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The Auger recombination coefficient in InAs and GaSb derived from the infrared dynamical plasma reflectivity

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Abstract

A dynamical model giving the infrared plasma reflection in a semiconductor is used to reproduce the transient reflectivity at 10.6 μm due to an intense photo-plasma. In this way we have derived the 'cubed' coefficient of the Auger recombination in indium arsenide and gallium antimonide from the stationary peak reflectivity produced by a ns Nd laser. We have derived the cubic coefficients $12(4) \times 10^{-27}$ cm^6 s^{-1} and $9(3) \times 10^{-28}$ cm^6 s^{-1} for InAs and GaSb respectively.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Auger recombination (AR) is an intrinsic process that dominates the hole–electron couple recombination at high carrier densities. In the AR process a hole–electron couple recombines and the resulting energy is transferred to a third carrier. The AR process can follow different channels that can be summed up in two processes: γ_{ehh} and γ_{eeh}, with a hole and an electron as the third body respectively. In dense neutral plasma with the hole and electron density given by N, the AR has a cubic dependence on N: $\mathrm{d}N/\mathrm{d}t = -(\gamma_{ehh} + \gamma_{eeh})N^3 = -\gamma_3 N^3$.

AR can be analysed on the basis of the dynamics of a plasma induced by a fast light pulse at a frequency above the band gap. This can be done in different ways: by observing the transient transmission and reflectivity of laser light at frequencies under or near the band gap [1], by analysing the behaviour of the radiative recombination [2–5], or by analysing the stationary photoconductivity [6–8]. For InAs, calculations are reported in [9] and compared to the experimental recombination time observed in fast photodiodes. Other calculations are reported in [10] both for doped InAs and for doped GaSb. From [9] we can derive a value of γ_3 around 1×10^{-26} cm^6 s^{-1} in InAs, while in [10] the sum of three different AR mechanisms for InAs and GaSb, at high p doping, gives total γ_{ehh}-coefficients of about 7×10^{-27} and 3×10^{-28} for InAs and GaSb respectively, corresponding to one half of γ_3.

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In [5] an experimental value for GaSb was derived from the radiative recombination; it lay in the range from 1×10^{-24} to 1×10^{-26}, at variance with the theoretical value. For InAs, in [2], $\gamma_3 = (11 \pm 1) \times 10^{-27}$ was derived, which is near the theoretical estimate. For InAs another experimental value was derived, in [6], from photoconductivity signals: $\gamma_3 = 1.6 \times 10^{-27}$. In [7], γ_3 is calculated to be about 40×10^{-27} for InAs at room temperature. Summarizing, the effective AR coefficient, for both InAs and GaSb, remains an open question.

Recently we have made an experimental study of AR by analysing the dynamics of the IR plasma reflectivity induced by a ns Nd pulse. By using this model it is possible to derive the AR coefficient from the ns stationary reflectivity in semiconductors such as InAs and GaSb.

A model relating the space-time plasma density $N(x, t)$ to the observed transmission and reflection of light with frequency under the band gap has been described in [11]. We have applied this model in [12–14]. The transient reflectivity can be derived, following Drude's theory, from the space-time-dependent complex dielectric constant ε of a material, with an internal space-time-dependent free-carrier distribution N. The details are reported in [11–14]. In this work, as far as the calculations are concerned, we have used the semiconductor constants for InAs and GaSb that are reported in [10].

The transient reflectivity is the sum of reflection effects of several different semiconductor sublayers with variable $N(x, t)$ carrier distribution giving different complex dielectric constants. The one-dimensional expression describing the $N(x, t)$ dynamics is [11]

$$\frac{\partial N(x,t)}{\mathrm{d}t} - D\frac{\partial^2 N(x,t)}{\partial x^2} = G(x,t) - R(x,t) \tag{1}$$

where D is the ambipolar diffusion coefficient, and G and R describe the space-time-dependent generation and recombination processes respectively. The ambipolar diffusion coefficient is not critical and it can be derived from the usual relations $D \sim (KT\,\mu_h)/q$ for $\mu_h \ll \mu_e$ with μ_h and μ_e the hole mobility and electron mobility respectively.

By assuming a pump pulse with angular frequency ω_p, a Gaussian shape with a FWHM $2\ln 2\Delta$ time width, and E the total energy absorbed on the area A, the expression for $G(x, t)$ becomes

$$G(x,t) \cong \frac{2\pi^{0.5}E}{A\Delta\alpha h\omega_p}\exp\left(-\frac{(t - xn/c)^2}{\Delta^2}\right)\exp(-\alpha x) \tag{2}$$

with n the diffraction index and α the absorption coefficient. The general recombination processes are given by

$$R(x,t) = -\gamma_3 N^3(x,t) - \gamma_2 N^2(x,t) - \gamma_1 N(x,t). \tag{3}$$

In [14] we described how several recombination processes can be mathematically summarized by equation (3). Moreover, as shown in [13, 14], the recombination process can be simply stated as $R(x, t) = \gamma_3 N^3$ at the large plasma densities necessary to produce a large ns MIR reflectivity, where γ_3 is the sum of all the cubic recombination channels discussed in [9, 10, 13]. In order to compute the dynamical probe reflection, we have to consider the semiconductor as a stratified stack of different sublayers. By using the approach of [11], the overall reflectivity at the front surface and the sample transmission can be calculated as functions of the time.

