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Theoretical study of photoresponse to pulsed radiation in n-InSb in the temperature range 77–300 K

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The results of a theoretical simulation of a transient experiment in n-InSb in the temperature range 77–300 K, are reported. Minority carrier lifetimes for the three recombination processes, radiative, SRH and Auger, have been calculated at different temperatures using the temperature dependence of intrinsic carrier concentration, n_i, and density of states effective mass of heavy holes, m_d. It was found that around room temperature the lifetimes for the three processes become comparable and at higher temperatures the Auger lifetime becomes dominant. This fact was ignored in previous work where only SRH and radiative processes were considered in the calculation of effective lifetime. The present results of effective lifetime in n-InSb are in reasonably good agreement with the results obtained previously. The effect of higher time modes on the decay of photoresponse to pulsed radiation is discussed. An instantaneous time constant has been defined and its variation with time at different temperatures has been studied.

1. Introduction

Indium antimonide is a III–V semiconductor having essentially similar crystal structure (zincblende) to that of silicon or germanium. Soon after the discovery of its semiconducting properties it was found that InSb had the smallest band-gap compared to any other semiconductor known at that time. The band-gap was found to be 0.171 eV at room temperature (300 K) and 0.22 eV at liquid nitrogen temperature (77 K). It was also noticed that it is a direct band-gap semiconductor and can be easily prepared in single-crystal form using conventional means. This immediately led to the realization that InSb can be used as a long wavelength infrared detector material. For optimum performance, infrared detectors are designed to operate in certain specified modes and temperatures. The infrared detectors are usually designed to operate in photoconductive (PC), photovoltaic (PV) and photoelectromagnetic (PEM) modes at room temperature (300 K), dry-ice temperature (195 K) and liquid nitrogen temperature (77 K). The responsivity, detectivity, etc. can be shown to be related to material parameters such as electron and hole concentrations, mobilities and lifetimes. However, lifetime, τ, is the principal factor in controlling the detector response. Therefore, it is important to determine τ correctly at different temperatures. From its temperature dependence information can be obtained about the dominant recombination mechanisms in different temperature ranges.

In the past much effort has been made to measure and calculate excess carrier lifetime in InSb at different temperatures using both steady state [1–5] and transient methods [6–11]. In most of the above steady state measurements, a joint photoelectromagnetic and photoconductive (PEM-PC) technique has been used to obtain the lifetime of both the carriers if the mobilities and carrier concentrations are known from other measurements. In the transient case, the material is irradiated by short pulses of light and the decay of induced photoconductivity due to recombination of excess carriers is measured. A straight line is fitted to the logarithm of photoconductivity versus time. If the decay is exponential, the slope of this line gives the lifetime. Using this method, the earliest reliable measurements of excess carrier lifetime in both p- and n-InSb were carried out by Wertheim [7] at different temperatures. He had observed that the decay of photoconductivity in n-InSb can be expressed by a single exponential function at all temperatures (130–250 K). In order to compare his experimental results, Wertheim [7] also calculated effective lifetime at different temperatures by including the contributions from SRH (Shockley-Read-Hall recombination) and radiative processes and using the intrinsic carrier concentration, n_i, as given by Hrostowskii *et al.* [12]. However, his measured results showed systematic deviations from his calculated values at higher temperatures. He attributed this to effects such as broadening of photon levels, temperature dependence of trap cross-section, surface recombination, etc. He also observed that the measured results of effective carrier lifetime can be made to agree with calculations provided the calculated results of radiative lifetime were

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reduced by nearly a factor of three. As far as we know, no effort has been made to look into this discrepancy.

In this paper we present the results of theoretical simulation of a transient experiment in n-InSb in the temperature range 77–300 K. The minority carrier lifetimes at various temperatures for the three recombination processes, radiative, SRH and Auger, have been calculated using the temperature dependence of the intrinsic carrier concentration, n_i, and density of states effective mass of heavy holes, m_d, as given by Oszwaldowski and Zimpel [13]. We have found that around room temperature the lifetimes for the three processes become comparable and at higher temperatures the Auger lifetime becomes dominant. It should be noted that Wertheim [7] considered only radiative and SRH processes in his calculation of effective lifetime. The present results of effective lifetime in n-InSb are in reasonably good agreement with Wertheim's measured results [7].

