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Citation: *AIP Advances* **5**, 087138 (2015); doi: 10.1063/1.4928731

View online: <http://dx.doi.org/10.1063/1.4928731>

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## Observation of suppressed Auger mechanism in type-I quantum well structures with delocalized electron-hole wavefunctions

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(Received 12 May 2015; accepted 5 August 2015; published online 13 August 2015)

We report the first observation of non-threshold Auger mechanism for a quantum well structure with Type-I band alignment. Excitation-dependent photoluminescence measurements were used to extract the Auger recombination coefficients from 77 K up to room temperature. The results verify the role of interface mediated momentum exchange as well as suppression of Auger recombination for delocalized electron-hole wavefunctions. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [<http://dx.doi.org/10.1063/1.4928731>]

Carrier recombination mechanisms in semiconductors play a crucial role for their applications in electronics and optoelectronics. For instance, the luminescence efficiency of an emitter, defined as the ratio of the radiative to nonradiative recombination rates, is an important figure of merit for light emitting diodes and lasers.<sup>1,2</sup> On the other hand, various recombination processes directly affect the sensitivity of light detection for a wide spectral range.<sup>3,4</sup> Therefore, it is essential to characterize various recombination rates of the active photonic materials for determining the required conditions to achieve the best performance. In previous work, the Auger recombination for a Type-II multiple quantum well (MQW) structure was characterized, and the non-threshold Auger recombination in those systems was demonstrated.<sup>5</sup> Here, we report similar Auger recombination behavior of a MQW structure with Type-I band alignment but with similar delocalized electron and hole wavefunctions. These structures have received special attention because they possess enhanced electro-optic effects.<sup>6,7</sup> Furthermore, the delocalization of electron hole wavefunctions is associated with an effective built-in electric field that can be reduced by applying external electric fields, resulting in the blueshift of transition energy with the applied bias. This effect can be employed to obtain excellent electro-absorption properties such as high on/off modulation contrast and enhanced optical modulation sensitivity to the externally applied voltages.<sup>8,9</sup> The non-threshold Auger mechanism has power-law temperature dependence and is predicted in heterostructures<sup>10,11</sup> where the momentum conservation law is violated orthogonal to the growth direction. In this regard, the dominant CCHC Auger mechanism in QW structures can be decomposed into two main parts:<sup>11</sup> (a) contribution of large momentum transfer to the electron in the conduction band  $\sim \sqrt{(2m_h E_g)}$ , where  $E_g$  is the bandgap energy and  $m_h$  is the heavy hole effective mass, and (b) contribution from small transferred momentum from heavy holes  $\sim \sqrt{(2m_h K_B T)}$ , where  $T$  is the temperature and  $K_B$  is the Boltzmann constant. The latter is dominant in QW systems and it has been theoretically predicted that the CCHC Auger process is drastically suppressed in MQW structures.<sup>12</sup> The experimental studies on simple structures comprising InGaAs quantum wells have verified the suppression of the Auger mechanism.<sup>13,14</sup> However, due to their limited temperature range, the described temperature characteristics of the non-threshold Auger process have not yet been reported until this letter. It is important to note that in Type-II structures, the Auger recombination can be further suppressed by the separation of the electron and hole wavefunctions that reduces the

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overlap integral.<sup>11,15</sup> Here we show that the same mechanism is responsible for significantly lower Auger recombination rate compared to other Type-I MQWs without delocalized electron and hole wavefunctions.

Each of the five periods of the grown MQW structure consists of 17 nm of InAlAs as a barrier for electrons, 18 nm of InGaAsP with a cut off wavelength of 1.4  $\mu\text{m}$ , 1 nm of InAlAs, 3 nm of InGaAs and 17 nm of InP as a barrier for holes. All of the layers are lattice matched to the InP substrate. The structure was grown by metalorganic chemical vapor deposition (MOCVD) and the quality of growth was confirmed by photoluminescence and X-ray measurements. The thin InAlAs barrier between the InGaAsP and the InGaAs separates electron and hole wavefunctions as shown in Fig. 1(a) similar to a type-II structure. We note that the quantum wells are embedded within the intrinsic region of a p-i-n structure with a uniform built-in electric field of 45 kV/cm. In order to simulate the structure, the energy band-lineups of the materials were obtained using the model solid theory,<sup>16</sup> and Luttinger parameters of each layer were used for finding the effective mass of electron and holes in that layer.<sup>17</sup>

