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Minority carrier lifetime in iodine-doped molecular beam epitaxy-grown HgCdTe

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The minority carrier lifetime in molecular beam epitaxy grown layers of iodine-doped Hg$_{1-x}$Cd$_x$Te (x~0.3) on CdZnTe substrates has been studied. The samples demonstrated extrinsic donor behavior for carrier concentrations in the range from $2 \times 10^{16}$ cm$^{-3}$ to $6 \times 10^{17}$ cm$^{-3}$ without any post-growth annealing. At a temperature of 77 K, the electron mobility was found to vary from $10^6$ cm$^2$/V s to $7 \times 10^3$ cm$^2$/V s and minority carrier lifetime from 1.6 $\mu$s to 790 ns, respectively, as the carrier concentration was increased from $2 \times 10^{16}$ cm$^{-3}$ to $6 \times 10^{17}$ cm$^{-3}$. The diffusion of iodine is much lower than that of indium and hence a better alternative in heterostructures such as nBn devices. The influence of carrier concentration and temperature on the minority carrier lifetime was studied in order to characterize the carrier recombination mechanisms. Measured lifetimes were also analyzed and compared with the theoretical models of the various recombination processes occurring in these materials, indicating that Auger-1 recombination was predominant at higher doping levels. An increase in deep-level generation-recombination centers was observed with increasing doping level, which suggests that the increase in deep-level trap density is associated with the incorporation of higher concentrations of iodine into the HgCdTe. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4935154]
measured using the photoconductive decay technique. Note that no post-growth annealing or surface passivation layer were applied on any of the samples. In all cases, based on the known laser power, for photoconductive decay measurements, beam spot size, sample layer thickness, and delay time, the calculated excess carrier concentrations was kept well below $5 \times 10^{14}$. Hence, it was assumed that low-level injection conditions were satisfied and, thus, the injection level did not influence the measurements. To avoid sweep-out effects, the sample biasing was kept low (300 mV), and all photoconductive decay curves were fitted exponentially to obtain the minority carrier lifetimes.

Several different recombination mechanisms determine the photogenerated minority carrier lifetime in n-type HgCdTe, such as Auger, radiative, and Shockley-Read-Hall mechanisms, which have been discussed extensively in the literature. We have applied these mechanisms to model the lifetime for minority carriers in our samples with relevant equations taken from the standard literature.

The measured minority carrier lifetime, carrier mobility, and other material parameters for the iodine-doped HgCdTe layers in samples A, B, and C are summarized in Table I. As evident from this table, these iodine-doped layers exhibit good lifetime even at high carrier concentrations, especially considering that no post-growth annealing was applied in order to annihilate Hg vacancies. The electron mobility at 77 K was found to decrease from $1 \times 10^6$ cm$^2$ V$^{-1}$ s$^{-1}$ for an electron concentration of $2.1 \times 10^{16}$ cm$^{-3}$, to $6.7 \times 10^5$ cm$^2$ V$^{-1}$ s$^{-1}$ for an electron concentration of $6 \times 10^{17}$ cm$^{-3}$. The carrier concentrations were extracted from the measured Hall coefficient data under varying magnetic field: that is, from $-2$ to 0 T and from 0 to 2 T.

The extracted lifetime values, from the temperature dependent photoconductive decay measurement results, are illustrated in Fig. 1 for the three investigated samples with varying iodine electron concentration. Generally, the three samples present long minority carrier lifetimes at low temperatures. As the temperature is increased from 77 K, minority carrier lifetime first increases slightly and then decreases exponentially at higher temperatures. For example, for sample A, the minority carrier lifetime increases from 1.6 $\mu$s at 77 K to 1.9 $\mu$s at 150 K, and then decreases exponentially to 75 ns at 250 K. Such a temperature-dependent behaviour for minority carrier lifetime is quite typical for direct band gap materials like HgCdTe. As the temperature is increased, the intrinsic carrier concentration increases with increasing temperature, thus reducing the Auger lifetime. At low temperatures, the temperature-independent lifetime is due to a combination of Auger and/or SRH scattering. The small increase in lifetime for the mid-temperature range is due to a shift in the Fermi level ($E_F$) relative to the energy levels of the dominant traps associated with SRH recombination. Since SRH levels tend to follow the valence band with an increase in temperature, whereas $E_F$ moves toward the conduction band, this results in a decrease in the SRH recombination rate and a slight increase in minority carrier lifetime. At higher temperatures, the lifetime decreases exponentially due to the dominance of Auger-1 recombination, as observed in Figure 1.

