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Uniform component of index structure induced in Ge-SiO$_2$ fibers by spatially modulated ultraviolet light

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Experimental data are presented to show that Ge(1) and Ge(2) centers are induced by trapping photoinduced electrons from the conduction band, in agreement with our previous proposal that both are trapped electron centers. The spacing (Λ) dependence of ultraviolet (UV) light bleaching of the pre-existing Ge E' centers illustrates that the electron diffusion length is greater than Λ of the spatially modulated UV light used in the fabrication of fiber Bragg gratings (FBGs) with Bragg wavelengths $\leqslant 1.5\ \mu$m (short period grating) for laser powers as low as 25 mJ/cm^2. The Ge(1) and Ge(2) centers are uniformly induced by the spatially modulated UV light and therefore contribute to the uniform component of the index structure of FBGs. [S0003-6951(98)01325-4]

Fiber grating devices are emerging as critical components for telecommunications and for sensor applications.[1] However, the physical structures associated with the index of fiber Bragg gratings (FBGs) have not been totally identified: The structures associated with the index modulation (Δn_{mod}) of FBGs in unloaded Ge-SiO$_2$ core fibers that have been identified are Ge E' centers[2] and densification.[2–4] In H$_2$-loaded fibers, besides the association of Ge E' and densification, GeH was also found[2] to contribute to Δn_{mod} of the FBG.

High concentrations of Ge(1) and Ge(2) are photoinduced along with Ge E' centers in the FBG fabrication process using a pulsed UV laser.[2] One thing that remains to be elucidated is the contribution of Ge(1) and Ge(2) centers to the index structure of FBGs via their optical absorptions[5] at 4.4 and 5.8 eV, respectively, through the Kramers–Kronig relationship.

Photobleaching of pre-existing Ge E' centers in Ge-doped silica fibers was reported previously,[6] and bleaching of these centers due to reactions with injected electrons and holes in Ge-SiO$_2$ thin films was recently reported.[7] Thus, photobleaching of pre-existing Ge E' centers by reactions with photoinduced electrons and holes can be used to study their diffusion into the dark regions using a spatially modulated UV light exposure.

In an ideal exposure through a 50% duty cycle amplitude grating with period 2Λ, the fraction of electrons or holes that diffuse into the dark regions is about $2L_d/\Lambda$, where L_d is the diffusion length of carriers (electrons or holes). For Λ comparable to L_d, a significant fraction of the photoinduced carriers can diffuse into the dark regions. This process reduces the population of defects induced in the light regions by trapping of these carriers. And if the intensity of UV laser light is chosen such that the concentration of the photoinduced carriers is comparable to that of pre-existing Ge E' centers, bleaching of these Ge E' centers by the carriers diffused into the dark regions is dominant. [In the case of uniform exposure with $\Lambda = 0$ reported in this letter (see Fig. 2), the observation of complete photobleaching of pre-existing Ge E' centers in Ge-SiO$_2$ suggests that bleaching has occurred before trapping to form Ge(1) and Ge(2) defects.] The diffusion length of the carriers can then be studied by photobleaching the pre-existing Ge E' centers.

In our experiments, uncoated Ge-SiO$_2$ core single mode fiber that contains $10^{17}/\mathrm{cm}^3$ pre-existing Ge E' centers was exposed to a single pulse of KrF laser light through a 50% duty cycle amplitude grating (Photo Sciences, Inc., CA) of grating period 2Λ with $\Lambda \geqslant 3\ \mu$m. Single pulse KrF exposure was used to avoid complications due to multishot effects. Paramagnetic defects induced in the exposed fibers were studied by use of electron spin resonance (ESR) on ≈ 1 cm sample lengths of fiber of total length 96 cm loaded into the sample tube. Computer simulations of ESR spectra were carried out to obtain the populations of the observed paramagnetic defects.

Figure 1 shows the Ge(1) and Ge(2) populations induced by 25 and 15 mJ/cm^2 KrF laser pulses in Ge-SiO$_2$ core fibers as a function of Λ. For the 25 mJ/cm^2 exposure, the induced populations of Ge(1) and Ge(2) for $\Lambda \geqslant 8\ \mu$m are about half that of the uniform exposure ($\Lambda = 0\ \mu$m), as anticipated for 50% duty cycle amplitude grating exposures. For $\Lambda \leqslant 5\ \mu$m, the populations of Ge(1) and Ge(2) decrease to $\sim 30\%$ of the uniform exposure, suggesting the loss of 20% of the photoinduced carriers in the light regions. Thus, the fraction of carriers that diffuse into dark regions, $2L_d/\Lambda$, is ≈ 0.2, and for $\Lambda = 5\ \mu$m, L_d is $\approx 0.5\ \mu$m.