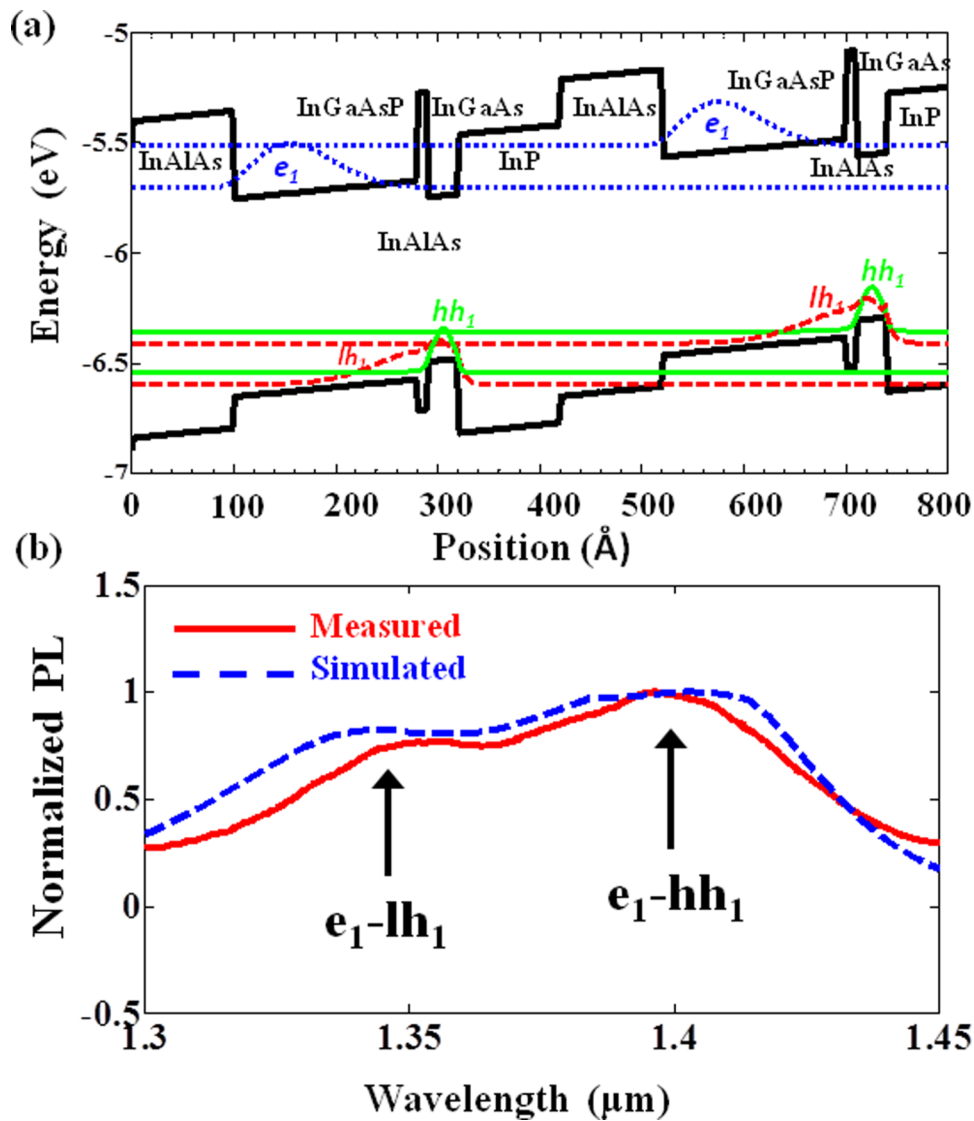


FIG. 1. (a) The simulated bandstructure of the two periods of multiple quantum well system under consideration. Three sets of wavefunctions have been shown. The electron wavefunction is shown by dotted lines whereas the first heavy-hole and light-hole functions are shown by solid and dashed lines respectively. It is evident that the electron and hole wavefunctions are separated spatially. (b) The measured (solid line) and the simulated (dashed line) photoluminescence spectrum. Each peak is assigned to its corresponding electronic transition.

The wavefunctions were then calculated by self-consistent solution of Schrodinger and Poisson equations using 8-band k.p approximation. In our previous publications we have verified the simulation results with the experimental measurements.<sup>6</sup> The simulated and measured photoluminescence, as shown in Fig. 1(b) agree very well, which confirms the quality of growth. In order to find the Auger recombination coefficient, we performed excitation-dependent photoluminescence experiments. This technique is based on the carrier density dependency of the non-radiative and radiative recombination mechanisms.<sup>18</sup> A laser diode with a wavelength of 980 nm (Agilent FPL4916-240) was used for pumping the material. The laser was current-modulated with a duty cycle of 1% to avoid heating the sample and reducing the accuracy of the measurement. The photoluminescence was collected from the excited area on the sample and was subsequently detected using a sub-nanosecond linear avalanche photodiode (Princeton Lightwave PLA-861) and displayed with an oscilloscope to obtain the photoluminescence waveform. The pump pulse width was 100 nsec and the jitter was negligible such that the middle of the pulse was used to evaluate the PL and pump peak intensity.

