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Influence of carrier concentration on the minority carrier lifetime in mid-wavelength infrared InAs/InAsSb superlattices

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HIGHLIGHTS

- Minority carrier lifetimes (MCL) in InAs/InAsSb superlattices were studied.
- A decrease of the MCL with increasing carrier concentration was observed in superlattices with intermediate carrier concentration.
- Decreasing MCL was attributed to dominating radiative recombination in superlattices.
- Good correlation between the experimentally observed trend and the theoretically expected decrease of radiative lifetime was obtained.
- The correlation between carrier concentration and MCL partly explains the spread in reported MCL for InAs/InAsSb superlattices.

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ABSTRACT

The influence of carrier concentration on the minority carrier lifetime was studied in mid-wavelength infrared InAs/InAsSb superlattices. A significant correlation between the carrier concentration and the minority carrier lifetime was observed, with lifetime decreasing from 3.6 μs to 1 μs when increasing the carrier concentration from 2×10^{15} cm^{-3} to 4.4×10^{15} cm^{-3}. From temperature dependence studies of the minority carrier lifetime, radiative recombination has been identified as the main recombination mechanism in these superlattices. The radiative recombination rate increases with carrier concentration which is consistent with our observations.

Infrared (IR) detectors have a multitude of applications ranging from night vision, firefighting and surveillance to medical diagnosis of skin cancer. The most sensitive photon detectors that are currently used for these applications include HgCdTe and InSb detectors. These detectors all need excessive cooling to operating temperatures around 77 K, which limits the lifetime and affects the cost of the IR camera system. Great effort is therefore being dedicated to develop novel IR detector materials that would enable higher operating temperatures, while maintaining low dark current and high quantum efficiency in the detectors. A key parameter that influences both the dark current and quantum efficiency in infrared detectors is the minority carrier lifetime. Among the detector materials that are currently used for infrared detection in the mid-wavelength infrared (MWIR, 3–5 μm) region, HgCdTe has the longest lifetime (9 μs) [1], while low doped InSb (5.5×10^{13} cm^{-3}) has a lifetime of 7 μs [2]. Recently, long minority carrier lifetimes have also been observed for Ga-free type-II InAs/InAsSb SLs with lifetimes up to 9 μs for MWIR SL and ~420 ns for a long-wavelength SL [3,4]. In addition, Sb-based superlattices also have the advantages of lower Auger generated dark current and reduced tunneling currents [5,6], which shows great promise for high temperature operation of infrared detectors based on this material. For MWIR InAs/InAsSb superlattices, the minority carrier lifetimes reported spread in the range from 1.8 μs to 9 μs and it is not clear what is causing the large spread in lifetime [3,7]. One parameter that could affect the minority carrier lifetime is the background doping, which varies between different molecular beam epitaxy (MBE) reactors and which also can vary between growths performed at different times in the same MBE reactor. In this paper, the correlation between minority carrier lifetime and carrier concentration was studied to understand the large spread in the lifetime values reported for these superlattices. Three samples with lifetimes ranging from 1 μs to 3.6 μs and with photoluminescence (PL) peak positions around 5.1 μm were selected for this study. Capacitance measurements were used to evaluate the carrier concentration in the superlattices. These measurements reveal a variation in carrier concentrations from 2×10^{15} cm^{-3} to 4.4×10^{15} cm^{-3} among the

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studied samples and a trend with decreasing minority carrier lifetime with increasing carrier concentration was observed. This was attributed to an increase in radiative recombination with increasing carrier concentration. The strong correlation between the carrier concentration and the minority carrier lifetime partly explains the large spread in reported minority carrier lifetimes. Information about the carrier concentration in addition to the minority carrier lifetime in the material is therefore crucial to get a better understanding of potential performance of devices based on this material.

To study the influence of carrier concentration, a set of three 2.8 μm thick SL structures with carrier concentrations varying from 2×10^{15} cm^{-3} to 4.4×10^{15} cm^{-3} were selected. The InAs/InAsSb SL structure and the growth conditions were nominally the same as described in detail in Ref. [7]. The SLs bandgaps and minority carrier lifetimes were measured by photoluminescence (PL) and optical modulation response (OMR). A laser diode (emission wavelength 643 nm) with both continuous wave (CW) and sine-wave modulation was used as excitation source for measurements of PL spectra and OMR. The laser was focused to an area $A = 2.5 \times 10^{-4}$ cm^{-2} and had a CW excitation power P_0 and a modulated excitation power P_1, with $P_1 \ll P_0$. To measure the PL spectra, the luminescence from the SL was directed into a Bruker FTIR spectrometer operating in the step-scan mode and the PL signal was detected by a cooled HgCdTe detector. For measurement of the OMR, the modulation frequency of the laser was varied between 25 kHz and 3 MHz, while the PL signal was measured at each frequency with a HgCdTe detector connected to a 100 MHz preamplifier and a 200 MHz lock-in amplifier. The OMR setup was calibrated towards other lifetime measurement setups using several reference samples with known lifetimes [8]. Capacitance–voltage (C–V) measurements were performed to extract the majority carrier concentration in the absorbers. Metal–oxide–semiconductor (MOS) capacitors were fabricated for measurement of carrier concentration in the superlattices. For the MOS capacitors, a 90 nm SiO_2 film was deposited on top of the superlattice structures using plasma enhanced chemical vapor deposition (PECVD) and circular Cr/Au contacts with diameters of 250 μm were used for C–V analysis. The samples were mounted with indium in a ceramic holder and individual capacitors were wire-bonded to the holder with gold wires. An HP4284A LCR meter was used for the C–V measurements that were performed at 77 K with an AC voltage of 20 mV and an AC voltage frequency of 1 MHz.

