
- determining the growth phase defect energy distribution of the FBG using the monitored growth characteristics;
- carrying out accelerated aging experiments on the FBG to obtain the decay characteristics including the normalized refractive index change, defect transformation rate, and defect demarcation energy, and thereby determining the decay phase defect energy distribution; and
- obtaining a scaling factor between decay phase defect energy distribution and growth phase defect energy distribution.

The abovementioned steps are explained in detail under the section ‘Experimental Details’.

The next step in the process is growing an FBG as represented by the reference numeral **104** on a photo sensitive fiber material by exposing the fiber material to Ultra Violet (UV) laser rays produced by a laser source under predetermined exposure conditions defined by selected combinations of exposure duration, exposure intensity, wavelength of the UV laser rays, pulse energy of the UV laser rays and repetition rate of the UV laser rays. A typical growing process involves inscription of periodic variation of refractive index into the core of the photo sensitive fiber using intense UV radiations obtained from UV lasers, typically excimer lasers. Typically, special germanium-doped silica fibers are used in the manufacture of fiber Bragg gratings. The refractive index of its core change on exposure to UV light, with the amount of change depending on the exposure intensity and duration. The fiber material is exposed to the UV rays until the refractive index change of the material reaches saturation. Typically, photo masks are placed between the UV light sources and the photosensitive fibers. Photo masks control the values of exposure duration and said exposure intensity by a diffractive phase photo mask. The intensity distribution determined by the photo masks determines the grating structure based on the transmitted intensity of light striking the fibers.

The next step is monitoring the growth of the FBG as represented by the reference numeral **106**. Monitoring is done to determine the different growth characteristics including the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength and the residual temperature as a function of exposure duration. The monitoring is done by exposing the FBG to the rays emitted by a compact broadband light source. The rays reflected from the FBG are then analyzed by an optical spectrum analyzer as a function of the duration of exposure of the FBG to the rays emitted by the compact broadband light source.

After monitoring the growth of the FBG, the defect demarcation energy, E_d is calculated from the values of the growth characteristics including the reflectivity (R) and Bragg wavelength (λ_B) measured as a function of time, the normalized index change (η), the initial defect transformation rate (k_1^0), and the residual temperature increase (ΔT_r) in the fiber during the growing process using the equation (1) given below as:

$$E_d = k_B(T_0 + \Delta T_r).\ln(k_1^0 t), \quad \text{equation (1)}$$

where 'k_B' is the Boltzmann constant, 'T_0' is the initial temperature and 't' is the exposure time. The normalized index change (η) can then be obtained as a function of the demarcation energy (E_d) for the grating as given by the equation (2) shown below.

$$\eta(t,T) = \frac{1}{1 + A_0 \exp(\beta E_d)} \quad \text{equation (2)}$$

where 'A_0' and 'β are the fit parameters.

The growth phase defect energy distribution, ($g(E)$) is then determined. This step is represented by the reference numeral **108**. The main step involved for obtaining the defect energy distribution is the calculation of the mean activation energy by differentiating the equation (2), $\eta(t,T) = \frac{1}{1 + A_0 \exp(\beta E_d)}$ with respect to the demarcation energy of the defect, E_d.

In step **110**, the FBG is compared with an FBG grown on a similar photo sensitive fiber material under exposure conditions similar to the predetermined exposure conditions which is stored in the database using a comparator to obtain the scaling factor corresponding to the compared FBG. In step **112**, the decay phase defect energy distribution of the compared FBG is deduced by scaling the growth phase defect energy distribution with the scaling factor. The decay phase defect energy distribution indicates the percentage of the shallow activation energy defects and the deep activation energy defects present in the grown FBG. The percentage of shallow activation energy defects is obtained from the decay phase defect energy distribution in step **114**.

In step **116**, the percentage of shallow activation energy defects obtained from the deduced decay phase defect energy distribution is compared with a threshold value for determining whether the compared FBG is to be retained or discarded. In case the shallow defect percentage is greater than a threshold value (typically 3-15%), the grating can be discarded without further processing.

In step **118**, the deduced decay phase defect energy distribution of the retained FBG is analyzed to determine the annealing temperature and annealing time for removing the shallow activation energy defects. Finally, the retained FBG is annealed in step **120** using the determined annealing temperature for the determined annealing time to obtain a stable FBG. The resulting FBG will be of high quality with tight tolerance required for the present day telecommunication applications.

In accordance with another aspect of the present invention, a block diagram of the system provided to execute the manufacturing process described above is illustrated in Figure 2. The system comprises an FBG growing mechanism, an FBG stabilizing mechanism and an FBG annealing mechanism.

The FBG growing mechanism **202** has a UV laser source adapted to produce UV rays directed to impinge on a photo sensitive fiber material under a predetermined exposure condition controlled by a photo mask, thereby growing an FBG.

