Nondestructive measurement of the minority carrier diffusion length in InP/InGaAs/InP double heterostructures

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The present work demonstrates a simple nondestructive method for the measurement of the minority carrier diffusion length in InP/InGaAs/InP heterostructures. In this measurement technique, a beam of helium-neon laser is applied on the 1 μm-thick InP cap layer of the InP/InGaAs/InP heterostructure, and the resulted InGaAs photoluminescence image is detected by an InGaAs focal plane array. The values of the minority carrier diffusion length which were deduced from the image scans will be presented and discussed. With a further work, this technique could become a useful tool for the selection of InP/InGaAs/InP layered structures prior to the fabrication of InGaAs detectors. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4754567]

The lattice matched InP/InGaAs/InP double heterostructure (DH) system has found broad application in advanced optoelectronic and electronic technology. In particular, this DH structure is currently used for the fabrication of very low dark current InGaAs p-i-n photodetectors[1] and focal plane array's (FPA)[2] operating in the short wavelength infrared (SWIR) region of 1.0–1.65 μm. The minority carrier diffusion length is an important parameter which is usually related to the material quality and hence determines the performance of these devices. In most cases, the measurement of the minority carrier diffusion length requires a special device design and additional processing. It is, therefore, desirable to have a simple and if possible a nondestructive measurement technique inorder to determine the value of the diffusion length prior to device fabrication.

This paper presents a nondestructive measurement of the minority carrier diffusion length in (n)InP(n)InGaAs(n)InP layered structures using photoluminescence (PL) technique. The details of the layer structure have been reported elsewhere.[1,3] The multilayer structures were grown on a 2-in.-diameter sulfur doped n^+-InP substrate by the metalorganic chemical vapor deposition growth method with the following layer sequence: a 1-μm-thick undoped n-InP buffer-layer, $n \sim 1 \times 10^{15}\,cm^{-3}$, a 3-$\mu$m-thick lattice matched InGaAs active-layer, $n \sim 5 \times 10^{15}\,cm^{-3}$, and a 1-$\mu$m-thick Si-doped n-InP cap-layer, $n \sim 3 \times 10^{16}\,cm^{-3}$. The PL measurement system is schematically illustrated in Figure 1. In this measurement setup, a beam of helium-neon (HeNe) laser 633 nm in wavelength and about 10 μm in diameter is applied on the top cap InP layer. The laser radiation which is partially absorbed in the InP cap and partially in the InGaAs active layer generates electron-hole pairs. A fraction of the electron-hole pairs generated in the InP cap diffuses into the InGaAs layer. Since the diffusion length is much larger than both the laser beam diameter and the InGaAs layer thickness, the excess minority hole generation region can be considered as a uniform line source of minority carriers which diffuse and recombine laterally. The lateral image distribution of the minority holes is then detected through the1.65 μm InGaAs luminescence using an InGaAs FPA. The value of the diffusion length can thus be determined from the lateral distribution of the 1.65 μm photoluminescence image. It should be pointed out that in the above simple measurement geometry, the HeNe laser radiation is completely absorbed in the InP substrate and hence only the 1.65 μm luminescence of the InGaAs layer is detected. The (n)InP(n)InGaAs(n)InP layered structures studied in this work were purchased from two different vendors. Several wafers from each vendor were measured and studied.

Figure 2 shows typical vertical and horizontal scans taken via the center of the InGaAs photoluminescence images of an (n)InP(n)InGaAs(n)InP layered structures purchased from vendor 1. The symbols ND1 and ND2 stand for a neutral density filters which reduces the HeNe laser intensity by a factor of 10 and 100, respectively. Excellent agreement between the vertical and horizontal scans is observed for each neutral density filter. The curves for the ND2 filter exhibit an exponential photoluminescence intensity vs. distance behavior with minority hole diffusion length (L_p) around 150 μm. Similar values for the minority carrier diffusion length were obtained using the optical beam induced current technique.[3] Trommer and Hoffmann[4] have also reported large minority carrier diffusion length in InGaAs/InP photodiodes grown by liquid-phase epitaxy. The shape of the curves measured with the ND1 filter deviates somewhat from exponential behavior. This deviation from exponential behavior is related to the associated high minority hole density generated in the InGaAs when the ND1 filter is used. The inset in Fig. 2 which shows the photoluminescence logarithmic images of the InGaAs further demonstrates the

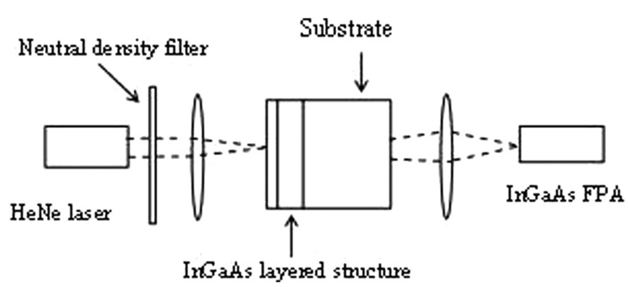

FIG. 1. Schematic diagram of the PL measurement system.