We also investigated the effect of higher time constants on the decay of photoresponse in n-InSb. In order to clarify the effect of higher time modes we have defined an instantaneous time constant and studied its variation with time at different temperatures. The mathematical formulation of the photoresponse to pulsed radiation is also briefly outlined, and expressions of lifetime corresponding to the three recombination mechanisms and the semiempirical relations for n_i and E_g, as given by Oszwaldowski and Zimpel [13], are presented.

2. Mathematical formulation

2.1. Photoresponse to pulsed radiation

Let us consider a slab of n-InSb (minority carriers being holes) of thickness, a, assumed to be much larger than the minority diffusion length, L, ($a \gg L$). The excess minority carrier concentration, Δp, is then given by

$$\frac{1}{D}\frac{\partial}{\partial t}\Delta p(x,t) = \frac{\partial^2}{\partial x^2}\Delta p(x,t) - k^2\Delta p(x,t) + \frac{g(x,t)}{D} \tag{1}$$

where $k^2 = 1/D\tau$, D being the diffusion coefficient.

For the case of pulsed radiation, the generation rate, $g(x,t)$ can be written as

$$g(x,t) = N_\lambda(1 - R_\lambda)\,\delta(t)\,\alpha e^{-\alpha x} \tag{2}$$

where N_λ is the number of photons $\mathrm{cm^{-2}\,s^{-1}}$, R_λ is the reflection coefficient, and α is the absorption coefficient. As we will be concerned with the recombination characteristics of the bulk material, we will assume recombination due to surfaces and contacts to be negligible. Therefore, we assume the surface recombination velocity to be zero and take

$$\left.\frac{\partial}{\partial x}\Delta p(x,t)\right|_{x=0} = 0 \tag{3a}$$

Because $a \gg L$, we can take the other boundary condition as

$$\Delta p(x,t)|_{x=a} = 0 \tag{3b}$$

Equation 1 has been solved earlier by taking Fourier transform [9], Laplace transform [10] and Sturm–Liouville transform [14, 15]. Here we solve Equation 1 by taking its Laplace transform. This gives

$$\frac{\partial^2}{\partial x^2}\overline{\Delta p}(x,s) - \beta^2\overline{\Delta p}(x,s) + C e^{-\alpha x} = 0 \tag{4}$$

where

$$\beta^2 = k^2 + s/D \tag{5}$$

$$C = \frac{N_\lambda(1 - R_\lambda)\alpha}{D} \tag{6}$$

and

$$\overline{\Delta p}(x,s) = \int_0^\infty e^{-st}\Delta p(x,t)\,\mathrm{d}t \tag{7}$$

is the Laplace transformed excess carrier density.

Because the boundary conditions for $\overline{\Delta p}(x,s)$ will be the same as for $\Delta p(x,t)$, using the boundary conditions as given by Equation 3, we get

$$\overline{\Delta p}(x,s) = \frac{C}{(\alpha^2 - \beta^2)}\left[\frac{\alpha\sinh\beta(a - x)}{\beta\cosh\beta a} + \frac{e^{-\alpha a}\cosh\beta x}{\cosh\beta a} - e^{-\alpha x}\right] \tag{8}$$

