

## Efficient drift dominated photodiodes using defected materials

Yanning Sun,<sup>a)</sup> Aristo Yulius, and Jerry M. Woodall  
 Yale University, Department of Electrical Engineering, 529 Becton Center, 15 Prospect St.,  
 PO Box 208284, New Haven, Connecticut 06520

(Received 28 September 2004; accepted 13 January 2005; published online 25 February 2005)

Lattice-mismatched crystal growth can result in a high density of defects, which usually degrades the performance of optoelectronic devices. We demonstrate a drift dominated photodiode, which has high responsivity even with defected material. A drift dominated InP grown on GaP substrate photodiode, with the 8% lattice mismatch, has been developed for InP on Si application. Meanwhile, a conventional *p-i-n* InP on GaP photodiode was also made as a control sample. Results show that with the same defected material, the drift dominated device has much higher quantum efficiencies than those of the *p-i-n* device, especially at short wavelengths. The internal quantum efficiencies of the drift dominated InP on GaP photodiode are higher than 70% in UV and visible region. © 2005 American Institute of Physics. [DOI: 10.1063/1.1875757]

By integrating InP photodiodes with Si, we can take advantage of the low cost and robustness of large Si substrates. Furthermore, the prospect of integrating InP optoelectronic devices with Si large-scale electronic circuits is very attractive. However, the major challenge of this strategy is the high density of defects in InP epitaxial layer grown on Si substrate, due to the 8% lattice mismatch and large difference in thermal expansion coefficient.<sup>1-3</sup> Large concentration of dislocations, which act as the recombination centers, will greatly deteriorate the performance of the InP photodiodes. We have developed InP photodiodes, whose photoactive regions have large electric fields, in order to achieve high quantum efficiencies, even with defected material. We use GaP substrate as the first step since GaP is lattice matched to Si, which could be used as a buffer layer between InP and Si later on. By directly growing InP on a GaP substrate via epitaxy, the defects in InP layers primarily result from the 8% lattice mismatch. We compared two different structures: a normal *p-i-n* structure and a drift dominated structure.

As a control sample we made a normal *n-i-p* structure of InP on a GaP substrate. The schematic layer structure is shown in Fig. 1(a). From the top, there is a 100 nm Si doped *n*-InP layer with a doping concentration of  $10^{18} \text{ cm}^{-3}$ , followed by a 250 nm undoped InP *i* layer, followed by a 500 nm Be doped *p*-InP layer with a doping concentration of  $10^{18} \text{ cm}^{-3}$ . A very thin (5 nm)  $10^{20} \text{ cm}^{-3}$  *n*<sup>++</sup>-InP layer on the surface is used for the front ohmic contact. The rest is heavily doped *p*-InP layer used for back ohmic contact. For the test sample, we designed and fabricated a drift dominated device shown in Fig. 1(b). In this structure, instead of doping uniformly, we varied the Si doping concentration in the top 100 nm layer from  $10^{20} \text{ cm}^{-3}$  at the surface to  $10^{16} \text{ cm}^{-3}$ , which results in a large electric field in the order of 10 kV/cm. After that, there is also a 250 nm undoped *i* layer which is fully depleted. Below the *i* layer there is a uniformly Be doped  $10^{18} \text{ cm}^{-3}$  100 nm *p* layer to form the graded *n*<sup>+</sup>-*i*-*p*<sup>+</sup> structure. In this layer, instead of doping concentration grading, large and uniform concentration of Be is used in order to produce a large potential difference across the intrinsic layer, and therefore, a large electric field. Below this

layer, there is a 500 nm graded doped *p* layer. The doping concentration is graded from  $10^{18}$  to  $10^{19} \text{ cm}^{-3}$ , which produces an electric field less than 1 kV/cm.

For the drift dominated InP on GaP photodiodes, minority carriers generated in the drift region, where an electric field exists, move with a large drift velocity and can get to the majority carrier side of the junction before being trapped by the recombination centers due to defects. As a result, this InP photodiode design enables the device to have high quantum efficiencies even if the material is highly defected. The *n-i-p* devices, on the other hand, are expected to have much lower quantum efficiencies, especially at short wavelengths. This is because, unlike the drift dominated device, there is no electric field in the top 100 nm layer of the *n-i-p* device. The photogenerated carriers in that region can only be collected by diffusion. In the case of InP on GaP photodiodes, most carriers generated in that region cannot be collected since the diffusion length is very small in defected materials.

