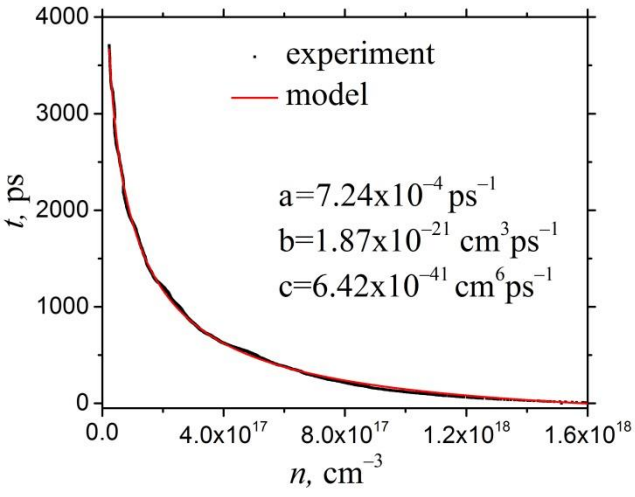
Supplementary Materials

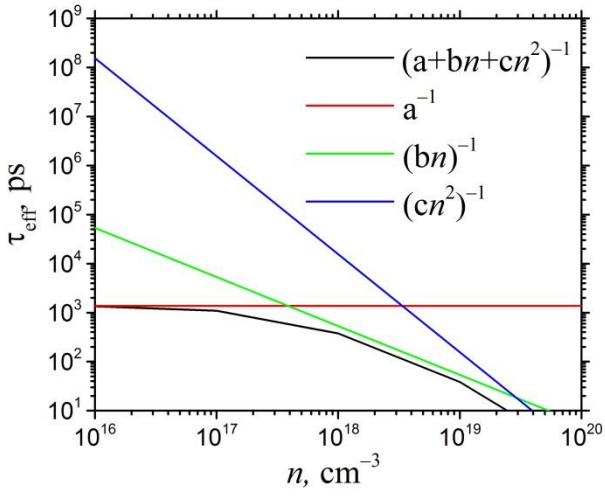
Optical Pump–Terahertz Probe Study of HR GaAs:Cr and SI GaAs:EL2 Structures with Long Charge Carrier Lifetimes

Irina A. Kolesnikova [1], Daniil A. Kobtsev [2], Ruslan A. Redkin [2], Vladimir I. Voevodin [3], Anton V. Tyazhev [1], Oleg P. Tolbanov [1], Yury S. Sarkisov [4], Sergey Yu. Sarkisov [3] and Victor V. Atuchin [5,6,7,8,*]

[1] Laboratory of Ionizing Radiation Detectors, R&D Center "Advanced Electronic Technologies", Tomsk State University, 634050 Tomsk, Russia; varsharova@mail.ru (I.A.K.); antontyazhev@mail.ru (A.V.T.); top@mail.tsu.ru (O.P.T.)
[2] Laboratory of Optical Structures and Applied Photonics, R&D Center "Advanced Electronic Technologies", Tomsk State University, 634050 Tomsk, Russia; danbers27@gmail.com (D.A.K.); redkin@mail.tsu.ru (R.A.R.)
[3] Laboratory for Terahertz Research, Tomsk State University, 634050 Tomsk, Russia; voevodinvova2013@yandex.ru (V.I.V.); sarkisov@mail.tsu.ru (S.Y.S.)
[4] Department of Physics, Chemistry and Theoretical Mechanics, Tomsk State University of Architecture and Building, 634003 Tomsk, Russia; sarkisov@tsuab.ru
[5] Laboratory of Optical Materials and Structures, Institute of Semiconductor Physics, SB RAS, 630090 Novosibirsk, Russia
[6] Department of Applied Physics, Novosibirsk State University, 630090 Novosibirsk, Russia
[7] Research and Development Department, Kemerovo State University, 650000 Kemerovo, Russia
[8] Department of Industrial Machinery Design, Novosibirsk State Technical University, 630073 Novosibirsk, Russia
* Correspondence: atuchin@isp.nsc.ru