On taking the inverse Laplace transform, we obtain

$$\Delta p(x,t) = \sum_{m=0}^{\infty} A_m(x)e^{-t/\tau_m} \tag{9}$$

where

$$A_m(x) = 2N_\lambda(1 - R_\lambda)\alpha \times\left[\frac{\alpha a + (-1)^m a\xi_m e^{-\alpha a}}{(\alpha a)^2 + (a\xi_m)^2}\right]\cos\xi_m x \tag{10}$$

$$\frac{1}{\tau_m} = \frac{1}{\tau} + D\xi_m^2 = \frac{D}{L^2} + D\xi_m^2 \tag{11}$$

and

$$\xi_m = (m + \tfrac{1}{2})\frac{\pi}{a} \tag{12}$$

From Equation 9 we find that photoresponse to pulsed radiation can be expressed at any distance x as the sum of decaying exponentials. The higher order modes ($m = 1, 2, 3, \ldots,$) will die out soon after the injection of the pulse and the decay will be governed by the zeroth order ($m = 0$) mode only. We then have

$$\Delta p(x,t) = A_0(x)e^{-t/\tau_0} \tag{13}$$

where

$$\frac{1}{\tau_0} = \frac{1}{\tau} + \frac{\pi^2 D}{4a^2} \tag{14}$$

2.2. Recombination mechanisms in bulk material

There are three recombination mechanisms by which thermodynamic equilibrium is achieved in semiconductors. These are radiative recombination, Auger recombination and Shockley–Read recombination.

The radiative and Auger recombinations are fundamental as they are determined by the electronic band structure of the semiconductor. The Shockley–Read recombination is determined by the energy levels due to lattice defects and impurities in a semiconductor. They, in principle, can be controlled by the procedure used to grow the material. In both radiative and Auger recombination, an electron in the conduction band combines with a hole in the valence band (interband recombination). The energy of recombination, equal to the energy gap, is either released by emission of a photon (radiative recombination) or is transferred to a second conduction band electron by electron–electron interaction (Auger recombination). These recombination mechanisms have been treated by a number of authors and we will here summarize the various results. We will write various expressions under the small signal approximation (i.e. for low illumination intensities). This would imply small departures from equilibrium such that $\Delta p \ll n_0$ for n-type material. Under this approximation the carrier lifetimes for different recombination mechanisms are given by

$$\tau_R = \frac{n_i^2}{g_{R_0}(n_0 + p_0)} \tag{15}$$

$$\tau_A = \frac{n_i^2}{g_{A_0}^{ee}(n_0 + p_0)} \tag{16}$$

and

$$\tau_{SR} = \frac{\tau_{p_0}(n_0 + n_1) + \tau_{n_0}(p_0 + p_1)}{(n_0 + p_0)} \tag{17}$$

We may note that in the above approximation of small departures from equilibrium and for a small density of recombination centres, the minority and majority carrier lifetimes are equal to each other. In writing Equation 17 for τ_{SR} it has been assumed that the recombination centres (or trap centres) correspond to a single level of energy, E_r, and with density, N_r, which is low ($N_r < n_0$). $g_{A_0}^{ee}$ is the thermal equilibrium electron–electron generation (or impact ionisation) rate and g_{R_0} is the thermal equilibrium spontaneous generation rate for electron-hole pair. τ_{p_0}, τ_{n_0}, n_1 and p_1 have the usual expressions and have been defined in [7].

For *n*-type material, in the simple case when $n_0 \gg p_0 \gg p_1$, we can write

$$\tau_R \sim 2\tau_{R_i}(n_i/n_0) \tag{18}$$

$$\tau_A \sim 2\tau_{A_i}(n_i/n_0)^2 \tag{19}$$

and

$$\tau_{SR} \sim \tau_{p_0}(1 + n_i/n_0) \sim \tau_{p_0} \tag{20}$$

where τ_{R_i} and τ_{A_i} are the respective radiative and Auger lifetime for the intrinsic material and are defined in terms of equilibrium electron–hole and electron–electron generation rate as

$$\tau_{R_i} = \frac{n_i}{2g_{R_0}} \tag{21}$$

and

$$\tau_{A_i} = \frac{n_0}{2g_{A_0}^{ee}} = \frac{n_i}{2g_{A_0}^{ee}} \tag{22}$$

From Equations 18 and 19 we find that for n-type extrinsic material $\tau_R \sim (n_i/n_0)$ whereas $\tau_A \sim (n_i/n_0)^2$.

