Interface-induced suppression of the Auger recombination in type-II InAs/GaSb superlattices

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The temperature dependence of the nonequilibrium carriers lifetime has been deduced from the measurement of the photocurrent response in InAs/GaSb superlattices. Based on the temperature dependence of the responsivity and modeling of the transport parameters we have found that the carrier lifetime weakly depends on temperature in the high-temperature region. This indicates the temperature dependence of the Auger recombination rate with no threshold that differs it from that in the bulk material and can be attributed to the interface-induced suppression of the Auger recombination in thin quantum wells. [S0163-1829(98)00548-7]

Study of the nonradiative channels of recombination in III-V-based multiquantum wells is of great importance for optoelectronic applications of these materials. The development of the semiconductor diode laser designed for more than 3-μm band requires the control of nonradiative processes. The Auger recombination is the main limiting factor that prevents the room-temperature operation, low-threshold current, and high-output power of the midinfrared light-emitting devices.

The material systems with type-II band alignment such as $InAs/In_xGa_{1-x}Sb$ superlattices (SL's) and quantum wells were recognized as promising materials for midinfrared diode lasers due to the predicted reduced Auger recombination rates.[1–4] The measurements of the Auger recombination coefficient by pump-probe transmission have also shown suppressed Auger rates in comparison with bulk materials.[5] The quantum confinement, strain splitting in the valence band, and off-resonance positions of the spin-orbit splitt-off band as a result of the type-II alignment were considered as factors contributing to suppression. However, there are intrinsic peculiarities of the Auger process in quasi-two-dimensional structures, which differ it from that in bulk material. As a result of the momentum-conservation violation in growth direction, the Auger process has no threshold and the recombination rate has weak power-law temperature dependence instead of a strong exponential one in the bulk.[6–8] In other words, the Auger process is less sensitive to temperature, and this means the effective interface-induced suppression of the Auger recombination.

To date, the temperature dependence of the Auger recombination rates in type-II SL's has not been investigated. In this paper we deduce the temperature dependence of the recombination rate from the measurements of the photocurrent response in the high-temperature region where the Auger recombination dominates the nonradiative processes. We report the weak (nonexponential) temperature dependence of the Auger recombination rates in type-II InAs/GaSb SL. The observed temperature dependence supports the theoretical predictions[6–8] of the thresholdless Auger process as a result of the interface-induced violation of the momentum conservation in thin quantum wells.

Short-period type-II superlattices for experiments were grown by molecular-beam epitaxy (MBE) on semi-insulating GaAs substrates as described elsewhere.[9,10] The superlattices consist of 48-Å InAs/48-Å GaSb layers with 1-ML-thick InSb-like interfaces. The InSb layers compensate the tensile effect of the InAs layers, and the average lattice constant of the superlattice is very close to the GaSb buffer layer. A thin layer of AlSb was grown before the superlattice. This layer reduces the leakage current through the GaSb buffer layer and increases the accuracy of the electrical measurements.

The photoconductor devices were prepared by making Ohmic contacts with either indium annealing or aluminum deposition and etching. No passivation or antireflection coating was used on the surface. The samples were then mounted to a cooper heatsink and attached to the cold finger of a liquid-nitrogen cryostat equipped with a temperature controller. Spectral photoresponse was measured using a Galaxy 3000 FTIR spectrometer system. The samples were illuminated through the front side at normal incidence. Absolute response of the photodetectors was calculated using a blackbody test set, which is composed of a blackbody source (Mikron 305), preamplifier (EG&G PA-6), lock-in amplifier (EG&G 5209), and chopper system (Stanford Research System LSR540).

We have found that the current responsivity at $\lambda = 10.6$ μm is proportional to T^{-2} in a wide temperature range $\approx 150-300$ K (Fig. 1). The temperature-dependent part of the current responsivity is given as[11]

$$R_i \propto \tau(\mu_e + \mu_h), \quad (1)$$

where τ is the lifetime of nonequilibrium carriers, and μ_e, μ_h are mobilities of electrons and holes, respectively. The experimental result in Fig. 1 means that the observed lifetime's temperature dependence is as follows:

$$\tau(T)^{-1} \propto (\mu_e + \mu_h) T^2. \quad (2)$$

In the high-temperature region ($T \geqslant 200$ K), the lifetime is mainly determined by Auger recombination. To be able to determine the Auger lifetime temperature dependence from Eq. (2), the mobilities of the electrons and holes must be known. We determined the mobilities from Hall measurement on the same SL for which the optical data shown in Fig. 1 were obtained. The samples were prepared to the Van der Pauw pattern with annealed indium contacts. The electrical field was perpendicular to the growth direction while the magnetic field was parallel to the growth direction.