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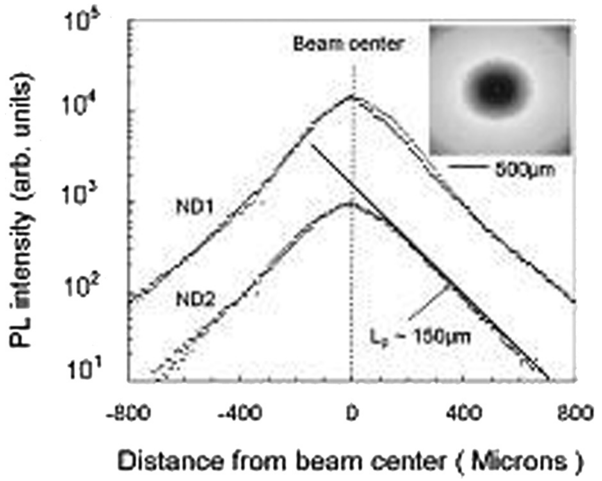

FIG. 2. Typical vertical and horizontal photoluminescence image scans taken via the beam center and measured on a layered structure of vendor 1 with ND1 and ND2 filters. The inset shows the photoluminescence image of the InGaAs layer measured with ND1 filter.

long minority hole diffusion length of the layered structures of vendor 1.

Figure 3 shows typical vertical photoluminescence image scans of the InGaAs layer via the beam center measured on the layered structure purchased from vendor 2. In this measurement, ND1, ND2, and ND0 filters were used. ND0 represents measurement without density filter. The general feature of the curves in Fig. 3 is similar to that measured on the layered structures purchased from vendor 1 (Fig. 2). In both cases, the curves measured with the ND2 filter exhibit exponential photoluminescence intensity vs. distance behavior and deviation from the exponential behavior for the higher beam intensities. The major differences in the figures are the significantly smaller InGaAs photoluminescence intensity and much smaller minority hole diffusion length of around 40 μm for the layers of vendor 2 compared to that of vendor 1 (Fig. 3 compared to Fig. 2).

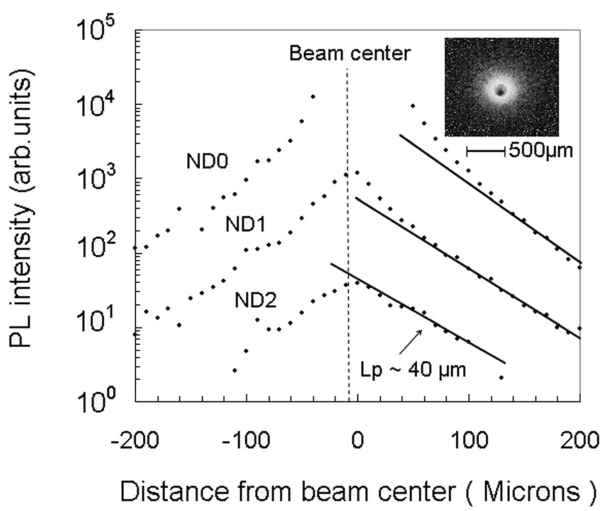

FIG. 3. Typical vertical photoluminescence image scans of the InGaAs layer taken via the beam center and measured on vendor 2 layered structure with ND1 and ND2 and ND0 filters. ND0 represents measurement without a density filter. The inset shows the photoluminescence image of the InGaAs layer measured with ND1 filter.