The equilibrium radiative generation rate as obtained by van Roosbroeck and Shockley [16] can be written as

$$g_{R_0} = \frac{8\pi n^2}{c^2}\left(\frac{kT}{h}\right)^3 \int_{u_0}^{\infty} \frac{\alpha(u)u^2}{e^u - 1} du \tag{23}$$

where $u(= h\nu/kT)$ is the variable of integration, c is the speed of light, n is the refractive index (its values have been taken as given in [7]) and $\alpha(u)$ is the absorption coefficient for photons of energy $h\nu$. The lower limit u_0 $(= E_g/kT)$ corresponds to the long wavelength limit of the characteristic absorption band of InSb. Gobeli and Fan [17] have given experimental curves showing variation of α with photon energy at temperatures 298, 77 and 5 K. The absorption curves at other temperatures can be obtained by shifting the absorption edge according to the temperature dependence of energy gap, E_g. The values of radiative equilibrium generation rate, g_{R_0}, at any temperature can be obtained by numerical integration of Equation 23.

Auger recombination (the e–e process) was first analysed in detail by Beattie and Landsberg [18]. Assuming transitions between conduction band and heavy hole valence band only, we can write the thermal equilibrium electron–electron generation rate as

$$g_{A_0}^{ee} = \frac{8(2\pi)^{5/2}e^4 m_0}{h^3} \frac{(m_e/m_0)|F_1 F_2|^2 (kT/E_g)^{3/2} n_0}{k^2(1 + \mu)^{1/2}(1 + 2\mu)\exp\{[(1 + 2\mu)/(1 + \mu)]\, E_g/kT\}} \tag{24}$$

where $\mu(= m_e/m_h)$ is the ratio of the conduction band to the heavy hole valence band effective mass, m_0 is the electron rest mass, E_g is the energy gap, k is the relative dielectric constant and F_1 and F_2 are the overlap integrals of the periodic parts of Bloch functions for the conduction and valance bands. Equation 24 has been widely used to calculate the equilibrium generation rate for the electron–electron process in n-type material. From Equations 22 and 24 one finds that Auger lifetime for the intrinsic material is independent of carrier concentration, because $g_{A_0}^{ee}$ varies linearly with n_0.

2.3. Temperature dependence of various parameters

Recently, Oszwaldowski and Zimpel [13] have reported the temperature dependence of intrinsic carrier concentration, n_i, in InSb between 150 K and the melting point of the compound (798 K). They proposed an empirical formula for the temperature variation of n_i in InSb as given by

$$\begin{aligned} n_i(T) &= 2.9 \times 10^{11}(2400 - T)^{3/4} \\ &\quad \times (1 + 2.7 \times 10^{-4}\,T)\,T^{3/2} \\ &\quad \times \exp[-(0.129 - 1.5 \times 10^{-4}\,T)/kT] \end{aligned} \tag{25}$$

It has been found that in InSb, the thermal energy gap has virtually a constant value ($=0.235$ eV) for $T < 40$ K and for $T > 100$ K it decreases linearly with temperature as given by

$$E_g(T) = 0.258 - 2.9 \times 10^{-4} T \qquad (26)$$

The density of states effective mass of heavy holes, m_d, is defined through classical expression for hole concentration, p. For intrinsic material ($p = n = n_i$), we have

$$p = n_i = \frac{4}{\pi^{0.5}} \left(\frac{2\pi m_d kT}{h^2}\right)^{1.5} F_{12}\left(-\frac{E_f + E_g}{kT}\right) \qquad (27)$$

where F_{12} is the Fermi integral. It has been shown by Oszwaldowski and Zimpel [13] that for $T > 100$ K, the hole concentration in intrinsic InSb can be assumed to be non-degenerate and Equation 27 can be simplified as

$$p = n_i = 2\left(\frac{2\pi m_d kT}{h^2}\right)^{1.5} \exp\left[-\left(\frac{E_f + E_g}{kT}\right)\right] \qquad (28)$$

Values of m_d at different temperatures can be obtained using $n_i(T)$ and $E_g(T)$ as given by Equations 25 and 26.