Figure 2 shows the results. The dashed lines and the dotted line show the slope for the Auger and radiative dominated processes. Based on the slope of the measured curves, it can be inferred that throughout the whole range of the pump powers and from 77 K up to room temperature, the Auger recombination dominates in our experiments. Therefore, from curve fitting to this data, the Auger recombination coefficient can be obtained with good accuracy. The radiative recombination coefficient ( $B$ ) at room temperature was calculated analytically based on van Roosbroeck-Shockley relationship<sup>19,20</sup> and it varies as  $T^{-3/2}$  with the temperature.<sup>20-22</sup> The calculation of  $B$  is in close agreement with the average experimental values, confirming that the analytical evaluation is robust and valid as reported by Ref. 18. The Extracted Auger recombination rates versus temperature are shown in Fig. 3. The behavior of the Auger mechanism can be explained by considering two different ranges of the temperature as proposed by Dyakonov and Kacaharovsky.<sup>10</sup> Based on their formalism for quantum wells, the non-threshold Auger coefficient below a certain temperature can be expressed as:<sup>10</sup>

$$C = \frac{32\sqrt{2}}{3\pi} \omega_B |O|^2 \frac{1}{k_g^4} \left[ \frac{E_0}{E_g} \right]^{7/2} \frac{U}{k_B T} \frac{m_e}{m_{hh}} \quad (1)$$

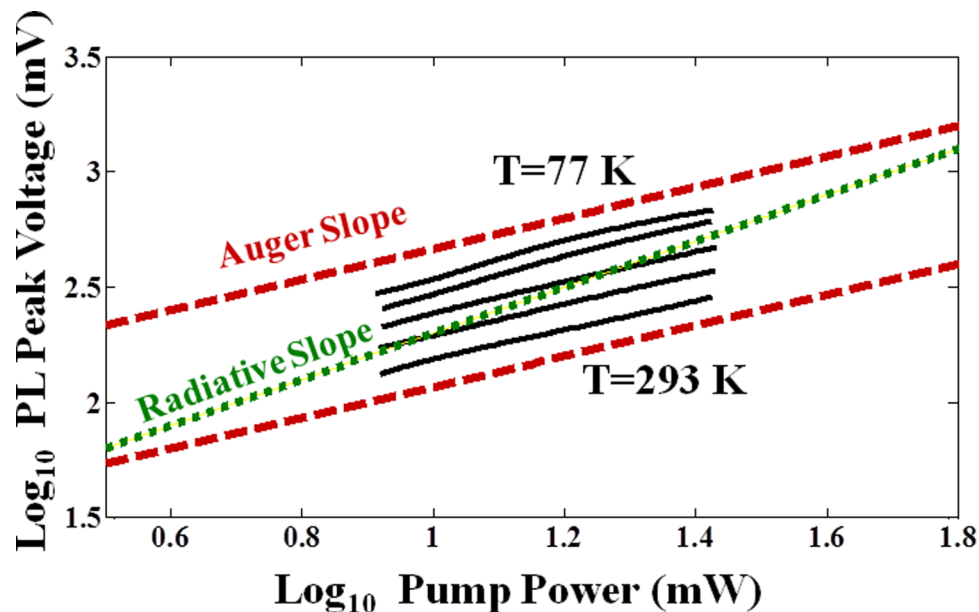


FIG. 2. The detected photoluminescence signal (in mV) versus pump power for temperatures ranging from 77 K up to 293 K. The Auger and Radiative dominated lines are also indicated. The slope of the measured values in logarithmic scale indicates that for most of pump power range, the auger recombination is dominant. Each measurement for obtaining the points in this figure was repeated ten times to ensure that the stability of the systems (with maximum error less than 2%).

