Influence of proton radiation on the minority carrier lifetime in midwave infrared InAs/InAsSb superlattices

L. Höglund, D. Z. Ting, A. Khoshakhlagh, A. Soibel, A. Fisher, C. J. Hill, S. Keo, S. Rafol, S. D. Gunapala

Center for Infrared Photodetectors, Jet Propulsion Laboratory, California Institute of Technology,

4800 Oak Grove Drive, Pasadena, California, USA 91109-8099

Influence of proton radiation on the minority carrier lifetime and on carrier concentrations in InAs/InAsSb superlattices has been studied for radiation doses up to 300 kRad. The lifetime decreased from 1.8 μs down to 430 ns as the dose was increased. A variation of the carrier concentration in the range 1-2×10^{15} with increasing radiation dose was observed. The lifetime drop was however mainly caused by added Shockley-Read-Hall defects in the material. The position of these Shockley-Read-Hall centers was estimated to ~60 meV below the conduction band edge from comparison between calculated and measured temperature dependencies of the minority carrier lifetime.

Proton radiation hardness is an important parameter for infrared (IR) detectors used in space applications. High energy protons impingent on the detectors can cause ionization damage or permanent displacement damage such as vacancy-interstitial pairs in the detector material. Ionization damage increases the number of free carriers in the material while vacancy-interstitial pairs act as defects, which could cause an increase of non-radiative recombination in the material. The IR detectors most frequently used in space instruments are HgCdTe photodiodes and their radiation tolerance have been the subject of numerous studies.[1] Recently, Ga-free InAs/InAsSb superlattices have shown promising material properties in terms of long minority carrier lifetimes in both the mid-wave (3-5 μm) and the long-wave (8-12 μm) infrared region[2,3] and could therefore be promising candidates for space based IR detectors. Preliminary studies of the influence of proton radiation on detectors based on InAs/InAsSb superlattices have however shown degradation of detector performance in terms of increased dark current and reduced quantum efficiency with an increasing dose of proton radiation.[4] It was suggested that these effects were due to a decrease in the minority carrier lifetime caused by the radiation damage in the material. Another plausible cause to the increase of the dark current is an onset of surface leakage current with increasing proton radiation.

In this study, the effects of proton radiation on the carrier concentration as well as on the Shockley-Read-Hall, radiative and Auger lifetimes were studied to distinguish how the material is affected by the radiation. It was observed that the carrier concentration in the material increased from ~1×10^{15} cm^{-3} to ~$1.5\text{-}2\times10^{15}$ cm^{-3} with proton radiation. The carrier concentration increase did, however, not affect the minority carrier lifetime to the same extent as the increase in defect concentration in the material due to the radiation damage. The defect concentration was estimated to increase by an order of magnitude by fitting calculated temperature trends of the SRH, Auger and radiative lifetimes to measured temperature dependencies of the minority carrier lifetime. The fitting of the different lifetime components to the measurements also revealed that the dominant defect level was located ~60 meV below the conduction band edge. We observed a decrease of the minority carrier lifetime from 1.8 µs to 430 ns when gradually increasing the radiation dose up to 300 kRad. These findings explain the drop in QE and the increase of the dark current observed in proton irradiated detectors based on InAs/InAsSb superlattices. [4]