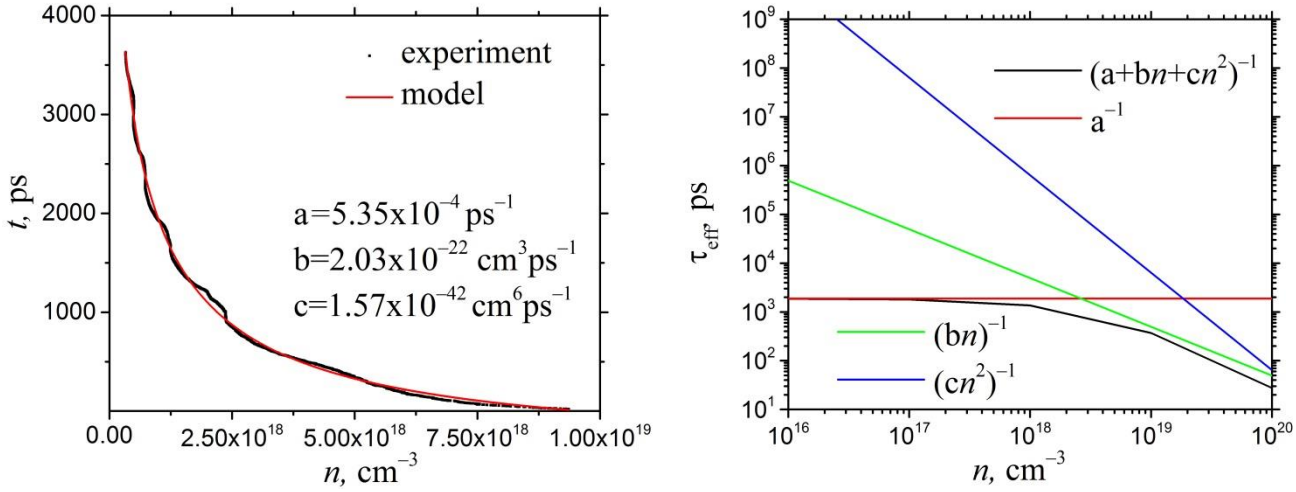


a)



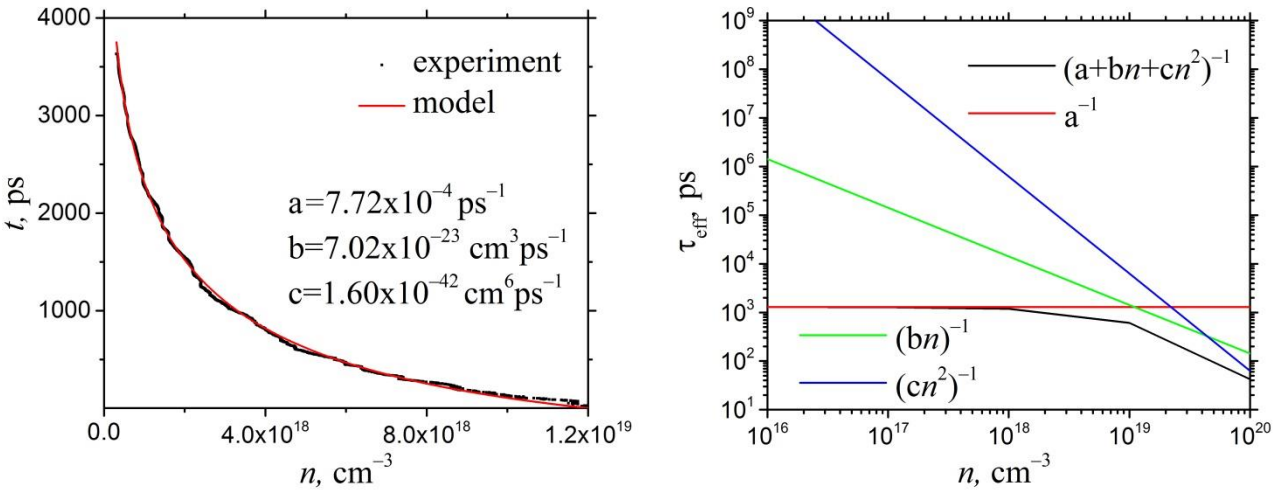
b)

Figure S1. The experimental and fitting (the parameters are given) time dependences of the nonequilibrium charge carrier concentration at the average photoexcitation beam power of 20 mW (**a**) in HR GaAs:Cr (**b**) related calculated injection level dependences of efficient charge carrier lifetime with the resolution into contributions from different recombination mechanisms.