The FBG stabilizing mechanism comprises a database **208** for storing the growth and decay characteristics and the scaling factor for different types of commercially available and used photo sensitive fiber materials under different exposure conditions. The other important components of the FBG stabilizing mechanism are a monitoring mechanism **204**, a comparator **206** and an analyzing mechanism **210** which are explained in detail as given below.

The monitoring mechanism **204** monitors the different growth characteristics of the FBG including the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength and the residual temperature as a function of exposure duration. Typically, the monitoring mechanism comprises a compact broadband light source used to produce light rays directed to fall on the FBG and an optical spectrum analyzer used to analyze the rays reflected from the FBG.

A comparator **206** compares the FBG with an FBG stored in the database **208** grown on similar photo sensitive fiber material exposure conditions similar to the predetermined exposure conditions and obtains the scaling factor corresponding to the compared FBG from the database **208**.

An analyzing mechanism **210** is provided to communicate with the comparator and to:

i. obtain the growth phase defect energy distribution of the FBG using the monitored growth characteristics;

ii. deduce decay phase defect energy distribution of the compared FBG by scaling the growth phase defect energy distribution with the scaling factor;

iii. obtain the percentage of the shallow activation energy defects and the deep activation energy defects in the compared FBG using the deduced decay phase defect energy distribution;

iv. analyze the percentage of shallow activation energy defects by comparing it with a threshold value for determining whether the compared FBG is to be retained or discarded; and

v. analyze the deduced decay phase defect energy distribution of the retained FBG to determine the annealing temperature and annealing time.

An FBG annealing mechanism **212** then anneals the retained FBG using the determined annealing temperature for the determined annealing time to remove the shallow activation energy defects and to obtain a stable FBG **214** which is highly stabilized and has very tight tolerance as required by the present day telecommunication applications. In accordance with the process and system of the present invention, the annealing time and annealing temperature are thus obtained from the growth data, thereby obviating the cumbersome and time-consuming accelerated aging procedure for every batch. Using this process and system for manufacturing FBGs, a cost saving of 20 - 30 % can be achieved.

Experimental Details

The typical steps involved in the step of creating the database **102** (as illustrated in Figure 1) for storing the growth and decay characteristics of the FBGs are described below:

Three photosensitive fibers from different vendors (Newport™ F-SBG-15, CorActive™ UVS-652 and Nufern™ GF1) were inscribed with Bragg gratings using ultraviolet radiations from KrF excimer lasers (BraggStar™ 500, Lambda Physik) operating at 248 nm with 2.5 mJ pulse energy and 200 Hz repetition rate. The gratings were fabricated using diffractive phase masks (1070nm period, Avensys) which transmit less than 5% of the zero-order. The grating growth was monitored in the reflection mode as a function of exposure time using a compact broadband light source (DL-BX9, Denselight), and an optical spectrum analyzer (IMON400-E, Ibsen). The photosensitive fibers were typically exposed until the index change reached saturation. The typical exposure time and the saturated index change along with the other results of the experiments are tabulated below:

Photosensitive Fiber	**Dopants**	**Numerical Aperture**	**Cutoff Wave length (nm)**	**FBG ID**	**Exposure Time(sec)**	**Saturated □n**
Newport F-SBG-15	GeO_2/B co-doped	0.12	1180 ± 80	NP200-4	26	$4x10^{-4}$
CorActive UVS-652	GeO_2	0.14	1200 ± 75	CA200-1	680	$3.9x10^{-4}$
Nufern GF1	GeO_2	0.13	1260 ± 80	GF200-3	455	$3.5x10^{-4}$

From the analysis of the results, Reflectivity (R) and Bragg Wavelength (λ_B) measured as a function of time, the normalized index change (η), the initial defect transformation rate (k_1^0), and the residual temperature increase (ΔT_r) in the fiber during the writing process were calculated. From the abovementioned values, the demarcation energy of the defects was calculated using the equation $E_d = k_B(T_0 + \Delta T_r)\ln(k_1^0 t)$, where '$k_B$' is the Boltzmann constant, 'T_0' is the initial temperature, and 't' is the exposure time. The normalized index change (η) was then plotted as a function of the demarcation energy (E_d) for the gratings fabricated in the different photosensitive fibers as shown by $\eta(t,T) = \frac{1}{1 + A_0 \exp(\beta E_d)}$, where '$A_0$' and '$\beta$' are the fit parameters. The defect energy distribution, ($g(E)$) during the growth phase was then calculated by differentiating the above curve with respect to E_d. The mean activation energy of defects was seen to be in the range of 0.5-0.7 eV, which was consistent with the theoretical estimations.