The SL structure studied was grown on 50 mm diameter Te-doped n-type GaSb (100) substrates in a Veeco Applied-Epi Gen III molecular beam epitaxy chamber. The structure consists of a 1.92 µm thick (48 Å, 13 Å)-InAs/$InAs_{0.55}Sb_{0.45}$ SL sandwiched between two 60 nm $AlAs_{0.08}Sb_{0.92}$ barriers. Five samples from this wafer were exposed to 68 MeV protons at room temperature with an isochronous cyclotron at the Crocker Nuclear Laboratory, University of California, Davis. Total ionizing doses (TID) of 30, 50, 100, 200 and 300 kRad were used, with corresponding fluences of 2.8, 4.8, 9.6, 19.2 and 28.8 × 10^{11} H+/cm^2. The corresponding displacement damage doses (DDDs) were 0.95, 1.6, 3.2, 6.4 and 9.6 × 10^9 MeV/g. The DDD was calculated, as $DDD = S \times \Phi p$, where Φp is particle fluence and $S = 3.3\times10^{-3}$ MeVcm^2/g for GaSb and 68 MeV protons. A week later, the samples were cooled down to cryogenic temperatures to measure the band gaps and minority carrier lifetimes of these superlattice samples using photoluminescence (PL) and optical modulation response (OMR)[5], respectively. Carrier concentrations in the samples before and after radiation were measured using Capacitance-Voltage (C-V) measurements on MOS devices fabricated from these samples. Details of these experiments have been described in Refs. 6 and 7.

Three experiments were performed to study the effect of proton radiation on the InAs/InAsSb superlattice material. In the first experiment, the influence of the proton radiation on the superlattice bandgap was studied using PL measurements. The PL peak wavelength (which approximately corresponds to the bandgap of the material) is approximately the same before and after exposure to proton radiation at all dose levels (Fig. 1), which has been observed also by other research groups.[8] A gradual decrease of the PL intensity was observed as the radiation dose was increased up to 300 kRad (Fig. 1). This indicates an increasing influence of non-radiative recombination in the material as the radiation dose is increased.

In the second experiment, the carrier concentrations in the superlattice samples were studied as a function of radiation dose (right axis, Fig. 2) and compared to the influence of radiation on the minority carrier lifetime (left axis, Fig. 2). Minor variation of the measured carrier concentration in the range ~1×10^{15} cm^{-3} - 2×10^{15} cm^{-3} was observed for non-irradiated and irradiated superlattices, however no clear correlation between radiation dose and carrier concentration could be observed. From minority carrier lifetime measurements performed at 77 K, it was observed that the lifetime gradually decreases with increasing radiation dose from 1.8 μs for a non-irradiated sample to 430 ns for a sample exposed to 300 kRad. The effect of the variation in carrier concentration ($1\text{-}2\times10^{15}$ cm^{-3}) on the radiative and Auger lifetimes is much smaller than the observed decrease of the minority carrier lifetime of up to a factor of 4. . An increase of the carrier concentration by a factor of two would reduce the radiative and the Auger lifetimes by factors of two and four, respectively (Eqs. 2-3)), while the SRH recombination would be unaffected. Since the Auger recombination has negligible influence of the minority carrier lifetime in these SLs and the effect on the radiative recombination is much smaller than the observed lifetime drop, the carrier concentration increase alone cannot explain the large decrease in minority carrier lifetime.

In the third experiment, the effect of proton radiation on the temperature dependence of the minority carrier lifetime was studied. The minority carrier lifetime (τ) is affected by three different recombination mechanisms; radiative, Auger and SRH recombination, and the lifetimes of these components (τ_i) add up as given in equation (1):

$$1/\tau = 1/\tau_{\mathrm{SRH}} + 1/\tau_{\mathrm{Rad}} + 1/\tau_{\mathrm{Auger}} \qquad (1)$$

The temperature dependencies of the different lifetime components carry information on how parameters such as carrier concentrations (n_0, p_0), trap density (N_t) and trap energy level positions (E_t) affect the minority carrier lifetime as shown in the equations (2-6):

$$\tau_{\mathrm{Rad}} = \phi \big/ \left(B(n_0(T) + p_0(T)) \right) \qquad (2)$$

$$\tau_{\mathrm{Auger}} = \frac{2(n_i(T))^2 \tau_i}{(n_0(T)+p_0(T))\left[(n_0(T)) + \beta(T)(p_0(T))\right]} \qquad (3)$$