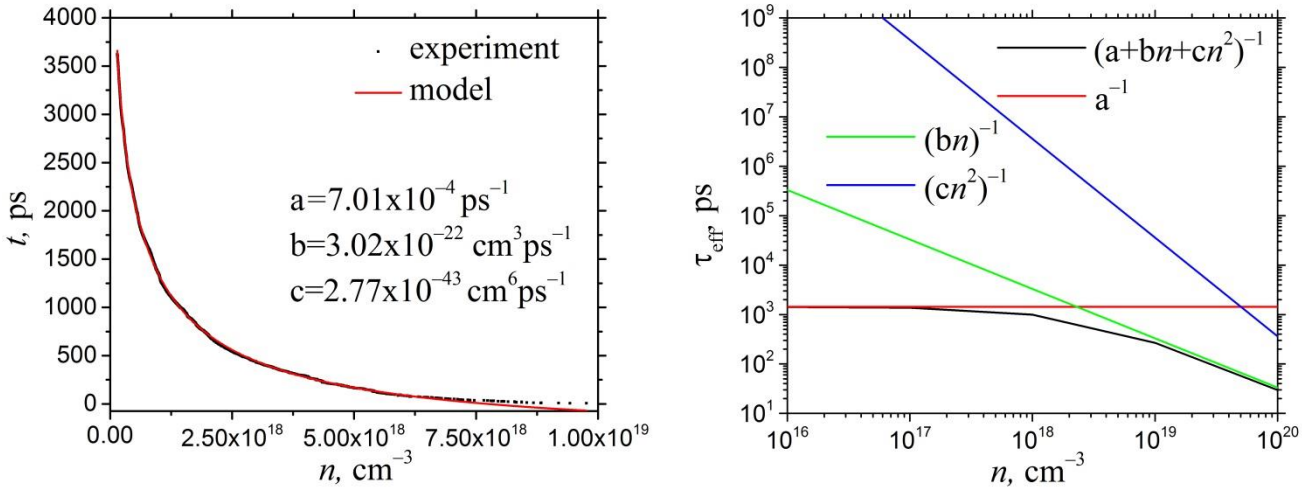
a) b)

Figure S2. The experimental and fitting (the parameters are given) time dependences of the nonequilibrium charge carrier concentration (**a**) in HR GaAs:Cr after SiO_2 film deposition (**b**) related calculated injection level dependences of efficient charge carrier lifetime with the resolution into contributions from different recombination mechanisms.



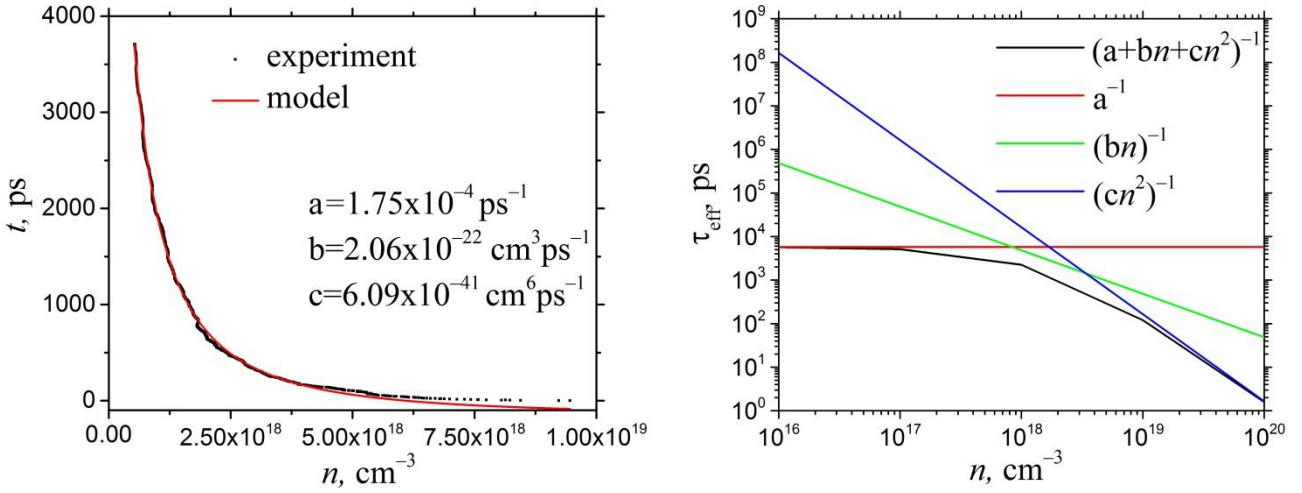
a) b)

Figure S3. The experimental and fitting (the parameters are given) time dependences of the nonequilibrium charge carrier concentration (**a**) in HR GaAs:Cr after etching in sulfuric acid solution (**b**) related calculated injection level dependences of efficient charge carrier lifetime with the resolution into contributions from different recombination mechanisms.



a) b)

Figure S4. The experimental and fitting (the parameters are given) time dependences of the nonequilibrium charge carrier concentration (**a**) in HR GaAs:Cr after oxidation in oxygen plasma (**b**) related calculated injection level dependences of efficient charge carrier lifetime with the resolution into contributions from different recombination mechanisms.



a) b)

Figure S5. The experimental and fitting (the parameters are given) time dependences of the nonequilibrium charge carrier concentration (**a**) in SI GaAs:EL2 after oxidation in running water (**b**) related calculated injection level dependences of efficient charge carrier lifetime with the resolution into contributions from different recombination mechanisms.