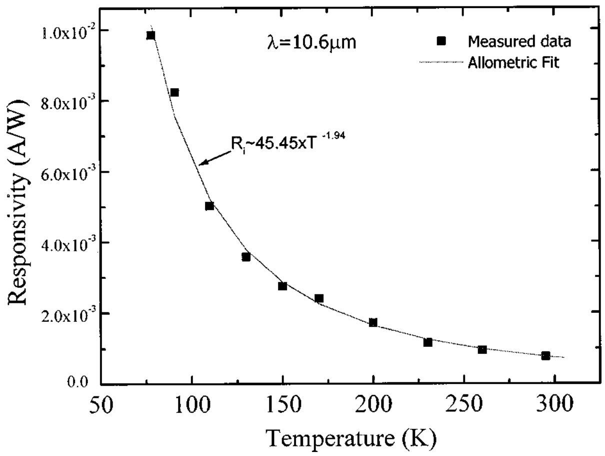

FIG. 1. The responsivity of the superlattice vs temperature.

The semiconductor energy gap in this SL was deduced from the photoresponse cutoff frequency ($E_g \approx 0.1$ eV). The SL was not doped intentionally, however the Fermi level at low temperatures is most likely shifted to the valence subband of the SL due to the thick p-type GaSb ($p \approx 10^{16}$ cm^{-3}) buffer layer, so acceptors with a density of $N_a \approx 10^{15}$ cm^{-3} and activation energy of 0.02 eV were assumed in the SL. First we found the Fermi level from the neutrality equation $n + N_a^- = p$, and then the temperature dependencies of the electron n (InAs) and hole p (GaSb) densities in the SL with the following parameters: $m_e = 0.023 m_0$; $m_h = 0.3 m_0$; volume densities are normalized to the period of the SL $D \approx 100$ A. In Fig 2, calculated partial densities of the electrons and holes are shown. The difference between the Hall concentration and partial densities is attributed to the compensation of the Hall voltage by particles of different signs with close densities and mobilities.

In order to determine mobilities $\mu_{e,h}$, we analyzed the Hall effect and resistivity data with a two-carrier model assuming a Hall factor to be unity. Experimental data on Hall concentration (Fig. 2) and Hall mobility (Fig. 3) were used. The mobilities were found by fitting to the experimental temperature dependence of the resistivity ρ and Hall coefficient R_H ($B = 0.5$ T is the applied magnetic field):

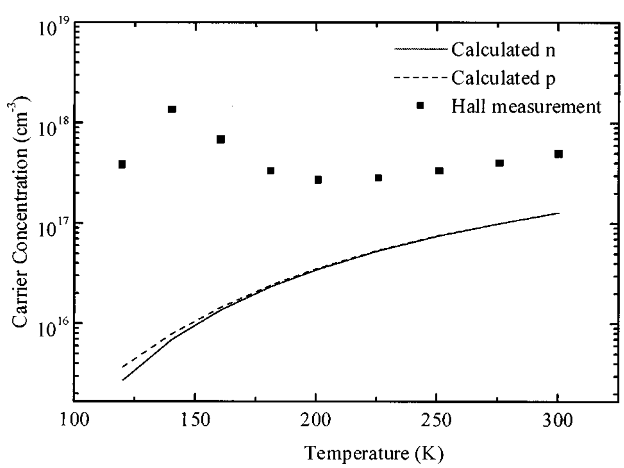

FIG. 2. Hall concentration and calculated partial densities of the electrons and holes.

