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Modeling of the RIA in silica-based optical fibers: contribution of the photoionization of radiation-induced trapped states

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ABSTRACT

The radiation-induced attenuation in silica optical fibers is usually attributed to the formation of color centers. The RIA spectrum is then considered a composition of several characteristic optical absorption bands. We argue, based on experimental and theoretical facts, that the photoionization of radiation-induced bandgap states may also contribute to the RIA. This contribution could notably play a role in the near-infra-red range where silica fibers are frequently operated but the origin of RIA poorly resolved.

PACS Keywords: optical fibers, radiation effects

1 INTRODUCTION

It is widely admitted that radiation-induced attenuation (RIA) of silica optical fibers is due to color centers (CC) formed upon trapping of free carriers excited by the ionizing radiation. RIA spectra are then considered a composition of several optical absorption (OA) bands associated with these CC. Most of the identified intrinsic or Al-, P-, and Ge-related centers were demonstrated to absorb in the UV-VIS ranges [1]. None of them have OA bands in the near-infrared (NIR) region, except self-trapped holes (one band reported at 1.63 eV [2]) that are however unstable above 200 K [2,3]. Lowest energy visible bands are centered at 2 eV (NBOHC and POR [1]) but are characterized by very small oscillator strength compared with UV-VIS OA bands (f = 1–5 x 10^{-4} [1,4]). Therefore, the origin of RIA in the NIR range is poorly elucidated; it is often simply attributed to the tail of visible bands above 2 eV. Yet the NIR RIA well deserves a refined understanding since silica optical fibers are usually operated in this region. We show that photoionization of radiation-induced trapped states by the guided light may contribute to the NIR RIA. This process differs from CC absorption in that it involves the transfer of a carrier from a localized state to a band.

2 EVIDENCE FOR PHOTOIONIZATION

In Fig. 1 we used the setup described in [5] to measure the 980 nm RIA continuously under irradiation. The fiber under test is an aluminosilicate-core fiber (named K04, 1.97 w% Al) fabricated by MCVD and solution doping techniques at INPHYNI, Nice. The optical power launched in the fiber sample was high, about 50 mW. The dose rate was changed at a few times during irradiation. At each dose rate, the RIA reaches a plateau which does not correspond to saturation (RIA takes higher values) but obviously to an equilibrium state. A photo-induced recovery therefore competes with radiation-induced degradation, as confirmed by the fact that lowering the dose rate lowers the RIA equilibrium level. In usual RIA measurements, the probe-light power is much lower so the transient towards equilibrium much longer. Then, saturation is reached before equilibrium. If color centers are trapped carriers, photo-bleaching must follow detrapping and/or recombination. This involves the photoionization of trapped states and the transfer of carriers from localized states to a band. Some light is absorbed in this process that necessarily contributes to RIA. The property illustrated here for an Al-doped fiber is in fact observed for a wide variety of doping conditions.

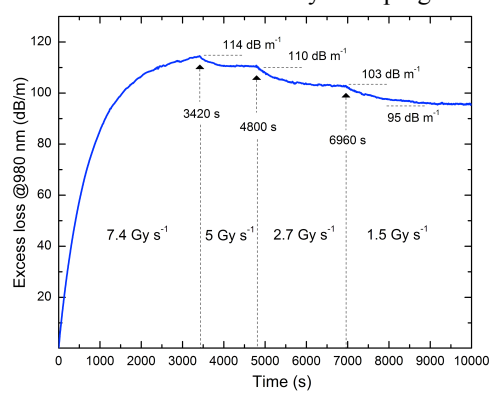

Figure 1: In-line 980 nm RIA of K04 at various dose rates

3 RECOVERY MECHANISM

Recovery was investigated by Thermally Stimulated Luminescence (TSL), a technique where carrier detrapping is due to heating (linear heating ramp applied to the sample [6]). Fig. 2 shows the spectrally-integrated TSL measured at 4 heating rates for K04 and K05 preform samples after a 7.4 kGy(SiO_2) dose. K05 is also an aluminosilicate sample, but with a lower Al concentration (0.53 w% Al). In the inset, the TSL from K04 is plotted versus wavelength and temperature (intensity increases from blue to red). The main TSL emission, around 2.95 eV with FWHM ~1 eV, can be assigned to AlODC centers [7]. AlODC are thus *re-formed* during the TSL readout which relaxes radiation effects: a recombination process reforms AlODC in excited state and produces TSL upon de-excitation. Fig. 3 shows the K05 RIA spectrum and its Gaussian decomposition with well-admitted band features [1]. Radiation-induced CC mainly consist of SiE', NBOHC, AlE' and AlOHC. This RIA is completely bleached by TSL readouts stopped at 450 °C.

The annealing of AlE' and AlOHC being accompanied by the reformation of AlODC, it is probable that SiODC are also reformed while SiE' and NBOHC are annealed, but the SiODC emission at 2.7 eV (459 nm) [1] is weak and hidden by the AlODC emission (it maybe appears as the light-blue tail at 460 nm).