The following analysis allowed to write the Equation (3) in the main text. For a semiconductor with *p*-type conductivity by definition, the lifetime of minority charge carriers τ is related to the charge carrier recombination rate *U* as

$$\tau = \frac{\Delta n}{U}, \tag{S1}$$

where Δn is the excess electron concentration.

For the SRH recombination, the expression for the recombination rate is written as [1]

$$U_{\mathrm{SRH}} = \frac{n \cdot p - n_0 \cdot p_0}{\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)}, \tag{S2}$$

where $\tau_{p0} = 1/(\sigma_p N_t v_t)$, $\tau_{n0} = 1/(\sigma_n N_t v_t)$, $n_1 = n_i \exp((E_t - E_i)/kT)$, $p_1 = n_i \exp(-(E_t - E_i)/kT)$, σ_p and σ_n are the hole and electron capture cross sections, respectively, N_t and E_t are the concentration of recombination centers and the energy position of the corresponding level in the band gap of the semiconductor, respectively, v_t is the thermal velocity of charge carriers, n and p are the electron and hole concentrations, respectively, n_0 and p_0 are the electron and hole concentrations, respectively, in an intrinsic semiconductor in equilibrium ($n_0 \cdot p_0 = n_i^2$). We assume that the excess concentration of minority charge carriers $\Delta n >> n_0$, then, $n \approx \Delta n$, $p \approx N_a + \Delta n$. With this in mind and in the approximation of a high injection level $\Delta n >> N_a$, we can assume that $n = p = \Delta n$. After the corresponding transformation of (2) and substitution it into (1) for the minority charge carrier lifetime due to the SRH recombination in the semiconductor bulk the following expression is obtained:

$$\tau_{\mathrm{SRH}} = \tau_{p0} + \tau_{n0}. \tag{S3}$$

That is, at a high injection level (excess concentration of minority charge carriers), the lifetime does not depend on the excess charge carrier concentration.

The Shockley–Read–Hall formalism is usually used for the surface recombination, taking into account that the concentration of defect states is replaced by the surface density of defect states N_{ts}, the energy distribution of the interface surface states in the band gap is replaced by one effective recombination level with the energy position E_{ts}. Also instead of the lifetime, the surface recombination rate *S* is introduced

$$\frac{1}{S} = \frac{\Delta n}{U}. \tag{S4}$$

Then, the expression for the surface recombination rate is written as [1]

$$U_{\text{s}} = \frac{S_{n0} S_{p0} (n_s p_s - n_i^2)}{S_{n0}(n + n_1) + S_{p0}(p + p_1)}, \tag{S5}$$

where $S_{p0} = \sigma_p N_{\text{ts}} v_t$, $S_{n0} = \sigma_n N_{\text{ts}} v_t$, n_{s} and p_{s} are the electron and hole surface concentrations, respectively. In case of high level of injection, we again have that there is no dependence of recombination rate on the injection level:

$$\frac{1}{S} = \frac{1}{S_{p0}} + \frac{1}{S_{n0}}. \tag{S6}$$

The radiative recombination rate is written as

$$U_{\text{rad}} = B_{\text{rad}} (n \cdot p - n_0 \cdot p_0). \tag{S7}$$

In the approximation of a high injection level, the lifetime for radiative recombination is inversely proportional to the injection level

$$\tau_{rad} = \frac{1}{B_{\text{rad}} \Delta n}. \tag{S8}$$

For the "band-to-band" Auger recombination, the recombination rate is written as [1]

$$U_{\text{Aug}} = C_n (n^2 p - n_i^2 n_0) + C_p (p^2 n - n_i^2 p_0), \tag{S9}$$

where C_n and C_p are the Auger recombination coefficients. In case of a high injection level, expression (9) is simplified and the minority charge carrier lifetime due to the "band-to-band" Auger – recombination is written as