As expected, the lifetime was found to decrease with increasing carrier concentration in samples B and C. The behaviour of the lifetime vs temperature for various concentrations of iodine in HgCdTe samples A, B, and C is shown in Figure 1. At 77 K, the lifetime decreased from 1.6 $\mu$s to 750 ns when the carrier concentration increased from $2.12 \times 10^{16}$ cm$^{-3}$ to $6 \times 10^{17}$ cm$^{-3}$.

In order to determine the dominant recombination mechanisms, the effective total minority carrier lifetime in HgCdTe was modelled by taking into account the following mechanisms: Auger recombination ($\tau_{\text{Auger}}$), Shockley-Read-Hall recombination ($\tau_{\text{SRH}}$), and Radiative recombination ($\tau_{\text{Radiative}}$): $1/\tau_{\text{total}} = 1/\tau_{\text{radiative}} + 1/\tau_{\text{Auger}} + 1/\tau_{\text{SRH}}$. The value of the overlap integral [$I_FJ_F$] was taken as 0.15. As a representative example, Fig. 2 shows the modelled and experimental data for the investigated sample A. Generally, the band-to-band recombination lifetime ($\tau_{\text{Auger}}$ and $\tau_{\text{Radiative}}$) is a strong function of temperature, due to both mechanisms being inversely proportional to the square of intrinsic carrier concentration. As the temperature is increased, the free electron density remains essentially constant initially, but then increases rapidly in the intrinsic regime. At higher temperatures, Auger recombination is the dominant process due to the high carrier density, which causes a rapid decrease of minority carrier lifetime. However, the lifetime data for these HgCdTe layers cannot be

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**TABLE I. Electronic properties of n-HgCdTe samples doped with different iodine concentrations.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>CdI$_2$ cell temperature (°C)</th>
<th>Hg$_{1-x}$/Cd$_x$Te X-value</th>
<th>Hg$_{1-x}$/Cd$_x$Te thickness (µm)</th>
<th>XRD (FWHM) arc sec</th>
<th>Electron concentration at 77 K (cm$^{-3}$)</th>
<th>Electron mobility at 77 K (cm$^2$/V·s)</th>
<th>Lifetime at 77 K (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>110</td>
<td>0.28</td>
<td>2.6</td>
<td>53</td>
<td>$2.12 \times 10^{16}$</td>
<td>10856</td>
<td>1.6</td>
</tr>
<tr>
<td>B</td>
<td>130</td>
<td>0.29</td>
<td>2.7</td>
<td>78</td>
<td>$8.34 \times 10^{16}$</td>
<td>8466</td>
<td>1.04</td>
</tr>
<tr>
<td>C</td>
<td>150</td>
<td>0.30</td>
<td>2.8</td>
<td>51</td>
<td>$6.02 \times 10^{17}$</td>
<td>6688</td>
<td>0.75</td>
</tr>
</tbody>
</table>
explained by only band-to-band recombination processes, since it is necessary to include SRH recombination mechanism to obtain a good fit to the experimental data. Results show that for the lower carrier concentration in sample A, SRH recombination processes become important in addition to the band-to-band Auger-1 process. Typically, as-grown HgCdTe layers contain Hg vacancies and, consequently, some level of compensation exists which could play an important role in the SRH recombination process. Inevitably, such Hg vacancies exist in all three investigated samples, but their impact on minority carrier lifetimes in samples B and C is limited due to the relatively high carrier density and, consequently, shorter Auger lifetime.