The variation of diffusion coefficient with temperature is taken into account through the relationship

$$D = \left(\frac{kT}{e}\right)\mu_p \qquad (29)$$

where the mobility of minority carriers (holes) in InSb has been taken as $\mu_p \sim T^{-1.7}$ with $\mu_p = 10^4\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ at 77 K [19].

3. Results and discussion

The values of radiative lifetime, τ_R, Auger lifetime, τ_A, and Read–Shockley lifetime, τ_{SR}, have been obtained at different temperatures for the n-type sample of Wertheim [7] with given $N_d - N_a = 2.3 \times 10^{14}\ \mathrm{cm^{-3}}$. The expressions used have been outlined in the preceding section. It is assumed that different recombination mechanisms operate in parallel and effective lifetime, τ, would be given by

$$\frac{1}{\tau} = \frac{1}{\tau_R} + \frac{1}{\tau_A} + \frac{1}{\tau_{SR}} \qquad (30)$$

The temperature variations of τ_R, τ_A and τ_{SR} are shown in Fig. 1. Also shown are the experimental and theoretical results of Wertheim [7]. Curves 2 and 2′ show, respectively, the temperature variation of radiative lifetime, τ_R, as obtained by Wertheim [7] and the present results. As mentioned earlier, Wertheim [7] used the expression for n_i as given by Hrostowskii [12] and band gap by Oswald [20], whereas the present calculations are based on the temperature dependence of n_i and E_g as suggested by Oszwaldowski and Zimpel [13]. In both the calculations, the absorption coefficient as a function of energy at different temperatures was obtained as discussed by Roosbroeck and Shockley [16] using the absorption curves given by Gobeli and Fan [17]. We observe that the present values of τ_R are lower than those of Wertheim [7] over the entire temperature range. In Fig. 1 the contributions due to Auger and SRH processes are shown by curves 1′ and 3′, respectively. The present τ_{SR} values and those of Wertheim [7] agree over the entire temperature range because the density of recombination centres and energy level values used here are the same as those used by Wertheim [7]. Further, τ_{SR} is less sensitive to minor changes in n_i (and hence in p_0) compared to n_0 (Equation 17). Around room temperature when the material is intrinsic the contributions from the three processes become comparable and at higher temperatures the contribution due to Auger recombination begins to dominate. The effective lifetime so obtained (curve 4′) is in reasonably good agreement with the experimental results of Wertheim [7]. Earlier, Wertheim [7] had tried to explain the experimental results using radiative and SRH processes alone, and concluded that lifetime at higher temperatures was governed by radiative processes. We have therefore been able to show that the earlier discrepancy between measured and calculated results of lifetime in n-InSb can be successfully explained.

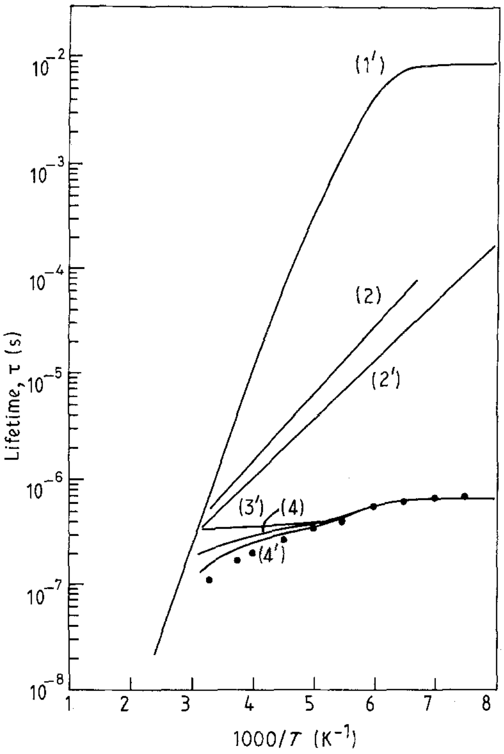

Figure 1 Relationship between lifetime and temperature for the three recombination processes: (1′) Auger, (2, 2′) radiative (2, Wertheim [7]; 2′, present) and (3′) SRH. (4) The effective lifetime $\tau(W)$ obtained from the data of Wertheim as $\tau(W) = (1/\tau_R + 1/\tau_{SR})^{-1}$ (4′) presently obtained effective lifetime. (●) Experimental results [7].