Both *n-i-p* and drift dominated InP on GaP photodiodes have been fabricated and characterized. The InP epitaxial layers were grown by the solid source molecular beam

5nm, n <sup>++</sup> -InP, 10 <sup>20</sup> cm <sup>-3</sup>	100nm, n-InP, 10 <sup>20</sup> -10 <sup>16</sup> cm <sup>-3</sup>
100nm, n <sup>+</sup> -InP, 10 <sup>18</sup> cm <sup>-3</sup>	250nm, undoped-InP
250nm, undoped-InP	100nm, p <sup>+</sup> -InP, 10 <sup>18</sup> cm <sup>-3</sup>
500nm, p <sup>+</sup> -InP, 10 <sup>18</sup> cm <sup>-3</sup>	500nm, p <sup>+</sup> -InP, 10 <sup>18</sup> -10 <sup>19</sup> cm <sup>-3</sup>
1500nm, p <sup>++</sup> -InP, 10 <sup>19</sup> cm <sup>-3</sup>	1500nm, p <sup>++</sup> -InP, 10 <sup>19</sup> cm <sup>-3</sup>
10nm, p <sup>++</sup> -InP, 10 <sup>20</sup> cm <sup>-3</sup>	10nm, p <sup>++</sup> -InP, 10 <sup>20</sup> cm <sup>-3</sup>
1000nm, undoped GaP	1000nm, undoped GaP
GaP Substrate	GaP Substrate

(a) (b)

FIG. 1. Schematic layer structures of the InP on GaP photodiode: (a) a *n-i-p* structure, (b) a drift dominated structure.

<sup>a)</sup> Author to whom correspondence should be addressed; electronic mail: yanningsun@yahoo.com

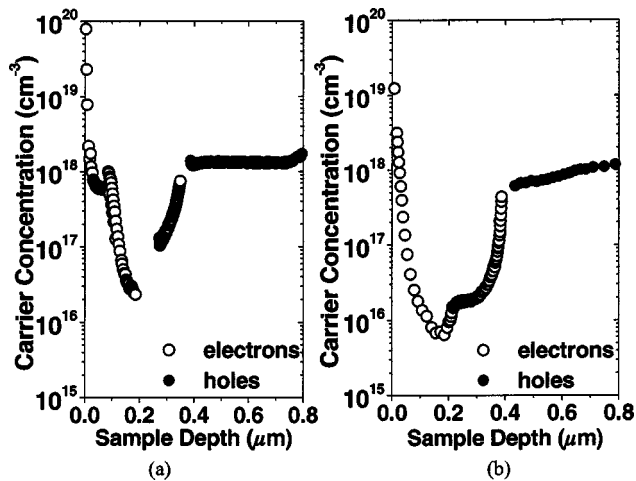


FIG. 2. Carrier concentration profile of the InP on GaP photodiode: (a) the *n-i-p* structure, (b) the drift dominated structure.

epitropy (MBE) and there was only a 1000 nm GaP buffer layer between the GaP substrate and InP epitaxial layers. Beryllium was used as the *p*-type dopant, and silicon was used as the *n*-type dopant for InP epitaxial layers. The GaP substrate was purchased and was sulfur doped *n* type with concentration around  $1 \times 10^{18} \text{ cm}^{-3}$ . The growth temperature was 430 °C. Both the *n-i-p* and the drift dominated InP on GaP devices were fabricated using the same following processing procedure. First, the wafer was etched down to the heavily doped *p*-InP contact layer using a solution of hydrochloric acid and nitric acid; then a 200 nm AuZn alloy with 5 wt% Zn was deposited and annealed at 410 °C in nitrogen for 90 s by rapid thermal annealing for *p* side ohmic contact. As-deposited Ti/Au (50 nm/150 nm) was used for front contact. The total area of the device is 25 mm<sup>2</sup>, and the front Ti/Au contact takes about 5% of the device area.