To determine the energy distribution of the decay phase, accelerated aging experiments were performed on the above gratings. Specifically, Iso-thermal accelerated annealing (ITA) within Iso-chronal accelerated annealing (ICA) approach was followed. Such an approach combines the best features of both ITA and ICA, providing a cross-referencing mechanism that improves the confidence in the decay analysis. The accelerated aging experiments consisted of annealing the test FBG at temperatures starting from 100 °C in steps of 75 °C until the grating decayed to <5% reflectivity. As part of the ICA routine, two different gratings were annealed for 5 minutes and 500 minutes respectively and their reflectivities were observed after each interval. During the 500 minutes annealing, the FBG reflectivity data was continuously observed and subsequently used for ITA analysis. Finally, the ITA and the ICA results were correlated to deduce the decay phase defect energy distribution. The scaling factor is also determined by finding out the factor with which the growth phase defect energy distribution is to be sized to arrive at the decay phase defect energy distribution.

The gratings fabricated in the three photosensitive fibers at 200 Hz pulse repetition rate of the excimer laser were analyzed. The gratings fabricated in the F-SBG-15 fiber (B co-doped) were found to grow relatively quickly and had mean activation energy of 0.55 eV. Such gratings were found to decay relatively quickly i.e., the mean activation energy deduced from the accelerated aging experiments was lower compared to the gratings in the other two fibers. Moreover, the energy distribution obtained through the decay analysis for gratings fabricated in the other two photosensitive fibers were also found to be roughly consistent with the energy distribution obtained during the growth phase. Figure 3 illustrates defect distributions calculated from FBGs in different photosensitive fibers during growth phase. Figure 4 illustrates defect distributions calculated from FBGs in different photosensitive fibers during decay phase.

The results obtained from the experiments were found to be in accordance with the theory postulated by B. Poumellec in 'Journal of Non-Crystalline Solids 239 (1998) 108-115' which tells that the period for which a Fiber Bragg Grating remains stable depends upon two factors:

1) the initial rate of transformation of the defects; and
2) the temperature at which the grating is grown.

The analysis is extended in a similar fashion to a variety of commercially available and used photosensitive fiber materials under different exposure conditions and the database is created and stored with each of their growth and decay characteristics including reflectivity, Bragg wavelength, normalized refractive index change, defect transformation rate, defect demarcation energy, defect activation energy, residual temperature increase and other relevant parameters including the scaling factor.

TECHNICAL ADVANCEMENTS

- The manufacturing process disclosed in the present invention helps in the development of high quality FBGs in lesser time; those can meet the tight tolerance requirements of optical communication and sensor applications.

- This process helps to avoid performing expensive and time consuming annealing experiments used to test and stabilize the decay behaviour of FBGs.
- This process helps in discarding the gratings which may be determined to be unusable based on the writing data without further processing.
- The manufacturing and maintenance costs of FBGs can be reduced considerably using this process.

While considerable emphasis has been placed herein on the particular features of this invention, it will be appreciated that various modifications can be made, and that many changes can be made in the preferred embodiments without departing from the principles of the invention. These and other modifications in the nature of the invention or the preferred embodiments will be apparent to those skilled in the art from the disclosure herein, whereby it is to be distinctly understood that the foregoing descriptive matter is to be interpreted merely as illustrative of the invention and not as a limitation.

CLAIMS:

1. A process for manufacturing stable Fiber Bragg Gratings (FBGs) using different types of photo sensitive fiber materials under different exposure conditions, said FBGs having specific growth and decay characteristics, said process comprising the following steps:

    - growing an FBG on a selected photo sensitive fiber material by exposing said fiber material to Ultra Violet (UV) laser rays produced by a laser source under predetermined exposure conditions defined by selected combinations of exposure duration, exposure intensity, wavelength of said UV laser rays, pulse energy of said UV laser rays and repetition rate of said UV laser rays;
    - monitoring the growth of said FBG to determine the different growth characteristics thereof including the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength and the residual temperature as a function of exposure duration;
    - determining the growth phase defect energy distribution of said FBG using said monitored growth characteristics;
    - deducing the decay phase defect energy distribution of said FBG by scaling said growth phase defect energy distribution of said FBG by a scaling factor determined by a step of comparing said FBG with an FBG grown on a similar photo sensitive fiber material under exposure conditions similar to said predetermined exposure conditions;

- obtaining the percentage of the shallow activation energy defects and the deep activation energy defects in said compared FBG from said deduced decay phase defect energy distribution;
- analyzing said percentage of the shallow activation energy defects by comparing it with a threshold value for determining whether said compared FBG is to be retained or discarded;
- analyzing said deduced decay phase defect energy distribution of said retained FBG to determine the annealing temperature and annealing time; and
- annealing said retained FBG using said determined annealing temperature for said determined annealing time to remove all shallow activation energy defects and to obtain a stable, high quality FBG.