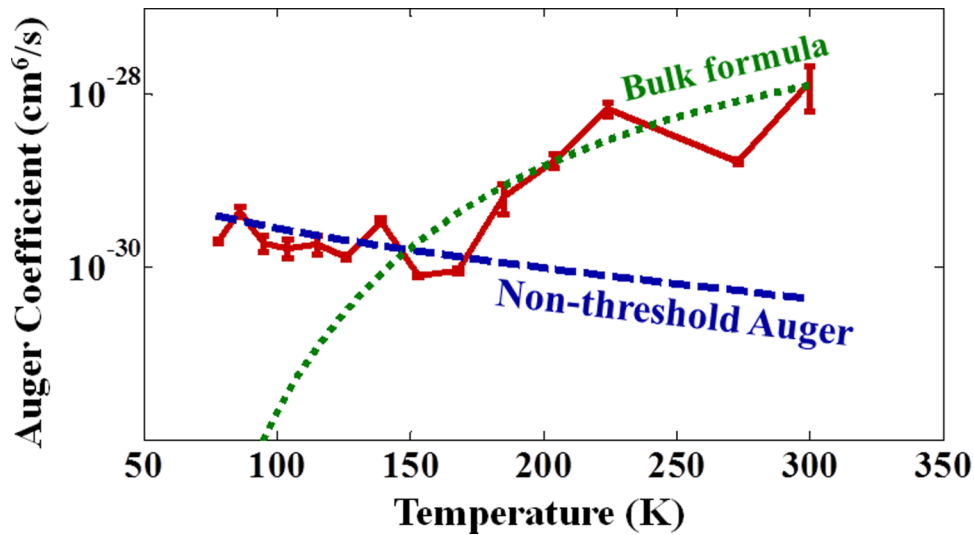


FIG. 3. The measured Auger recombination coefficient ( $C$ ) for the MQW structure (solid line). While the behavior of the Auger mechanism at temperatures lower than 160 K is consistent with non-threshold Auger mechanism as shown by the dashed line (obtained from Eq.(1)), at higher temperatures a bulk-type Auger behavior was observed (dotted line, obtained from Eq.(2)). Each measurement was performed ten times to obtain the statistical error bars.

where  $\omega_B$  is the electron Bohr frequency,  $E_g$  is the bandgap,  $E_0$  is the electron energy in the first excited state,  $U$  is the conduction band offset.  $m_e$  and  $m_{hh}$  denote the effective electron and heavy hole mass respectively and  $k_g = \sqrt{2m_e E_g}/\hbar$ . We have also included the the overlap integral ( $O$ ) in order to take into account the reduction of Auger matrix element due to the spatial separation of the electron and hole pair. We note that the absorption and radiative recombination decrease in proportion to the square of the overlap integral as well. The results are plotted in Fig. 3 and are consistent with our measurements at low temperature. As the temperature increases, carriers occupy higher energy subbands and therefore the hetero-barrier becomes less effective and the above equation is not valid.<sup>10</sup> When the carriers are away from the band edges, a bulk-type Auger mechanism is predicted for quantum well structures:<sup>25</sup>

$$C = C_0 \exp\left(-\frac{\mu}{1 + \mu} \frac{E_g}{k_B T}\right) \quad (2)$$

Where  $C_0$  is a coefficient of proportionality and  $\mu$  is the ratio of the electron to heavy-hole effective mass. The trend of the Auger coefficient versus temperature has been predicted very well with the above equation as shown in Fig. 3. We note that compared to the reported data for quantum well structures without electron-hole wavefunction delocalization, the Auger recombination is significantly lower (see Table I). The significant reduction, similar to a type-II structure, is attributed

TABLE I. Comparison of Auger recombination coefficient at  $T = 200$  K in our structure to the quantum well structures without electron and hole wavefunction separation and also the bulk material with similar composition.

Structure	Auger coefficient(cm <sup>6</sup> /s)
Our structure	$6.5 \times 10^{-30}$
Type-I In <sub>0.53</sub> Ga <sub>0.47</sub> As QW (Lattice matched) <sup>a</sup>	$1.3 \times 10^{-28}$
Type-I In <sub>0.46</sub> Ga <sub>0.54</sub> As QW (tensilely strained layer) <sup>b</sup>	$6 \times 10^{-29}$
Type-I In <sub>0.66</sub> Ga <sub>0.34</sub> As QW (compressively strained layer) <sup>b</sup>	$7 \times 10^{-29}$
Bulk InGaAsP (Q1.3) <sup>c</sup>	$2.5 \times 10^{-29}$

<sup>a</sup>Reference 13.

<sup>b</sup>Reference 23.

<sup>c</sup>Reference 24.

to electron-hole wavefunction delocalization that can lead to suppression of Auger recombination pathways which involve small momentum transfer from heavy holes.<sup>11</sup>

In conclusion, we characterized the Auger recombination mechanism in a Type-I quantum well structure with delocalized electron hole wavefunctions. We used the excitation-dependent PL measurements to extract the Auger recombination coefficients from 78 K up to room temperature. The results are consistent with the theory for the two different regions of temperature and indicate that the dominant Auger mechanism is CHCC. A significant suppression of Auger recombination was observed due to the spatial separation of electron and hole wavefunctions. The reduced Auger recombination in these structures can be employed to improve the performance of optoelectronic devices in the near infrared region of light spectrum.

We would like to acknowledge the partial support from NSF award #ECCS-131062, DARPA award # W911NF-13-1-0485 and ARO award # W911NF-11-1-0390.

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