The SRH limited lifetime is predominant in the extrinsic temperature range, whereas Auger lifetime becomes progressively more important in the intrinsic temperature range. At higher temperatures, parallel combinations of SRH and Auger-1 recombination cause lifetimes to decrease exponentially with increasing temperature. The results indicate a significant dependence of Auger lifetime on the Fermi level, which is heavily affected by temperature and carrier concentration, and also affected considerably by the position of the extrinsic impurity energy level in the forbidden gap. Lifetime data from Kinch and Buss have indicated that the defect level is at 30 meV above the valence band, whereas other researchers have argued that the defect level is slightly deeper. In our case, lifetime data on HgCdTe show a best fit to calculations when the dominant recombination centre is assumed to be 0.42Eg above the valence band.

A significant difference in the dominant recombination mechanisms was observed between the three samples, as shown in Fig. 3. Only the charge neutral defects with defect energies near the Fermi level and with low formation energies were considered when modelling $\tau_{\text{SRH}}$. The Te-antisite (TeCd) has two defect levels near mid-gap. Similar to CdTe, HgCdTe is grown under tellurium rich conditions and has formation energy of almost 1 eV. Therefore, it is very likely that a significant concentration of TeCd defects will be created when the growth is under Te rich conditions. Defect densities and capture cross sections for holes and electrons were extracted by fitting with experimental lifetime data and are presented in Table II.

In addition to Te-related and native vacancy defects, it is reasonable to expect that at higher doping levels, iodine atoms may form complexes with other impurity atoms or Te interstitials and other point defects. This defect formation has been explained in another paper, where structural aspects...
of these samples were studied. All of these complexes could act as SRH recombination centres if they have well-defined energy levels within the band gap. Consequently, HgCdTe materials with higher iodine concentration would be expected to have a shorter SRH lifetime. Pines and Stafsudd showed that an acceptor recombination centre limits the photoconductive lifetime of HgCdTe when SRH lifetime dominates the Auger lifetime. Fig. 4 clearly indicates that at 77 K, SRH dominates for low doped samples.

The trap density extracted by fitting the modelling results in the experimental photoconductivity data, correlated with the etch pit density (EPD) measurements that were performed on samples A, B, and C as shown in Table II. The EPD was found to increase in a well behaved manner with carrier concentration. Fig. 5 shows minority carrier lifetime at low temperatures was limited by SRH recombination for comparatively low doping levels, while the Auger recombination mechanism limited lifetime in samples with higher carrier concentration. However, SRH still plays an important role, even at higher carrier concentration levels. More work is required before an unambiguous interpretation of the generated minority carrier lifetime in iodine doped HgCdTe grown by MBE will be possible.

TABLE II. Samples A, B, and C with deep level trap parameters obtained from fitting the experimental data.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>X-value</th>
<th>Carrier concentration (cm$^{-3}$)</th>
<th>Etch pit density (cm$^{-3}$)</th>
<th>Lifetime (µs)</th>
<th>Trap density (cm$^{-3}$)</th>
<th>Electron capture cross-section (cm$^{2}$)</th>
<th>Hole capture cross-section (cm$^{2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.28</td>
<td>$2.12 \times 10^{16}$</td>
<td>$1.6 \times 10^{5}$</td>
<td>1.6</td>
<td>$6 \times 10^{14}$</td>
<td>$4 \times 10^{-15}$</td>
<td>$3 \times 10^{-15}$</td>
</tr>
<tr>
<td>B</td>
<td>0.29</td>
<td>$8.84 \times 10^{16}$</td>
<td>$8 \times 10^{5}$</td>
<td>1.04</td>
<td>$2 \times 10^{14}$</td>
<td>$3.5 \times 10^{-14}$</td>
<td>$6.3 \times 10^{-14}$</td>
</tr>
<tr>
<td>C</td>
<td>0.30</td>
<td>$6.02 \times 10^{17}$</td>
<td>$1.3 \times 10^{6}$</td>
<td>0.75</td>
<td>$6.5 \times 10^{14}$</td>
<td>$5 \times 10^{-14}$</td>
<td>$8 \times 10^{-14}$</td>
</tr>
</tbody>
</table>

FIG. 4. Comparison of experimental and calculated lifetime at 77 K for samples A, B, and C.

FIG. 5. Correlation between experimental lifetime and dislocation density for samples A, B, and C.

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10. See supplementary material at http://dx.doi.org/10.1063/1.4935154 for theoretical models for lifetime calculations and an example of exponential fit of photoconductive decay data.