2. A process for manufacturing stable FBGs as claimed in claim 1, which includes:

   i. a step of creating a database populated with the growth and decay characteristics of FBGs grown on different types of photo sensitive fiber materials under different exposure conditions according to the following steps:

      - growing an FBG on a selected photo sensitive fiber material by exposing said fiber material to Ultra Violet (UV) laser rays produced by a laser source under predetermined exposure conditions defined by selected combinations of exposure duration, exposure intensity, wavelength of said UV laser rays, pulse energy of said UV laser rays and repetition rate of said UV laser rays;

- monitoring the growth of said FBG to determine the different growth characteristics thereof including the reflectivity of said FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength, and the residual temperature as a function of exposure duration;
- determining the growth phase defect energy distribution of said FBG using said monitored growth characteristics ;
- carrying out accelerated aging experiments on said FBG to obtain the decay characteristics including the normalized refractive index change, defect transformation rate, and defect demarcation energy, and thereby determining the decay phase defect energy distribution; and
- obtaining a scaling factor between decay phase defect energy distribution and growth phase defect energy distribution; and

ii. a step of providing a comparator adapted to compare said FBG being manufactured with an FBG grown on a similar photo sensitive fiber material under exposure conditions similar to said predetermined exposure conditions and retrieving the scaling factor corresponding to said compared FBG from said database.

3. A process for manufacturing stable FBGs as claimed in claim 1, wherein the step of growing said FBG includes a step of impinging said photo sensitive fiber material with UV rays produced from an excimer laser source.

4. A process for manufacturing stable FBGs as claimed in claim 1, wherein the step of growing said FBG includes a step of exposing said photo sensitive fiber material to said UV rays until the refractive index change of said photo sensitive fiber material reaches saturation.

5. A process for manufacturing stable FBGs as claimed in claim 1, wherein the step of growing said FBG includes a step of controlling the spatial distribution of the exposure intensity by a photo mask.

6. A process for manufacturing stable FBGs as claimed in claim 1, wherein the step of growing said FBG includes a step of controlling the spatial distribution of the exposure intensity by a diffractive phase photo mask.

7. A process for manufacturing stable FBGs as claimed in claim 1, wherein the step of monitoring the growth of said FBG includes a step of said FBG using radiations emitted by a compact broadband light source.

8. A process for manufacturing stable FBGs as claimed in claim 1, wherein the step of monitoring the growth of said FBG includes a step of analyzing the rays reflected from said FBG by an optical spectrum analyzer.

9. A system for manufacturing stable Fiber Bragg Gratings (FBGs) comprising: i) an FBG growing mechanism having a UV laser source adapted to produce UV rays directed to impinge on a photo sensitive

fiber material under predetermined exposure conditions controlled by a photo mask, thereby growing an FBG; ii) an FBG stabilizing mechanism; and iii) an FBG annealing mechanism, said FBG stabilizing mechanism comprising:

- a monitoring mechanism adapted to monitor different growth characteristics of said FBG including the reflectivity of the FBG, the refractive index modulation, the saturated refractive index modulation, the Bragg wavelength and the residual temperature as a function of exposure duration;
- a comparator adapted to:
  i. compare said FBG grown on said photo sensitive fiber material with an FBG grown on a similar photo sensitive fiber material under exposure conditions similar to said predetermined exposure conditions; and
  ii. obtain the scaling factor corresponding to said compared FBG; and
- an analyzing mechanism adapted to:
  i. obtain the growth phase defect energy distribution of said FBG using said monitored growth characteristics;
  ii. deduce decay phase defect energy distribution of said compared FBG by scaling said growth phase defect energy distribution with said scaling factor;
  iii. obtain the percentage of the shallow activation energy defects and the deep activation energy defects in said compared FBG using said deduced decay phase defect energy distribution;

iv. analyze said percentage of shallow activation energy defects by comparing it with a threshold value for determining whether said compared FBG is to be retained or discarded; and

v. analyze said deduced decay phase defect energy distribution of said retained FBG to determine the annealing temperature and annealing time.

10. A system for manufacturing stable FBGs as claimed in claim 9, wherein said FBG stabilizing mechanism co-operates with a database populated with the growth characteristics, decay characteristics and the scaling factor of FBGs grown on different types of photo sensitive fiber materials under different exposure conditions.

11. A system for manufacturing stable FBGs as claimed in claim 9, wherein said predetermined exposure conditions include exposure conditions selected from a group consisting of different combinations of the exposure duration, exposure intensity, wavelength of said UV rays, pulse energy of said UV rays and repetition rate of said UV rays.

12. A system for manufacturing stable FBGs as claimed in claim 9, wherein said monitoring mechanism comprises a compact broadband light source adapted to produce radiations directed to fall on said FBG.

13. A system for manufacturing stable FBGs as claimed in claim 9, wherein said monitoring mechanism comprises an optical spectrum analyzer adapted to analyze the rays reflected from said FBG.

14. A system for manufacturing stable FBGs as claimed in claim 10, wherein said comparator is adapted to co-operate with said database to compare said FBG grown on said photo sensitive fiber material with an FBG grown on a similar photo sensitive fiber material under exposure conditions similar to said predetermined exposure conditions.

15. A system for manufacturing stable FBGs as claimed in claim 10, said comparator is adapted to retrieve the scaling factor corresponding to said compared FBG from said database.

