Minority Carrier Lifetime in MOCVD-grown C- and Zn-doped InGaAs

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Abstract

Heavily C-doped p-type InGaAs has been successfully grown by metalorganic chemical vapor deposition using CBr_4 as a C precursor. A doping concentration as high as $2\times10^{19}cm^{-3}$ has been reached for as-grown (non-annealed) samples. Photoluminescence measurements have been employed to obtain and compare the non-radiative lifetimes in C- and Zn-doped InGaAs. The minority carrier lifetime of as-grown InGaAs:C samples is significantly lower than for as-grown InGaAs:Zn for the same doping concentration. Carrier lifetimes range from 373ps ($p=6.6\times10^{16}cm^{-3}$) to 1.5ps ($p=2.3\times10^{19}$ cm^{-3}) in as-grown InGaAs:C, and from 6.8ns ($p=5.0\times10^{16}cm^{-3}$) to 16.8ps ($p=2.1\times10^{19}cm^{-3}$) in InGaAs:Zn, respectively. InGaAs:Zn grown at the same low temperature (450°C) as InGaAs:C has a higher minority carrier lifetime. The minority carrier lifetime difference between InGaAs:Zn and InGaAs:C samples is attributed to lower V/III ratio and hydrogen passivation, as well as, lower growth temperatures for the carbon doped InGaAs samples.

1. Introduction

Using C doping for p-type InGaAs is very attractive for high performance InGaAs/InP Heterojunction Bipolar Transistors (HBTs) due to its low diffusivity compared to traditionally used dopants such as Zn or Be [1-2]. The resulting stability of carbon doped epilayers makes them very suitable for enhanced reliability HBTs [3]. We have previously reported [4] the successful growth of heavily C-doped p-InGaAs by using metalorganic chemical vapor deposition (MOCVD). Carrier concentration levels using the reported approach were as high as $7x10^{19}cm^{-3}$ for samples annealed at 600°C. Since carbon is of amphoteric nature in InGaAs, careful optimization of growth conditions is necessary in order to ensure the appropriate level of carbon doping. The optimization objective is to favorably substitute carbon into As-sites rather than group III sites. Low growth temperature and low V/III ratio were used for this purpose and permitted to achieve heavily C-doped p-type InGaAs by MOCVD [5-6]. The low growth temperature and low V/III ratio may degrade the material quality and some important characteristics, i.e. minority carrier lifetime, which impact performance of devices such as HBTs. It is therefore of great interest to study the effect of C doping, as well, as low growth temperature and low V/III ratio on the minority carrier lifetime of InGaAs:C layers.

Although minority hole lifetimes in n-type InGaAs have been previously reported [7-8], very little information is currently available on minority electron lifetimes in p-type InGaAs [9-10]. Henry and coworkers [9] reported lifetimes in both n-type and p-type $In_{0.53}Ga_{0.47}As$. The reported lifetimes were based on experimental data of luminescence decay time and luminescence efficiency and the non-radiative electron lifetime at $p=2x10^{18}cm^{-3}$ was found to be 7ns.

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In this study, room temperature and low temperature photoluminescence (PL) measurements, as well as, Hall measurements have been performed to investigate the recombination mechanisms of InGaAs:C and InGaAs:Zn layers grown by MOCVD. Minority hole lifetimes have been measured in lattice matched InGaAs:Zn and InGaAs:C samples to study the impact of growth conditions and dopant type.

2. MOCVD Growth of InGaAs:C and InGaAs:Zn

The InGaAs samples were grown in-house using an EMCORE GS3200 LP-MOCVD system. Trimethylindium (TMIn) and trimethylgallium (TMGa) were used as In and Ga sources, respectively. Pure arsine (AsH_3) and phosphine (PH_3) were used for group V elements. Liquid CBr_4 was used as C precursor and DEZn was used as Zn source. The pressure of the growth chamber was maintained at 60torr. The susceptor was rotated at 100 rpm to improve compositional and thickness uniformity [11]. All growth experiments were carried out on Fe-doped semi-insulating (100) InP substrates.