The lifetime can be influenced by several recombination mechanisms, such as Auger processes, SRH recombination and radiative recombination. The lifetimes of these processes will contribute to the recombination lifetime as shown in Eq. (1):

$$1/\tau = 1/\tau_{SRH} + 1/\tau_R + 1/\tau_{Auger} \tag{1}$$

where τ_{SRH}, τ_R and τ_{Auger} correspond to the SRH-, radiative- and Auger lifetime, respectively [9]. In a recent study, the recombination mechanism limiting the minority carrier lifetime in these superlattices was identified as the radiative lifetime [7]. In that study, the SRH and Auger lifetimes were estimated to ~10 μs and ~50 μs, respectively, at 77 K, whereas the radiative lifetime was in the order of 3 μs [7]. The terms in Eq. (1) related to SRH and Auger recombination are consequently expected to only have minor influence on the minority carrier lifetime as compared to the radiative lifetime. These lifetimes are dependent on the background carrier concentration, n_0 and the excess carrier concentration, n_e, respectively. For n-type material at low excess carrier densities this dependence can be expressed as in Eq. (2):

$$1/\tau = 1/\tau_{SRH} + \frac{B}{\phi}(n_0 + n_e) + C(n_0 + n_e)^2 \tag{2}$$

where B and C are the radiative and Auger recombination coefficients, respectively, and ϕ is the photon recycling factor. With the modulated laser excitation power used in the OMR measurement technique, the excess carrier density, n_e is governed by the stationary and the modulated generation rates G_0 ($\sim P_0/(AdE_{ph})$) and G_1 ($\sim P_1/(AdE_{ph})$), respectively, as given by Eq. (3):

$$n_e = G_0\tau + \frac{G_1\tau}{\sqrt{1+\omega^2\tau^2}}\cos(\omega t - \phi) \tag{3}$$

where ω, A, d and E_{ph} correspond to the angular frequency, the area of the laser spot, the absorber thickness and the photon energy, respectively [10]. The first term in Eq. (3), $G_0\tau$, corresponds to the concentrations of electrons and holes added to the steady-state background carrier concentration, and the second term corresponds to oscillating concentrations of electrons and holes. The frequency dependence of the PL intensity can be used to study the recombination lifetime. The recombination lifetime is obtained by fitting the frequency response curve to Eq. (4):

$$I_{PL}(\omega) \propto P_1\tau/\sqrt{1+\omega^2\tau^2} \tag{4}$$

for each excess carrier density. For the SLs studied, the recombination lifetime was measured for excess carrier densities varied from $\sim 1.4 \times 10^{14}$ cm^{-3} to $\sim 1.2 \times 10^{15}$ cm^{-3} by increasing G_0 (Fig. 1(a)–(c)). The inverse of the recombination lifetime was plotted against the excess carrier density and the expected dependence is given by Eq. (2). In sample A, the measured lifetime stayed approximately constant (~1 μs) when the excess carrier density was varied from $\sim 1.4 \times 10^{14}$ cm^{-3} to $\sim 5.5 \times 10^{14}$ cm^{-3} (inset, Fig. 1(a)). This behavior is expected when the excess carrier concentration $n_e \ll n_0$ (Eq. (2)). For a radiatively limited sample, the carrier concentration could be estimated as $n_0 = \phi/(B\tau) \sim 5 \times 10^{15}$ cm^{-3} (using $\phi \sim 1.55$ and $B \sim 3.1 \times 10^{10}$ cm^3/s)[7]. This is in good agreement with the value obtained from C–V measurements for this sample (4.4×10^{15} cm^{-3}), which supports the previous observations of radiatively limited lifetimes. In the lifetime measurements of sample B and C, slightly higher excess carrier densities ($n_e < n_0$) were utilized and linear relations between the inverse lifetimes and the excess carrier concentrations were observed (insets Fig. 1(b) and (c)). The linearity of the inverse lifetimes implies that the contribution from Auger recombination is negligible in these superlattices (see Eq. (2)), which agrees with previous observations [7]. The minority carrier lifetimes of samples B and C were estimated to 2.6 and 3.6 μs, respectively, by linear extrapolation of the inverse carrier lifetime to zero excess carrier density. The minority carrier lifetimes for the different samples consequently vary from 1 μs to 3.6 μs, even though the SL structures are very similar. One parameter that could cause such a spread of the minority carrier lifetime is the carrier concentration in the material. Since the radiative lifetime is inversely proportional to the carrier concentration ($\tau_R = 1/Bn_0$), a variation in the carrier concentration would directly affect the minority carrier lifetime.

A commonly used method to measure the carrier concentration in semiconductors is to study the capacitance in metal–oxide–semiconductor (MOS) structures. The measured MOS capacitance (C) is dependent on both the oxide capacitance (C_{ox}) and the semiconductor capacitance (C_s) as given in Eq. (5):

$$\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_s} \tag{5}$$

where $C_{ox} = \varepsilon_0\varepsilon_{ox}A/d$ and $C_s = \varepsilon_0\varepsilon_s A/W$. ε_0, ε_{ox}, ε_s, A, d, and W correspond to the permittivity, the dielectric constant of oxide, the dielectric constant of the semiconductor, the capacitor area, oxide thickness and depletion width in the semiconductor, respectively [11]. When sweeping the DC bias applied to the capacitor, the semiconductor region closest to the oxide–semiconductor interface will