For the 15 mJ/cm^2 exposure, the decrease in the populations of the Ge(1) and Ge(2) centers appears to occur $\sim 3\ \mu$m, as shown in Fig. 1, although it is only slightly greater than the variations in observed defect populations due to pulse-to-pulse variations in laser power. However, the populations with $\Lambda = 3\ \mu$m are less than the largest variation from the average of the populations. Using this value, a diffusion length $\approx 0.3\ \mu$m is obtained. The carrier diffusion length is found to increase with laser power (15 vs 25 mJ/cm^2), implying that their diffusion is photoassisted. Note from Fig. 1 that the average population ratio of Ge(1)

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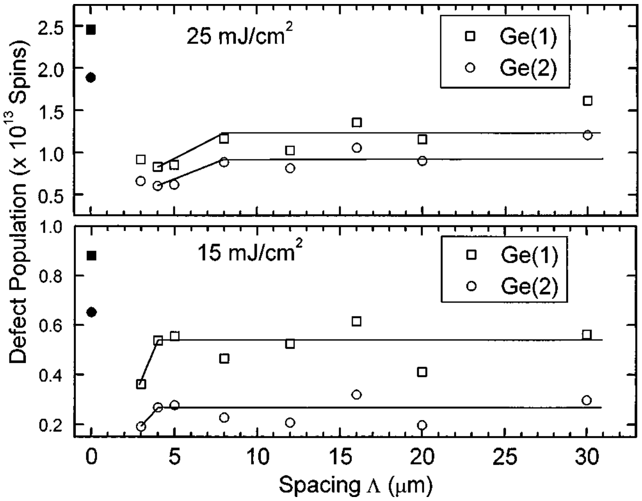

FIG. 1. Ge(1) and Ge(2) defect center populations observed in 1 cm lengths of Ge-SiO$_2$ core fibers of total length 96 cm after exposure to a single pulse of a KrF laser through amplitude gratings of various spacing (open points). The solid lines are draw to aid the eyes. The solid points are for uniform exposure.

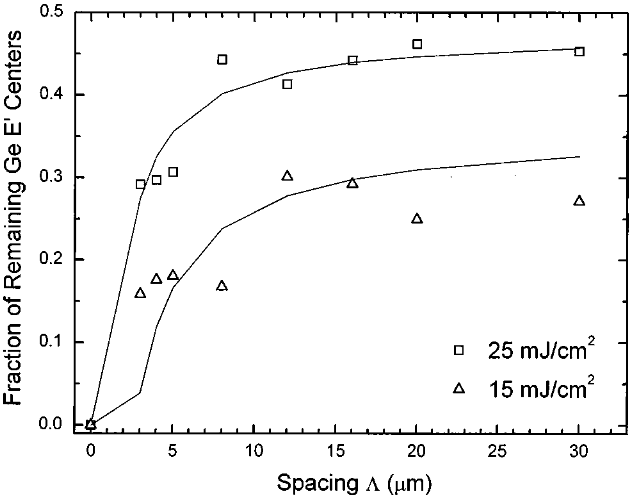

FIG. 2. Fraction of remaining Ge E' centers after exposure to single pulse of KrF laser through amplitude gratings of various spacing Λ (points). The solid lines are fits to Eq. (3) for the 15 mJ/cm^2 exposure with $L_d = 0.2\ \mu$m, $z_0 = 0.49\ \mu$m, and $f_d = 0.02$, and for the 25 mJ/cm^2 exposure with $L_d = 0.3\ \mu$m, $z_0 = 0.81\ \mu$m, and $f_d = 0.14$.

and Ge(2) centers induced by 25 and 15 mJ/cm^2 pulses is 0.38 ± 0.02, which is equal to $(25/15)^2 = 0.36$ within experimental error. This result supports the hypothesis that Ge(1) and Ge(2) are induced by two-photon absorption processes.[8]

The similarity in Λ dependence of the induced populations of Ge(1) and Ge(2) centers shown in Fig. 1 suggests that both are generated by trapping of carriers with comparable mobilities, i.e., either electrons or holes but not both since the electron mobility in SiO$_2$ is nine orders of magnitude greater than that of the holes as reported by Hughes.[9] This is in disagreement with the proposal[10] that Ge(1) is an electron trapping center, while Ge(2) is a hole trapping center. The diffusion length of $\approx 1\ \mu$m calculated above suggests that the trapped carriers are electrons trapped from the conduction band of Ge-SiO$_2$, in agreement with our proposal[11] that both Ge(1) and Ge(2) are trapped electron centers. This is also consistent with the conclusion that these are induced by two-photon absorption processes since excitation of electrons from the valence to the conduction band in Ge-SiO$_2$ (band gap[8] ≈ 7.2 eV) requires two KrF photons ($h_v = 5$ eV).