Growth temperature was 450^{o}C for heavily p-doped InGaAs:C (10^{18}-10^{19}cm^{-3}) to provide the best trade-off between doping concentration and surface morphology. Higher growth temperature (530^{o}C) was used for low and medium p-doping concentration (10^{16}-10^{17}cm^{-3}) in order to improve the material quality and surface morphology. This temperature approaches the highest limit where p-type InGaAs can be obtained using CBr_4 as C precursor. Further temperature increase results in n-type InGaAs due to the amphoteric nature of the carbon dopant. V/III ratios were optimized to achieve heavily doped p-type InGaAs:C (5-10 for InGaAs:C compared with 30-50 for InGaAs:Zn) and still maintain good surface morphology. Further decrease of the V/III ratio results in degradation of the surface morphology. The InGaAs:Zn samples were grown at an optimized growth temperature of 570^{o}C. In order to investigate the effect of growth temperature and dopant type, a Zn-doped sample was also grown at 450^{o}C.

3. Photoluminescence Characterization

PL measurements at various excitation levels [12], [13] have been employed to obtain direct information on the non-radiative lifetime in carbon and zinc doped InGaAs samples. The theoretical expression for the photoluminescence (PL) intensity vs. excitation density (I) contains a linear and a quadratic term. At low excitation conditions, the PL signal depends on both the non-radiative lifetime and the doping density. At high excitation conditions, the PL signal depends mainly on the non-radiative lifetime. Therefore, the slope of the linear part of the curve of PL intensity vs. excitation density of the laser can be used to obtain the lifetime of minority carriers. The work presented in this paper extends previously reported basic studies on carrier lifetime [13] by systematically exploring the impact of dopant choice, doping density, and growth temperature in carbon and zinc doped InGaAs layers designed for use in devices such as HBTs.

The PL measurements were performed at The University of Michigan using an Ar-ion laser with a maximum power of 150mW. Fig. 1 shows typical curves for PL vs. I for C- and Zn-doped InGaAs, indicating good agreement between theory (lines) and measurement (points). The InGaAs:Zn and InGaAs:C samples had doping concentrations of 4.5x10^{18}cm^{-3} and 4.7x10^{18}cm^{-3} respectively. A large difference can be observed between the C- and the Zn-doped InGaAs samples at approximately the same doping concentration, indicating a shorter lifetime in C-doped InGaAs. In order to obtain absolute carrier lifetime values, some samples were measured using the time-resolved PL facility at CNET. A mode-locked Ti-Sa laser at a wavelength of 870nm was used for this purpose and the signal was detected with a sychroscan streak camera. This allowed us to establish a carrier lifetime reference value to which all other samples could be compared.

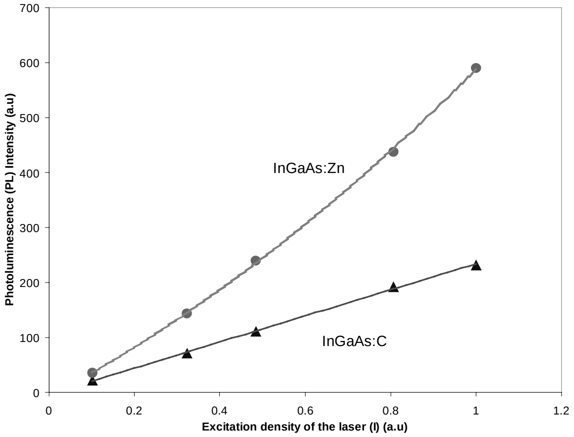

Fig. 1 Typical experimental relationships between PL intensity (PL) and excitation density (I)

4. Minority Carrier Lifetime in MOCVD-grown p-InGaAs

Minority carrier lifetimes of InGaAs:C and InGaAs:Zn samples with different concentrations were measured using this technique. Hall measurements were performed to obtain the doping concentration and mobility of these samples. For InGaAs:Zn, samples grown at 570°C and 450°C were measured for comparison. The Hall mobility as a function of doping concentration for InGaAs:C and InGaAs:Zn samples is shown in Fig. 2. The Hall mobility decreases as the doping concentration increases for both InGaAs:Zn and InGaAs:C samples. Fig. 2 also shows that the Hall mobility of InGaAs:C is approximately the same as that of InGaAs:Zn samples over the entire doping range. Also, as the growth temperature decreases from 570°C to 450°C, there is little impact on Hall mobility values.

