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LETTER TO THE EDITOR

Direct determination of Shockley–Read–Hall trap density in InSb/InAlSb detectors

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Abstract. Accurate determination of trap density in the active region of mid-infrared narrow-bandgap detectors is crucial in the development towards background-limited performance at higher operating temperatures. We have used both optical and electrical measurements to determine the trap density in InSb/InAlSb nonequilibrium detector structures. Both of these techniques result in very good agreement with trap densities of 5×10^{14} cm^{-3}.

For acceptable performance in minimally cooled, narrow-bandgap infrared detectors, the excess carrier generation–recombination rate must approach the radiative rate. The higher the generation–recombination rate, the larger the reverse leakage current through the photodiode, and the greater the current noise will be, reducing the photodiode's detectivity. In InSb detectors operating near room temperature, the dominant generation–recombination processes are Auger and Shockley–Read–Hall (SRH) processes. A reduction in these processes can be achieved through direct device design, for example utilizing carrier extraction and exclusion [1], bandstructure engineering [2] and optimization of crystal growth conditions [3]. High-operating-temperature photodiodes in the mid-infrared have been demonstrated in $\mathrm{In}_{1-x}\mathrm{Al}_x\mathrm{Sb}$ with enhanced detectivity due to Auger suppression in the active region [1]. This nonequilibrium operation reduces the Auger transition rate, and the noise associated with these processes. In this situation, the dominant source of generation–recombination in the active region is due to SRH processes [3]. A reduction in the trap density will reduce the diode leakage current further, thus increasing detector performance. Accurate determination of the trap density in the active region is thus important in optimizing device performance.

Direct measurement of the trap density has been carried out on an unbiased InSb/InAlSb detector using a free-electron laser balanced pump–probe experiment. The raw transmission data were converted to carrier concentration so that the decay rate of excited carrier concentration, N_e, could be obtained. The trap density was found by fitting the decay curves to theory using the active region trap density, N_T, as a fitting parameter. As a comparison to the direct optical measurements, positive and negative luminescence output from a diode of the same material was measured as a function of temperature. The results were also fitted to the theory to obtain a value of N_{T}.

The samples measured were InSb/InAlSb nonequilibrium detector structures, the operation of which has been described previously [1]. Figure 1 shows the bandstructure of the detector at zero bias. Absorption occured in the p-type contact layer, which is very thin (and is ignored in the analysis), and in the π region of the diode. The carrier exclusion barrier of $\mathrm{In}_{0.75}\mathrm{Al}_{0.15}\mathrm{Sb}$ is labelled as $\bar{\mathrm{p}}^{+}$. Degenerate doping of the n-type contact layers and substrate meant that these layers did not absorb at the wavelength of interest. Wavelength-degenerate pump–probe experiments were performed at the Dutch free-electron laser facility in Nieuwegein (FELIX). The laser produced macropulses at 5 Hz, where each macropulse consisted of a train of micropulses, each several picoseconds long with a separation of 44 ns. Lattice heating effects have been found to be negligible, with temperature increases of only approximately 0.02 K per micropulse [4]. The three-beam method described previously [4] was used to minimize noise due to power fluctuations between macropulses. Light was focused onto the samples with a $f = 25$ cm parabolic mirror, which resulted in a beam waist of 100–150 μm. The laser was tuned to $\lambda = 6.5$ μm, just above the bandgap of the π active region at 300 K. Band filling by the photoexcited carriers resulted in a strong dynamic Moss–Burstein shift and bleaching near the excitation energy. The relative transmittance of the probe was measured as a function of pump–probe delay to obtain a measure of the excited carrier lifetime.

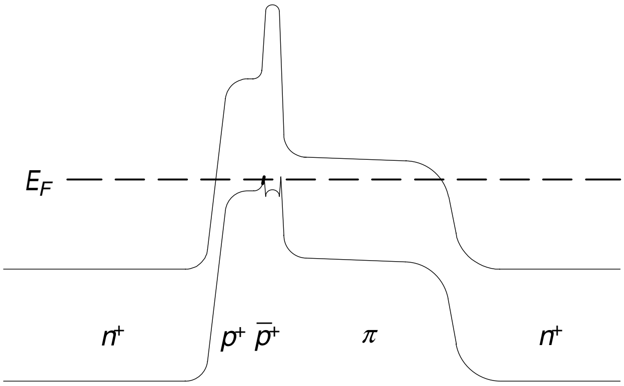

Figure 1. Schematic diagram of the equilibrium bandstructure of the InSb/InAlSb detector structure (not to scale). The doping of each layer is shown along with the Fermi energy, E_{F}.