$$\tau_{\mathrm{SRH}} = \frac{\tau_{n0}(p_0 + p_1) + \tau_{p0}(n_0 + n_1)}{(n_0 + p_0)} \qquad (4)$$

$$n_1 = n_0 \exp\left[\frac{E_t - E_f}{k_B T}\right], \quad p_1 = p_0 \exp\left[\frac{E_f - E_t}{k_B T}\right] \qquad (5)$$

$$\tau_{n0}, \tau_{p0} = \frac{1}{N_t \sigma v_{th}} \qquad (6)$$

, where ϕ, B, n_i, τ_i E_f, k_B, σ, v_{th}, *and* T correspond to the photon recycling constant, recombination coefficient, intrinsic carrier concentration and intrinsic lifetime, Fermi level, Boltzmann's constant, capture cross section, thermal velocity and temperature, respectively.[6] The temperature dependencies of the measured minority carrier lifetimes were therefore compared with calculated temperature trends of the lifetime components. For temperatures lower than 200K, the temperature dependence of minority carrier lifetimes changed with increasing radiation dose (Fig. 3a). In the non-irradiated sample, the minority carrier lifetime increased from 1.8 μs to 2.8 μs as the temperature was increased from 77 K to 200 K. This temperature dependence of lifetime was attributed to dominant radiative recombination in this material in one of our previous studies (Ref. 6). In the samples exposed to proton radiation, the lifetime temperature dependence gradually changed to constant or slightly decreasing with increasing temperature (Fig. 3a). The radiative, SRH and Auger lifetimes were calculated for the samples exposed to different radiation doses using equations (2)-(6). The carrier concentrations were taken from the measurement data (Fig 2) while N_t and E_t were used as fitting parameters to get the best possible fits to the measured temperature trends of the minority carrier lifetime (Fig 3a). From the fitted temperature trends, slightly reduced Auger lifetime (blue dotted lines, Fig 3b) and radiative lifetime (red dashed lines, Fig 3b) were observed due to the increased carrier concentrations. The non-monotonic behavior of the Auger and radiative lifetimes are directly caused by the variation in carrier concentration observed (Fig 2). The main difference between the samples is seen in the SRH recombination rate (green solid lines, Fig. 3b). As the radiation dose was increased, the influence of the SRH recombination gradually became stronger. For radiation doses > 100 kRad, SRH clearly is the dominating recombination mechanism in the temperature range 77 K – 225 K (Fig. 3b). A SRH lifetime component of ~1.4 μs was observed at 100 kRad and ~490 ns at 300 kRad at 77 K. This should be compared to the SRH lifetime component for the non-radiated sample, which is in the order of 7 μs at 77 K. For the non-irradiated sample, the best fit was obtained when using the intrinsic Fermi level as the main trap level. For the irradiated samples, the best fits were obtained for E_t located 60 meV below the conduction band edge (E_c), and with N_t

increasing approximately linearly with increasing radiation dose from 3×10^{14} cm^{-3} at 30 kRad to 1.7×10^{15} cm^{-3} at 300 kRad (Fig. 4, $\sigma = 4.4\times10^{-16}$ cm^2 was used). The proton radiation consequently has a major influence on the concentration of trap levels and thereby also on the minority carrier lifetimes in the superlattices. In a detector based on this material, this decrease of the minority carrier lifetime would lead to increased dark current and shorter diffusion lengths. This is consistent with the observed degradation of QE and dark current with increasing radiation dose, reported in Ref. 4.