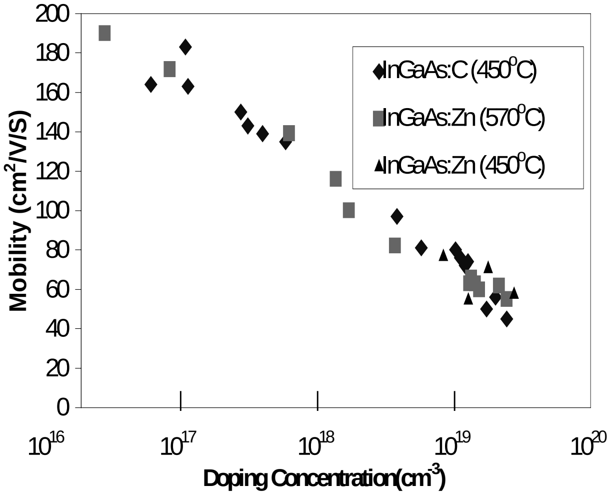

Fig. 2. Hall mobility as a function of doping concentration and growth temperature of InGaAs:C and InGaAs:Zn samples

Fig. 3 shows the results of carrier lifetime as a function of doping concentration for InGaAs:Zn and InGaAs:C samples. InGaAs:Zn has an approximately 10 times higher carrier lifetime than InGaAs:C. As an example, for the doping concentration of $2\times10^{19}cm^{-3}$, the InGaAs:Zn sample has a minority lifetime of 16.8ps while the InGaAs:C sample has a value of 1.5ps. The lower minority lifetime in InGaAs:C may be due to low growth temperature and low V/III ratio during growth, which is necessary for realization of p-type doping. As the doping concentration decreases, the minority carrier lifetime is found to increase to 373ps and 6.8ns for InGaAs:C ($6.6x10^{16}cm^{-3}$) and InGaAs:Zn ($5.0x10^{16}cm^{-3}$) respectively.

To investigate the possible reasons causing the reduced lifetime in InGaAs:C, the impact of growth temperature on minority carrier lifetime was studied by measuring the InGaAs:Zn sample grown at 450°C. Fig. 4 shows the PL intensity for InGaAs:Zn samples grown at 570°C and 450°C. The doping concentrations for the two samples grown at 570°C ($3x10^{18}cm^{-3}$) and 450°C ($4.5x10^{18}cm^{-3}$) are approximately the same. As can be seen from Fig. 4, the stronger PL intensity for the sample grown at 570°C indicates a better material quality than the one grown at 450°C.

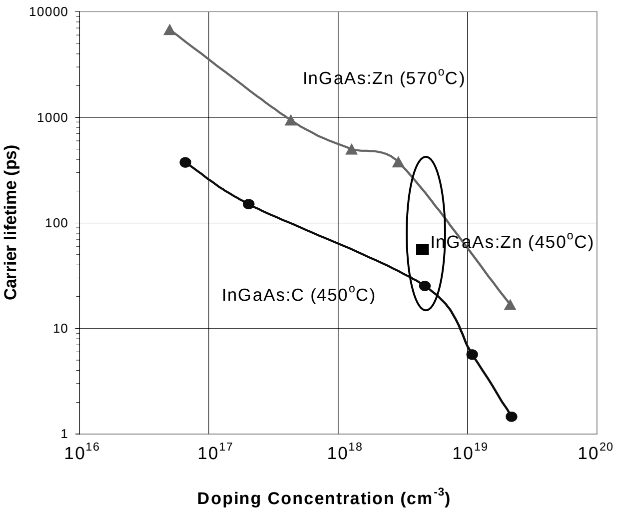

Fig. 3 Minority carrier lifetime in InGaAs:C and InGaAs:Zn samples as a function of doping concentration at various growth temperatures.