With knowledge of the bandstructure of InSb [5] and thus the density of states and Fermi energies, the excited electron and hole concentrations were calculated as a function of energy. The absorption was then calculated for each assumed value of Fermi energy with the relation [4]

$$\alpha = \sigma[1 - f_{\mathrm{e}}(E_{\mathrm{e}}) - f_{\mathrm{h}}(E_{\mathrm{h}})]J_{\mathrm{cv}}(E).$$

$f_{\mathrm{e(h)}}(E_{\mathrm{e(h)}})$ is the electron (hole) Fermi occupation probability as a function of electron (hole) energy and J_{cv} is the joint density of states. The absorption cross-section, σ, was found by fitting the theoretical transmission at the equilibrium Fermi energy to the small-signal absorption spectrum of InSb that was measured using a Fourier transform spectrometer. Approximating the relationship between absorption and transmission as $T(t) \approx (1-R)^2 \exp[-\alpha(t)d]$, where R is the sample reflectivity and d the thickness, we calculated the value of excited carrier concentration, $N(t)$, for each value of $T(t)$.

To model the Auger transition rates, a flat valence band analytical model was used. This model has been shown to give good agreement with the full four-band Kane model calculation, including perturbations from more remote bands [6]. The SRH rate was calculated from the expression given by Shockley and Read [7], while the analytic approximation of Beattie and White [8] was used to calculate the radiative contribution. The Auger rate was fixed for a given doping concentration and temperature so that the model had only one fitting variable, the trap density, N_T.

A plot of the experimental data, presented as carrier concentration, is given in figure 2. The decay was found to have two temporal components. For delay times less than approximately 400 ps, a fast, purely exponential decay dominates. This fast component has been fitted with a pure exponential (dashed curve in figure 2), although one can see that a single exponential term is insufficient to fit the data over all measured times. At times less than 400 ps, photoexcited carriers drift out of the π region in a time related to the minority carrier lifetime [9]. Due to this drift, the open-circuit n^+–π junction becomes forward biased such that the net current flow across this junction is zero. Once this has occured, the dominant recombination processes in the π region will be Auger, SRH and radiative processes. Thus, to determine the trap density in the π region, only data at delay times longer than 400 ps are of interest.

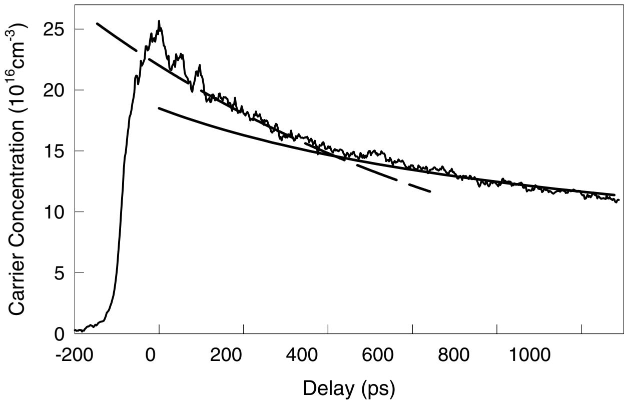

Figure 2. Experimental carrier concentration decay of the InSb/InAlSb detector structure at $\lambda = 6.5$ μm, $T = 300$ K. The thick solid curve is the fitted theory of the slow component; the dashed curve is an exponential fit of the fast component.

The experimental data were fitted with the sum of an exponential with a decay constant of $0.9\times$ the minority carrier lifetime [9] and the modelled decay due to Auger, SRH, and radiative processes. These summands are due to the fast and slow components respectively. The trap density in the π region was varied to give the best fit to the data. The slow component of the fit is shown in figure 2 as the thick, solid line for a trap density of $N_T = 5 \times 10^{14}$ cm^{-3}. This value of N_T results in an SRH coefficient of $A = 9.26 \times 10^6$ s^{-1}. This value of trap density should be regarded as an upper limit for the active region. Extraneous transitions, for example at interface defects and in the p^+ region, could well affect the measurement, although we believe that this effect will be relatively minor.

Electrical measurements can also be used to measure the trap density in the active region of the diode, although in a somewhat less direct manner. Diodes were fabricated so that a voltage could be applied across the junction region. With a forward bias the diode will operate as an LED [1], and with a reverse bias as a source of negative luminescence [10]. The output of the diode was measured with both positive and negative constant currents as a function of temperature from 0–50 °C. These data were then fitted using the same models for carrier recombination as used for the pump–probe experiments. Using N_T as a fitting parameter, a value of $N_T = 5 \pm 2 \times 10^{14}$ cm^{-3} resulted in the optimum fit. It is worth noting that, in more recent samples grown at lower temperatures [3], trap densities of less than 10^{14} cm^{-3} are expected.

The trap density in the active region of an InSb/InAlSb nonequilibrium detector structure has been determined using both direct optical and indirect electrical measurements. Measured carrier lifetimes in the material were fitted to theory using the trap density as a fitting parameter. The two methods are in good agreement, giving fitted trap densities of 5×10^{14} cm^{-3}.

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