From these studies, insight has been obtained on the damage proton radiation causes in InAs/InAsSb superlattices. A minor increase of the carrier concentration in the material was observed, however no clear trend was observed that could be attributed to the increasing radiation dose. The increased carrier concentration lead to a slight increase in Auger and radiative recombination rates, however, this effect was relatively small compared to the effect of defect creation in the material by the impingent protons. A significant increase of the density of SRH centers by up to an order of magnitude in the studied radiation range was observed. The nature of the defects is not known but they could be vacancy-interstitial pairs as suggested in a previous study.[4] The position of the defect energy level that caused the major SRH recombination was identified at ~60meV (~1/4 of the bandgap) below E_c. Since these defects are located above the intrinsic Fermi level of the superlattice, fairly large defect concentrations could be tolerated before severe reduction of the minority carrier lifetime occurred (on the order of 1×10^{15} cm^{-3}), as observed in the estimate of the trap density (Fig. 4c). Defects located close to the intrinsic Fermi level are more efficient recombination centers and would require lower trap densities to cause a similar decrease or the lifetime.[9] The increase of the SRH center density and decrease of the minority carrier lifetime will reduce the performance of detectors based on this material, as observed in Ref. 4. Further investigations on how to improve the radiation hardness of InAs/InAsSb superlattice detector material is needed.

In summary, the influence of proton radiation on the carrier concentration and on the minority carrier lifetime in an InAs/InAsSb superlattice has been studied. A slight increase of the carrier concentrations by a factor 1.5-2 was observed when exposed to total ionizing doses in the range 30-300 kRad. The minority carrier lifetime decreased from 1.8 μs for a non-radiated sample down to 430 ns for a sample exposed to 300 kRad. Defect levels generated by the proton radiation ~ 60 meV below the conduction band edge were identified as the main non-radiative recombination center in the material. By fitting calculated Auger, radiative and SRH lifetime trends to the measured temperature dependence of the minority carrier lifetime, the trap density in the material was estimated to increase approximately linearly from 3×10^{14} cm^{-3} to 1.7×10^{15} cm^{-3} when increasing the proton radiation dose from 30 to 300 kRad.

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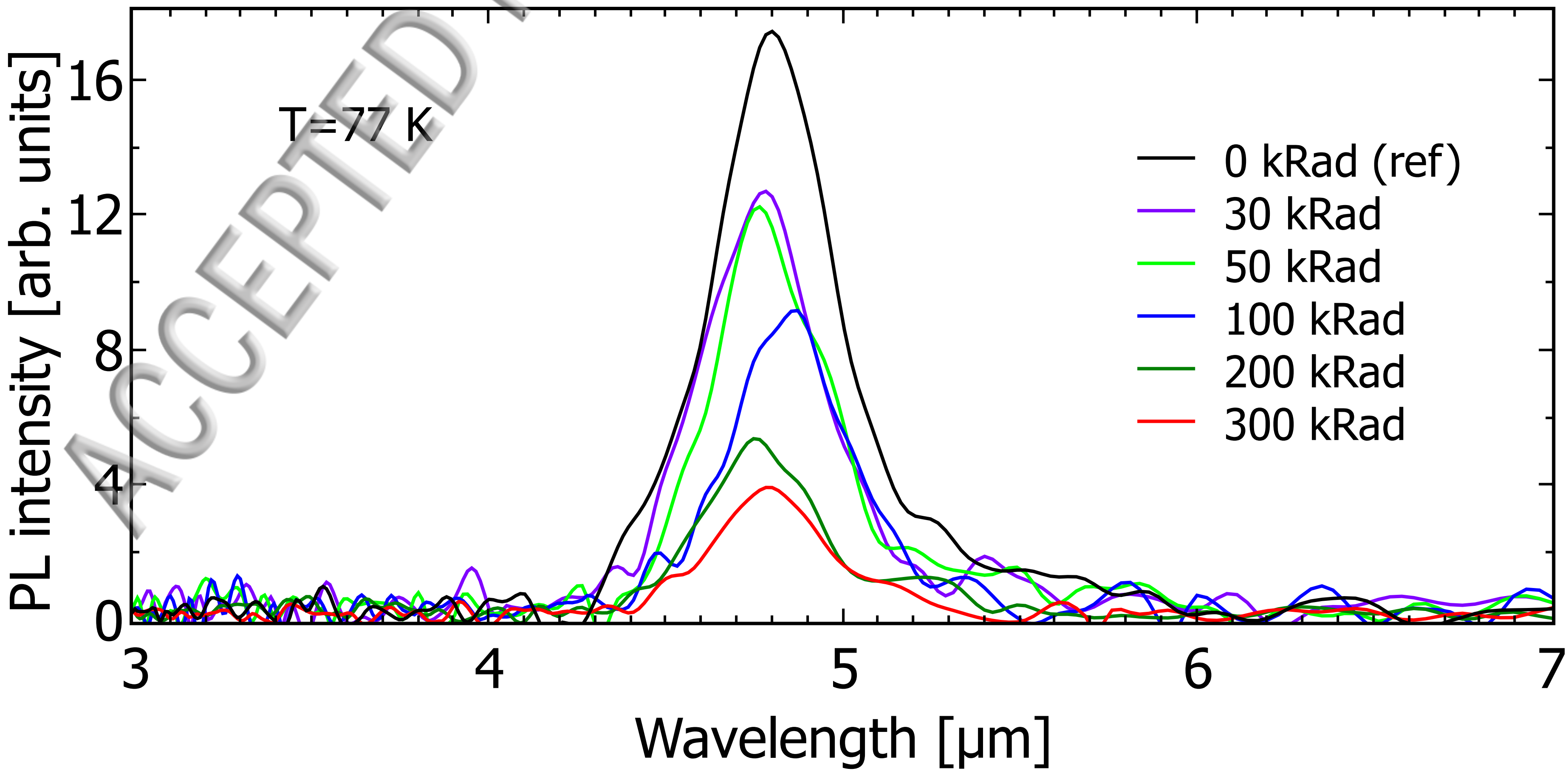
Figure captions:

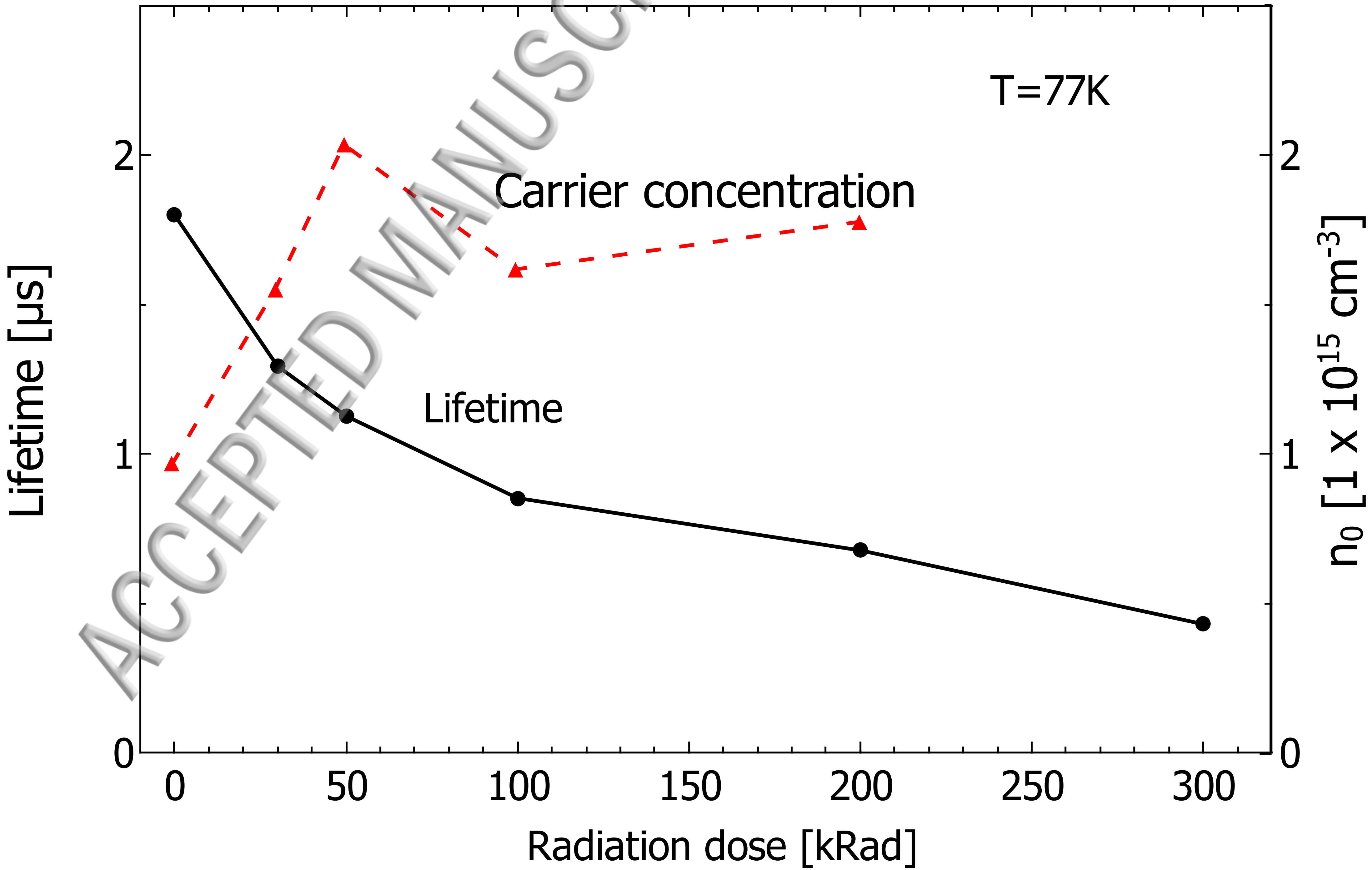
Fig 1. PL spectra of the InAs/InAsSb superlattice before and after exposure to proton radiation at five different doses: 30, 50, 100, 200 and 300 kRad.