Before device fabrication, the carrier concentration profile of the InP epitaxial layers for both the *n-i-p* structure and the drift dominated structure was determined. The carrier profile is very important since the carrier concentration distribution determines the electric field distribution, and hence, the carrier collection efficiencies. We used an electrochemical *C-V* profiler to obtain the carrier concentration as a function of sample depth. The results for the *n-i-p* structure and the drift dominated structure are shown in Figs. 2(a) and 2(b), respectively. Figure 2 shows that in the top 100 nm layer, the profile of the *n-i-p* structure is different from the profile of the drift dominated structure. For the *n-i-p* structure, the electron concentration is uniform around  $10^{18} \text{ cm}^{-3}$ , while for the drift dominated structure, the electron concentration grades from  $10^{19} \text{ cm}^{-3}$  at the surface to  $10^{16} \text{ cm}^{-3}$ . These are consistent with the layer structures shown in Fig. 1. For the rest of the layers, the profiles measured are similar for both structures, which include a 250 nm fully depleted intrinsic region, and a  $10^{18} \text{ cm}^{-3}$  *p* layer. The carrier concentration profiles for both structures agree with the original design, indicating that the epilayers were successfully grown by MBE.

The quantum efficiency as a function of wavelength was determined for both structures. The results are shown in Fig. 3. For comparison, we also show the spectral response of the drift dominated InP homoepitaxy device which has ten times less dark current than that of InP on GaP devices for both

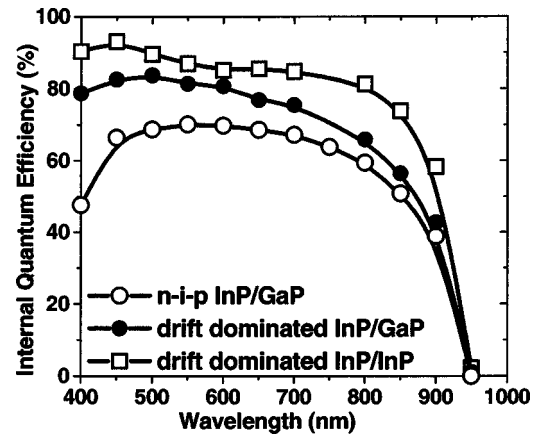


FIG. 3. Spectral response of the *n-i-p* InP on GaP, the drift dominated InP on GaP and the drift dominated InP on InP devices.

structures. Figure 3 shows that the internal quantum efficiencies for the drift dominated photodiode are higher than 70% for most wavelengths, a lot higher than the *n-i-p* photodiode, especially at short wavelengths. Compared with the drift dominated InP on InP device, the drift dominated InP on GaP photodiode only has less than 10% degradation in the visible range. There is a larger degradation at longer wavelengths since a larger portion of the illumination is absorbed outside of the high electric field region, where the photogenerated carriers are collected by diffusion, hence many carriers generated have been trapped by defects and dislocations. Based on these results, we have demonstrated that for a drift dominated device design, in which electric fields exist in the active regions and carriers are collected by drift instead of diffusion, high quantum efficiencies can be achieved even if the device contains a large concentration of defects, e.g.,  $>10^9 \text{ cm}^{-2}$  threading dislocation.

In conclusion, we have developed InP-on-GaP photodiodes as a precursor for InP-on-Si applications. We use a drift dominated structure, where carriers are collected by drift due to electric fields in the active regions. As a control sample, we also compared the performance of a normal *n-i-p* InP on GaP photodiode. Both samples were grown by MBE. The measured quantum efficiencies show that the drift dominated InP-on-GaP photodiode has an excellent spectral response, especially in UV and visible range, where we observe higher than 70% internal quantum efficiency, and only about a 10% lower efficiency compared to drift dominated InP photodiodes grown on InP substrates. The normal *n-i-p* InP-on-GaP photodiode shows more degradation in quantum efficiency, especially at short wavelengths, since at that wavelength most photons are absorbed in the top 100 nm layer, where there is no significant electric field and carriers are collected by diffusion. Based on the above results, we demonstrate the robustness of the drift dominated devices in defected material; hence, they are very promising for InP/Si applications.

<sup>1</sup>M. Kostrzewa, P. Regreny, M. P. Besland, J. L. Leclercq, G. Grenet, P. Rojo-Romeo, E. Jalaguier, P. Perreau, H. Moriceau, O. Marty, and G. Hollinger, Indium Phosphide and Related Materials, International Conference, 12–16 May 2003, pp. 325–328.

<sup>2</sup>A. Fathimulla, J. Abrahams, H. Hier, and T. Loughran, Indium Phosphide and Related Materials, Second International Conference, 23–25 April 1990, pp. 57–61.

<sup>3</sup>T. E. Crumbaker, M. J. Hafich, G. Y. Robinson, A. Davis, and J. P. Lorenzo, in Ref. 2, pp. 131–134.