2. Experimental results and discussion

We have measured the InAs and GaSb 10.6 μm transient reflectivity near the Brewster angle with the apparatus described in [12, 14]. The CO_2 laser emits 300 ns FWHM multimode pulses with a μs tail while Nd emits typically up to 40 mJ a 1.3 ns FWHM single pulse at a 0.5 Hz repetition rate. The beams are matched, unfocused, on the semiconductor plate near the

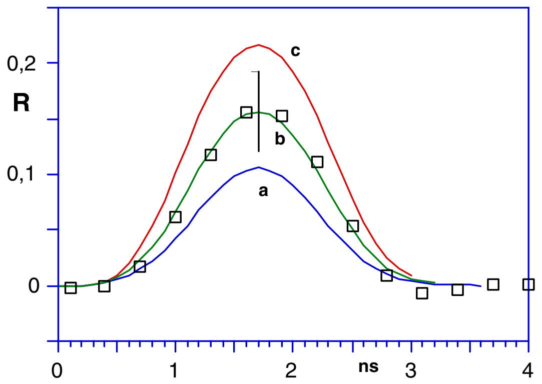

Figure 1. R, the experimental reflectivity pulse, versus the time at 10.6 μm (squares) in InAs compared with the theoretical pulses: (a) $\gamma_3 = 20 \times 10^{-27}$; (b) $\gamma_3 = 10 \times 10^{-27}$, (c) $\gamma_3 = 5 \times 10^{-27}$. The vertical segment is the experimental error on the peak value.

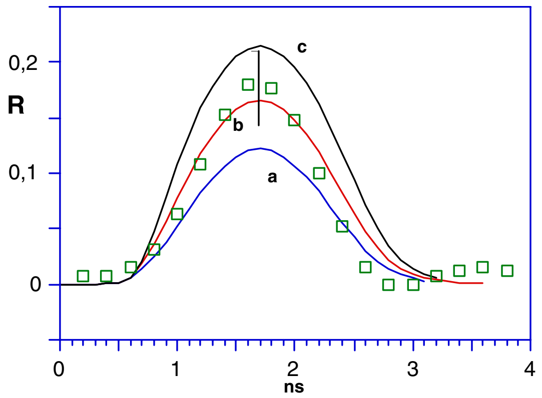

Figure 2. R, the experimental reflectivity pulse, versus the time at 10.6 μm (squares) in GaSb compared with the theoretical pulses: (a) $\gamma_3 = 20 \times 10^{-28}$; (b) $\gamma_3 = 10 \times 10^{-28}$, (c) $\gamma_3 = 5 \times 10^{-28}$. The vertical segment is the experimental error on the peak value.

Brewster incidence angle. The residual 10 μm reflectivity allows one to calibrate the intensity of the dynamical reflectivity. The reflected 10 μm beam is detected by using a fast Molectron P5 pyroelectric and the signals are recorded with a Tektronix digital oscilloscope with 500 MHz bandwidth. Because of the multimode CO_2 laser structure, the observed reflected pulses are averaged over several shots to eliminate the mode beat modulations.

Because of the fast AR in InAs and GaSb, the 10 μm FWHM reflected pulse has the same time behaviour as the driving Nd pulse, but the peak reflectivity is related to the recombination constant γ_3 and depends on the electron mass [14]. We can fit the experimental result by calculating the theoretical pulse height. In the fit we have used the material parameters reported in [10]. Other constants used in the fit are: $E/A = 7$ mJ cm^{-2}, $\Delta = 0.7$ ns, $\alpha(\mathrm{InAs}) = 3 \times 10^4$ cm^{-1} [6] and $\alpha(\mathrm{GaSb}) = 2 \times 10^4$ cm^{-1}, estimated from [15] as an intermediate value for InAs and Ge.

Following [14] we have not considered the effect of a change of mobility on the plasma density, because this changes mainly the carrier collision time and not the electron mass.

In figure 1 we report the experimental InAs reflected pulse compared with some theoretical fits obtained by varying γ_3. By considering several fitting choices we derive $\gamma_3 = 12 \pm 4 \times 10^{-27}$.

In figure 2 we report the experimental GaSb reflected pulse compared with some theoretical fits obtained by varying γ_3. By considering several fitting choices we derive $\gamma_3 = 9 \pm 3 \times 10^{-28}$.

As reported in figures 1, 2 the main source of error is due to the estimation of the transient reflectivity peak. At the plasma density necessary to produce a detectable 10 μm reflectivity, the slow quadratic and linear plasma recombination channels are negligible, so they cannot affect our derived γ_3-values

Our experimental γ_3-estimates are in good agreement with the theoretical ones and there is a good agreement with the InAs experimental results reported in [1].

3. Conclusions

The dynamical IR peak reflectivity induced in InAs and GaSb has been used to derive the constant of the AR process. By applying a complex dynamical model for a stratified semiconductor structure where a transient distribution of photocarriers is induced, it is possible to obtain an estimate of the AR coefficient. We have obtained γ_3-coefficients in quite good agreement with the theory.

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