To accurately estimate the electron diffusion length, the Λ-dependent photobleaching of pre-existing Ge E' centers was analyzed using a one-dimensional diffusion model of electrons along the fiber axis z. Among the photoinduced electrons, only those located at the boundary of the light and dark regions within a length, δ, of the order of electron diffusion length can diffuse into dark regions. The total population of electrons involved in diffusion is then $n_e\delta$, where n_e is the photoinduced electron concentration. With a 50% duty cycle amplitude grating exposure of spacing Λ, the remaining pre-existing Ge E' center population $[\mathrm{Ge}E']_r$ in a period 2Λ can be calculated as

$$[\mathrm{Ge}E']_r = \int_{z_0}^{\Lambda - z_0} \left[(\mathrm{Ge}E_p) - \frac{n_e \cdot \delta}{\sqrt{\pi} \cdot L_d} \cdot [e^{-(z/2L_d)^2} + e^{-[(\Lambda - z)/2L_d]^2}] \right] dz, \tag{1}$$

where $(\mathrm{Ge}E_p)$ is the concentration of pre-existing Ge E' centers and z_0 is the diffusion distance below which total bleaching of pre-existing Ge E' centers occurs. Z_0 satisfies the following equation:

$$(\mathrm{Ge}E_p) = \frac{n_e \cdot \delta}{\sqrt{\pi} \cdot L_d} \cdot [e^{-(z_0/2L_d)^2} + e^{-[(\Lambda - z_0)/2L_d]^2}]. \tag{2}$$

The fraction of remaining Ge E' centers, $f_{\mathrm{Ge}E'} = [\mathrm{Ge}E']_r / [2\Lambda(\mathrm{Ge}E_p)]$, is then

$$\begin{aligned} f_{\mathrm{Ge}E'} &= \frac{1}{2} - \frac{z_0}{\Lambda} - \sqrt{\pi} \cdot \frac{L_d}{\Lambda[e^{-(z_0/2L_d)^2} + e^{[(\Lambda - z_0)/2L_d]^2}]} \\ &\quad \cdot \left[\mathrm{erf}\left(\frac{\Lambda - z_0}{2L_d} \right) - \mathrm{erf}\left(\frac{z_0}{2L_d} \right) \right], \quad \Lambda > 2z_0 \\ &= 0, \quad \Lambda \leqslant 2z_0, \end{aligned} \tag{3}$$

where

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \cdot \int_0^x e^{-y^2} dy. \tag{4}$$

Figure 2 shows the fraction of remaining Ge E' centers as a function of Λ for laser powers of 15 and 25 mJ/cm^2. The solid lines are fits using Eq. (2) with z_0 and L_d as adjustable parameters and an additional parameter, f_d, which is the fraction of Ge E' centers bleached by UV light diffracted into the dark regions. (Since the amplitude gratings used in our experiments consist of 1000 Å chrome with an optical density of 3.0 to 3.2 in the UV and they have an antireflective coating, we assume no UV light transmission or scattering into dark regions. However, a calculation using the geometry of our setup indicates that up to 6% of the UV photons in the light region are diffracted into dark regions.) From the fit of the data in Fig. 2, the electron diffusion lengths are found to be 0.19 and 0.26 μm for the 15 and 25 mJ/cm^2 exposures, respectively, consistent with the above conclusion that the diffusion of electrons is photoassisted. To the best of our knowledge, this is the first report of the electron diffusion length in Ge-SiO_2. That the electron diffusion length is about 1 μm provides additional support for the electric-field-induced second-harmonic generation (SHG) mechanism[12] in Ge-SiO_2 core fibers, for which charge migration over macroscopic distance (>1 μm) is needed.

The period of the spatially modulated UV light for fabricating FBGs with Bragg wavelengths $\leqslant 1.5\,\mu$m is $\leqslant 0.3\,\mu$m, which is comparable to the electron diffusion length of $\approx 0.3\,\mu$m estimated in the 25 mJ/cm^2 KrF exposures. Thus, about the same concentrations of Ge(1) and Ge(2) centers are induced in the dark and light regions. Since they are almost uniformly distributed in the Ge-SiO_2 fiber core, they contribute to the uniform component of the index of FBGs.

In summary, the Λ dependence of Ge(1) and Ge(2) centers photoinduced by spatially modulated UV light in Ge-SiO_2 core fibers suggests that they are induced by trapped electrons from the conduction band. The electron diffusion length, obtained from the Λ dependence of bleaching of preexisting Ge E' centers, is found to be equal to or greater than the spacing of the spatially modulated UV light used for fabricating short period, fiber Bragg gratings for KrF laser powers as low as 25 mJ/cm^2. Ge(1) and Ge(2) centers are therefore almost uniformly induced throughout the exposed fiber core and thus contribute to the uniform component of the index of FBGs in Ge-SiO_2 fibers.

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