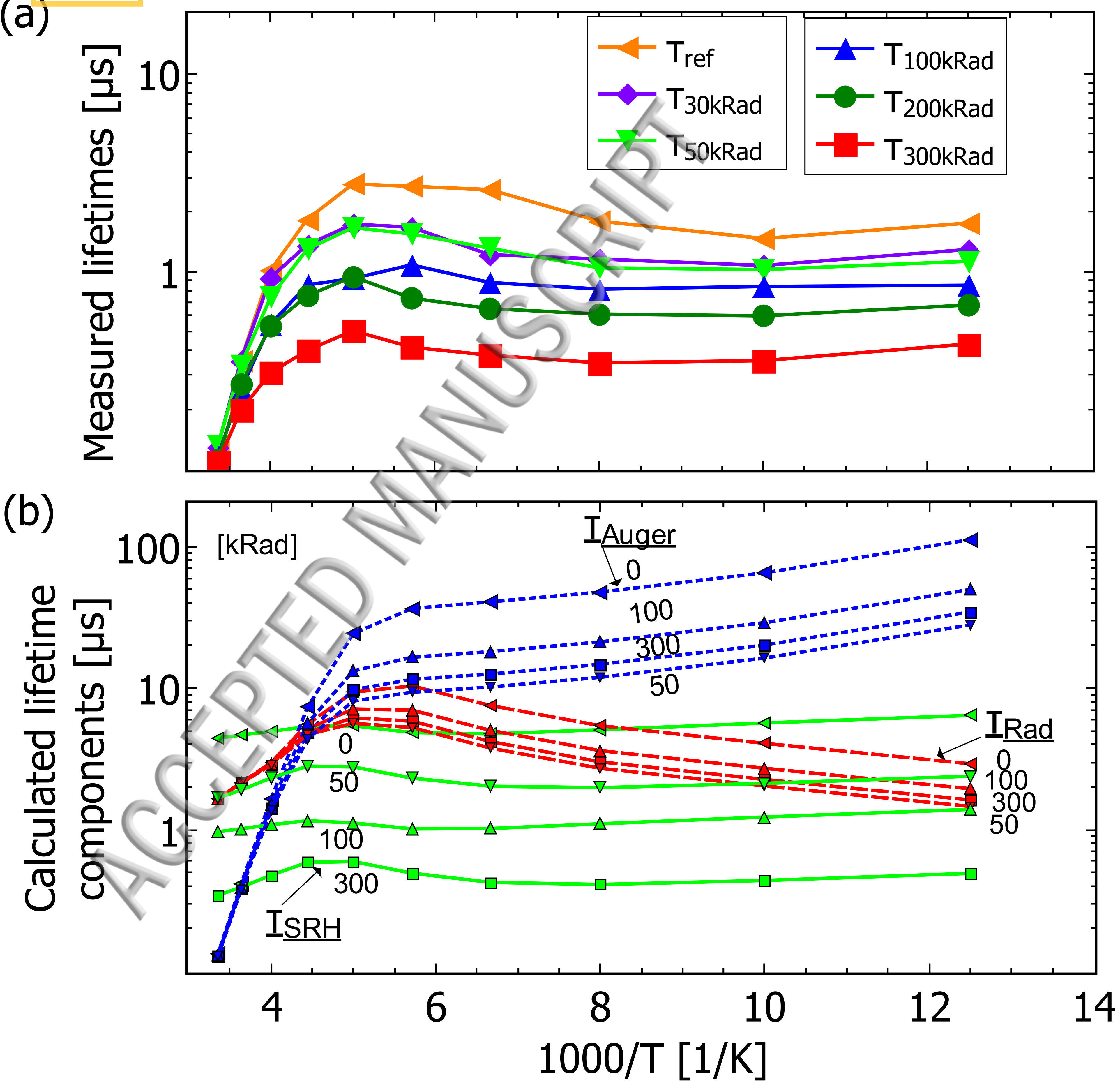
Fig. 2. Influence of proton radiation dosage on the minority carrier lifetime (left axis) and on the carrier concentration in the material (right axis).