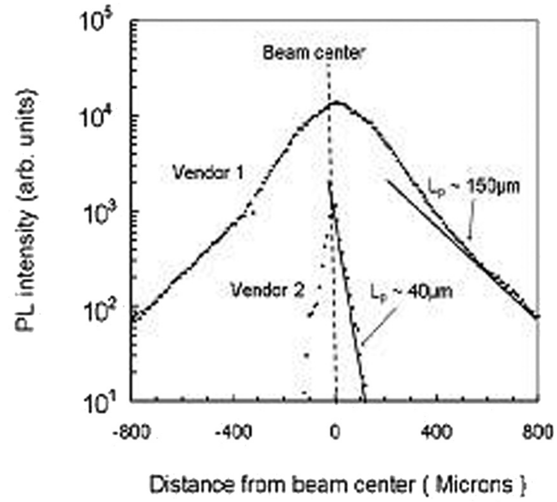

FIG. 4. Photoluminescence vertical image scans of InGaAs measured on the layered structures purchased from vendor 1 and vendor 2. The measurement was carried out using ND1 filter.

The inset in Fig. 3 shows a photoluminescence logarithmic image of InGaAs layer measured with ND1 filter on the layered structures purchased from vendor 2. Figure 4 compares the photoluminescence vertical image scans of InGaAs measured on the vendor 1 and the vendor 2 layered structures using ND1 Filter. The insets in Figures 2 and 3 and the plots in Fig. 4 provide a clear further demonstration of the above observation, namely, the significantly higher InGaAs photoluminescence intensity and much higher minority hole diffusion length for the layers of vendor 1 compared to that of vender 2.

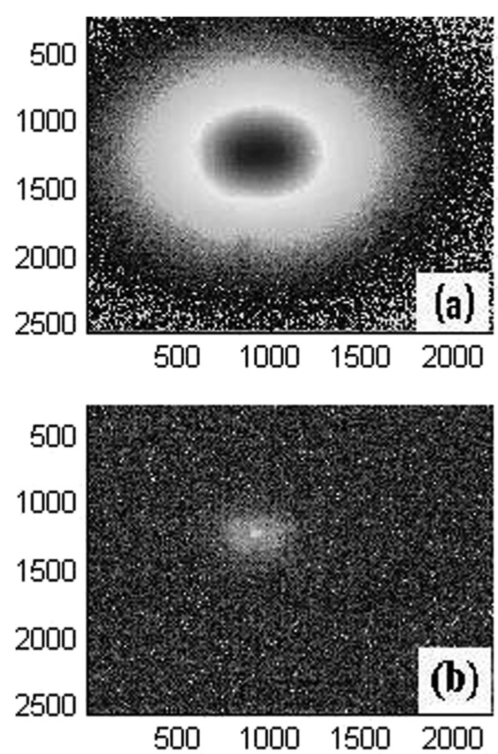

FIG. 5. Photoluminescence images of InGaAs detected on the layered structure of vendor 1 with InP cap (a) and after cap removal (b). The measurements were carried out with ND2 filter. The units in the x and y axis are microns.

Zinc-diffused p-i-n diodes were fabricated on the (n)InP(n)InGaAs(n)InP layered structures of vendors 1 and 2 and the dark current (Id) was measured and studied. Values of Id around 2×10^{-8} A/cm^2 at -0.1 V bias were found in diodes fabricated on the layered structures purchased from vendor 1. The currents, in this case, were found to be dominated by diffusion carrier transport mechanism. On the other hand, Id values as high as 3×10^{-7} A/cm^2 were found in the diodes fabricated on the layered structures of vendor 2 at the same reverse bias and the currents exhibit generation-recombination mechanism.

Finally, for further demonstration of the usefulness of the measurement technique presented here, the photoluminescence logarithmic images of InGaAs measured on the layered structure purchased from vendor 1 with InP cap (a) and after cap removal (b) are shown in Fig. 5. The measurement was carried out with ND2 filter. The units in the x axis and the y axis of the images are microns. The striking observations in the figure are the substantial reduction of the image intensity and the minority hole diffusion length due to the InP cap removal. This result clearly demonstrates the usefulness of InP for surface passivation of InGaAs.

In conclusion, this work clearly demonstrates that the photoluminescence measurement technique presented in this work provides a simple and nondestructive method for measuring minority carrier diffusion length in InGaAs semiconductor material. It is found that the value of the dark current of Zn-diffused p-i-n photodiodes fabricated on (n)InP(n)InGaAs(n)InP layered structures correlates with the value of the diffusion length. Longer diffusion length values results in lower values of dark current. With a further work, it could become a useful tool for the selection of (n)InP(n)InGaAs(n)InP layered structures prior to the InGaAs detector fabrication. The measurement technique presented here could be extended to other material systems as well.

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