$$\tau_{\text{Aug}} = \frac{1}{(C_n + C_p) \Delta n^2}. \tag{S10}$$

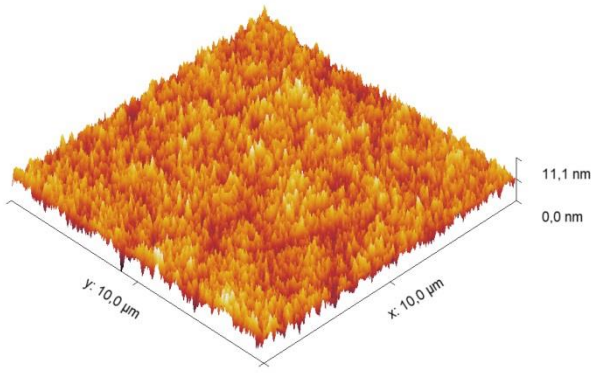
That is, in this case, the lifetime is inversely proportional to the square of the excess concentration of minority charge carriers. Finally, for the case of Auger recombination involving an impurity level, the recombination rate is written as [1,2]

$$U_{\text{Aug1}} = N_t \frac{(n \cdot p - n_1 p_1)(C_{n1} n + C_{n2} p)(C_{p1} n + C_{p2} p)}{C_{n1}(n^2 + n \cdot n_1) + C_{n2}(n \cdot p + p \cdot n_1) + C_{p1}(n \cdot p + n \cdot p_1) + C_{p2}(p^2 + p \cdot p_1)}, \tag{S11}$$

where C_{n1}, C_{n2}, C_{p1}, and C_{p2} are the Auger recombination coefficients for various recombination events involving the capture of electrons or holes to a defect level and the transfer of energy to an electron in the conduction band or hole in the valence band. In case of a high injection level, expression (11) is simplified and the lifetime of minority charge carriers due to the Auger recombination involving an impurity level is written in as

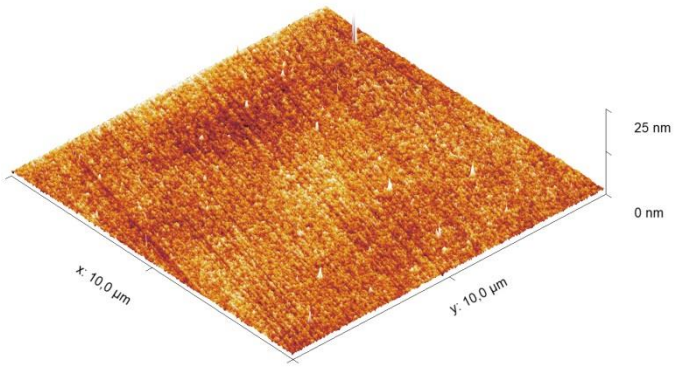
$$\tau_{\text{Aug1}} = \frac{C_{n1} + C_{n2} + C_{p1} + C_{p2}}{N_{\text{ts}} (C_{n1} + C_{n2})(C_{p1} + C_{p2}) \Delta n}.$$

Thus, combining all the obtained dependencies of the lifetime of minority charge carriers τ on powers of Δn at high injection level we can write the expression (3) in the main text.



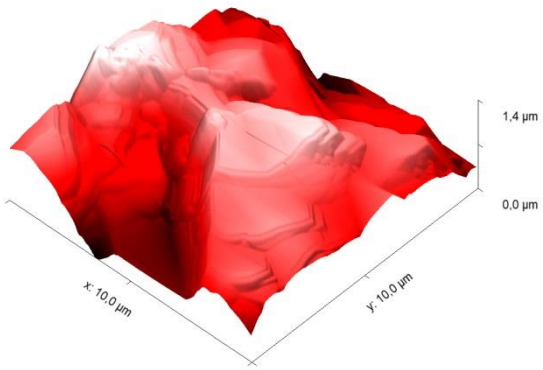
Peak-to-peak, Sy 11.0683 nm
Root Mean Square, Sq 1.28405 nm

a)



Peak-to-peak, Sy 47.016 nm
Root Mean Square, Sq 0.467805 nm

b)



Peak-to-peak, Sy 1441.14 nm
Root Mean Square, Sq 267.849 nm

c)

Figure S6. The AFM data for HR GaAs:Cr wafers: (a) – initial, (b) – after etching in sulfuric acid solution and (c) after grinding the surface.

1. Blackmore J.S., Semiconductor statistics. Oxford: Pergamon press, 1962, 392 pp.
2. Staub, F., Rau, U., Kirchartz, T. Statistics of the Auger recombination of electrons and holes via defect levels in the band gap - Application to lead-halide perovskites. *ACS Omega* **2018**, *3*, 8009-8016.