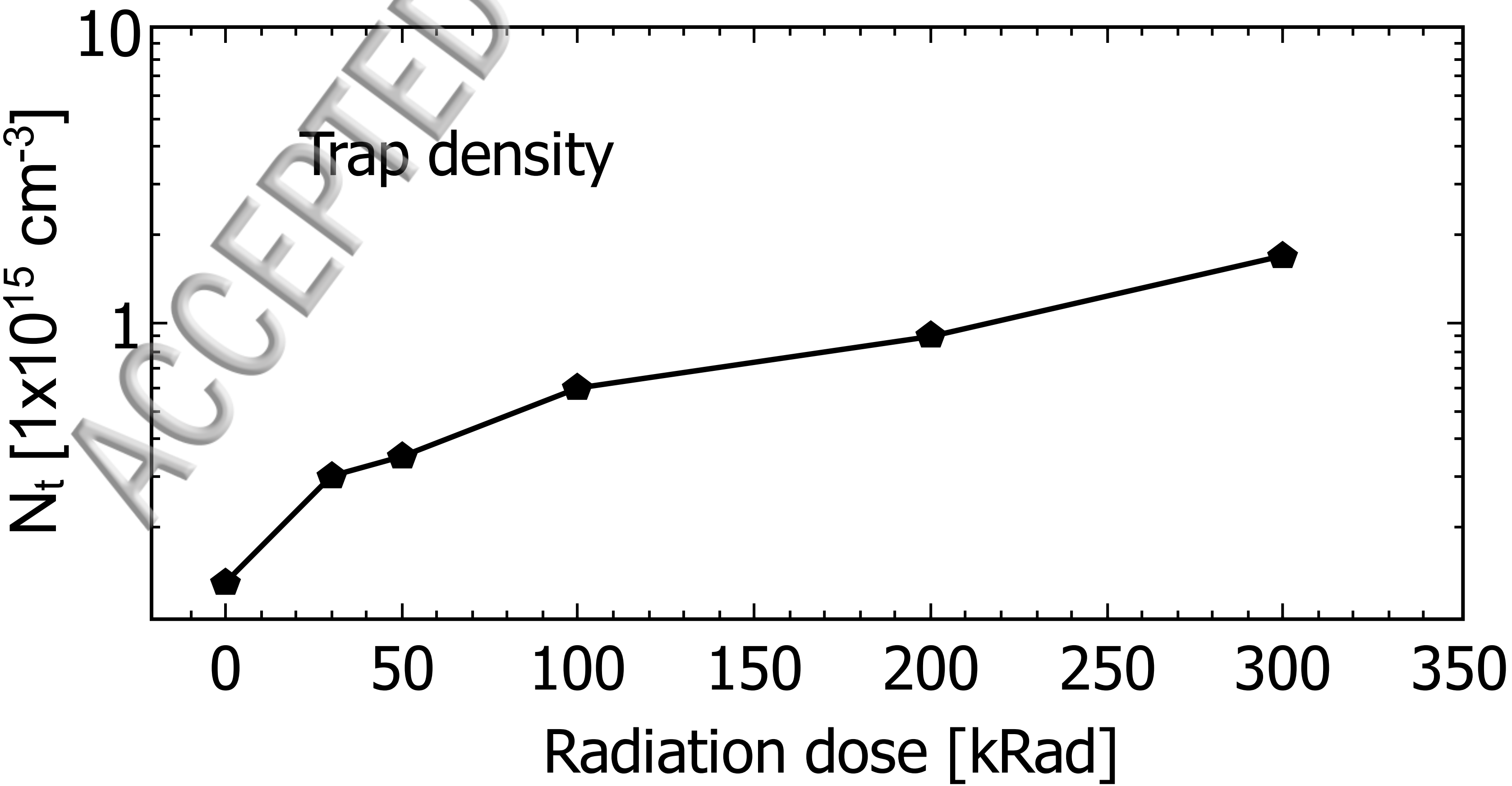
Fig. 3. (a) Measured temperature dependence of the minority carrier lifetime for InAs/InAsSb superlattices exposed to proton radiation with total ionizing dose (TID) varying from 0-300 kRad. (b) Fitted temperature trends of the SRH (green solid lines), Auger (blue dotted lines) and radiative (red dashed lines) lifetime components that gave the best correlation with the measured minority carrier lifetimes in Fig 3(a). Temperature trends for TID of 0 kRad, 50 kRad, 100 kRad and 300 kRad are shown. Increasing influence of SRH recombination is observed as the radiation dose increases.

Fig. 4. Trap density as function of radiation dose estimated from fitting the different lifetime components to the measured minority carrier lifetime (Fig 3).


PL intensity [arb. units]
0
4
8
12
16
Wavelength [μm]
3
4
5
6
7
T=77 K
0 kRad (ref)
30 kRad
50 kRad
100 kRad
200 kRad
300 kRad


T=77K
Carrier concentration
Lifetime
Lifetime [µs]
n_0 [1 x 10^{15} cm^{-3}]
Radiation dose [kRad]
0
1
2
0
1
2
0
50
100
150
200
250
300


(a)
Measured lifetimes [μs]
10
1
T_ref
T_30kRad
T_50kRad
T_100kRad
T_200kRad
T_300kRad
(b)
Calculated lifetime components [μs]
100
10
1
[kRad]
τ_Auger
0
100
300
50
τ_Rad
0
100
300
50
0
50
100
300
τ_SRH
4
6
8
10
12
14
1000/T [1/K]


Trap density
N_t [1x10^15 cm^-3]
10
1
0
50
100
150
200
250
300
350
Radiation dose [kRad]