16. An FBG manufactured in accordance with a process as claimed in any one of claims 1 to 8.

17. An FBG manufactured by a system as claimed in any one of claims 9 to 15.

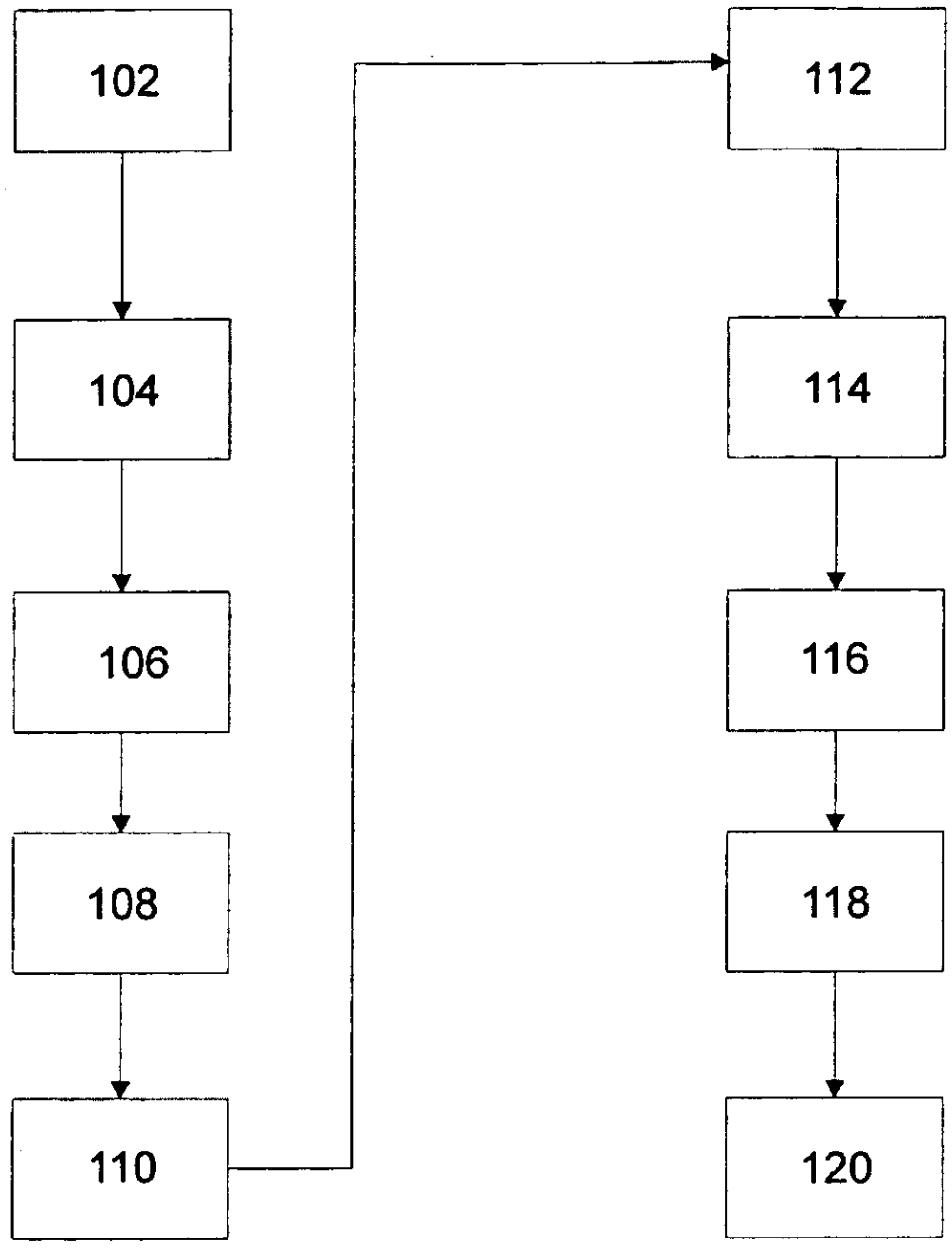


FIGURE 1

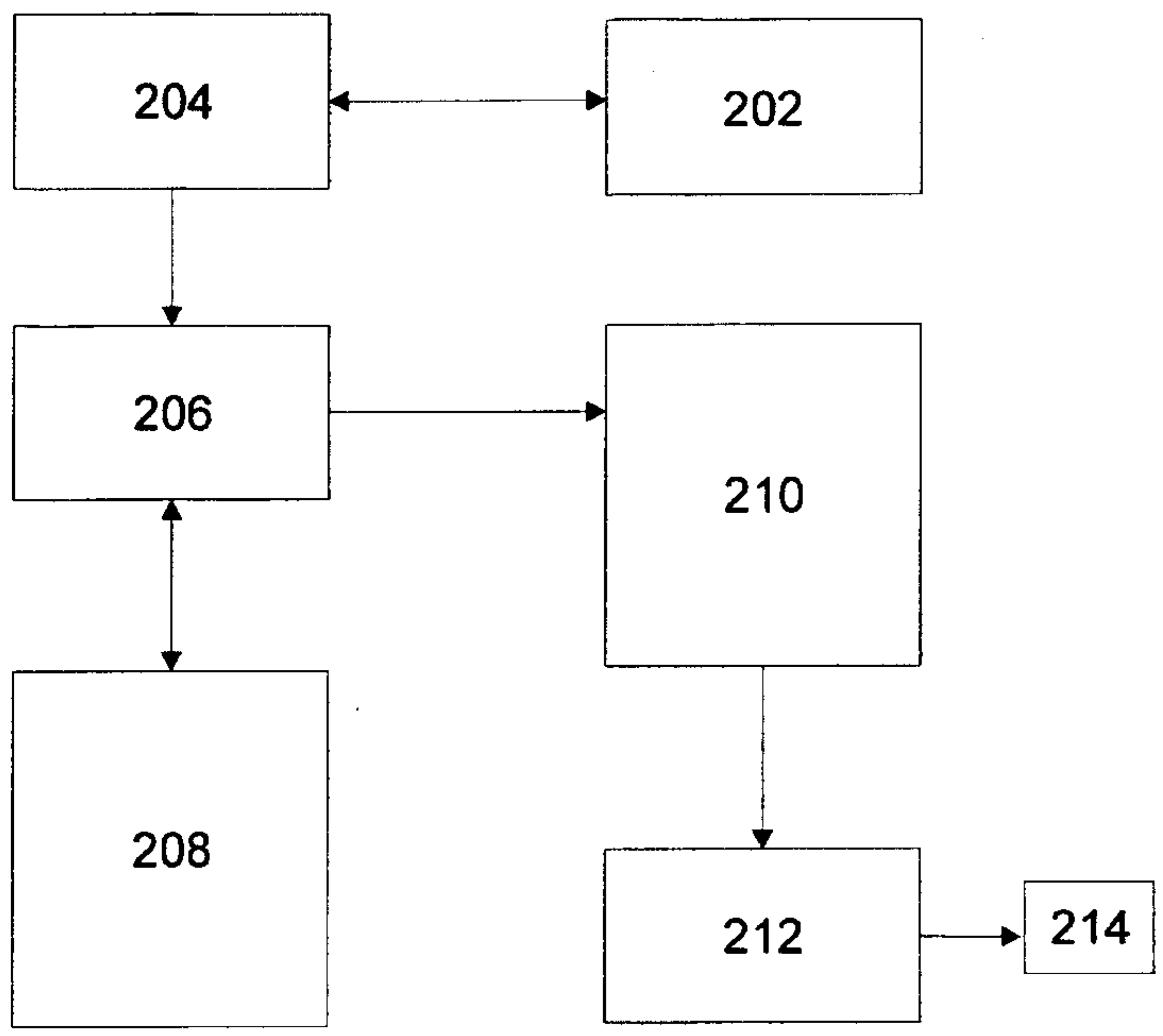


FIGURE 2