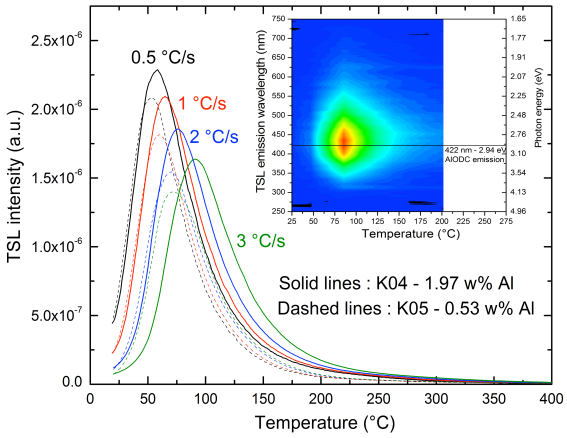

Figure 2: TSL curves from K04 and K05 at 4 heating rates and TSL spectrum of K04 (inset) at 2 °C/s.

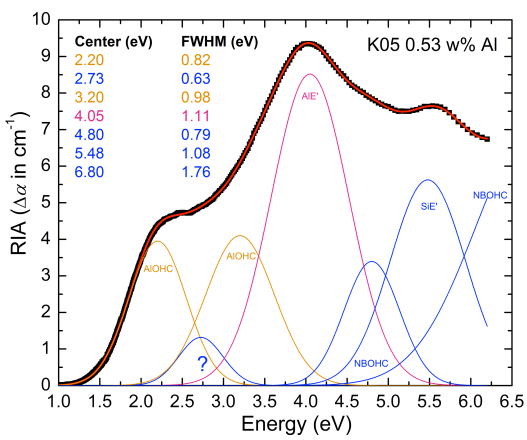

Figure 3: Typical RIA spectrum and its Gaussian decomposition, here for K05.

Fig. 4 presents the thermal bleaching map of K05 during the TSL readout at 2 °C s^{-1} (built following [8]). The color scale gives the percentage of the RIA annealed at given temperature (abscissa) and wavelength (ordinate). AlE' and NBOHC centers anneal rather continuously up to 350 °C, in a way that parallels TSL and the AlODC emission. Whereas this annealing goes with that of AlOHC around 75°C (main TSL peak), it accompanies the disappearance of SiE' around 275 °C.

4 MODELING

TSL is usually interpreted through energy level schemes distinguishing "traps" (trapped states that can be thermally emptied within the temperature range of TSL readouts)

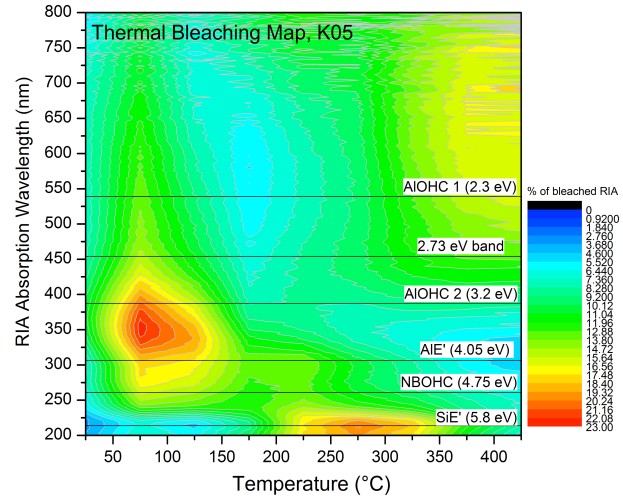

Figure 4: K05 bleaching map during TSL at 2 °C s^{-1}.

from "recombination centers" (deeply trapped carriers that can only disappear when a carrier of opposite polarity released from a trap recombines with them). As SiODC, AlODC are associated with an electron occupying a gap level above the valence band [7] and may therefore capture holes during irradiation to form CC. Since AlODC are reformed by recombination during thermal bleaching, the recovery process probably involves the detrapping and recombination of electrons. As the annealing of AlE' centers parallels this process, the AlE' seem to serve as the recombination centers (just as free electrons can recombine with SiE' to form SiODC [1]). Fig. 4 shows that carriers are released around 75 °C with a significant tail up to 300 °C, and around 275 °C. Released carriers are of the same nature in both cases, namely electrons, because we observe the same recombination center throughout the TSL readout. We implemented such a physical picture into the simulation of TSL at various heating rates (first-order TSL analysis). For the preform K05, we obtained a very good agreement with all data using a single set of parameters shown in Fig. 5 (σ_C is the capture cross-section). This figure notably displays the trapped-electron distribution achieved by the 7.4 kGy(SiO_2) dose and its decomposition into two components (red and blue) corresponding to the two above mentioned groups of traps. Simulated TSL curves are validated against data in Fig. 6. The TSL emission from AlODC is submitted to thermal quenching, as proved by the decrease of its intensity observed when the heating rate is increased (this shifts the TSL processes towards high temperature). With the luminescence yield parameters of Fig. 5, it is possible to simulate the TSL that would be obtained without thermal quenching. The renormalized TSL curve at 2 °C s^{-1} corrected from quenching, shown in Fig. 6, reveals hidden TSL components at ~225 and 315 °C. The latter are due to the "blue" density of trapped electrons peaking at 1.25 and 1.44 eV below the conduction band (Fig. 5) and are obviously related to the annealing of SiE' centers around 275 °C (Fig. 4).