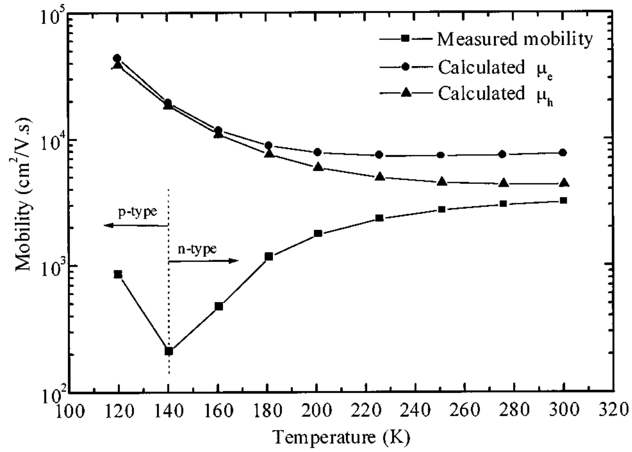

FIG. 3. Measured Hall mobility and calculated mobilities of the electrons and holes vs temperature.

$$R_H = \frac{\sigma_{xy}/B}{\sigma_{xy}^2 + \sigma_{xx}^2}, \quad \rho = \frac{\sigma_{xx}}{\sigma_{xy}^2 + \sigma_{xx}^2}, \tag{3}$$

where

$$\sigma_{xx} = q\left(\frac{n\mu_e}{1+\mu_e^2 B^2} + \frac{p\mu_h}{1+\mu_h^2 B^2}\right),$$

$$\sigma_{xy} = qB\left(\frac{p\mu_h^2}{1+\mu_h^2 B^2} - \frac{n\mu_e^2}{1+\mu_e^2 B^2}\right).$$

The result of the calculation reveals that mobilities weakly depend on temperature in the high-temperature region as is shown in Fig. 3.

Electron and hole mobilities from the above calculations were used to obtain the magnetic-field dependence of the Hall coefficient $R_H(B)$. The comparison of the measured with the calculated $R_H(B)$ is shown in Fig. 4. The observed dependence of the $R_H(B)$ at low fields cannot be explained by the two-carrier model (electrons in InAs and holes in GaSb, solid line in Fig. 4) and is explained by including in modeling the small number of holelike carriers of the third type with high mobility $\mu B \gg 1$. To obtain a good agreement with the experiment we assume the third type of carriers with a density of 10^{13} cm^{-3} and mobility of 10^5 cm^2/V s (dashed

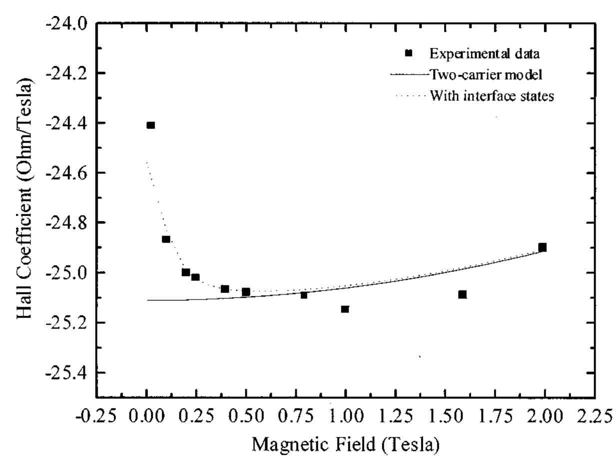

FIG. 4. Hall coefficient vs magnetic field.

line in Fig. 4). The nature of these interface carriers is under question and is beyond the scope of the present paper. It can be said that in the GaSb/InAs SL these fast carriers are attributed most likely to the one-two-monolayers-thick InSb at interface. Besides, at interface of this kind the electron- or holelike Tamm states may exist, and this possibility has been discussed in detail elsewhere.[12] It should be noted that similar behavior of $R_H(B)$ has also been observed in the PbTe/SnTe short period SL's and the existence of the fast carriers, attributed to interface states, has been supposed[13] in order to explain the low-field behavior of the $R_H(B)$.

In the high-temperature region, where lifetime is supposed to be due to Auger recombination, the parameter $\mu_e + \mu_h$ in Eq. (1) is almost independent of temperature (see Fig. 3). Weak temperature dependence of the mobility up to ambient temperature has also been observed in the InAs/$Ga_{1-x}In_xSb$ SL's and it was attributed to the fact that interface roughness contribution dominates the momentum relaxation time.[14]

From Eq. (2) we obtain the Auger coefficient $C(T)$ in the form

$$C(T) = \frac{1}{\tau n p} \propto \frac{T^2}{np}. \tag{4}$$

For comparison, in the bulk material we have (electron and holes are nondegenerate)[15]

$$C(T) \propto \frac{T^{5/2} \exp\left(-\frac{\varepsilon_A}{k_B T}\right)}{np}, \tag{5}$$

where ε_A is the activation energy for the Auger process in which the recombination of an electron in the conduction band and a hole in the valence band leads to excitation of an electron in the conduction band to a higher energy.