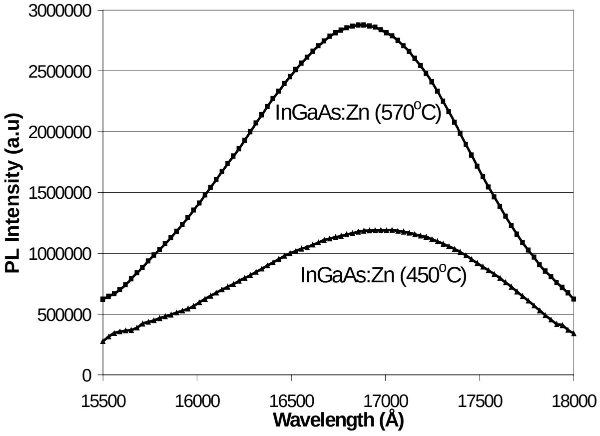

Fig. 4 The PL intensity for InGaAs:Zn grown at 570°C and 450°C

As can be seen from the circled data points in Fig. 3, the carrier lifetime for InGaAs:Zn grown at 450°C (56ps) is lower than the one grown at 570°C (~200ps) for approximately the same doping concentration. This is an indication of the degradation of the material quality as the growth temperature decreases and is expected to hold for InGaAs:C, too. In other words, the use of low growth temperature for InGaAs:C permits to ensure enhancement in carbon incorporation efficiency but results in degradation of minority carrier lifetimes compared with values that would have been achieved if the material is grown at higher temperatures. Fig.3 also shows that for nearly the same doping concentration and the same growth temperature (450°C), a minority carrier lifetime of 25ps is found for InGaAs:C (4.7×10^{18}cm^{-3}) compared to 56ps for InGaAs:Zn (4.5×10^{18}cm^{-3}). The difference of minority carrier lifetime between the two samples may be due to the fact that lower V/III ratio is used for InGaAs:C growth in order to realize p-type doping. The significant passivation of carbon acceptors by hydrogen atoms may also attribute to the lower minority carrier lifetimes of as-grown InGaAs:C layers than those of as-grown InGaAs:Zn layers.

The measured carrier lifetime can be used to extract the gain β of HBTs and, therefore, to evaluate the impact of dopant choice on device performance. The diffusion coefficient in the p-InGaAs base was obtained for this purpose from the Einstein relationship by using mobility values available from Hall measurements. For a base doping concentration of 2×10^{19}cm^{-3} and base width of 600Å, the base transit time estimated from $\tau = W_B^2 / 2D$ is to be approximately 0.35ps. Using a carrier lifetime of 16.8ps for InGaAs:Zn as measured by the described PL tests for a doping concentration of $2.1\text{x}10^{19}$cm^{-3}, a β of approximately 50 can be estimated. This value of gain agrees very well with measured gain characteristics of InGaAs:Zn/InP HBT devices on layers grown with our system. Moreover, the significantly lower minority carrier lifetime for as-grown InGaAs:C samples suggests some limitation in achieving high performance InP/InGaAs HBTs using carbon as dopant. The low growth temperature and low V/III ratio during growth required for the realization of high p-type doping concentrations in InGaAs:C are considered to be the main factors influencing the device characteristics.

Conclusion

In conclusion, heavily p-type carbon doped InGaAs samples latticed matched to InP have been grown by MOCVD using CBr_4 as precursor. Photoluminescence as well as, Hall measurements have been performed on both InGaAs:C and InGaAs:Zn epilayers. Minority carrier lifetimes have been evaluated using room temperature PL measurements. A systematic comparison of the impact of dopant (C vs. Zn) choice, doping density and growth temperature on carrier lifetime was presented. The obtained results can be related to the electrical characteristics of InP-based HBTs. The minority carrier lifetime of as-grown InGaAs:C was found to be lower than that of as-grown InGaAs:Zn samples at the same doping concentration. The low growth temperature and low V/III ratio, which are necessary to obtain heavily p-type carbon doped InGaAs and the significant hydrogen passivation of carbon acceptors in InGaAs:C are considered to be the main factors responsible for these characteristics.

Acknowledgment

The authors would like to thank A. Philippe and C. Bru-Chevallier for help on PL measurement setup and testing. This work is supported in part by MURI (Contract no. DAAH04-96-1-0001)

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