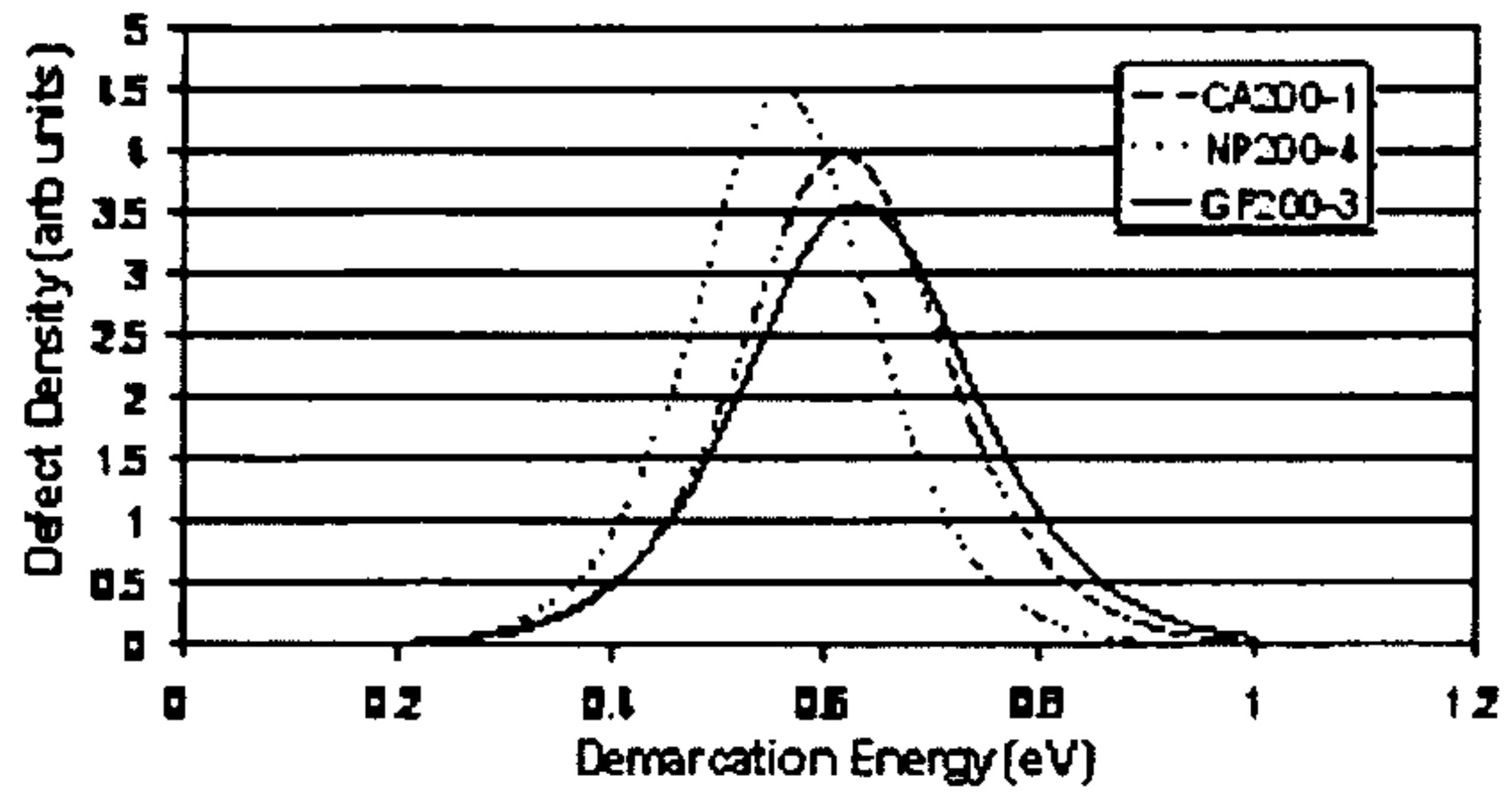


FIGURE 3

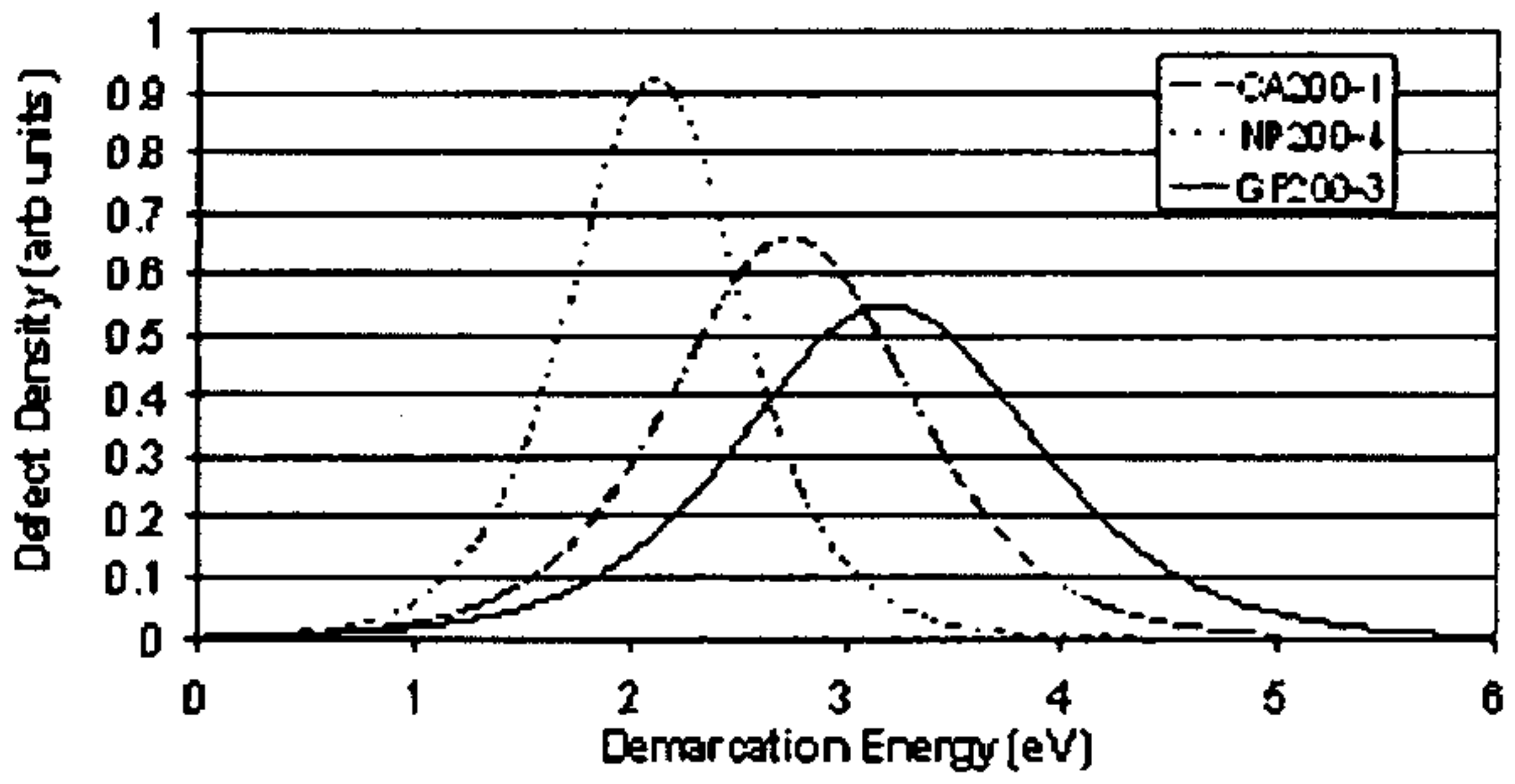
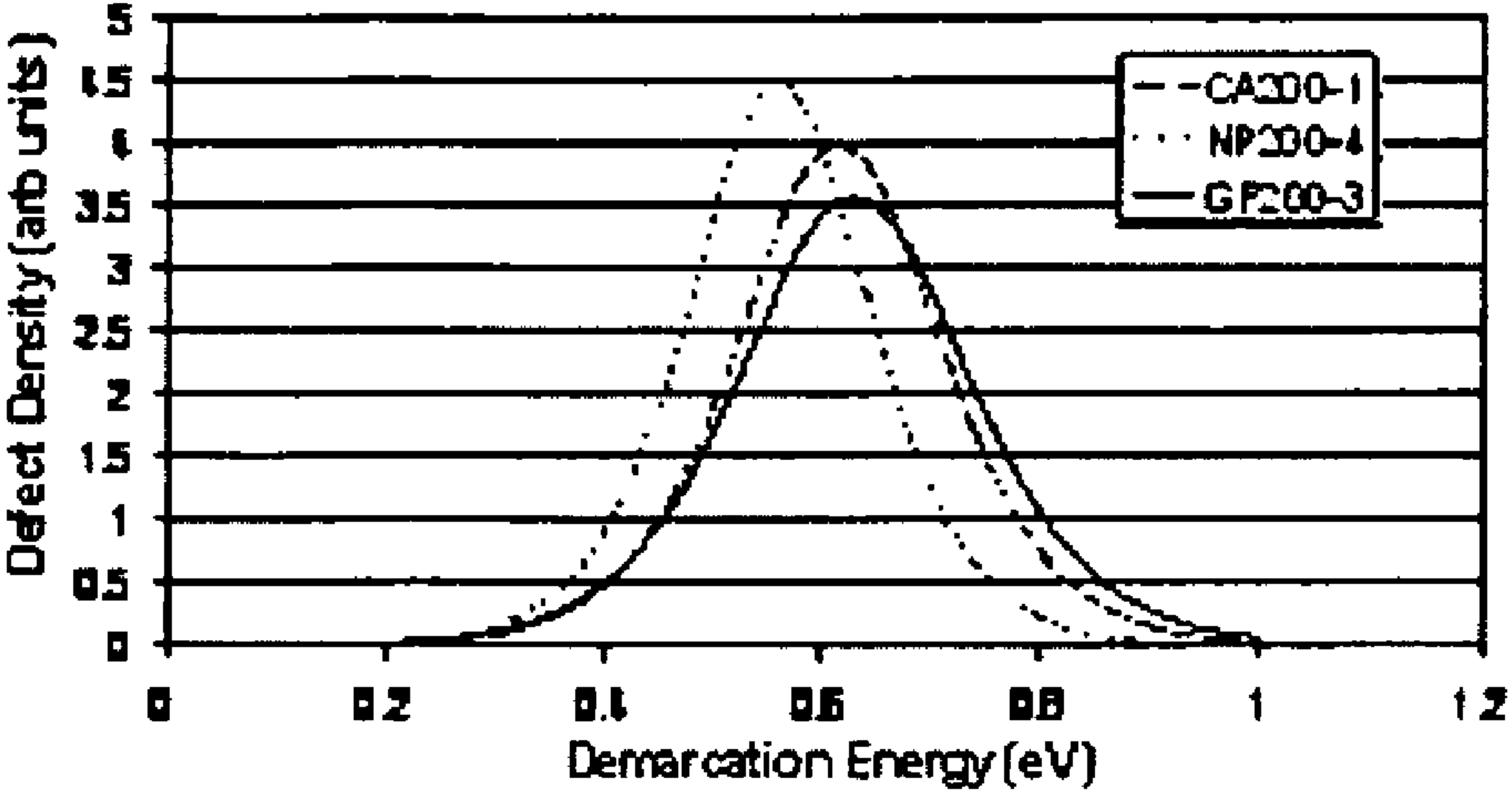


FIGURE 4



Defect Density (arb units)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
1.2
Demarcation Energy (eV)
CA200-1
NP200-4
GP200-3