The power-law temperature dependence in Eq. (4) as opposed to an exponential dependence in Eq. (5) reflects the absence of threshold in the Auger process in the type-II SL under consideration. The thresholdless temperature behavior has been predicted for thin quantum wells of type-I (Refs 6 and 7) and type-II,[8] and it is a consequence of an interface-induced violation of momentum conservation in the Auger recombination process.

The actual temperature dependence of the Auger coefficient $C(T)$ in InAs/GaSb SL's [in Eq. (4)] depends on carrier statistics. For laser applications of the multiple quantum well and SL, the most important case is strong excitation, when the transparency carrier density $n = p$ depends on temperature as $n \propto T$. It means that in the high-temperature region the Auger coefficient is almost independent on temperature. Thus, at laser threshold, the Auger coefficient $C(T)$ should reveal the weak temperature dependence, indicating the effective suppression of the temperature sensitivity of the laser emission in lasers, based on SL InAs/GaSb.

In conclusion, the Auger recombination coefficient in InAs/GaSb SL's, deduced from optical and electrical measurements, reveals temperature behavior that differs from the bulklike Auger process. This can be considered as an experimental evidence of the role of interfaces in the Auger process. Qualitatively, it is in agreement with theories that predict the power-law temperature dependence of the Auger recombination rate in thin quantum wells. To date, there is no calculation of the Auger recombination rate, which could be used for quantitative comparison with our experimental data, because calculations made for type-II quantum wells[8] are not valid for the type-II broken-gap structure investigated here.

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[1] C. H. Grein, P. M. Young, and H. Ehrenreich, J. Appl. Phys. **76**, 1940 (1994).
[2] E. R. Youngdale, J. R. Meyer, C. A. Hoffman, F. J. Bartoli, C. H. Grein, P. M. Young, H. Ehreinreich, R. H. Miles, and D. H. Chow, Appl. Phys. Lett. **64**, 3160 (1994).
[3] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, IEEE Photonics Technol. Lett. **9**, 170 (1997).
[4] M. Flatte, C. H. Grein, and H. Ehreinreich, Appl. Phys. Lett. **72**, 1424 (1998).
[5] C. M. Ciesla, B. N. Murdin, C. R. Pigeon, R. A. Stradling, C. C. Philips, M. Livingston, I. Galbraith, D. A. Jaroszynski, C. J. G. M. Langerak, P. J. P. Tang, and M. J. Pullin, J. Appl. Phys. **80**, 2994 (1996).
[6] G. G. Zegrya, A. D. Andreev, N. Gun'ko, and E. Frolushkina, Proc. SPIE **2399**, 307 (1995).
[7] M. I. Dyakonov and V. Yu. Kachorovskii, Phys. Rev. B **49**, 17 130 (1994).
[8] G. G. Zegrya and A. D. Andreev, Appl. Phys. Lett. **67**, 2681 (1995).
[9] H. Mohseni, E. Michel, J. Sandven, M. Razeghi, W. Mitchel, and G. Brown, Appl. Phys. Lett. **71**, 1403 (1997).
[10] H. Mohseni, E. Michel, M. Razeghi, W. Mitchel, and G. Brown, Proc. SPIE **3287**, 30 (1998).
[11] V. E. Chishko, A. I. Dirochka, I. L. Kasatkin, V. V. Osipov, E. I. Slynko, and V. V. Teternik, Appl. Phys. A: Solids Surf. **57**, 567 (1993).
[12] H. Kroemer, C. Nguyen, and B. Brar, J. Vac. Sci. Technol. B **10**, 1769 (1992).
[13] V. Litvinov, M. Oszwaldowski, T. Berus, and O. Mironov, Phys. Status Solidi A **145**, 503 (1994).
[14] C. A. Hoffman, J. R. Meyer, E. R. Youngdale, F. J. Bartoli, and R. H. Miles, Appl. Phys. Lett. **63**, 2210 (1993).
[15] B. L. Gelmont and Z. N. Sokolova, Fiz. Tekh. Poluprovodn. **16**, 1670 (1982) [Sov. Phys. Semicond. **16,** 1067 (1982)].