In order to see the effect of higher modes clearly, we have found it useful to define an instantaneous time constant as given by

$$\frac{1}{\tau'(x, t)} = -\frac{\partial}{\partial t} \ln \Delta p(x, t) \qquad (31)$$

While calculating $\Delta p(x, t)$ (Equation 9) it was found that at all temperatures it is sufficient to include terms

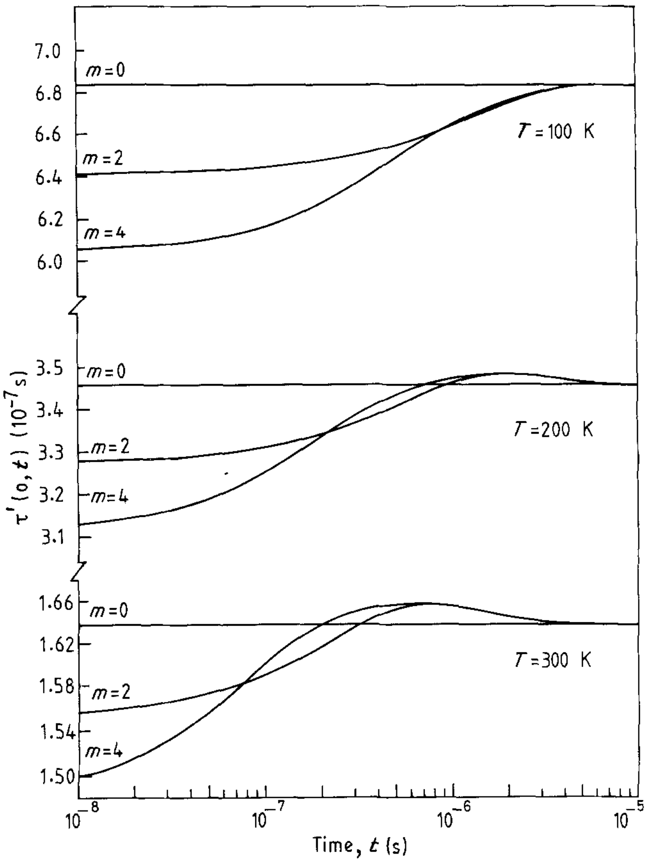

Figure 2 Relationship between $\tau'(0, t)$ and time at three different temperatures, 100, 200, and 300 K. Curves for $m = 0$ correspond to the fundamental mode, whereas curves for $m = 2$ and $m = 4$ represent contributions for the first three and the first five modes, respectively.

up to $m = 4$, the contribution from higher modes ($m > 4$) being less than 1%–2%. We have computed $\tau'(0, t)$ as a function of time at different temperatures. In Fig. 2, $\tau'(0, t)$ has been plotted as a function of time, t, at three different temperatures, 100, 200 and 300 K, showing the contribution of the fundamental mode ($m = 0$), the first three modes ($m = 2$) and the first five modes ($m = 4$). It is seen that at any temperature the τ' curves for $m = 2$ and $m = 4$ merge with the curve for $m = 0$ (fundamental mode) after a certain time interval from the injection of the pulse which may be called the waiting time, τ_w. The waiting time is found to be about 10τ for lower temperatures (100 and 200 K) and about 20τ around room temperature (300 K). This is the time after which a true exponential decay will be observed. The fundamental mode ($m = 0$) is found to correspond to

$$\frac{1}{\tau'(0, t)} = \frac{1}{\tau_0} = \frac{1}{\tau} + \frac{\pi^2 D}{4a^2} \tag{32}$$

As we have assumed $a \gg L$, we obtain

$$\frac{1}{\tau'(0, t)} \sim \frac{1}{\tau} \tag{33}$$

This is in conformity with the observation of Wertheim [7].

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