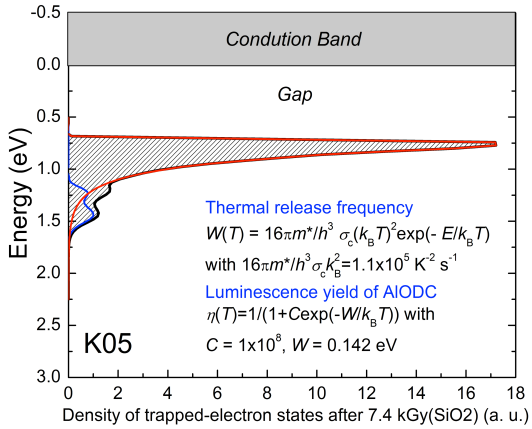

Figure 5: Parameters of the TSL simulation for K05.

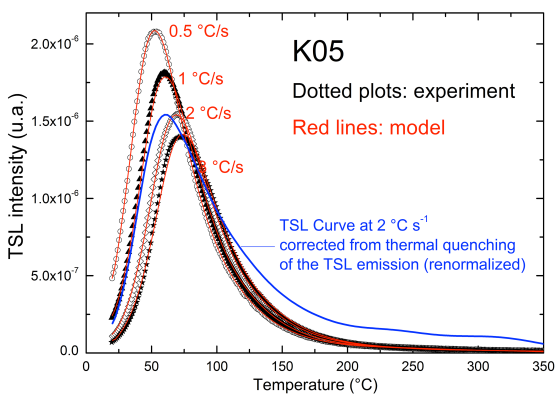

Figure 6: Simulated TSL curves compared to data.

5 PHOTOIONIZATION

Whereas OA bands of CC lie in the UV-VIS regions, trapped electrons of Fig. 5 can be excited to the conduction band by photons whose energy is > 0.7 eV. Each thermal activation energy E is associated with a photoionization cross-section $\sigma(\lambda,E)$ (Lucovsky's or more refined models [9]) so the corresponding absorption coefficient $\Delta\alpha$ is

$$\Delta\alpha(\lambda) = \int n(E)\sigma(\lambda,E)\mathrm{d}E, \qquad (1)$$

where $n(E)$ is the volume density of electrons trapped between E and $E + \mathrm{d}E$. With the density of trapped states of Fig. 5, and considering the intensity of the 0.75 eV peak is 10^{17} cm^{-3}, we can estimate the order of magnitude of $\Delta\alpha$. This also requires gauging $\sigma(\lambda,E)$. Assuming a maximum $\sigma_{max}(E = 1\text{ eV}) = 10^{-18}$ cm^2 for traps located at 1 eV from the band edge, we obtain the NIR RIA plotted in Fig. 7 for 2 usual models of $\sigma(\lambda,E)$ (see figure). Even with the reasonable estimates of $n(0.75\text{ eV})$ and $\sigma_{max}(E = 1\text{ eV})$, photoionization can be responsible for RIA levels of a few tens of dB m^{-1}. This contribution to the total RIA should not be neglected.

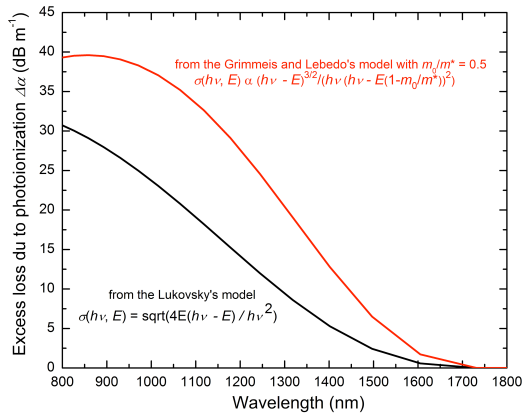

Figure 7: NIR RIA due to photoionization of the electron distribution of Fig 5.

6 CONCLUSION

Photoionization of carriers trapped close to the band edges may induce a significant RIA, notably in the NIR region. This contribution, most often forgotten, should be considered in the RIA modeling. The final paper will give much more experimental details and a clear explanation of the TSL modeling. Various models will be compared, several compositions will be treated to discuss composition and concentration effects.

7 AKNOWLEDGMENTS

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